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ORIGINAL

Design and Development of a Podiatric Station Prototype for the Diagnosis of Diabetic Foot

Diseño y desarrollo de un prototipo de estación podológica para el diagnóstico del pie diabético

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ABSTRACT

Diabetic foot is one of the most frequent complications of type 2 diabetes mellitus, characterized by the development of ulcers, infections, and a high risk of amputation. In Bolivia, approximately 6,5 % of the adult population lives with this condition, and progressive foot injuries are common. In response to this problem, a functional prototype of a podiatric station—named PODIATECH—was designed and developed to support early diagnosis through structural and thermal foot analysis. The system comprises two main modules: a structural module that uses a flatbed scanner to capture the plantar footprint and applies the Hernández-Corvo index; and a thermal module that uses infrared imaging to detect temperature differences associated with circulatory alterations. The entire system is managed through a web-based platform that enables patient registration, clinical record consultation, and automated report generation. During preliminary validation, ten participants were evaluated, five of whom had a confirmed diagnosis of diabetes. In four of these cases, temperature differences greater than 2 °C were detected, corresponding to clinically relevant risk zones. No significant alterations were found in healthy participants. These results suggest that the system may serve as an effective tool for early diabetic foot screening. Further clinical trials with a larger sample size are recommended to assess the system's performance and reliability in real-world settings.

Keywords: Diabetic Foot; Thermography; Plantar Footprint; Early Diagnosis; Health Technology.

RESUMEN

El pie diabético es una de las complicaciones más frecuentes de la diabetes mellitus tipo 2, caracterizada por la aparición de úlceras, infecciones y riesgo elevado de amputación. En Bolivia, aproximadamente el 6,5 % de la población adulta convive con esta enfermedad, siendo común el desarrollo progresivo de lesiones en los pies. Ante esta problemática, se diseñó y desarrolló un prototipo funcional de estación podológica denominado PODIATECH, orientado a apoyar el diagnóstico temprano mediante el análisis estructural y térmico del pie. El sistema cuenta con dos módulos principales: uno estructural, que emplea un escáner plano para capturar la huella plantar y aplicar el índice de Hernández-Corvo; y otro térmico, que utiliza imágenes infrarrojas para identificar zonas con diferencias de temperatura asociadas a alteraciones circulatorias. La gestión integral del sistema se realiza a través de una plataforma web, que permite registrar pacientes, consultar historiales clínicos y generar reportes automatizados. Durante la validación preliminar, se evaluó a diez personas, cinco de ellas con diagnóstico confirmado de diabetes. En cuatro de estos casos, se detecta ron diferencias térmicas superiores a 2 °C, coincidiendo con regiones clínicas de riesgo. En los participantes sin diagnóstico, no se identificaron alteraciones significativas. Los resultados sugieren que el sistema podría constituir una herramienta eficaz para el cribado temprano del pie diabético. Se recomienda ampliar el número de pacientes y escenarios clínicos para validar su aplicabilidad en contextos reales.

Palabras clave: Pie Diabético; Termografía; Huella Plantar; Diagnóstico Temprano; Tecnología en Salud.

INTRODUCTION

Diabetic foot is a chronic complication of type 2 diabetes mellitus that affects millions of people worldwide and is considered a leading cause of hospitalization, severe infections, and non-traumatic amputations. It is estimated that 15-25 % of diabetic patients will develop plantar ulcers at some point in their lives.[1] In Bolivia, approximately 6,5 % of the adult population has this pathology,[2] and a significant percentage of cases progress to foot lesions that, if not treated promptly, can lead to irreversible complications.

From a pathophysiological point of view, the development of diabetic foot is associated with factors such as peripheral neuropathy, ischemia due to peripheral vascular disease, and structural deformities of the foot that increase plantar pressure. These elements cause a decrease in sensitivity and venous return, preventing the patient from identifying lesions and delaying treatment initiation.[3] Added to this is the alteration of the morphology of the plantar vault, especially in patients with flat feet or pes cavus, which favors the appearance of abnormal pressure points, generating areas prone to ulceration.

The clinical diagnosis of diabetic foot is based on traditional techniques such as visual inspection, use of the Semmes-Weinstein monofilament, ankle-brachial index (ABI), and palpation of peripheral pulses. However, these tests require specialized personnel and may be insufficient for the early detection of incipient disorders. In the face of these limitations, recent research has explored complementary non-invasive technologies such as digital footprint analysis to assess foot morphology[4] and automated clinical recording and visualization systems.

In this context, developing integrated solutions combining structural and thermal analysis adapted to primary care settings and at-risk populations becomes essential for preventing complications. The main objective of this work is to design and develop a functional prototype of an automated podiatric station, PODIATECH, that is aimed at the early diagnosis of diabetic foot. The system integrates two modules: one for evaluating the plantar footprint by scanning and morphometric analysis based on the Hernandez-Corvo index and the other for thermal analysis using digitally processed infrared images. The information obtained is managed on a web platform that allows the registration of patients, the storage of clinical histories, and generating automated reports. This research aims to validate the technical and clinical utility of the developed system as a tool to support early diagnosis in patients with diabetes.

In Bolivia, technologies such as infrared thermography or static footprint analysis have not yet been systematically incorporated in Bolivian public health centers. However, their application in other countries has proven helpful in detecting early signs of ulceration. Conventional assessment usually involves lengthy procedures combining pulse palpation, sensitivity tests, and imaging studies such as Doppler or radiography, which require 30-40 minutes per patient and depend on the judgment of highly trained personnel. Given this reality, the need was identified to design an alternative system to optimize assessment times, generate quantifiable data, and support clinical decision-making through accessible and automated tools. The project is not intended to replace traditional clinical methods but as an initial screening tool to identify at-risk patients and facilitate timely referral to appropriate specialists for further diagnostic studies.

METHOD

Study design

A mixed sequential design with an exploratory approach and functional validation was used. The qualitative phase of the study began with a systematic literature review, entered into three key components: a) analysis of plantar morphology by digital scanning and processing, b) pathophysiological and clinical rationale of thermography applied to the diabetic foot, and c) developments of digital podiatric stations. This review allowed us to establish the design parameters, thermal sensitivity, required image resolution, and structural characteristics necessary for developing the prototype.

The quantitative phase focused on building the PODIATECH system, integrating it with a web platform, and validating it through structured tests on volunteer patients. This approach allowed comparing the system's results with expected clinical findings, prioritising the collection of thermographic and morphological data under controlled conditions.

System design

Hardware design

The PODIATECH system was conceived as a modular station that combines structural acquisition and thermal analysis of the foot. Its physical design prioritised stability, ease of assembly, and diagnostic accuracy.

Figure 1 shows the general structure of the system, as well as the distribution of modules and communication with the software.

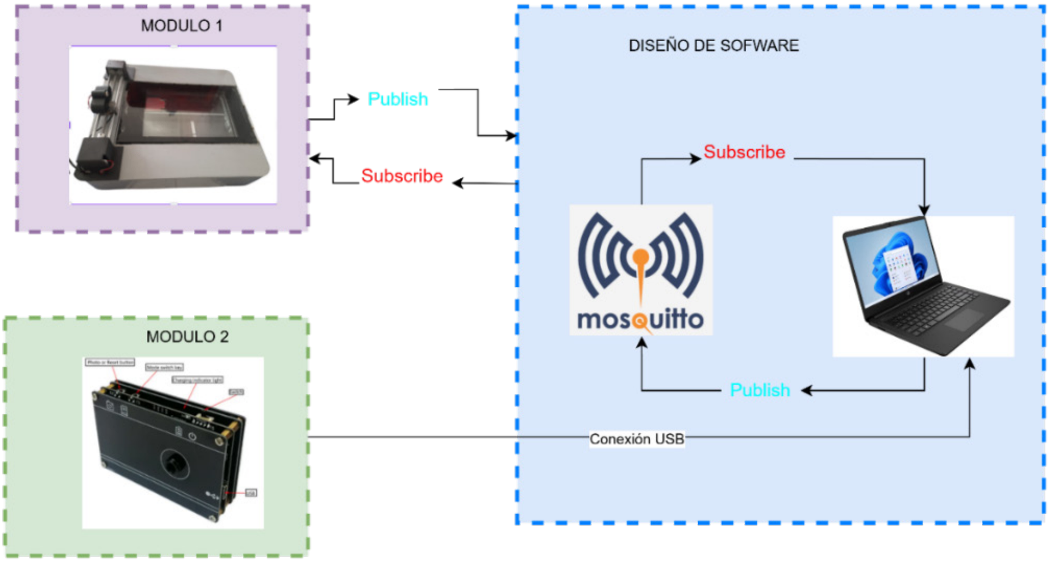

Figure 1. general structure of the system

The main structure was constructed from 1,5 cm wide and 1,5 mm thick metal tubes, welded together to form a robust frame, and covered with 0,7 mm metal sheets. A 10 mm thick (26,5 × 44,5 cm) tempered glass (26,5 × 44,5 cm) was installed on top, which allowed the capture of footprints from a Canon LiDE 100 flatbed scanner mounted on the bottom. A green LED strip was integrated around the glass to improve contrast during scanning.

For the analysis of the hindfoot, a linear displacement system consisting of smooth rods, worm gear, and a 3D-printed mobile support that housed a webcam and a laser pointer was implemented. This mechanism was driven by a NEMA 17 motor controlled by a DRV8825 driver, with instructions sent from the web interface. Its design and layout are presented in figure 2.

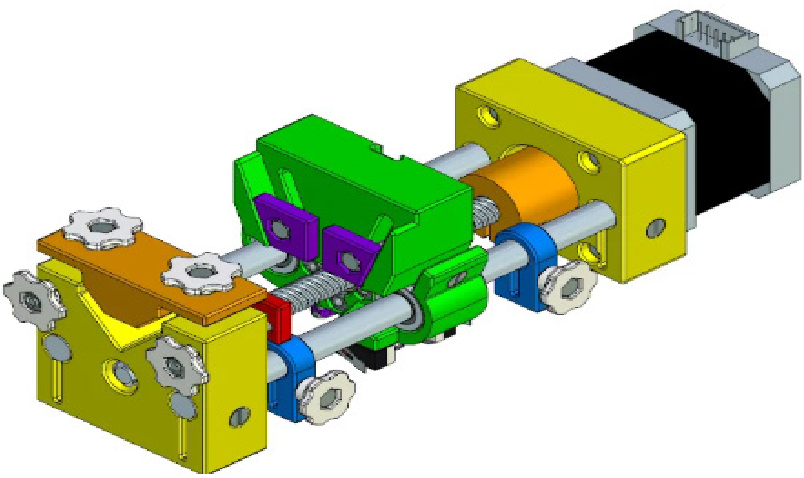

Figure 2. Engine movement mechanism

The thermal module operated independently and used an MLX90640 camera, manually manipulated 30 cm from the foot—a black acrylic plate with physical demarcations, standardized foot placement, and improved measurement repeatability.

The entire system was managed by an ESP32 DevKit v1 microcontroller, which controlled the actuators via

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MQTT protocol. IRFZ44N MOSFET transistors were used to switch power devices, and an LM2596 regulator was used to derive 5V voltages from a 12V source. A custom PCB was designed to consolidate all the components on a single compact board to integrate these elements. The circuit design can be seen in figure 3.

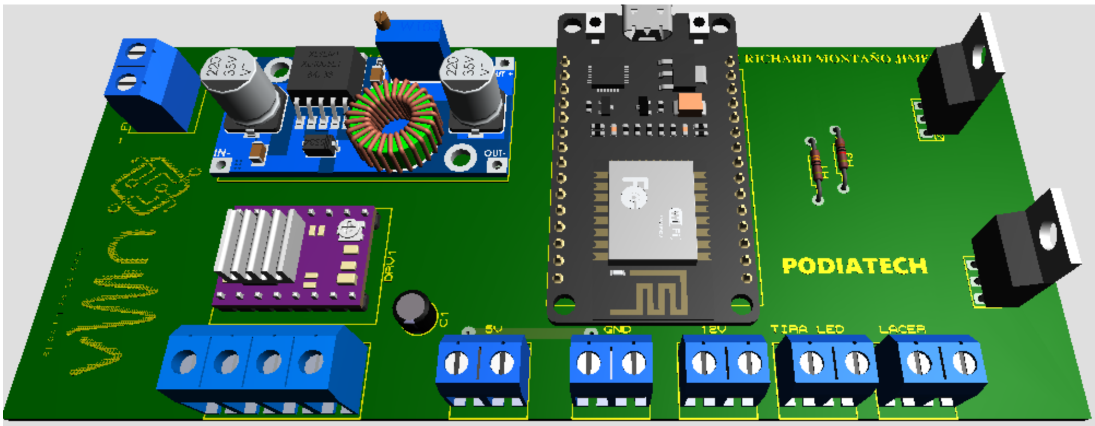


Figure 3. 3D modelling of PCB board

Software design

The software design of the PODIATECH system responded to the need to integrate, in the same platform, patient clinical management, physical device control, digital processing of structural and thermal images, and result storage and consultation. The application was conceived as a multi-platform web environment developed under a client-server architecture that allowed real-time analysis and access to clinical information from any computer connected to the local or remote network.

The software was implemented mainly in Python, using the Flask microframework for the backend logic. Standard web technologies such as HTML5, CSS3, and JavaScript were used for the front-end development, while the relational database was managed using MySQL. Additionally, the MQTT messaging protocol was used to establish efficient communication between the web application and the ESP32 microcontroller in charge of the system's physical control.

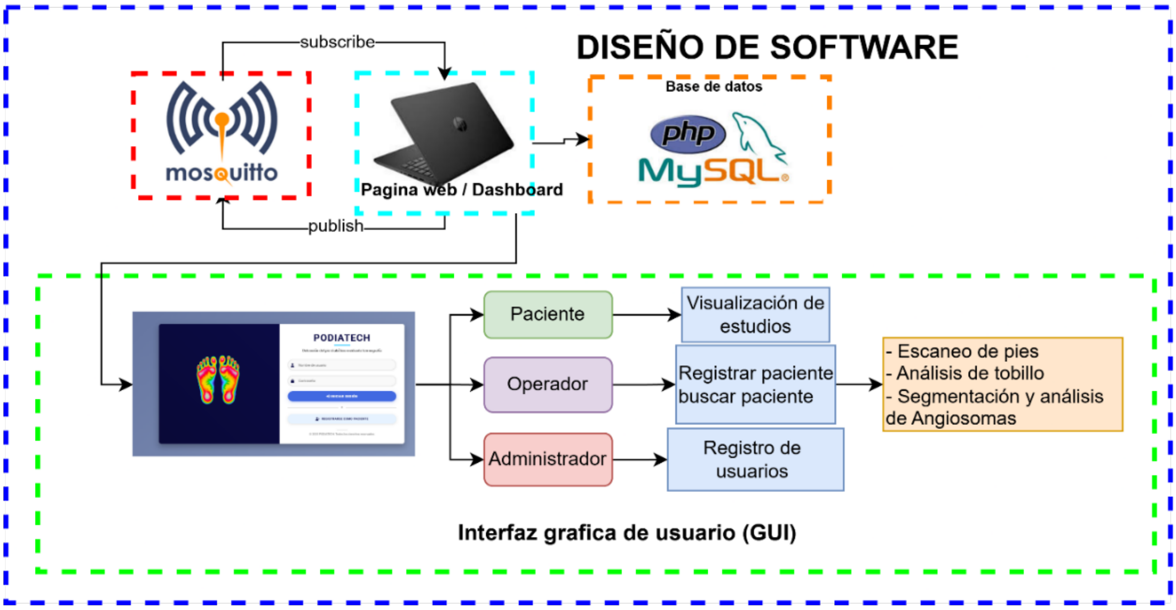


Figure 4. PODIATECH software design scheme

Digital footprint image processing algorithms

The platform also automated the image acquisition and analysis flow. The footprints were acquired using the Canon LiDE 100 scanner for the structural module, controlled from Python scripts using the comtypes library. Parameters such as 100 DPI resolution, greyscale, and JPEG format were configured to optimize the analysis. The images were converted to greyscale, binarised, and treated with morphological filters (erosion, dilation, denoising, and Gaussian smoothing). Subsequently, the operator placed four anatomical markers using a graphic interface, according to Hernández Corvo's methodology, which allowed the X (width of the metatarsal) and Y (surface of the midfoot) distances to be calculated. From these distances, the morphological index was calculated using the formula:

$$I = \frac{X-Y}{X} * 100 \qquad (1)$$

Where:
X is the width of the metatarsal.
Y is the width of the midfoot.

This value classified the foot as flat, usual, or cavus, and all generated information (processed images, diagnostic values, technical parameters) was stored in the patient's digital medical record.

The system also generated visualizations with guidelines, textual diagnosis, and graphics, ensuring a clear presentation of the results. These functions were natively integrated into the web interface, facilitating review by operators and clinicians.

The complete flow of structural foot image processing is visually summarised in figure 5.

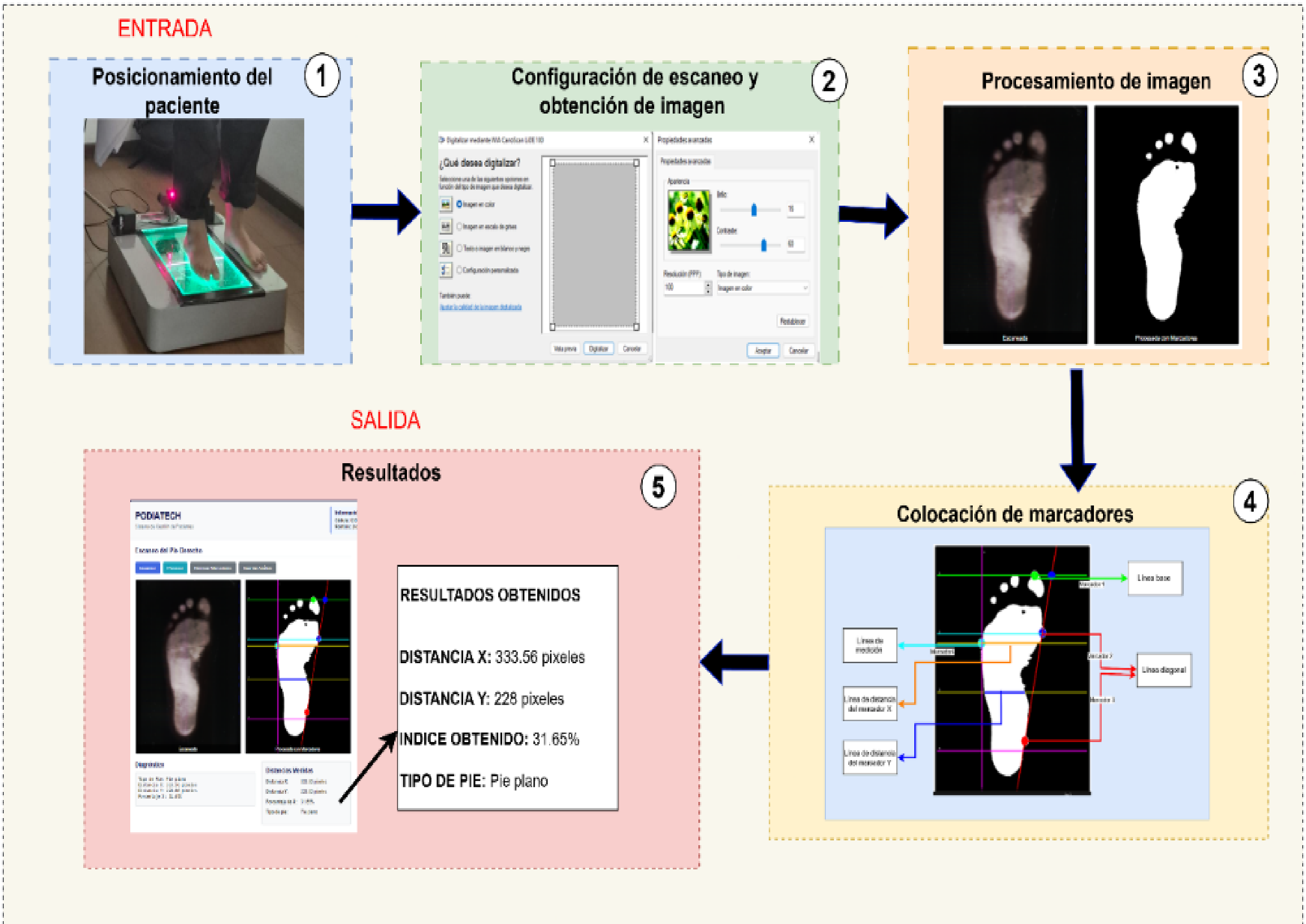


Figure 5. Flow of the structural analysis of the plantar footprint

1. Position the patient on the tempered glass surface with activated LED illumination.
2. Configuration of the scanner from the web interface to define resolution, format, and scan area.
3. Image capture and pre-processing, including greyscale conversion, thresholding, and morphological cleaning.
4. Manually place the interactive anatomical markers on the footprint, following the steps of the Hernández Corvo index.

5. Obtaining and visualization of results, including automatic calculation of X and Y distances, index value, and classification of foot type (flat, normal, cavus).

Digital processing of thermal images

Thermal images were obtained with the MLX90640 camera and manually loaded into the system in BMP format. These captures were performed under controlled light conditions, with an emissivity set to 0,98 (the standard value for human tissue) and a thermal range set between 20 °C and 50 °C.

Thermal processing started with the conversion of the image to greyscale. Then, segmentation was applied using Hamadani's method[5] based on statistical thresholding:

$$Topt = k1 \cdot \mu + k2 \cdot \sigma \qquad (2)$$

Once the binary mask was generated, the thermal matrix was reconstructed by applying the formula of Chou et al.[6]:

$$T_{REAL} = Tmin + \left[\frac{T_{gray-level}}{255}\right] * (Tmax - Tmin) \qquad (3)$$

Where:

$T_{gray-level}$: is the greyscale intensity value of the pixel.

T_{max} y T_{min}: represent the thermal range as defined by the operator (in this study, between 20 °C and 50 °C)

T_{REAL}: corresponds to the estimated temperature of the pixel in °C.The sole of the foot was divided into four angiosomal regions: MPA, LPA, MCA and LCA as shown in figure 6:

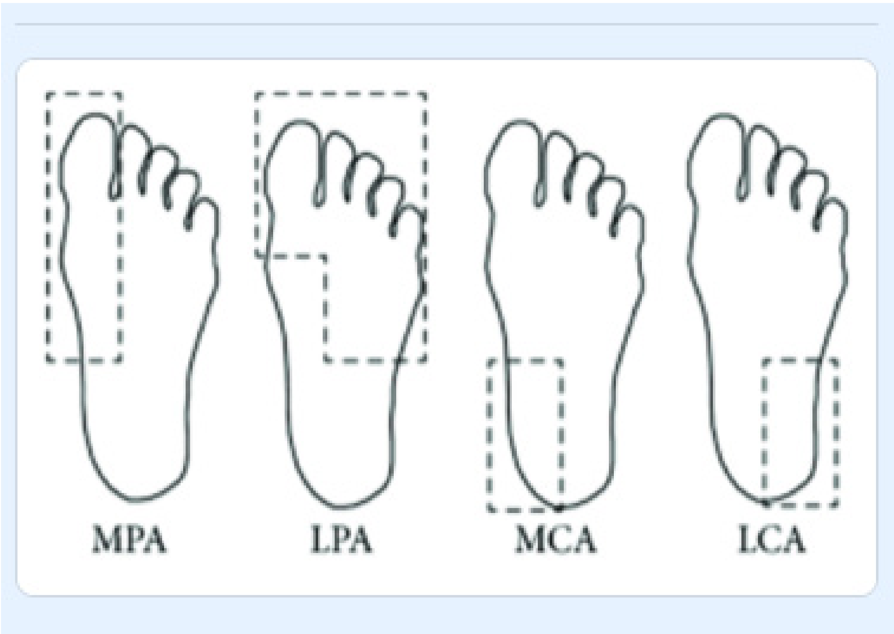


Figure 6. Angiosome segmentation

Estimated temperature (ET):

$$ET = \frac{a_{j-1}C_{j-1} + a_j C_j + a_{j+1}C_{j+1}}{a_{j-1} + a_j + a_{j+1}} \qquad (4)$$

Bilateral thermal difference (ETD):

$$ETD = | ET_{izquierda} - ET_{derecha} | \qquad (5)$$

Hot Spot Estimator (HSE):

$$HSE = \mid C_l - ET \mid \qquad (6)$$

Where:

C_l is the maximum temperature value recorded? According to Gatt et al.[7], a temperature difference greater than 2,2 °C is clinically relevant.

RESULTS

Results of the structural module

Plantar footprint images of 20 patients were processed using the Hernandez Corvo formula. The system allowed the placement of interactive markers to obtain the X and Y values and automatically calculate the morphological index. The result was classified into one of the following categories: flat foot, regular flat foot, normal, normal cavus, cavus, or extreme cavus.

Additionally, images of the hindfoot were captured with laser pointer alignment. Three markers were placed on the heel to automatically calculate the angle of inclination. These values were stored together with the processed images.

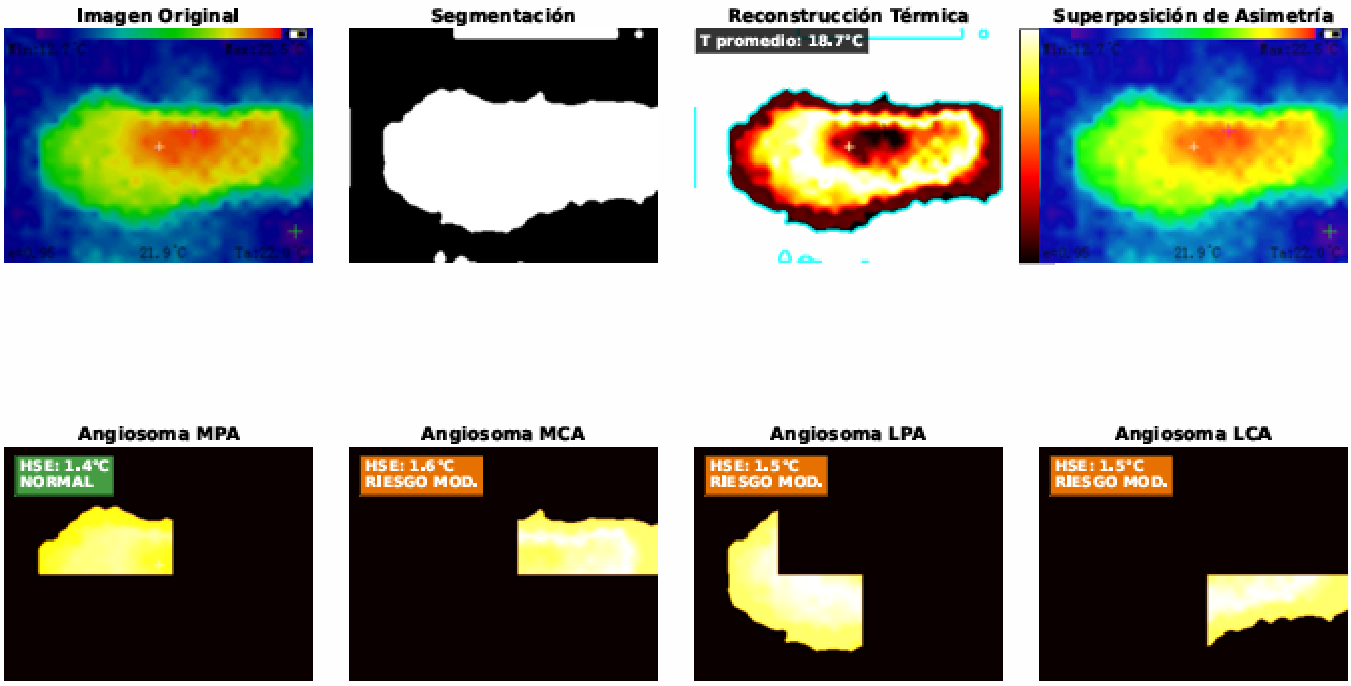
Figure 7. Evaluation of the planting footprint

Thermal modulus results

The thermal images of both feet were automatically segmented. The system calculated the following indicators:

- ET (Estimated Temperature) per angioma.
- ETD (Bilateral Thermal Difference), in °C.
- HSE (Hot Spot Estimator), detecting the difference between the hottest area and the estimated average temperature.

The results were presented per patient, with a visual representation of the segmented angiosomes, as shown in figure 8.



Resumen de Angiosomas

Angiosoma	HSE (°C)	Estado
MPA	1.4°C	OK
MCA	1.6°C	Mod
LPA	1.5°C	Mod
LCA	1.5°C	Mod

Diagnóstico General

Parámetro	Valor	Estado
Asimetría Térmica	0.0%	NORMAL
Angiosomas Riesgo	0/4	NORMAL
Temp. Promedio	18.7°C	Amb: 22.0°C
Emisividad	0.98	Configurado

Figure 8. Diagnosis of angiomas and asymmetry

DISCUSSION

The results allow us to contextualize the clinical usefulness of the PODIATECH system as a support tool in the static diagnosis of the diabetic foot. The structural module showed an agreement of 66,7 % with traditional clinical diagnoses, suggesting adequate accuracy in identifying the type of plantar arch using the Hernandez Corvo index.

As for the thermal modulus, a clear differentiation between healthy and type 2 diabetes patients was achieved, with thermal differences greater than 2,2 °C detected in 82 % of cases with diabetes. Angiosome segmentation facilitated the localization of risk areas without intensive manual intervention. However, thermal false positives were detected in 23,1 % of the healthy group, indicating the need to adjust physiological normality ranges.

The system demonstrated advantages in automation, graphical visualization, and digital traceability, although future improvements could include more accurate thermal calibration and a larger sample size to strengthen its clinical validation.

CONCLUSIONS

This study validated the performance of the PODIATECH system as a tool to support structural and thermal diagnosis of the diabetic foot. Integrating automated image acquisition and processing modules enabled a more accurate, systematic, and visually enriched clinical assessment.

In structural analysis, the system reliably classified plantar arch type from digitized images, reaching a 66,7 % agreement with traditional clinical diagnosis. This agreement shows that, despite the difference in methodologies (unimodal digital assessment versus bipedal clinical observation), the system was able to identify relevant alterations in the plantar arch.

Regarding the thermal modulus, significant thermal differences (greater than 2,2 °C) were observed in at least one of the niosomes analyzed in 82 % of patients with type 2 diabetes. Regional segmentation allowed the localization of areas of increased risk, representing a significant clinical value for the early detection of possible ulcerative foci. However, false positives were identified in healthy patients (23,1 %), indicating the need for adjustments in physiological thresholds and a larger number of cases to define more robust reference ranges.

The system demonstrated smooth operability through its web interface, facilitating prototype control, visualization of results, and secure storage of clinical records. This architecture allowed for an efficient and replicable workflow in different environments.

Finally, although it is acknowledged that the validation was limited in sample size and there were no certified clinical teams as a reference, the results allow projecting future iterations of the system oriented to an extended clinical validation and its eventual implementation in real podiatric care scenarios.

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FINANCING

None.

CONFLICT OF INTEREST

Authors declare that there is no conflict of interest.

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