AI and angiosome based analysis of diabetic foot thermal images for the diagnosis of ulcer risk

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***Abstract*—Infrared thermography holds an important place in the medical domain due to its wide usefulness in the diagnosis of several diseases, including the detection of diabetic foot problems. This paper presents a new method for classifying diabetic foot patients into risk groups for ulceration based on contralateral variations in plantar angiosomes temperatures.**

A total of 140 type II diabetic patients without ulceration or amputation were included in this study and classified into three risk groups for developing ulcers. Foot angiosomes temperatures were measured using an AI mobile application developed for this study, which employs the DE-ResUnet architecture for image segmentation and the Iterative Closest Point method for image registration. Results show that our method effectively separates medium-risk and high-risk patients for developing an ulcer with $p < 0.01$. Infrared thermography, combined with the advanced capabilities of our AI mobile application, proves to be a valuable tool for the early diagnosis and prevention of diabetic foot complications.

***Index Terms*—Diabetic foot, Thermal images, Segmentation, Registration, AI mobile health.**

I. Introduction

Diabetes is a major public health issue, imposing a significant economic burden on healthcare systems due to high medical costs and a considerable mortality rate. A serious complication of diabetes is diabetic foot, characterized by infection, ulceration, or destruction of the deep tissues of the foot, associated with neuropathy and peripheral arteriopathy of the lower limbs.

Diagnosis of diabetic foot is a difficult task due to the range of complications, which can include ulceration and total or partial amputation of the lower limbs. To improve patient management and reduce ulcer risk, specialists have adopted a classification system based on ulceration risk: patients classified as R0 (low risk) are diabetic individuals without foot issues; patients classified as R1 (moderate risk) have neurological problems; and patients classified as R2 (high risk) have arterial problems and/or neurological problems [1].

Infrared thermography is a widely used technique for the evaluation of diabetic foot. Many studies have shown a significant relationship between temperature variation and diabetic foot problems, particularly with the approach based on asymmetric analysis. This approach involves comparing the temperature of a plantar region with that of the same region on the contralateral foot. If the temperature difference exceeds a certain threshold, it may indicate a potential complication. One of the first studies in this area was conducted by Armstrong et al., who aimed to evaluate asymmetric temperature monitoring to reduce the incidence of foot complications in high-risk patients [2]. Similarly, Kaabouch et al. identified ulcerated areas by performing a symmetrical analysis of the superposed feet, calculating the difference in pixel intensity between the left and right foot to detect anomalies [3].

Matthew Carabott et al. conducted a study to compare the temperatures of three angiosomes: Hallux, Medial Forefoot, and Lateral Forefoot, between diabetic patients with and without peripheral arterial disease. A significant difference was found in the temperatures of the Medial and Lateral Forefoot angiosomes [4]. Astasio-Picado et al. demonstrated that infrared thermography can provide valuable clinical information for diagnosing patients at risk of diabetic foot complications. They were able to distinguish the temperature variations between four study areas: the 1st and 5th metatarsal heads, the heel, and the pulp of the big toe [5]. Arjaleena Ilo et al. studied temperature variations in five areas of the foot, both on the plantar and dorsal surfaces of diabetic patients' feet. This method revealed significant local temperature differences in high-risk diabetic feet [6]. D. Hernandez-Contreras et al. proposed a thermal index to measure thermal variations in four angiosomes of the foot. Based on this index, they developed a classification of thermal changes into five levels [7].

This study aimed to evaluate the potential effectiveness

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of infrared thermography in classifying diabetic patients according to their risk of ulceration. To achieve this, we employed an asymmetric angiosome analysis approach and used the maximum value of temperature differences to differentiate between the risk groups.

II. Materials and Methods:

A. Materials

The acquisition of images was performed using the FLIR ONE Pro thermal camera attached to a Samsung Galaxy S8 smartphone. The FLIR ONE Pro provides a thermal image resolution of 160x120 pixels and operates within a spectral range of 8-14 µm. It is capable of detecting temperature differences as small as 0.1°C, which is ideal for identifying subtle temperature variations. Additionally, the camera can simultaneously capture thermal and RGB images, with spatial calibration to ensure precision. Temperature measurements were recorded and analyzed using the IA mobile application, which will be described in detail later, installed on an Oppo A78 smartphone.

B. Study groups:

A total of 140 type II diabetic patients without ulceration or amputation, with a mean age of 63.19 years (54 men, 39%, and 86 women, 61%), participated in the data acquisition campaign at National Hospital Dos de Mayo in Peru and were included in this study [8]. Clinical examinations were performed by specialists to diagnose diabetic foot complications such as neuropathy and ischemia. Patients were classified into three diabetic foot risk groups: low-risk (R0, n=66), moderate-risk (R1, n=32), and high-risk (R2, n=42). Ethical approval for was obtained from the Biomedical Research Ethics Committee of National Hospital Dos de Mayo (No. 075-2021-CEIB-HNDM) on January 10, 2019.

C. Segmentation and registration process

In the context of diabetic feet, segmentation aims to isolate the foot area from the background. In our study, we employed the DE-ResUnet module developed by Doha et al. [9]. This advanced neural network architecture is specifically designed for image segmentation by integrating both thermal and RGB information. DE-ResUnet is built upon the U-Net architecture, incorporating two distinct encoders, one for thermal images and another for RGB images, that extract features from each type of input. These encoders use ResNet blocks to enhance feature extraction. The decoder reconstructs the segmented image from the encoded features, employing upsampling layers and skip connections to preserve detailed information. This design allows DE-ResUnet to leverage the strengths of U-Net's encoder-decoder structure while integrating multimodal inputs (see Fig. 1) . According to [9], this method has demonstrated significant effectiveness in thermal image segmentation.

Registration is a crucial process in image analysis where two or more images are aligned to ensure that they correspond to the same spatial coordinates. This alignment allows for accurate comparison and analysis of features across the images. In our case, after segmentation, the resulting image is divided into two separate images, one for each foot. The right foot image is used as the reference, and the left foot image is flipped vertically to match its orientation. Then, using the Iterative Closest Point (ICP) method [10], both feet are registered (see Fig. 2).

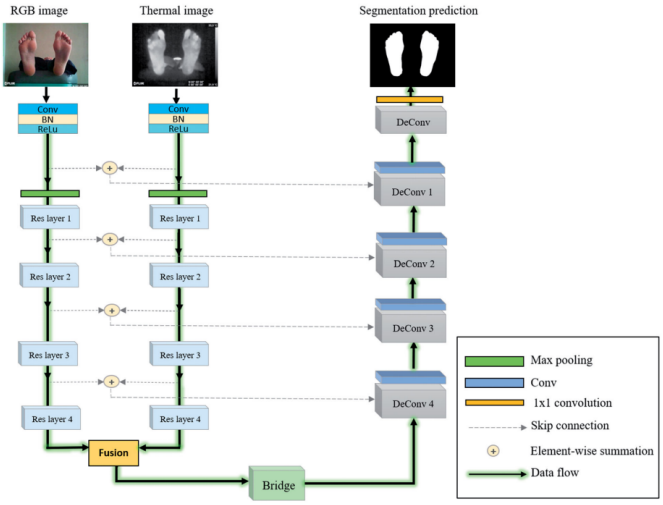

Fig. 1: The architecture of the DE-ResUnet.

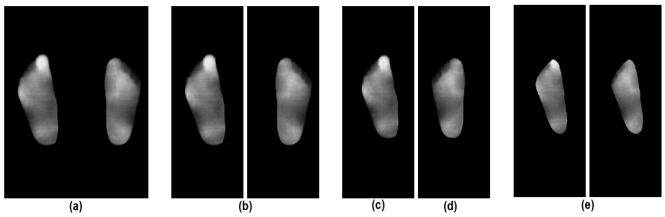

Fig. 2: ICP registration: (a) Segmented image, (b) Split images, (c) Reference image (Right foot), (d) Flipped left foot, (e) Regestred feet.

D. AI mobile application

As part of the European Standup project and to make the image acquisition and analysis process user-friendly while replicating hospital conditions, we developed an Android AI mobile application in Java that enables the segmentation and registration of the plantar regions of both feet. For segmentation, we implemented the DE-ResUnet architecture using the PyTorch Lite library, which is designed for the efficient deployment of deep learning models on mobile devices. For registration, we used ICP method to align the two feet, as detailed in Section II-C.

Once segmentation and registration are completed, we use OpenCV-Java to divide each foot into four areas of interest based on angiosome regions: Medial Plantar Artery (MPA), Lateral Plantar Artery (LPA), Medial Cuneiform Artery (MCA), and Lateral Cuneiform Artery (LCA) (see Fig. 3). We then calculate the mean temperature for each region by

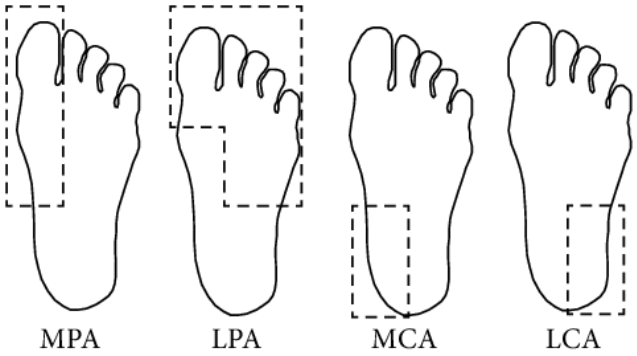

Fig. 3: Regions of interest according to angiosome.

averaging the pixel temperature values within these areas. Finally, we analyze the differences between the temperatures of the corresponding angiosomes (see Fig. 4). The image analysis process within the mobile AI application is illustrated in Fig. 5.

E. Statistical Analysis

Descriptive statistics were calculated, with the arithmetic mean used as a measure of central tendency and the standard deviation as a measure of dispersion. An ANOVA test was employed to assess the significance of differences between the three ulceration risk groups: low-risk (R0, n=66), moderate-risk (R1, n=32), and high-risk (R2, n=42). An independent samples t-test was used to determine the significance of differences between each pair of groups or between the combination of two groups compared to the third group. In all cases, the significance level for all tests was set at $p < 0.05$.

III. Results

From Table I, we observe that the mean temperatures of both feet are higher in the R1 group (RF: 28.57°C, LF: 28.49°C) compared to the other two groups, R0 (RF: 27.70°C, LF: 27.67°C) and R2 (RF: 27.87°C, LF: 27.72°C). This finding was previously demonstrated in the study conducted by Bagavathiappan et al. [11]. Furthermore, the mean temperatures of all angiosomes, both left and right, are also higher in the R1 group compared to the R0 and R2 groups. The contralateral temperature difference between angiosomes is, on average, higher for the R2 group (MPA: 0.41°C, LPA: 0.43°C, MCA: 0.54°C, LCA: 0.62°C) compared to the R0 group (MPA: 0.36°C, LPA: 0.39°C, MCA: 0.37°C, LCA: 0.50°C) and the R1 group (MPA: 0.28°C, LPA: 0.26°C, MCA: 0.36°C, LCA: 0.39°C). Additionally, we observe that the three groups have higher temperature differences on average in the LCA region compared to the other angiosomes (R0: 0.50°C, R1: 0.39°C, R2: 0.62°C), as shown in Table II.

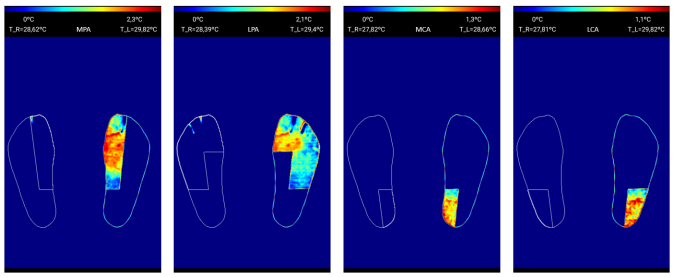

Fig. 4: Mean temperature results of the angiosome regions.

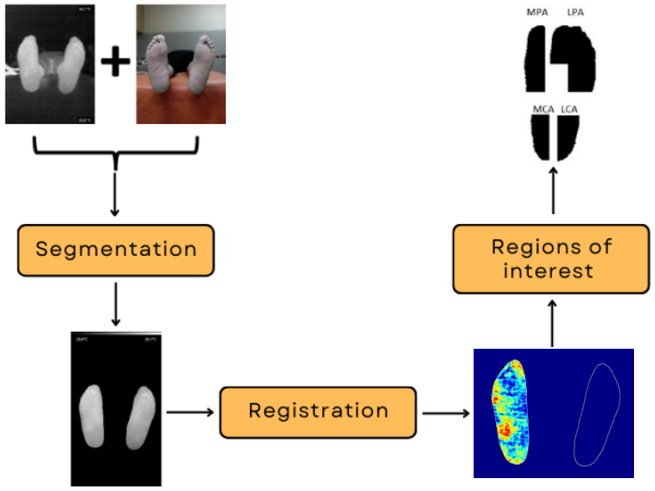

Fig. 5: Image analysis process in the mobile AI application.

Looking at the maximum temperature difference between the contralateral angiosomes, we observe an increase in the R2 group compared to the R0 group, with $p < 0.1$, and a significantly larger increase compared to the R1 group, with $p < 0.01$. When combining the R0 and R1 groups (non-ischemic patients) into a single group and comparing it to the R2 group (ischemic patients), we find that this temperature difference is significantly higher for the ischemic group, with $p < 0.05$, as shown in Table III.

These results indicate that thermal measurements can aid in the diagnosis of diabetic foot and provide indicators for distinguishing between risk groups.

IV. Conclusion and Perspectives

The AI approach of asymmetric temperature analysis of angiosomes studied in this paper shows good agreement in separating medium-risk and high-risk patients for developing an ulcer with $p < 0.01$. This could be of great interest to physicians in clinical decision-making concerning the diabetic foot, as well as in reducing complications associated with this serious disease. Results show that the maximum temperature differences of contralateral angiosomes are lower in the R1 group, whereas they are significantly higher in the R2 high-risk group. As future perspectives, demonstrating that this thermal analysis based on contralateral variations in plantar angiosome temperatures using an AI mobile application could assist doctors in hospitals or medical centers in achieving a better diagnosis of diabetic foot would be interesting. Additionally, the results should be tested on diverse populations to ensure the approach is broadly applicable.

TABLE I: Mean temperatures of the study areas among the three risk groups (°C).

	Site of measurement	low risk group mean (SD)	moderate risk group mean (SD)	high risk group mean (SD)
Right foot	general	27.70 (1.81)	28.57 (2.23)	27.87 (2.22)
	Medial Plantar Artery (MPA)	27.95 (1.80)	28.76 (2.25)	28.15 (2.22)
	Lateral Plantar Artery (LPA)	27.89 (1.88)	28.75 (2.30)	28.13 (2.26)
	Medial Cuneiform Artery (MCA)	27.75 (1.82)	28.65 (2.21)	27.78 (2.26)
	Lateral Cuneiform Artery (LCA)	27.69 (1.84)	28.66 (2.21)	27.84 (2.29)
Left foot	general	27.67 (1.87)	28.49 (2.20)	27.72 (2.30)
	Medial Plantar Artery (MPA)	27.92 (1.89)	28.73 (2.26)	28.05 (2.26)
	Lateral Plantar Artery (LPA)	27.8 (1.97)	28.60 (2.28)	27.88 (2.33)
	Medial Cuneiform Artery (MCA)	27.74 (1.90)	28.58 (2.19)	27.63 (2.35)
	Lateral Cuneiform Artery (LCA)	27.95 (1.89)	28.75 (2.26)	28.04 (2.30)

TABLE II: Mean contralateral temperature differences of the study areas among the three risk groups (°C).

Site of measurement	low risk group mean (SD)	moderate risk group mean (SD)	high risk group mean (SD)	p-value (ANOVA)
Medial Plantar Artery (MPA)	0.36 (0.3)	0.28 (0.24)	0.41 (0.40)	0.24
Lateral Plantar Artery (LPA)	0.39 (0.40)	0.26 (0.24)	0.43 (0.42)	0.12
Medial Cuneiform Artery (MCA)	0.37 (0.45)	0.36 (0.34)	0.54 (0.59)	0.16
Lateral Cuneiform Artery (LCA)	0.50 (0.40)	0.39 (0.45)	0.62 (0.56)	0.10
Max diff	**0.68 (0.44)**	**0.54 (0.40)**	**0.87 (0.64)**	**0.018**

Max diff : the maximum temperature difference.

TABLE III: P-value associated with the Max diff argument.

Groups to compare	Max Diff p-value
R0, R1	0.140
R0, R2	0.089
R2, R1	**0.008**
R0, R1 $\cup$ R2	0.539
R2, R0 $\cup$ R1	**0.031**

R1 $\cup$ R2: Ischemic and/or Neuropathic.
R0 $\cup$ R1: Non-ischemic.

DECLARATIONS

Disclosure statement:

The authors declare that there are no potential conflicts of interest.

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