A Cost-effective Infrared Thermographic System for Diabetic Foot Screening

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***Abstract*—According to the World Health Organization (WHO), Diabetes Mellitus (DM) is one of the most prevalent diseases in the world. Recent data reveals that the global prevalence of diabetes in 2021 was 537 million people, among adults between 20 and 79. Moreover, half of the patients with diabetes are unaware of their condition and, consequently, are more tending to develop diabetes-related complications. One of the most common complications among patients with diabetes is diabetic foot disease. Diabetic foot disease has been defined as the presence of foot ulcers associated with diabetic neuropathy that, in the most severe cases, can lead to amputation. To prevent this, early detection and treatment of foot ulcers are paramount. Recent studies reveal that regular foot inspection using infrared thermography can help patients detect signs of ulcers in their early stages. In this context, this work aims to develop a cost-effective infrared thermographic system to help patients inspect their feet to detect signs of future ulcers. To that end, we propose a device comprising a low-cost thermal camera connected to a Raspberry Pi to monitor the foot and early detection of lower limb ulceration. The proposed device can detect zones with temperature differences of about 2.2 ºC within the foot and classify them as suspected to be an ulcer.**

***Index Terms*—Diabetic Foot Screening, Infrared Thermography Inspection, Telehealth.**

I. Introduction

Diabetes Mellitus (DM) is called the silent epidemic. Indeed, the global prevalence of diabetes in 2021 was 537 million people, among adults between the ages of 20 and 79. Moreover, by 2030, this number is expected to be 643 million and about 783 million by 2045. Worse still, diabetes was responsible for 6.7 million deaths worldwide in 2021 [1]. In Portugal, the scenario is also of great concern. In 2018 the estimated prevalence of DM in the Portuguese population aged between 20 and 79 years (i.e., about 7.7 million individuals) was 13.6%, meaning that more than 1 million Portuguese in this age group has diabetes [2].

Diabetes Mellitus is a metabolic disease characterized by chronic hyperglycemia, i.e., high blood sugar levels. Chronic hyperglycemia is associated with long-term complications resulting from the damage or failure of several organs. The most common include retinopathy, nephropathy, and peripheral neuropathy. In its turn, peripheral neuropathy can lead to foot ulcers known as Diabetic Foot Disease (DFD) [3]. DFD is the most frequent diabetes-related complication, affecting 15 to 25% of patients with DM [4]. Moreover, in the most extreme scenarios, DFD can lead to the amputation of the affected limbs, imposing traumatic consequences on patients [5]. Indeed, DFD is not only the most traumatic but also the most costly of all diabetes-specific complications [6]. However, early detection of signs indicating a developing ulcer can prevent or delay foot ulceration, improving the patient's quality of life and reducing treatment costs [7]. Therefore, foot inspection for early detection of ulcers is vital.

Recent studies indicate that regular foot inspection using infrared thermography can help detect ulcer development [7]. In this context, this work aims to develop a cost-effective infrared thermographic system to help patients inspect their feet. To that end, we propose a device comprising a low-cost thermal camera, the FLIR Lepton 2.5, connected to a Raspberry Pi to scan the foot and identify signs of possible ulcer development. The proposed device uses thresholding techniques to detect zones with temperature differences of about 2.2 ºC within the foot and classify them as suspected to be an ulcer [7].

The remainder of this paper is organized as follows, section II investigates related works focusing on infrared thermography for early detection of signs indicating ulcer development. Section III provides precise information regarding the proposed system. Section IV presents the assessment procedure and discusses the results obtained. Finally, Section V presents the conclusions and future work.

II. Related Work

Complications related to DFD, such as amputations, can be avoided or delayed if treated early. Therefore, patients must assess risk factors as early as possible regularly. Nowadays, technology plays a role in interventions for the early detection of DFD in DM patients. Instrumented footwear, connected to a data acquisition system, has been used to assess foot pressure and detect risk factors. Unfortunately, patients cannot use this technology without the assistance of a healthcare professional. Alternatively, interventions using temperature monitoring to assess the foot temperature profile and detect changes indicating a possible ulcer development are starting to be widely used and accepted by medical personnel. Moreover, patients can use this technology for self-assessment in any place at any time, making DFD assessment easier [7]. Nevertheless, to promote the mass

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use of this technology, it must be sufficiently accurate and at a low-cost.

Three temperature monitoring technologies have been developed and are available as commercial products for the early detection of DFD complications, two of which have had experimental clinical application [8]. The technologies are infrared thermometer scanning, liquid crystal thermography, and temperature sensors integrated into a weighing scale [9]. In addition, this work aims to study the use of low-cost infrared thermographic systems to assess foot temperature for early detection of DFD complications. In comparison to liquid crystal thermography, Infrared Thermography (IRT) has the advantage of being a non-invasive technology with the possibility of automatic analysis [10], [11]. Thermometers, despite their low-cost, have the disadvantages of low spatial resolution (n.b., the temperature is measured only at selected individual points), the need for patients to perform the measurement themselves and lack of automatic analysis options [12]. Although IRT is one of the most promising technologies for performing DFD assessment and prevention, more studies are needed to validate it. In particular, regarding the use of low-cost devices [7], [8].

IRT systems allow for the assessment of the temperature profile of the foot through the acquisition of thermal images based on the heat emitted by the foot. The detection of temperature gradients of at least 2.2 ºC indicates the possibility of ulcer development. Further, IRT systems allow for visualization of the temperature profile of the foot, highlighting the zones identified as suspected to develop an ulcer. Another relevant utility of using ITR is that it can measure the temperature distribution of any surface, regardless of its shape [7], [10], [11].

Different approaches to using IRT for DFD risk assessment are available in the literature. Fraiwan *et al.* [10], propose a smartphone-based system comprising an IRT camera, the FLIR ONE PRO, connected to a smartphone. The proposed mobile thermal imaging system successfully identified the locations with a temperature increase of 2.2 ºC, indicating the possibility of ulcer development. The authors claim that their system may give DM patients the ability for regular self-assessment of DFD complications.

Maldonado *et al.* [13], proposes a more sophisticated IRT camera, the FLUKE TI32, to detect risk zones in DFD patients. The risk zones include temperature increments to find possible ulcers and decrements to identify necrosis. The system operates in a non-controlled environment without room temperature control and a non-homogeneous background. The authors also highlight that patients can use the system for self-assessment without the help of healthcare professionals.

Table I shows some characteristics of the IRT cameras used by Fraiwan and Maldonado. As found previously, the technical capabilities of these cameras allow them to identify DFD complications in its early stages. However, since the main objective of this work is to develop a low-cost thermographic system to reach as many people as possible, the FLIR Lepton 2.5 was included and will be used on this work.

TABLE I: IR Thermal Camera Characteristics.

Camera	Resolution	FOV	Range (ºC)	Price (€)
FLIR Lepton 2.5	80 x 60	50º	-10 to 140	130
FLIR ONE PRO [10]	160 x 120	50º	-20 to 120	409
FLUKE TI32 [13]	320 x 240	46º	-20 to 600	1100

As shown in Table I, the most relevant differences between these three cameras are the image resolution and the price. Therefore, the technological challenge of this work is to demonstrate that the image resolution of the FLIR Lepton 2.5 allows the early detection of ulcers development in DFD patients.

III. Proposed System

For the implementation of the proposed system, a low-cost infrared thermal sensor has been considered for the acquisition of thermographic images. Each acquired image is then analyzed and processed using image processing techniques with the main goal of detecting temperature variations, in a specific foot, above 2.2 ºC. This variation represents the temperature difference that enables the development of foot ulcers in diabetic patients. To analyze the results, the images were processed and segmented according to the algorithm that will be presented in the subsections below. Figure 1 depicts the block diagram of the evaluation system that has been considered in image acquisition. The system takes advantage of a IR thermal imaging system to collect IR foot images that are then transmitted to a laptop computer for further image processing.

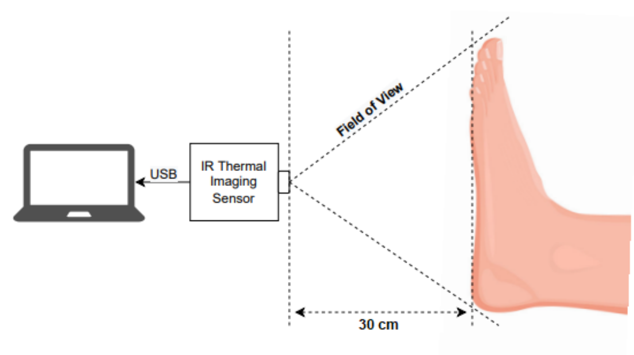


Fig. 1: Block diagram of the evaluation setup.

A. Materials

For thermal image acquisition, a PureThermal 2 dev board equipped with a FLIR Lepton 2.5 sensor has been used. The thermal image acquisition system is then connected via USB to a Raspberry Pi and interfaced with the Lepton SDK [14]. As mentioned in Table I, the FLIR Lepton 2.5 camera is a long-wave infrared (LWIR) camera with radiometric capability and a resolution of 80×60 pixels with a Field Of View (FOV) of 50º. It can produce a factory-calibrated temperature value for all the 4800 pixels present in a frame, with an accuracy of +/-5 ºC and features a thermal sensitivity of 50 mK [14].

B. Methods

Image segmentation aims to extract certain objects from the original image. In the followed approach, the image segmentation technique has been used twice, the first has been used to extract the object of interest from the thermal image, which is the foot, while in the second segmentation, the zones of possible diabetic foot ulcer are extracted. This segmentation technique, known as thresholding, is here used to perform the background extraction. Once the background is removed from the image, leaving this way only the area of interest for the analysis, another threshold is applied to the pixels formed by the foot plant, which in turn becomes the background of the image, and the areas of interest to extract, become the areas of possible ulcer development. Then, several tests are performed to verify if the difference between the foreground (suspected ulcer) and background (diabetic feet) is greater than 2.2 °C. If the difference is greater than 2.2 °C, then the foreground region is considered a possible ulcer location.

Another technique that can be applied for the detection of possible ulcers is called point-to-point temperature difference [13]. In this technique, the pixel-by-pixel temperature difference of each of the feet is computed. The image processing includes both feet and is automatically divided into two parts: one part being the left foot and another part being the right foot. During the image acquisition, people are informed that they should keep their feet in the center of the camera's FOV for increased accuracy. After this, one foot is chosen to be the reference. During this technique, it is necessary that both feet become aligned, and then two steps are applied: 1) mirroring both feet so that it is identical to the reference foot; 2) image registration is performed, which consists of aligning both feet together. Image registration allows both feet to be spatially aligned, corresponding to each other. The result will be the difference between the right and left foot, and the position of the pixel where the temperature difference is greater than 2.2 °C will represent the areas identified as possible areas of ulcer formation.

The testing and classification process begins with the image acquisition phase, followed by the segmentation phase. The thermal images were taken from people with healthy feet, so to simulate the presence of an ulcer, a coin has been heated and placed against the foot to transfer heat and consequently increase the temperature of a specific foot area. This procedure was used based on the study conducted by Fraiwan *et al.* [10], [15]. Due to the low resolution of the camera, an image of each foot has been acquired separately, which makes it impossible to implement the point-to-point temperature difference technique. Using the method of average temperature difference by zones, which will be the method under study, the average temperature of the foot plant and the average temperature of the suspicious zones have been computed. After these calculations, the difference in these temperatures has been computed and, finally, the results analyzed.

C. Thermal imaging acquisition

The images were acquired and stored locally on the computer with radiometric values. The goal was to capture an image of the foot plant, and, for this, an initial procedure has been considered. The procedure consisted in asking the person to remove their shoes and socks and then remain seated or in a supine position for fifteen minutes so that the results would be as viable as possible. In addition, it was also necessary to regulate the temperature of the place where the images were acquired to reduce environmental artifacts and thus not compromise the segmentation of the images. The system evaluation has been performed with healthy people, therefore, to simulate a temperature increase of more than 2.2 °C, a heated coin was used and pressed against the person's foot.

D. Thermal imaging processing algorithm

The image processing chain was developed with OpenCV, the Lepton SDK, and the libraries Numpy and Matplotlib for computing and image visualization. Figure 2 shows the complete processing chain, from thermal image acquisition to image processing. After thermal image acquisition, the radiometric values have been extracted and converted to an 8-bit grayscale image, where the pixel values ranged from 0 to 255. Values close to zero represent the lowest temperatures in the radiometric data, and values near 255 represent the highest temperatures. On the grayscale images, the Binary Thresholding technique was applied.

Then the average value of the grayscale image is used to define a dynamic threshold. After a threshold value is computed, the image processing algorithm moves to the next stage. If the pixel value is lower than the threshold, the value becomes 0, if the value is above the defined threshold, the value in question becomes the maximum, in this case, 255 [16]. With this, it was possible to perform the proper segmentation and thus extract the results of the foot zone. To make the segmentation of the hottest zones, another higher threshold value was applied, close to the hotter zones that were set manually, to the already segmented gray image. To eliminate undesirable values in the implemented segmentation, a smoothing technique was applied, which is a digital image processing technique that reduces and suppresses image noise [17]. Since the radiometric values from the Lepton 2.5 camera are expressed in centiKelvin, T_K, it was necessary to convert them to degrees Celsius, T_C, using Equation 1:

$$T_C = \frac{T_K - 27315}{100} \text{ ºC} \tag{1}$$

Temperatures in the foot plant (already segmented area) and in the suspect areas (warmer foot area) were averaged. Finally, a comparison was made for each of the zones: if the value of the suspected zones exceeded the average temperature foot value

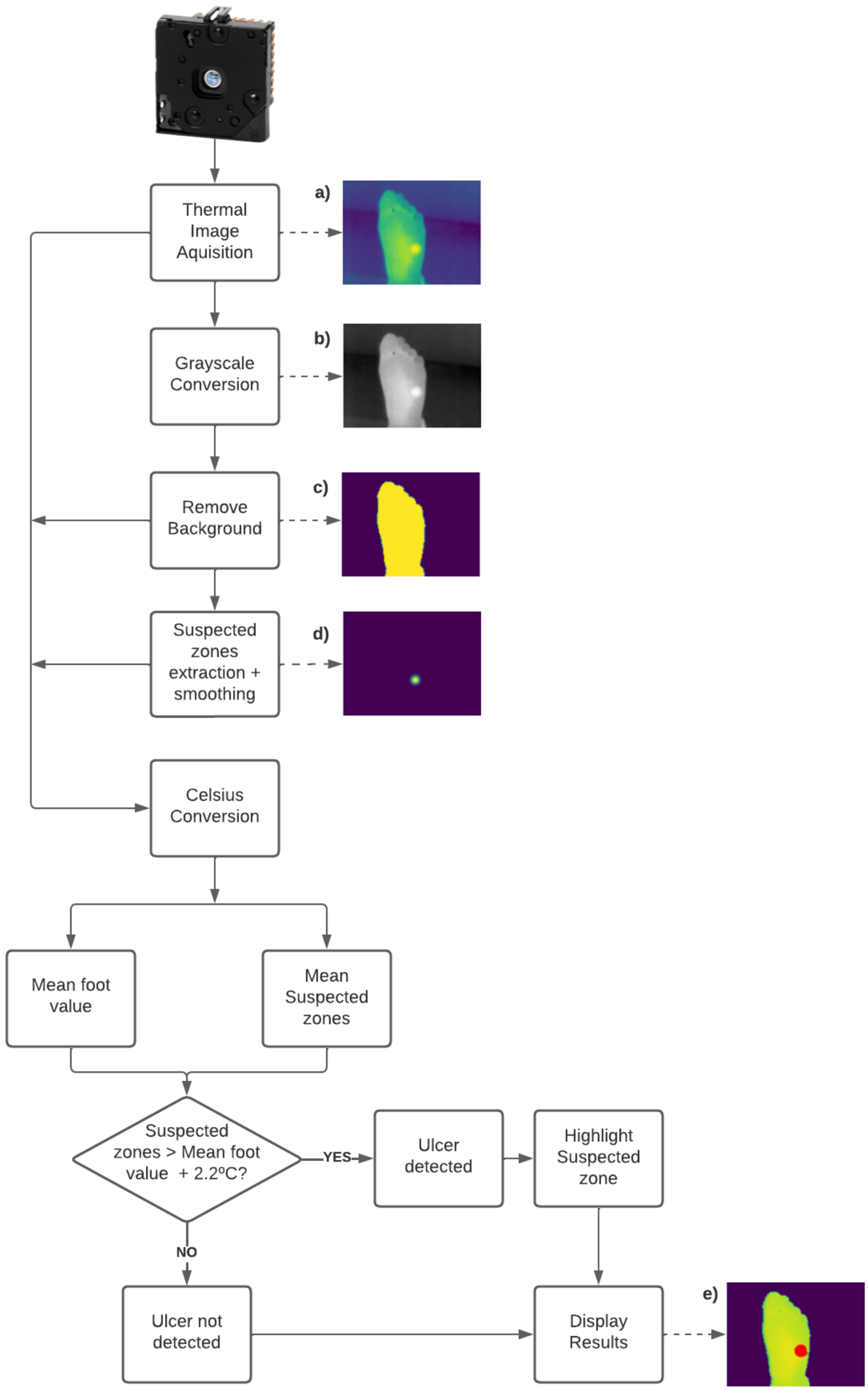


Fig. 2: Proposed algorithm flowgraph. **a)** Thermal image acquired. **b)** Grayscaled image. **c)** Mask extraction. **d)** Suspected zone extraction. **e)** Segmented foot with suspected zone highlighted.

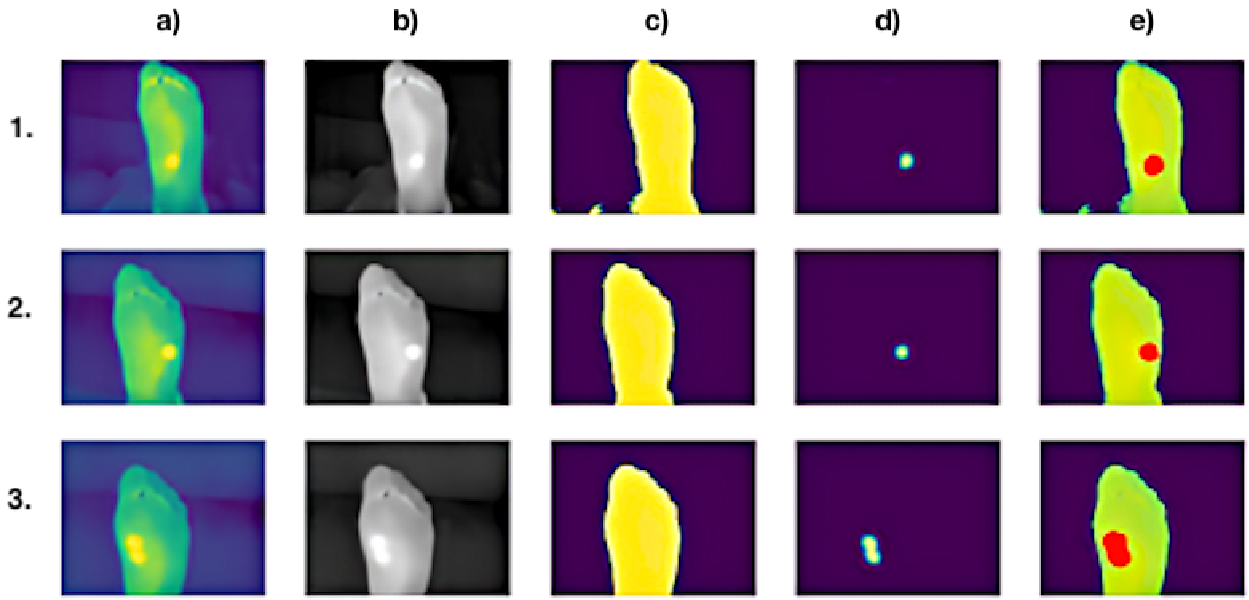
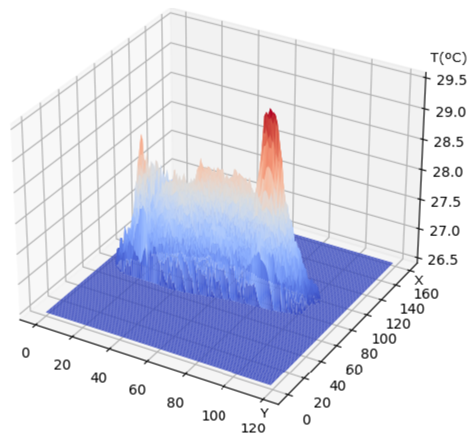


Fig. 3: Three image processing output examples according to the algorithm presented in Figure 2.

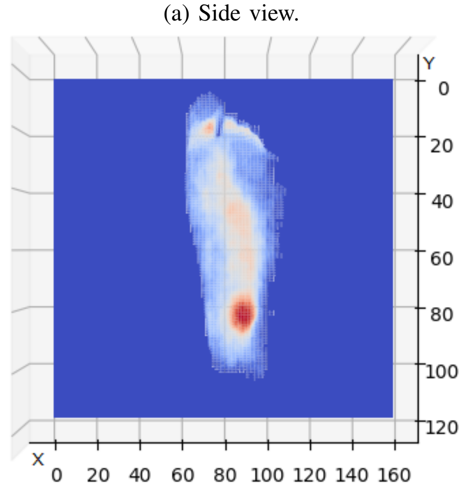
(greater than 2.2 ºC), they were marked in red and represented as suspicious to be available in the final images of the sole of the foot visualized.

IV. System Evaluation

The results were obtained through several views of the foot with the help of the segmented images shown in Fig. 3. The temperature difference is visualized by the color change, if the hottest region of the foot shows red color, it means that the temperature difference is greater than 2.2 ºC and the algorithm selects this region as a suspected ulcer. Due to the resolution of the camera, it was decided to separate the algorithm to take pictures of one foot at a time for better visualization of the results. To better visualize the algorithm output, results are presented in 3D graphics, cf. Fig 4, which relate the position of the pixel and the respective temperature, being possible to distinguish the peaks of higher temperature, which correspond to the hottest regions in the foot plant (zones in red), from the parallel plane that represents the average temperature of the foot. With these values, it was possible to produce Table II, where the mean values of the foot temperature and the average temperature values of the suspect zones are computed from the images presented in Figure 3.



(a) Side view.



(b) Upper view.

Fig. 4: 3D graphics corresponding to Fig. 3a.

TABLE II: Comparison of foot temperatures in Figure 3.

Figure	Foot Sole Mean Temperature (ºC)	Suspected Region Mean Temperature(ºC)	Mean Difference (ºC)
2 a)	26.47	29.15	2.68
2 b)	27.80	30.27	2.47
2 c)	26.52	29.32	2.80

The main goal of this work was to evaluate if low-cost IR thermal cameras could be used to detect small temperature differences for diabetic foot screening. This proposal incorporates the camera part, as well as the techniques necessary for image processing and interpretation of results. Based on the results obtained, this system was able to identify areas with a temperature gradient greater than 2.2 ºC which are known to have higher probability of evolving to ulcers in diabetic patients.

V. Conclusion and Future Work

Diabetes Mellitus is a metabolic having several long-term complications associated. Diabetic foot is one of the most expensive and traumatic complications, causing disability and impairing the quality of life. Thus, early detection of foot ulcers and proper medical treatments can avoid such overwhelming consequences. This work proposes a methodology for diabetic foot monitoring using low-cost infrared cameras. It is important to remember that this system is not a diagnostic tool but only an indicator to identify regions of possible ulcer development. The patient should always consult a healthcare professional to obtain a proper diagnosis and treatment. Further work will require testing and validation of the proposed system in patients on a clinical environment, as in this work, all tests were simulated.

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