Detection of Diabetic Foot Hyperthermia by Infrared Imaging

L. Vilcahuaman, R. Harba, R. Canals, M. Zequera, C. Wilches, M.T. Arista, L. Torres and H. Arbañil

Abstract— **In diabetic foot, the occurrence of an ulcer is often associated with hyperthermia. Hyperthermia is defined as a temperature greater than 2.2ºC in a given region of one of the foot compared to the temperature of the same region of the contralateral foot. Unfortunately, hyperthermia is not yet assessed in current diabetic foot therapy. In this paper, we propose an easy way to detect a possible hyperthermia by using an infrared camera. A specific acquisition protocol of the thermal images is proposed. A dedicated image analysis is developed: it is composed of a contour detection of the 2 feet using the Chan and Vese active contour method associated to the ICP rigid registration technique. Among 85 type II diabetes persons recruited in the Dos de Mayo hospital in Lima, Peru, 9 individuals show significant hyperthermia. It is expected that the new possibility of detecting hyperthermia in hospitals or in diabetic health centers which is now available, thanks to the proposed method, will help in reducing foot ulcer occurrence for diabetic persons.**

I. Introduction

Diabetes is a major public health problem that mainly concerns eyes, cardiovascular system, kidneys and feet. It is a rapidly growing problem as it will affect 500 millions of people worldwide in 2030 compared to 350 millions nowadays [1][5].

In the UE27, for example, 30 millions of persons suffer from diabetes. The annual incidence of foot ulceration is approximately 2% each year, and approximately 15% of these will lead to a lower-limb amputation [8]. It corresponds to 600,000 foot ulcers and 90,000 amputations each year. It is more than necessary to develop new ways to reduce this dramatic figure. The general goal of our project, that includes several universities and hospitals in Peru, France and Colombia, is to analyze the potential of thermography in the early diagnosis of diabetic foot in medical centers and to help in reducing foot ulcer occurrence.

In diabetic foot, the occurrence of an ulcer is often associated with hyperthermia. Hyperthermia is defined as a temperature greater than 2.2ºC in a given region of one foot compared to the same region of the other foot [2]. Temperature monitoring could be a complementary diagnostic method in the prevention of major foot complications, but cannot replace any of the current steps in modern diabetes care. Early diagnosis and early treatment are crucial for the healing of diabetic foot lesions and resources for early interventions must therefore be available to take care of a higher number of suspected foot complications [8]. Unfortunately, hyperthermia is not yet assessed in current diabetic foot therapy.

Regular temperature monitoring of diabetic feet has a strong potential to reduce the incidence of foot ulcers, assuming that diagnosed foot complications are followed up and adequately treated [2]. In this last study, it was found that the number of foot ulcers was reduced by 3 using a thermal therapy. Thermal therapy is roughly as follows: when hyperthermia is detected, the patient is asked to reduce his activity until the hyperthermia disappears. The Temp Touch technology which was used in the above medical study to monitor the temperature can now be replaced by new technologies such as, for example, infrared (IR) cameras. Main advantages of IR thermography are that it is simple to use, non-invasive, contactless, non-irradiant, and fast.

In this paper, we propose to detect a possible hyperthermia in diabetic foot by using an IR camera. A specific acquisition protocol of the thermal images is proposed and a dedicated image analysis is developed. The proposed method is tested on type II diabetic persons without ulcers. Section II relates to the Patients, Material and Methods, Section III presents the results. Conclusions and perspectives are finally given.

II. Materials and Methods

A. Subjects

A transversal clinical study has been conducted from the 1st of February 2013 to the 30th of June 2013, with a population of type II diabetes before a possible ulceration occurs. Hospital National Dos de Mayo (HNDM), Lima, Peru, has authorized the completion of this study and all of the patients provided informed written consent. The Ethic committee "Office support for teaching and research" OADI and the clinical responsible Dr. Hugo Arbañil have approved the 15th of February 2012 the agreement N°190 named: "Determination of the predictive diagnosis capacity for late injuries of diabetic foot using periodic reviews of thermography".

The type II diabetic patients who came from outside the hospital for a regular exam in the diabetes service of the HNDM were first taken in charge by experimented nurses. The exclusion criteria were: patients with ulcer, neurodegenerative diseases, in the pediatric age, current

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L. Vilcahuaman is with the Pontifical Catholic University of Peru PUCP, Lima 32, Ave. Universitaria 1800, Peru. (email: lvilcah@pucp.edu.pe).

R. Harba and R. Canals are with the University of Orleans, 12 rue de Blois, BP 6744, 45067 Orléans Cedex 2, France (e-mail: rachid.harba@univ-orleans.fr, raphael.canals@univ-orleans.fr).

M. Zequera and C. Wilches are with the Electronic Department, School of Engineering, Pontificia Universidad Javeriana, Bogotá, Colombia, (e-mail: mzequera@javeriana.edu.co, c.wilches@javeriana.edu.co).

M.T. Arista, L. Torres and H. Arbañil are with the National Hospital Dos de Mayo HNDM, Lima 1, 1300 Ave. Grau, Peru (email: aristateresa@hotmail.com).

presence of acute pancreatitis, acute cholecystitis, or obstructive jaundice or cholangitis, hereditary spherocytosis, pregnant or lactating women, patients with intention to donate blood during the study, failure to give informed consent, patients participating in other research studies, presence of onco-proliferative processes and/or decompensated chronic ischemic heart disease, diabetes mellitus (ketoacidosis and/or diabetic coma), renal insufficiency (creatinine > 200 mmol / L + oligoanuric), and holders of psychiatric illness that prevented him/her from giving informed consent. These rules are comparable to those used in other similar studies.

Patients may be withdrawn from the study for any of the following reasons: the patient decides not to continue in the study and/or follow-up visits; the patient does not cooperate or fails the criteria for follow-up. Patients with uncontrolled hypertension are removed from the study.

Eighty-five individuals were recruited from the Diabetic Foot Unit in HNDM. Clinical data, including age, gender, time of diabetes diagnosis, and body mass index, were collected on the evaluation day as shown in table I. Mean age was of 63.18 ± 10.56 years for the 56 females and 29 males that were recruited.

TABLE I. PATIENT CHARACTERISTICS

Variables	Data
Subjects number	85
Age (yr)	63.18 ± 10.56
Gender (F | M)	56 | 29
Time of Diagnosis (yr)	10.19 ± 8.51
Weight (Kg)	69.62 ± 14.11
Height (cm)	152.92 ± 9.85
BMI (Kg/m²)	29.74 ± 5.32

Following this, the same medical doctor (Dr. Julio Torres) conducted a barefoot medical exam that lasted about 30 minutes from which a risk classification [7] resulted (see Table II):

TABLE II. CLASSIFICATION BY RISK

Low Risk	Medium Risk	High Risk
Meets all of the following criteria:	*Meets one or more of the following criteria:*	*Meets one or more of the following criteria:*
The patient perceives the monofilament at all points of the points at risk.	Lack of perception of the monofilament in one or more of dark spots.	Lack of perception of monofilament in one or more of points at risk.
No previous ulcer.	Difficult perception of the tibial pulse.	Pedal pulses absent.
The patient shows no severe deformity.	Shows a deformity.	The patient has two or more deformities.
Pedal pulses present.	Shows callus formation.	The patient has a history of foot ulcer.
No amputation.		The patient shows previous amputation.
		Patient with foot ischemic or mixed.
Next appointment in 12 months	*Next appointment from 3 to 6 months*	*Next appointment from 1 to 3 months*

- Low risk: people with no ischemia, nor neuropathy;
- Medium risk: first signs of ischemia or neuropathy;
- High risk: strong signs of neuropathy or ischemia.

This risk classification (Low, Medium and High) used in HNDM is similar to that used in Europe (grade0, grade 1 and grade 2 respectively).

B. Choice of the IR camera

In this project, 5 parameters were taken into account for the selection of the IR camera:

1. Resolution: The larger foot that we consider here is 30 cm (Peruvian foot will be of interest in the medical study). The field of view will be of 40 cm: 30 cm for the foot plus a margin of 10 cm. In the other dimension, 40 cm is enough to contain both feet including a margin. The Field of view (FOV) is then of 40×40 cm^2. The smallest areas at risk are more or less a circle of 1 cm of diameter. According to the first Shannon theorem and to values used in image processing, 2 pixels are needed to see an object. It means that any camera with more than 80×80 pixels is suitable.
2. Sensitivity: A point to point difference between right and left foot higher than 2.2°C is considered as abnormal. Thus a sensitivity of 0.1°C is enough for the camera to detect these possible variations which are of interest.
3. Accuracy: In this work, the medical study will be performed in only one medical center using the same camera. As the accuracy is a systematic bias, and that only comparisons or differences are of interest, the bias will not be a limitation factor.
4. Spectral range: The average skin temperature of a healthy person in normal conditions is of 32°C. According to the Wien law, it is related to a peak wavelength number of 9.5 µm. This corresponds to the low infrared zone. The chosen camera should include the IR spectral range of the skin.
5. Emissivity: The emissivity of human skin is between 0.97 and 0.98. The chosen camera should be able to include such a data.

Another important feature is the price of the camera. The technology we intend to develop should be widely used. For that reason, only low price cameras that fulfilled the required criteria are of interest. Three cameras have all the necessary technical characteristics to be used in the study: FLIR i5, FLUKE Ti9, and HGH IRCAM 82. Taking into account the criteria and analysis above, the FLIR i5 is the best choice: it has the necessary performances combined to a very low price (1,595 US Dollars). The FOV of 40×40 cm^2 is associated to the angular FOV of the camera which is of 21°×21°. This means that the distance between the object and the camera should be of 1.1 m.

C. Acquisition protocol

The acquisition of the thermal image was performed immediately after the medical exam. The patient must be given sufficient time to equilibrate with the ambient conditions such that thermodynamic equilibrium of feet can be reached: a minimum period of 15 minutes should be observed [4][6]. The 30 minutes duration of the barefoot medical exam performed by the medical doctor is greater than the 15 minutes requested for the thermal equilibrium to be reached. Thus the patients went immediately in a room next to the doctor office. This 4×3 m^2 room has a temperature of 23°C ± 3°C. During the exam, we monitored the temperature was not varying more than 0.5°C.

An experimented nurse from the HNDM took care of the patient. Another person took care of the camera and was in charge of the image acquisition.

A complete infrared survey of the room should be performed to inspect for any infrared sources and leakage (i.e. windows, heating ducts, light fixtures, hot water pipes, etc.). Any significant findings need to be covered or shielded to prevent outside infrared radiation from affecting the measurements.

The arrangement of the elements is presented in Figure 1. Remember that the distance between the camera and the feet was set to 1.1 m. A black cover assimilated as a Lambertian surface is used to ensure an homogeneous background. 2 holes are also present in the black cover in which the patient feet can go through it.

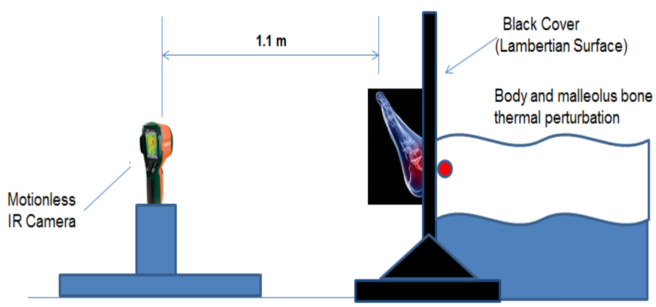

Figure 1. Image acquisition arrangement.

This black cover is a polyurethane foam. It has the following physical characteristics: density = 19.2 Kg/m^3 (1.2 lb per cubic ft.); tensile strength = 34.5- 51.7 kPa (5.0 – 7.5 lbs/sq. in). It should be larger than 40×40 cm^2 which is the desired FOV. It was chosen to be of 80×80 cm^2. Additionally, the polyurethane cover must adapt to the feet ankle size. A 6 cm thickness was chosen. Two holes for the feet to go through the cover are also present. They are two circles of 7 cm of diameter each, and separated of 20 cm. Figure 2 shows an image obtained using the proposed image acquisition protocol.

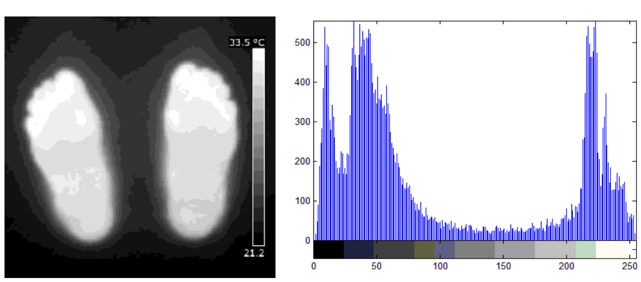

Figure 2. Thermal image and the image histogram.

As seen, the plantar foot clearly appears as a white surface on an homogeneous dark background. The temperature of the image is between 21.2°C (the room temperature) to 33.5°C (the hottest point of the plantar foot).

D. *Image Processing*

The image is divided so that we obtain two images, one for each foot. The left foot is flipped horizontally in order to look like the right foot; the right foot is the reference foot.

Afterwards, the process of segmentation is carried out. For segmenting the 2 feet, the Chan and Vese active contour algorithm was implemented [9], in order to find the contour of the feet. This algorithm was chosen because feet contours are not sharp. The number of iterations is of 300, and the alpha value is 0.2.

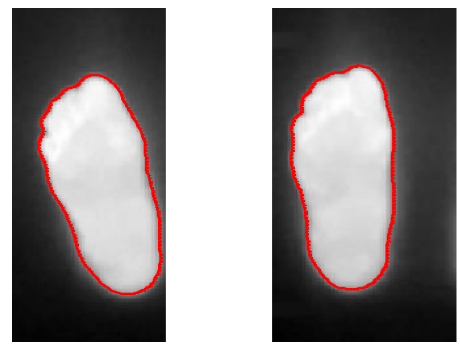

Figure 3. Chan and Vese active contour based segmentation of right and left (flipped) feet.

Results obtained after this segmentation step are of high quality. The following step is registration of the two feet; a straightforward rigid registration method, efficient and easy to implement, called the iterative closest point (ICP) [10], is then applied to minimize the difference between the two contours.

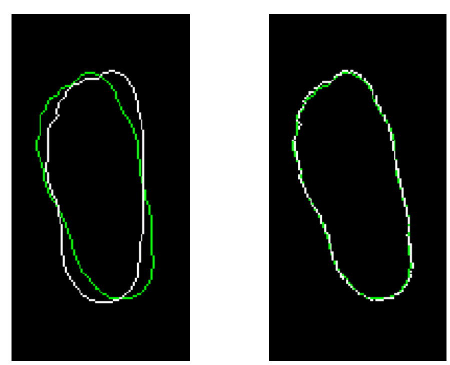

Figure 4. ICP based rigid registration.
Left: original contours. Right: registered contours.

The point-to-point absolute difference between the right foot and the left foot is named $|\Delta T|$. It is calculated for each pixel and such an image is presented in Figure 5. Because of feet asymmetry, registration is not always optimal and some foot zones where $|\Delta T|$ is impossible to evaluate disappear.
The temperature variations that are found are from 0°C (for the background and some parts of the plantar foot surface) to 2.99°C (only parts of the plantar foot surface). This image allows a precise analysis of the thermal differences that occur on the plantar foot surface.

III. RESULTS

Temperature of corresponding area of the right and left feet do not usually differs more than 1°C in diabetic foot. Values of $|\Delta T| > 2.2°\mathrm{C}$ show possible hyperthermia [2]. Remember that this upper limit can be an early sign of ulcer. The percentage of such points are called HT%. When HT% is greater than 1%, it roughly corresponds to a surface of 1 cm of diameter. It is also the smallest area at risk for the foot. This limit was therefore chosen.

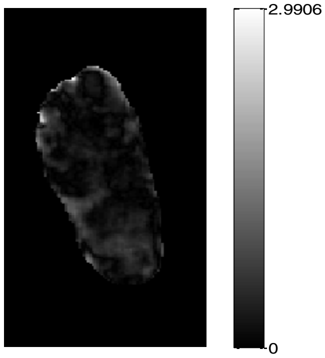

Figure 5. Image of $|\Delta T|$ °C.

9 images out of the 85 images of the database have a percentage greater than 1%. 6 persons are from the Medium risk group, and 3 from the High risk group. They are presented in Figure 6.

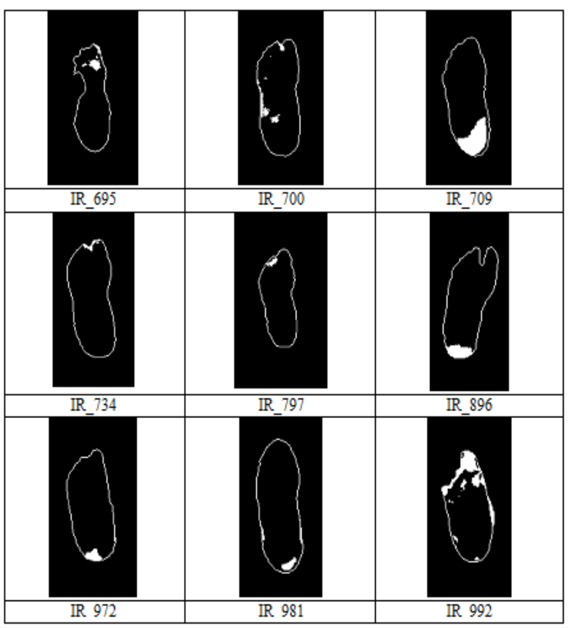

Figure 6. The 9 feet contours with significant hyperthermia (white areas).

In the domain of foot ulcer analysis, it is the first time to our knowledge that detection of hyperthermia with an IR camera is available for medical doctors. This indication may be of a substantial help because it allows detecting and precisely locating significant hyperthermia areas with a temperature difference greater than 2.2°C, early signs of foot ulcers. In this clinical trial, 10% of people having a regular exam in a hospital presented a significant hyperthermia of the plantar foot.

IV. CONCLUSIONS AND PERSPECTIVES

The overall objective of the study was to develop new strategies to reduce the occurrence of ulcers using thermography. A dedicated and effective image processing method was proposed. It is composed of two steps: segmentation and registration. From these steps, |ΔT°|, the point-to-point absolute difference temperature between the right and left feet can be assed. The abnormal hyperthermia regions have been found and analyzed. A transversal clinical study was conducted including a population of type II diabetes before a possible ulceration occurs. It is found that around 10% of type II diabetes persons coming in the hospital for an ordinary consultation in the diabetes service have a significant region of hyperthermia. It would be interesting to know if this analysis could help medical doctors in Hospital or in medical centers.

Several perspectives of this work will be developed in a near future.

The image processing software will be improved in order to be more robust regarding possible acquisition problems that occur mainly in the toes region, or in the malleolus area. In addition, a reproducibility study will be performed to evaluate influence of all possible variations.

The polyurethane foam makes positioning a patient for the image acquisition a long and difficult process, especially for old people. It is expected to develop an image processing method that could be operational when no polyurethane foam is present.

Finally, a longitudinal study, similar to that proposed in [2], will take place in the HNDM. The general objective will be to evaluate the potential of this proposed technology, *i.e.* using an IR camera, in ulcer prevention for type II diabetic foot.

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