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A quantitative index for classification of plantar thermal changes in the diabetic foot

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HIGHLIGHTS

- Advances in the study of the thermal changes associated to the Diabetic through Infrared Thermography.
- Classification of thermal changes according to a difference of temperature regarding to the control pattern.
- Identification of the wide variety of thermal distributions in a DM group.

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ABSTRACT

One of the main complications caused by diabetes mellitus is the development of diabetic foot, which in turn, can lead to ulcerations. Because ulceration risks are linked to an increase in plantar temperatures, recent approaches analyze thermal changes. These approaches try to identify spatial patterns of temperature that could be characteristic of a diabetic group. However, this is a difficult task since thermal patterns have wide variations resulting on complex classification. Moreover, the measurement of contralateral plantar temperatures is important to determine whether there is an abnormal difference but, this only provides information when thermal changes are asymmetric and in absence of ulceration or amputation. Therefore, in this work is proposed a quantitative index for measuring the thermal change in the plantar region of participants diagnosed diabetes mellitus regards to a reliable reference (control) or regards to the contralateral foot (as usual). Also, a classification of the thermal changes based on a quantitative index is proposed. Such classification demonstrate the wide diversity of spatial distributions in the diabetic foot but also demonstrate that it is possible to identify common characteristics. An automatic process, based on the analysis of plantar angiosomes and image processing, is presented to quantify these thermal changes and to provide valuable information to the medical expert.

1. Introduction

Diabetes mellitus (DM) is a metabolic disorder in which the abnormal absorbtion of sugar impairs the body's ability to use glucose. High levels of glucose in the blood can damage the vessels that supply blood to vital organs [1]. The International Diabetes Federation (IDF) reported that 387 million people in the world had DM in 2014, and that the healthcare expenditure on DM and its complications is high. Nevertheless, 77% of diabetics live in low and middle income countries [2]. A study estimated that the global health expenditure of DM in 2010 was about 376 billion USD, and that this expenditure is expected to increase by 30–34% in 2030 [3]. One of the main complications of DM is the development of peripheral neuropathy, which causes not only a loss of sensitivity in the foot, but along with high plantar pressure, it can also represent an increased risk of ulceration [4]. Moreover, foot ulcers are the main cause of lower extremity amputation in diabetics. In addition, the mortality risk in diabetic patients has been reported to be significantly higher when a foot ulceration occurs [5]. Therefore, the importance of knowing the status of the diabetic foot is evident in order to take preventive actions.

Since neuropathy is related to ulceration risks, several test have been developed to evaluate the changes of the diabetic foot caused by neuropathy. Some of the most common techniques are: nerve conduction velocity, which assesses the electrical conductivity in the foot nerves, as well as vascular ultrasound Doppler and laser Doppler techniques, which monitor blood flow [6–8]. However,

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these techniques are either invasive, qualitative or difficult to implement. Infrared thermal imaging (thermography) is a technique that provides information about skin temperature distribution. Thermography is a non-contact, safe, and non-invasive tool that provides anatomical information. Furthermore, since the association between disease and temperature is well known in medicine, thermography can provide relevant information about the status and the evolution of a disease. Peripheral neuropathy and ulceration risks have been associated to an increase in temperature in the plantar region, and several works have studied this increase by using thermography, as reported in [9]. The effectiveness of thermography has been demonstrated in the reduction of diabetic foot ulceration by patient self-monitoring with infrared thermometers. The groups that continuously monitored their plantar temperature were found to have a significantly lower percent of ulcerations [10–12]. The authors in [13,14] analyzed the plantar thermal patterns of diabetic and non-diabetic subjects and proposed a qualitative classification based on the angiosome concept. They reported that high plantar temperatures can be an early sign for the identification of pre-ulcer inflammation. Nonetheless, the analysis of thermal changes is carried out according to the visual perception of the specialist. Other works have addressed the problematic aspects of the diabetic foot from quantitative estimations by providing information that allows the detection of abnormal temperature increases associated to high ulceration risks. In 2013, an automatic methodology to estimate regional plantar temperatures in diabetic subjects and to detect abnormal differences was proposed [15]. This estimation was focused only on the case where the changes were asymmetrical, and it was able to detect the presence of small hot spots. The study evaluates the foot per sections, but it does not provide information about the status of the whole foot; the participants show significant thermal changes. Also, Liu et al. [16] proposed the automatic detection of diabetic foot complications with an estimation of abnormal differences comparing both feet point to point; in that study, cases of open ulceration and Charcot foot were included. Although previous studies provide important information regarding thermal changes, they struggle with important limitations, such as: the dependence of a contralateral comparison between the feet to estimate abnormalities, the analysis of only some plantar regions instead of the entire foot, a difficulty in detecting or evaluating small hot spots in the initial stages, and the lack of a reference when the contralateral foot cannot be used for comparison [17]. Therefore, there is a need to continue developing methods to identify and quantify thermal changes in the diabetic foot.

In this work, the goal is to develop a methodology for identifying and characterizing the diversity of thermal changes in the plantar region of control and DM groups. This is important since it is known that temperature increment is related to high risk ulceration. To do so, a quantitative indicator will be provided to medical specialists, which will enable them to classify and analyze the progress of the temperature variations. We have found that by using the angiosome concept and by measuring their temperature, it is possible to detect thermal changes even in the early stages. This is a difficult task to achieve by using qualitative methods. Furthermore, an automatic methodology is proposed to offer a fast and reliable procedure, providing an indicator index which can be used by the medical expert to monitor DM subjects.

2. Materials and methods

2.1. Population study

This study was conducted considering two groups: a DM group, formed by subjects diagnosed with DM type 2, and a control group, formed by non-diabetic subjects. In the recruiting process of these groups, not only did specialists, but also volunteers from the Hospital General del Norte, Hospital General del Sur and from the INAOE (Puebla city, Mexico) provided support. Approval for this study was obtained from an ethics committee; the participants were informed about the tests and voluntarily agreed to participate in the study. Participant data were collected by nurses, and the thermograms were taken under medical supervision. The tests were performed during the health campaign in March 2014 and September 2015. The inclusion/exclusion criteria suggested by Lavery in a preventive monitoring study [12] were taken into account. Both study groups included male and female participants. Participants with a history of amputation, current or previous ulcers, foot infections and fractures, Charcot arthropathy, surgery of lower limbs, and severe peripheral vascular disease were excluded. Participants with habits of drugs or alcohol abuse were also excluded. The DM group included participants with a diagnosis of diabetes with peripheral neuropathy. The control group was composed of 40 participants and DM group by 100 participants (see Table 1).

2.2. Imaging protocol

In order to obtain accurate and useful thermograms for clinical practice, the recommendations obtained from the Thermography Guidelines of the International Academy of Clinical Thermology were followed [18]. The preparation of participants was done in a room with a temperature of 20 ± 1 °C. The participants were asked to remove their shoes and socks and to clean their feet with a damp towel in order to remove any particles or products (e. g., cream or talc). Then, the participants were asked to rest in a supine position during 15 min in order to reach a state of thermodynamic equilibrium and to improve the accuracy of temperature variation detection [19,20]. During the resting time, the feet remained uncovered. The infrared (IR) device used for the acquisition of thermograms was the FLIR E60 IR camera. In order to obtain only the thermal radiation of the feet, an obstructive IR device was placed at the area of the malleolus, thereby avoiding the radiation of the rest of the body. The IR camera was placed at a 1 m distance from the feet. Thus, a thermogram of the isolated plantar region was obtained, as shown in Fig. 1a. The IR camera automatically adjusted the temperature scale according to the hottest and the coldest points in the scene. The temperature values were associated with a color palette in order to represent and distinguish them graphically. The thermogram dimensions are 320×240 pixels, and each one has a corresponding temperature file of equal dimensions, in which the temperature value of each point (pixel in the thermogram) is stored.

2.3. Plantar region segmentation

Only the plantar region must be extracted from the thermogram in order to process its temperatures. Since feet are warmer than the obstructive device surface, it is possible to extract plantar region data by using a temperature threshold (h). In this case, we want to segment the image base according to temperature values to separate the plantar region from the rest of the image. For this,

Table 1
Demographic information (mean ± standard deviation).

	Control group	DM group
Volunteers	40	100
Gender (male/female)	26/14	64/36
Age	39.1 ± 11.7	54.0 ± 9.8