Thermography as a Diagnostic Tool for Early Detection of Diabetic Foot Ulceration Risk: A Review

Cesar A. Salazar(✉) and Martha L. Zequera Díaz

Electronics Department, School of Engineering, BASPI/FootLab, Bioengineering, Signal Analysis and Image Processing Research Group, Lab focused on Diabetes research, Pontificia Universidad Javeriana, Bogotá D. C., Colombia
cesar_salazarc@javeriana.edu.co, mzequera@javeriana.edu.co

Abstract. Type 2 Diabetes Mellitus (DM2) is a disease that affects the following physiological systems: the central nervous system (CNS), the peripheral nervous system (PNS), the vascular system (VS), and the peripheral vascular system (PVS). When the PNS and PVS are affected, those complications are well known as diabetic neuropathy (DN) and diabetic vasculopathy (DV) respectively. These complications may cause lesions on the feet such as ulcers and are associated with other risk factors such as plantar pick pressure, friction from not wearing ergonomics footwear, the presence of biomechanics foot alterations, or significant temperature changes on the foot producing tissue infection that may cause lower limb amputation. The most important physiopathologies reported on the feet caused by the DN and DV are hypoesthesia and hyperthermia. These complications cause the loss of sensitivity and increase in temperature at the plantar surface respectively, and with continuously applied pressure, may initiate an ischemic or inflammatory problem. This multicausal condition of DM2 is known as Diabetic Foot Syndrome (DF), one of the main complications of the disease. Several studies have reported the correlation between ulcers and high temperatures under the plantar surface of the foot. Those temperature changes may be detected by using different methods. According to literary reviews, thermography is one of the methods most implemented by different researchers in laboratory environments. This method seems accurate in detecting temperature changes in the plantar foot anatomical regions by using image processing techniques, computer vision, and intelligent systems for improving ulcer detection in early stages of DF. The aim of this study is to define the benefits of using thermography as a future diagnostic tool for DF in a clinical environment based on the systematic literary review done in the last 15 years by BASPI-FootLab research group. Preliminary results of our review are reported in this paper.

Keywords: Type 2 Diabetes Mellitus · Diabetic foot · Image processing techniques · Protocol · Region of interest · Thermography

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1 Introduction

Type 2 Diabetes Mellitus (DM2) is a pandemic disease, which is found to affect the metabolism of carbohydrates, the central nervous system (CNS), the peripheral nervous system (PNS), the vascular system (SV), and the peripheral vascular system (PSV). When the upper and lower extremities are affected it is known as diabetic neuropathy (DN) and diabetic vasculopathy (DV). These complications of DM2 are the precursors of the main cause of physical disabilities in diabetic patients due to biomechanical alterations in the biological systems involved on in motion, balance control, perception, and regulation of temperature related to metabolic disorders [1–3]. Among the changes at the neurological and vascular level associated with this disease, the loss of sensitivity and the increase in temperature was also found on the plantar surface respectively. Combined with other alterations such as the sustained presence of peak pressure on the plantar region, continuous friction due to the use of unsuitable footwear, the presence of osteomuscular deformities in the feet, among others, lead to the cause of imperceptible lesions that evolve rapidly. If these manifestations are detected at an earlier stage, more serious damage could be prevented such as ulcers, and therefore, amputations could be decreased. Those conditions combined with metabolic disorders due to the presence of DM2, also referred to as Diabetic Foot Syndrome (DFS), is the main cause of amputation in patients with DM2 in the world [4,5].

The complications of DM2 can be microvascular or macrovascular. The microvascular complications are lesions in the small blood vessels of the body. In these we find retinopathy, nephropathy, neuropathy, vasculopathy, DF, among others. In contrast, macrovascular complications are lesions in the larger blood vessels such as cardiovascular diseases [6].

In this way, the pathophysiology of DFS that affects the sensory systems of the body, known as DN, produce a direct relationship between DM2 and neuropathy, which is evident as the conduction of action potentials through the sural nerves and medial plantar decrease, which leads to hypoesthesia (decreased sensitivity); one of the main causes for the appearance of an ulcer [7–9]. At the same time, the pathophysiology of DFS induced by sustained hyperglycemia generates DV, which shows a degeneration of the vascular structure in the feet, arising from a thickening of the vascular structure blocking blood flow, causing hyperthermia (temperature increase) and anatomical and functional alterations in the sensory, motor, and autonomous systems [10–12]. With this, the DN and DV creates a relationship between the generation of tissue lesions and the increase in temperature at a continuously applied pressure, which initially produces damage to the deep tissue, and continues with cutaneous and subdermal damage, ultimately leading to the generation of ulcers based on pressure [13].

Statistics show that DM2 is among the 10 leading causes of death worldwide, equivalent to more than 80% of all deaths from noncommunicable diseases. Its prevalence between ages 20 and 79 corresponds to 425 million people and this in turn represents 8.8% of the world. Additionally, the number of deaths is 4 million people. One of the complications of DM2 is DFS which, associated with the DN and the DV, causes hypoesthesia and hyperthermia respectively on the plantar surface in anatomical regions of interest such as the toes, the metatarsal heads, the medial plantar region, the lateral plantar region, the tibial plantar region, among others, where significant alterations of body temperature generated from high levels of pressure applied continuously have been reported. This causes ischemia resulting in ulcers, and when infected ends in amputation. Furthermore, it is reported that its prevalence is between 16% and 66%, and the risk of amputations is 10 to 20 times more frequent compared to people who do not suffer from DN [14,15].

In conclusion, when the surface of the foot is losing sensitivity due to the DN, there is no perception of the pain caused by mechanical pressures applied continuously inside the shoes, while at the same time the DV causes an increase of temperature that may produce different lesions on the foot (ulcers), managing to generate loss of members.

2 Methodology and Methods

Previous studies have reported that thermography is an important technique in the detection of temperature changes [16,17]. In the DFS, significant temperature changes are detected on different anatomical regions of interest previously mentioned by means of image processing techniques, computer vision, and intelligent systems [18]. The normal values for temperature distribution in a healthy foot are defined as the "butterfly pattern" [19], but it has been shown that even without having a specific temperature value as a reference, the correlation between both feet is used where if the temperature difference is greater than 2.2 °C, there is a high risk of ulceration [20].

Below is a diagram that, after a systematic search of approximately 30 articles indexed in the last 15 years (2006–2019), will describe the progress, relevance, relationship, and implementation of thermography in detecting temperature changes for the prevention of possible areas of ulceration on the plantar surface of the diabetic foot (Fig. 1). Similarly, a detailed description is included of each protocol implemented for the acquisition of thermal images and videos, the use of various thermal imaging cameras, and the different regions of interest studied for each investigation implemented with thermography.

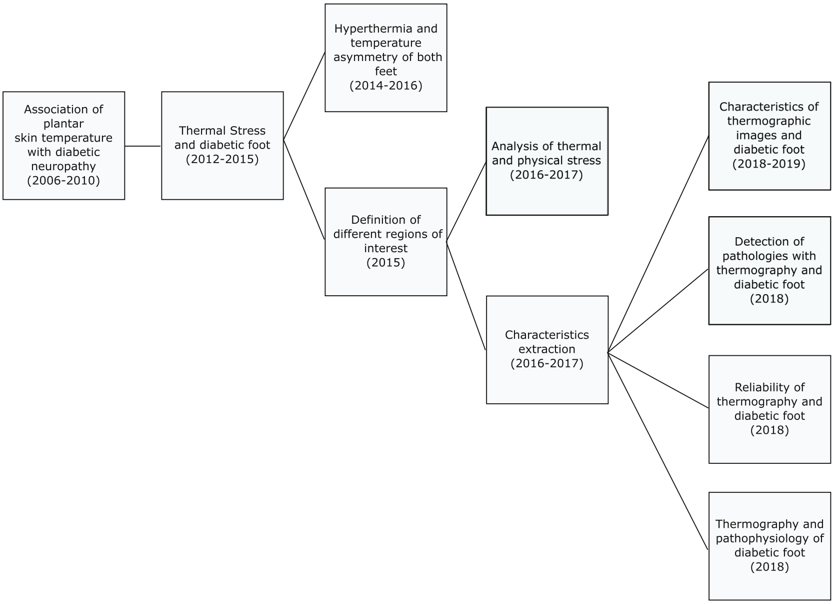

Fig. 1. Research timeline.

3 Thermography and the Diabetic Foot

It has been found according to literary review, that thermography is a technique which contributes to the detection of temperature changes in the biomedical areas such as breast cancer, varicocele, inflammatory diseases, skin abnormalities, among others. In the specific case of DFS, thermography detects temperature changes which may correspond to ischemic or inflammatory problems due to DV on possible anatomical regions of interest. These are obtained from image processing techniques, computer vision, and intelligent classification systems [21]. In addition, through the implementation of a good acquisition protocol which should be taken as reference from the "International Academy of Clinical Thermology (IACT)" [22], a non-profit organization committed to research, education, and the establishment of both standards and delineation in clinical thermography, where they demonstrate that thermography is completely non-invasive and does not require the use of radiation.

3.1 Association of Plantar Skin Temperature with Diabetic Neuropathy

The first studies between 2006 and 2010 (Table 1) showed that there is a relationship between temperature and DN through the design and implementation of a protocol, which should focus on the measurement of temperature in a certain number of regions of interest with the objective of being able to characterize the foot.

Table 1. Association of plantar skin temperature with diabetic neuropathy.

Reference (Year)	Study group	Protocol	Regions	Camera
Sun *et al.* (2006) [23]	25 control subjects and 29 (of 69) diabetic patients	Measurements in the mornings to eliminate the diurnal influence of the patients, remain in a sitting position for 15 to 20 min in a room temperature of 21 ± 1 °C	6 regions of interest (hallux, lesser toes, forefoot, arch, lateral sole and heel)	Spectrum 9000 MB (640 × 480 pixels)
Armstrong *et al.* (2007) [24]	225 high-risk diabetic patients with neuropathy and deformity in the structure of the foot, or with a history of ulceration or partial amputation	No protocol	6 regions of interest	Infrared skin thermometer TempTouch
Bagavathiappan *et al.* (2010) [25]	112 subjects with DM2	Remove both shoes and socks, remain in a supine position on a sofa for 5 min in a room with controlled temperature of 25 °C (air conditioning)	6 regions of interest (hallux, lesser toes, arch, lateral sole, forefoot, and heel)	No camera

Sun *et al.* [23] were the first research group that reported finding a relationship between the temperature of the plantar skin and the DN in a clinical study. The Sympathetic Skin Response (SSR) was found in both feet. They concluded that there was a significant abnormality in sweating with respect to thermoregulation over early sympathetic damage in the DFS. On the other hand, Armstrong *et al.* [24] evaluated the efficiency of measuring temperature to decrease the incidence of ulcers. Patients who presented a temperature difference between both feet higher than 2.2 °C, had to decrease their activity until the temperature normalized. For this measurement the opposite extremity was used as a control since both feet were exposed to the same stress during walking. In other words, they evaluated the efficiency of reducing the incidence of ulcers mainly in patients who had subsequently developed some type of ulcer. Similarly, Bagavathiappan *et al.* [25] reviewed the correlation between foot plantar temperature and DN. They found that patients with DN had higher temperatures on their feet compared to patients without neuropathy and also a correlation between the big toe of the right and left foot.

3.2 Thermal Stress and Diabetic Foot

During the period from 2012 to 2015 (Table 2), studies on thermal stress were started using image processing and thermographic video with the purpose of evaluating the recovery time generated by thermoregulation in response to VS in certain regions of interest.

Table 2. Thermal stress and diabetic foot.

Reference (Year)	Study group	Protocol	Regions	Camera
Barriga *et al.* (2012) [26]	8 people (3 controls, 3 diabetics without neuropathy and 2 diabetics with neuropathy)	Clean feet after removing shoes and socks, apply reflective markers and measure initial temperatures in the regions of interest with a thermometer, record a video for 2 min to get the base thermal signal (reference), submerge feet for 5 min in cold water (13 °C–14 °C), measure again with a thermometer and record a video for 15 min	6 regions of interest (great toe, third toe, third metatarsal, medial arch, lateral arch and heel)	FLIR SC305 (320 × 240 pixels)
Balbinot *et al.* (2013) [27]	20 patients (10 diabetics and 10 controls)	Recommendations given by The American Academy of Thermology, remain in a face-down position for 15 min in a controlled environment between 23 °C and 24 °C, apply a cold stress in order to increase the sensitivity in the diagnosis of neuropathy, by submerging feet in cold water (15 °C) for 60 s, obtain a base (reference) before thermal stress and then 10 min after applying thermal stress	5 regions of interest (big toe, first metatarsal, third metatarsal, fifth metatarsal and heel)	IRISYS® IRI 4010 (160 × 120 pixels)
Agurto *et al.* (2015) [28]	12 patients (7 controls and 5 diabetics)	Apply a cold stimulus on feet to lower the temperature to 13 °C in order to trigger the thermoregulation, make a video for 15 min to capture the recovery time	Spatial regions that were relevant for the classification of DM2	FLIR SC305 (320 × 240 pixels)

With reference to the above table, Barriga *et al.* [26] presented a computer-based system for the analysis of thermal images with the aim of detecting preclinical states of peripheral neuropathy. They monitored thermal videos of microcirculatory recovery in the sole of the foot. They concluded that the magnitude of recovery was significantly different in the 2 study groups. Similarly, Balbinot *et al.* [27] used infrared thermography as a complementary diagnosis in distal diabetic neuropathy. They applied a cold stress in order to increase the sensitivity in the diagnosis of neuropathy, with the purpose of evaluating the induced thermoregulation response based on thermal stress (cold). In the same way, Agurto *et al.* [28] characterized the DN by using an infrared imaging device and Independent Component Analysis (ICA). They separated the temporal and spatial components to be able to represent the thermoregulation in response to the cold stimulus between control and diabetic patients, identifying the spatial regions that were relevant for the classification of DM2.

3.3 Definition of Different Regions of Interest on the Diabetic Foot

Already aware of the temperature relationship in the DFS and the first indications that there is a correlation between the temperature of both feet, in 2015 (Table 3), D. Hernández *et al.* began to perform a variety of studies of foot characterizations using different methods based on thermographic image processing.

Table 3. Definition of different regions of interest on the diabetic foot Part 1.

Reference (Year)	Study group	Protocol	Regions	Camera
Hernandez-Contreras *et al.* (2015) [29]	44 participants (24 non-diabetics and 20 diabetics)	Recommendations given by the International Academy of Clinical Thermology: remove shoes and socks, clean feet with a humid towel, remain in a supine position for 15 min in a temperature-controlled room of 21 ± 1 °C	Regions with higher temperature)	Spectrum 9000 MB (640 × 480 pixels)
Hernandez-Contreras *et al.* (2015) [30]	60 participants (30 non-diabetics and 30 diabetics)	Recommendations given by the International Academy of Clinical Thermology: removing shoes and stockings, clean feet with a damp towel, remaining in a supine cube position for 15 min in a temperature-controlled room of 21 ± 1 °C, use an obstructive device of infrared light to separate the temperature of the feet from the rest of the body	No regions	FLIR E60 (320 × 240 pixels)

In the first study [29], they presented a preliminary classification method to detect temperature patterns based on thermal image processing. They identified areas of higher temperature related to the high risk of patients by acquiring the thermal images of the areas of interest in isolation, followed by an analysis of these areas for their classification. In the second study [30], they characterized and identified temperature patterns in thermographic images of the sole of the foot, identifying the areas of higher temperature. They were able to establish characteristic vectors based on the patterns of the spectrum and the relative position of their 3D morphology, creating a system to quantify and discriminate characteristics using a neural network with which they obtained a classification rate of 94.33% in the extractions.

That same year (Table 4), studies continued in relation to the different regions, and in turn, with its correlation (asymmetry) between the temperature of both feet, reached the definition of different regions based on various studies of temperature, all this, using thermographic image processing techniques.

Table 4. Definition of different regions of interest on the diabetic foot Part 2.

Reference (Year)	Study group	Protocol	Regions	Camera
Neves *et al.* (2015) [31]	44 volunteers (22 women and 22 men) with DM2	Temperature and humidity controlled at 20 ± 1 °C and 55% respectively by using a thermohydrometer	3 regions of interest (the first finger, the fifth finger and the heel)	FLIR SC2000 (320 × 240 pixels)
Nandagopan and Bhargavi Haripriya (2016) [32]	20 people (10 diabetics and 10 controls)	Keep feet on a bench, cover the wall with a black cloth to eliminate the reflection radiation and cover feet with a black cardboard box to eliminate the body temperature	No regions	FLIR SC305 (320 × 240 pixels)

In this way, Neves *et al.* [31] conducted a cross-sectional study. The region with more asymmetric temperatures in comparison between both feet (regions greater than 2.2 °C) was selected for the DFS risk analysis, showing that there was a correlation between the temperatures of both feet. The next year, Nandagopan and Bhargavi Haripriya [32] implemented two techniques for segmentation of thermal images of the foot. They compared the soles of the feet with the help of asymmetrical temperatures, in order to try to identify ulcers in patients at an early stage.

3.4 Hyperthermia and Temperature Asymmetry of both Feet

During 2014, 2015 and 2016 (Table 5) different results were published corresponding to studies in thermography applied to the early detection of ulcers, in which the concept of hyperthermia was defined in the DFS to relate to the temperature correlation (asymmetry) of both feet through the development of different protocols for the acquisition of thermographic images.

Table 5. Hyperthermia and temperature asymmetry of both feet.

Reference (Year)	Study group	Protocol	Regions	Camera
Vilcahuaman *et al.* (2014) [33]	85 diabetic people	Stay for 15 min in the controlled temperature environment of 23 ± 3 °C to reach the thermodynamic equilibrium, cover feet by a black cover (polyurethane foam) to eliminate the temperature of the body	No regions	FLIR i5 (100 × 100 pixels)
Vilcahuaman *et al.* (2014) [34]	82 diabetic patients in a pre-ulcerative	Stay for 15 min in the controlled temperature environment of 23 ± 3 °C by eliminating external infrared sources to reach the thermodynamic equilibrium and cover feet with a black cover (polyurethane foam) to eliminate the body temperature	No regions	FLIR i5 (100 × 100 pixels)
Liu *et al.* (2016) [35]	60 diabetic patients	Stay for 15 min in the controlled temperature environment of 23 ± 3 °C to reach the thermodynamic equilibrium and cover feet with a black cover (polyurethane foam) to eliminate body temperature	No regions	FLIR i5 (100 × 100 pixels)

Two out of three studies were demonstrated by Vilcahuaman *et al.*, in the first one (2014) [33], proposed a simple way to detect hyperthermia. They developed a dedicated analysis of the thermographic images, which consisted of a contour detector on both feet using Chan-Vese active contours associated with the Rigid Interactive Closest Point registration technique. In this way, they were able to detect the hyperthermia in the DFS in the regions of interest which corresponded to the areas that had a temperature greater than 2.2 °C when compared on both feet. In the second one (2015) [34], analyzed the variation of temperatures. They developed an image processing software, performing 3 types of analysis. First, the average temperature of the plantar surface of the feet based on the segmentation of Chan-Vese active contours. Second, the absolute average difference between the 2 ft using a registration method based on Rigid Interactive Closest Point. And third, in the regions of interest which determined the hyperthermia, they highlighted the areas where the absolute difference in comparison of both feet was greater than 2.2 °C. One year later, Liu *et al.* [35] developed a system which processed essential medical images by segmentation, localization and regionalization based on an adaptive algorithm of active contours, acquiring the absolute average temperature in seven different regions (four plantar angiosomes), where hyperthermia was studied comparing both feet in the regions mentioned above.

3.5 Characteristics Extraction on the Diabetic Foot

In parallel and as a complement to the studies realized with the definition of different regions of the foot and implementation of protocols in 2016 and 2017 (Table 6) the characteristics extraction based on different regions was continued by D. Hernández *et al.* in three studies. They evaluated the correlation (asymmetry) between the temperatures of both feet.

Table 6. Characteristics extraction on the diabetic foot.

Reference (Year)	Study group	Protocol	Regions	Camera
Hernandez-Contreras *et al.* (2016) [36]	No study group	Remove shoes and socks, and remain seated in a supine position during 15 to 20 min in order to reach the thermal equilibrium	No regions	No camera
Hernandez-Contreras *et al.* (2017) [37]	140 patients (40 controls and 100 diabetics)	Recommendations given by the International Academy of Clinical Thermology: remove shoes and socks, clean feet with a damp towel to remove any particles or product, remain in a supine position for 15 min to reach the thermodynamic equilibrium in a temperature-controlled room of 21 ± 1 °C, use an obstructive infrared light device to separate the temperature of the feet of the rest of the body	4 angiosomes (medial plantar artery, lateral plantar artery, medial calcaneal and lateral calcaneal artery)	FLIR E60 (320 × 240 pixels)
Hernandez-Contreras *et al.* (2017) [38]	135 volunteers (35 controls and 100 diabetics)	Remove shoes and socks, clean feet with a damp towel and remain in a supine cube position for 15 min, place feet in an upright position in order not to affect the temperature by the blood pressure	Temperature distribution that may cause some complication	FLIR E60 (320 × 240 pixels)

In the first one (2016) [36], the relationship between temperature variation and DFS problems was demonstrated using infrared thermography. They presented a literature review corresponding to different protocols, regions of interest, methods of analysis with their respective advantages and disadvantages, analysis of asymmetrical temperatures between both feet of each method, and the potential of infrared thermography for DFS. In the second study (2017) [37], spatial temperature patterns dividing the foot into four angiosomes was identified. They proposed a quantitative method of measurement on temperature changes in the plantar region with participants diagnosed with DM2. This demonstrated a great diversity in the spatial distribution of DFS identifying common characteristics.

Therefore, they defined the concept of the "butterfly pattern" to describe the temperature distribution of the control group and to arrive at a comparison with the diabetic group. They concluded that the asymmetry of the temperatures of both feet had its limitations at the moment in which the patient had similar complications in both feet. In the third study (2017) [38], they identified changes in the distribution of plantar temperatures related to DFS complications. Based on the divergences of Kullback-Leibler and Jesen-Shannon they identified changes in the distribution of the plantar temperature in 82% of the 200 samples in which they presented a distribution that may cause some complications.

3.6 Analysis of Thermal and Physical Stress on the Diabetic Foot

That same year (2017), an analysis of thermal and physical stress was again carried out using thermography. This time, it was a comparison of different techniques where the objective was to study the reaction of the body's thermoregulation system in an environment where thermal stress (apply cold or hot water), and/or physical stress (running or walking) was applied.

Based on the above, Adam *et al.* [39] performed an exploration of physiopathology, conventional evaluation methods, infrared thermography and infrared thermography based on the CAD analysis (Computer-Aided Diagnosis) of the DFS was performed, deepening the infrared thermography analysis. In this they presented a literature review corresponding to the analysis of the temperature of the lower limbs, the analysis of the asymmetrical temperatures, the analysis of the temperature distribution, and the analysis of both thermal and physical stress. Included in the description of the analysis of asymmetrical temperatures is a proposal for the detection of inflammation and prediction of ulcers by using infrared thermography through an asymmetry analysis, an analysis based on a scalable scanning technique of asymmetry, with the purpose of comparing both feet of different sizes and shapes. In addition, a method with which they evaluated the temperature of the skin by means of taking the average of the temperatures between the right and left foot was included, showing the possibility of being a good marker to determine the necessity of treatment. For the analysis of the temperature distribution, they commented on an observational study where the temperature distribution of a healthy foot is described as symmetrical known as the "butterfly pattern," and they commented on a proposal for a method of characterization of thermal plantar patterns based on the concept of plantar angiosomes. Finally, the analysis of thermal and physical stress, where they describe that the pattern of abnormal temperature changes is classified into 3 types: increasing, decreasing, and flat. The cold induced in infrared thermography helps in the evaluation of the peripheral atherosclerosis condition and identification of patients with microvascular abnormalities. Likewise, they confirm that the low recovery rate in diabetic patients is for peripheral arterial sclerosis, abnormal blood coagulation (fibrinolysis), sympathetic nerve dysfunction, and the correlation between plantar stress and the increase in temperature in the sole of the foot after exercising through the use of infrared thermography.

3.7 Characteristics of Thermographic Images and Diabetic Foot

At present, in 2018 and 2019 (Table 7), different lines of research are defining the use of infrared thermography. The first study focuses on the continuation of the extraction of characteristics and segmentation of thermographic images of the foot.

Table 7. Characteristics of thermographic images and diabetic foot.

Reference (Year)	Study group	Protocol	Regions	Camera
Adam *et al.* (2018) [40]	33 healthy people and 33 individuals with DM2	Removed shoes and socks, clean feet, remain in a supine position for 15 min in a controlled temperature and humidity room of 21 ± 1 °C and 55 ± 5% respectively	No regions	VarioCAM® HD (640 × 480 pixels)
Astasio-Picado *et al.* (2018) [41]	277 diabetic patients	No protocol	4 regions of interest (head of the first metatarsal bone, head of the fifth metatarsal bone, heel and first finger pulp)	FLIR E60bx (320 × 240 pixels)
Bandalakunta Gururajarao *et al.* (2019) [42]	82 patients (62 diabetics and 20 controls)	Remove shoes and socks, remain seated or in a supine position for 15 to 20 min in order to reach thermal equilibrium	6 regions of interest (region of the big toe, region given by the other fingers, region of the plantar arch, region of the lateral medial plant, internal region of the heel and external region of the heel)	No camera
van Doremalen *et al.* (2019) [43]	32 participants with DM2	Sit in a supine position for 5 min at room temperature to reach the temperature equilibrium of the foot	9 regions of interest (big toe, first, third and fifth metatarsal head, metatarsal cuneiform joint, cuboid, third and fifth toe and lateral cuneiform metatarsal joint)	FLIR ONE (160 × 120 pixels), FLIR SC305 (320 × 240 pixels)

As stated by Adam *et al.* [40], who carried out a study of the thermograms of the sole of the foot, they managed to acquire images which were treated with the techniques of Discrete Wavelet Transform and Higher-Order Spectra, extracting different characteristics of texture and entropy, obtaining a precision of 89.39%, a sensitivity of 81.81%, and a specificity of 96.67% with only 5 characteristics. Likewise, Astasio-Picado *et al.* [41] studied the use of infrared thermography finding that there was a correlation (asymmetry) when comparing the temperature of both feet in diabetic patients. As a result, they made an analysis of the temperature variability in the feet, achieving segmentation of the sole of the foot, and concluding the importance of the use of infrared thermography in the assessment of the risk of DFS.

Similarly, Bandalakunta Gururajarao *et al.* [42] used medical infrared thermography and Deep Learning algorithms for evaluation of DFS, where they extracted abnormal regions by qualifying the level of complexity and making decisions to suggest some additional action based on the processing output. They studied the patterns of the distribution of the surface of the sole of the foot in the control group (butterfly pattern) and the diabetic groups (with and without complications) and the correlation between regions of interest where the temperature was higher than 2.2 °C when being compared in both feet to finally establish temperature differences capable of making an early diagnosis. In the same way, van Doremalen *et al.* [43] used two smartphone cameras for DFS evaluation capturing the infrared images with both cameras. They found contralateral temperature differences in the whole sole of the foot by the implementation of the correlation coefficients between classes (asymmetry of temperatures higher than 1.35 °C between the lateral parts of both feet and temperatures higher than 2.2 °C between the parts against the sides of both feet) and the Bland-Altman graphs. They concluded that the infrared smartphone camera shows an excellent validation of the DFS evaluation.

3.8 Detection of Pathologies with Thermography and Diabetic Foot

The following group of studies (Table 8) is based on the detection and comparison of the DFS against different pathologies; either DM2 or any other disease that affects peripherals, mainly in the lower extremities.

Adam *et al.* [44] proposed an automatic system for the detection of DFS in diabetics with and without neuropathy. They segmented the thermograms of the sole of the foot by decomposing them into coefficients using the Double Density-Dual Tree-Complex Wavelet Transform (DD-DT-CWT). The developed a system with 93.16% of accuracy, 90.91% of sensitivity and 98.04% of specificity using only 4 characteristics of Local Sensitivity Discriminant Analysis (LSDA). Similarly, Gatt *et al.* [45] investigated the heat emitted by the feet. They used thermographic images and automatically segmented regions extracted by the temperature data finding significant differences between both groups, mainly in diabetics, based on the correlation (asymmetry) of the temperature difference of both feet (values higher than 2.2 °C).

Table 8. Detection of pathologies with thermography and diabetic foot.

Reference (Year)	Study group	Protocol	Regions	Camera
Adam *et al.* (2018) [44]	51 healthy individuals and 66 diabetics (33 with and 33 without neuropathy)	Remove shoes and socks, clean feet, and remain in a supine position for 15 min in a controlled temperature and humidity room of 21 ± 1 °C and 55 ± 5% respectively	No regions	VarioCAM® HD (640 × 480 pixels)
Gatt *et al.* (2018) [45]	84 patients with DM2 and Peripheral Arterial Diseases (PAD)	Recommendations given by American Academy of Thermology: remain in a supine position for 15 min in a room with controlled temperature of 22.63 ± 2.28 °C and a relative humidity of 33.50 ± 8.10%, avoiding external air sources and sunlight on the camera lens	6 regions of interest (5 toes and mean forefoot)	FLIR SC7200 (320 × 250 pixels)

3.9 Reliability of Thermography and Diabetic Foot

Another current line (Table 9) focuses on the reliability during the acquisition of thermographic images, which shows that thermography has been and continues to be a very important tool for studies related to DFS.

Table 9. Reliability of thermography and diabetic foot.

Reference (Year)	Study group	Protocol	Regions	Camera
Silva *et al.* (2018) [46]	51 diabetic patients	Remain in the supine cube position for 15 min, during this time do not touch feet, electronic equipment that could modify the measurement was removed, controlled room of 23 °C, place a black box on feet in order to eliminate the heat generated by the body	9 regions of interest (first, third and fifth toe, first, third and fifth metatarsal head, cuboid, internal region of the heel and external region of the heel and heel)	FLIR E60 (320 × 240 pixels)

(continued)

Table 9. (*continued*)

Reference (Year)	Study group	Protocol	Regions	Camera
Seixas *et al.* (2018) [47]	13 diabetic patients with DM2	Take the photos in the morning away from air and infrared sources, take 10 min of acclimatization for the room with a controlled temperature of 23.3 ± 0.6 °C and a relative humidity of 54.4 ± 5.5%	6 regions of interest (the sole foot and 5 angiosomes: anterior tibial artery, posterior tibial artery, peroneal artery, medial calcaneal artery and lateral plantar artery)	FLIR E60 (320 × 240 pixels)

Silva *et al.* [46] rated the intra-reliability and inter-reliability of the images evaluated by infrared thermography of the plantar surface. They found a 95% correlation in all the points analyzed. In addition, Seixas *et al.* [47] evaluated the intra-reliability and inter-reliability of foot skin temperature analysis based on the angiosome concept. They associated skin temperature in 6 different sizes of RoI (Regions of Interest). They performed the respective evaluation of the study using the Intraclass Correlation Coefficient (ICC) and the measurements agreed upon by Bland and Altam and the Standard Error Measurement (SEM).

3.10 Thermography and Pathophysiology of Diabetic Foot

Finally, the last line of study (Table 10) focuses on the comparison and relationship of thermography with the pathophysiology of DFS, by relating changes in sensitivity and temperature-related lesions.

Table 10. Thermography and pathophysiology of diabetic foot.

Reference (Year)	Study group	Protocol	Regions	Camera
Renero-C (2018) [48]	186 patients with DM2	Recommendations given by the Academy of Clinical Thermology Standards and Protocols	No regions	FLIR E6 (320 × 240 pixels)

Renero-C [48], identified different regions of the plantar skin with deficiencies in the blood supply and the behavior of the thermoregulation process. By means of analysis of local regions with low and high temperatures they identified that these corresponded to ischemia or inflammatory problems, and in turn, the distribution of temperature in normal regions of the foot did not vary more than 2.2 °C when both feet were compared (asymmetry). Finally, they found specifically in two patients during a follow-up session a considerable increase in temperature, loss of sensitivity, and development of ulcers in the regions identified above.

4 Discussion

As described above, the implementation of the different protocols since 2006 (Tables 1, 2, 3, 4, 5, 6, 7, 8, 9 and 10), shows us a clear idea of the importance in having a rigorous protocol in thermography. The evolution of these protocols tells us that taking a good thermographic image is required in a controlled environment (temperature) as described by [23,25,29–31,33–35,37,40,44–47], and at the same time, a relaxing position for the patients like the supine position described by [25,29,30,36–38,40,42–46] is required in order to reach thermal equilibrium.

Thermal and physical stress described by [23,26–28,39] are useful to analyze the recovery time and the dynamic temperature of the foot. As it is known that the alterations generated by diabetes increases this recovery time compared with a healthy foot, it's important to improve the actual protocols as well as the protocols that analyze the static temperature in a thermal image.

In addition, these studies used a variety of thermal cameras with different thermal image sizes but didn't appear to need to calibrate each camera sensor according to its specifications (emissivity and reflected temperature) to get a good temperature measurement.

Despite being performed with few patients, several studies show us a good complementation when using the distribution of temperatures in the healthy foot described by [20,37,39,42] known as the "butterfly pattern," with the help of the correlation that exists when comparing the different temperatures in both feet as described by [19,25,39,41,42,45,48], in order to detect and classify DFS in different regions of interest. This include 3 regions according to [31], 4 regions according to [37,41], 6 regions according to [23–27,42,45,47] and 9 regions according to [43,46]. The distribution of temperatures and the correlation when comparing both feet are the most transcendental characteristics for the detection of possible areas of risk of ulceration based on heat maps. In addition, thermography is a non-invasive technique, simple to implement, and easy for patients to accept. For those reasons it is a technique that requires and deserves further exploration.

5 Conclusions

Based on the literature research reported in this paper seems that thermography could be a relevant diagnostic tool for early detection of diabetic foot ulceration risk. The first reason could be due to the relationship between thermography and DFS documented in previous studies, and in addition it was found associations between Hypoesthesia and hyperthermia with the pathophysiology of DFS, which is affecting the nervous and vascular systems, producing a loss of sensitivity and increase temperature, and leading to the appearance of ulcers. The second reason is because thermography is a non-invasive method that may easily detect temperature changes on the sole of the foot at low cost. In the other hand, it was mentioned initially of this paper highlighting of the importance to implement of a good protocol for the acquisition of the plantar surface thermographic images and video, taking into account all the parameters described in this review such as a: controlled environment and a relaxed position for the patient, defined the anatomic foot areas of interest were the main Author Proof Thermography: also a review was made of 17 studies in images processing and computer vision; the better the capture is made, the less processing must be done on the image. It was concluded that is possible to implement those studies at our research FootLab in Colombia in order to use thermography as a diagnostic tool for the early detection of diabetic foot ulceration risk in our region.

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