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Automated characterization of diabetic foot using nonlinear features extracted from thermograms

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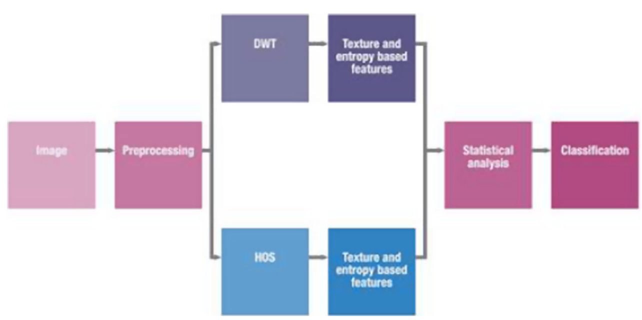
HIGHLIGHTS

- Characterization of diabetic foot is proposed using Infrared thermography.
- Nonlinear features extracted from thermograms.
- Ranked features are subjected to SVM classifier.
- Maximum accuracy of 89.39% using only *five* features.

GRAPHICAL ABSTRACT



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ABSTRACT

Diabetic foot is a major complication of diabetes mellitus (DM). The blood circulation to the foot decreases due to DM and hence, the temperature reduces in the plantar foot. Thermography is a non-invasive imaging method employed to view the thermal patterns using infrared (IR) camera. It allows qualitative and visual documentation of temperature fluctuation in vascular tissues. But it is difficult to diagnose these temperature changes manually. Thus, computer assisted diagnosis (CAD) system may help to accurately detect diabetic foot to prevent traumatic outcomes such as ulcerations and lower extremity amputation. In this study, plantar foot thermograms of 33 healthy persons and 33 individuals with type 2 diabetes are taken. These foot images are decomposed using discrete wavelet transform (DWT) and higher order spectra (HOS) techniques. Various texture and entropy features are extracted from the decomposed images. These combined (DWT + HOS) features are ranked using t-values and classified using support vector machine (SVM) classifier. Our proposed methodology achieved maximum accuracy of 89.39%, sensitivity of 81.81% and specificity of 96.97% using only *five* features. The performance of the proposed thermography-based CAD system can help the clinicians to take second opinion on their diagnosis of diabetic foot.

1. Introduction

Diabetes Mellitus (DM) is a progressive and chronic disorder due to either lack of insulin production by the pancreas or

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ineffective use of insulin by the body [1]. Over time, the high blood glucose levels may cause complications to the kidneys, heart, eyes, blood vessels and nerves [2]. An estimated 422 million people globally were living with diabetes in 2014 as compared to 108 million in 1980 [3]. The diabetic foot is a serious diabetes complication characterized by bacterial infection, foot ulceration, and deep tissues destruction which may be due to neuropathy and arterial disease in the lower limb [4]. The inability to sustain the stress makes diabetic foot significantly vulnerable to various foot complications that may lead to limb amputation. Diabetic foot ulcers (DFUs) complication critically affect around 15% of the diabetic population [5]. Moreover, diabetic patients are having 12–25% lifetime risk of developing foot ulcers [6] and almost 85% of the lower limb amputations are due to non-healing foot ulcers [7].

Diabetic foot complications can be prevented by early detection and proper clinical treatment. Based on International Working Group on the Diabetic Foot (IWGDF) risk category [8], diabetic patients need to screen their feet at least once every year to detect foot at risk of ulceration. The feet examination comprised of medical history and foot examination and, neuropathy assessment [8]. The medical history and foot examinations include previous history of amputation or ulceration and, health status of the vascular, skin, joint and bone [8]. Subsequently, neuropathy is assessed by performing these methods: enquiring on tingling or pain signs in the lower extremity; vibration perception using 128 Hz tuning fork; pressure perception using Semmes-Weinstein monofilaments; tactile sensation using cotton wool or by lightly touching the toes tips with index fingers; discrimination using pin prick on dorsum of foot superficial; and assessing the Achilles tendon reflexes [8].

The advancement in infrared camera technology has revolutionised the field of measuring temperature whereby it is now being widely used for medical purposes [9]. The IR thermography is fast, nonintrusive and non-contact method. It is also passive in which no harmful radiation passes through the body and captures only body heat radiation [9]. In this study, we are using IR thermography for the detection of complications related to diabetic foot based on the plantar temperature distribution. This plantar temperature distribution provides details related to blood perfusion impairment [10], which is typical among the diabetic patients [11]. During the conditions when the blood circulation is significantly reduced (ischemic), especially at the periphery limbs, the temperature pattern will change [12]. The IR thermography is contactless and hence has the advantage over the other assessment tools such as the monofilament and vibration sensation tests [13]. It limits the unnecessary contact and pressure that may affect the temperature reading and mitigate the spread of infection through the apparatus [14]. Moreover, it permits the measurement of temperature distribution of the whole foot regardless of the shapes or surfaces, particularly the medial arch which is a non-contact surface of the foot. Hence, analyzing the plantar temperature distribution can be effective for early detection of diabetic foot complications.

Infrared thermography has been used in many diabetic foot studies that relate plantar temperature variations with diabetic foot linked complications [15]. These studies are further categorised as separate lower limb temperature, asymmetric temperature, temperature distribution and, independent thermal and physical stress analysis. The separate lower limb temperature analysis in Table 1 represent the temperature ranges for the respective study groups. In 2010, Bagavathiappan et al. [16] studied the relationship between diabetic neuropathy patients and foot temperature. The study observed that diabetic neuropathy patient recorded highest foot temperature (32–35 °C) than non-neuropathy diabetes patients (27–30 °C). Also, diabetic neuropathy patients have higher mean foot temperature (MFT). Table 2 presents the studies on asymmetric analysis of diabetic foot thermograms. In general, the asymmetric temperature analysis compares the temperature between one foot and the contralateral foot. Liu et al. [17] performed an asymmetric analysis technique using coloured image segmentation and non-rigid landmark based registration B-splines of the right and left foot. The proposed method was able to detect diabetic foot ulcers and including all Charcot foot. Meanwhile, studies on temperature distribution analysis are summarised in Table 3. Both Nagase et al. [14] and Bharara et al. [18] proposed a characterization technique for plantar thermography patterns based on plantar angiosomes concept. The drawbacks may be the bias of variations in the control group due to smaller number of participants. The gender and age are unmatched in the control group, which may lead to confounding factors for data interpretation. Besides, the proposed manual classification method of 20 categories may not be suitable for clinical purposes. The studies based on independent thermal and physical stress analysis prior to thermogram acquisition is depicted in Table 4. In 2015, Agurto et al. [19] proposed a method to classify diabetic peripheral neuropathy patients using IR thermography and independent component analysis (ICA) method. The limitations are that few initial frames are not considered for the analysis and some areas, particularly the toes, present artefacts which require stabilizing the toes to avoid significant movements. Therefore, continuous development of algorithms is needed to better determine and analyse the thermal changes in the diabetic foot.

The purpose of this study is to develop an early detection system for diabetic foot using plantar foot thermograms. The plantar thermal patterns and distributions among the normal and diabetes subjects are analyzed and classified. The proposed system can be introduced as a screening tool in diabetic clinic to provide clinician with medical supports in diagnosing the magnitude of diabetic foot cases. In this proposed system, the normal and diabetic plantar foot thermograms are first segmented and warped. These warped foot images are subjected to discrete wavelet transform (DWT) and higher order spectra (HOS) techniques and then various texture and entropy features are extracted from the coefficients. The combined extracted features are ranked using t-values. Then these ranked features are fed to the SVM classifier for automated classification.

2. Materials & methodology

2.1. Population study

The normal and diabetes without neuropathy groups were considered in this study. A total of 33 healthy subjects and 33 non-neuropathic diabetic patients were recruited from Ngee Ann Polytechnic and Singapore General Hospital (SGH), Diabetes & Metabolism Centre (DMC) respectively under identical conditions. The diabetic foot thermograms data collection has been approved by SingHealth Centralised Institutional Review Board (CIRB) **(CIRB Ref: 2016/3044)** while normal foot thermograms data collection has been approved by Ngee Ann Polytechnic-Institutional Review Board (NP-IRB) **(NPIRB-P0175-2017-ECE-AMA6)**. The details of diabetes and normal groups are presented in Table 5. The participants in both groups were informed about the study prior to obtaining inform consent from them. Importantly, participants with past ulcerations or amputation, peripheral vascular disease, ischemic heart disease and neurological disorder were excluded.

2.2. Acquisition of thermogram

The plantar foot thermograms acquisition was carry out in a controlled room temperature of 20 ± 1 °C and humidity of