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Automated detection of diabetic foot with and without neuropathy using double density-dual tree-complex wavelet transform on foot thermograms

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ABSTRACT

Diabetic foot is the most common problem among diabetic patients, mainly due to peripheral vascular and neuropathy induced capillary perfusion changes. These pathogenic factors cause superficial temperature changes that can be qualitatively and visually documented using infrared thermography (IRT). Hence, IRT can potentially be used to evaluate the diabetic foot. However, it is tedious to manually interpret these subtle temperature variations by inspecting the feet thermal image. Therefore, an automated system to detect diabetic foot with and without neuropathy is proposed. In this study, 51 healthy individuals and 66 diabetic patients (33 with and 33 without neuropathy) are considered. The segmented plantar foot thermograms are decomposed into coefficients using double density-dual tree-complex wavelet transform (DD-DT-CWT). Several entropy and texture features are extracted from the decomposed images of left, right and bilateral foot. These features are reduced using various dimensionality reduction techniques and subsequently ranked using *F*-values. The ranked features are fed individually into the different classifiers one by one. The developed system yielded 93.16% accuracy, 90.91% sensitivity and 98.04% specificity using only *four* locality sensitive discriminant analysis (LSDA) features obtained from bilateral foot thermal images with k-nearest neighbour (kNN) classifier. This automated diabetic foot detection system can be introduced in polyclinics and hospitals to clinically support the clinicians to confirm their manual diabetic foot diagnosis.

1. Introduction

Diabetes mellitus is a chronic major endocrine disorder caused by deficiency in the production of insulin, or inefficacy in the usage of insulin [1]. Such an inadequacy may raise the glucose concentration levels in the blood, potentially damaging the blood vessels and nerves [1]. In 2014, approximately 422 million adults globally were living with diabetes and the diabetes global prevalence has almost doubled since 1980, from 4.7% to 8.5% [2].

Progressively, diabetes can damage the various parts of the body. The most common problem of diabetes is diabetic foot disease (DFD). The pathologies of DFD are primarily peripheral arterial disease and peripheral neuropathy which may lead to foot ulceration [3]. The lifetime risk of a diabetic patient in developing a foot ulcer is about 15–25% [4]. Moreover, it is estimated that 45–60% of the diabetic patients with foot ulcers are attributed to neuropathy, whereas about 45% of them may be due to the combination of both ischemic and neuropathic conditions [5–8]. The foot ulceration may further result in amputation particularly when osteomyelitis or wound infection is present. In fact, almost 85% of lower limb amputations are because of infectious and non-healing foot ulcerations [9].

Humans are regarded as homeotherms with the ability to maintain inner body temperature, despite the surrounding temperature variations, by adjusting the heat production and heat loss rates [10–12]. Nonetheless, the human body thermoregulatory mechanism may still be altered by pathologies especially autonomic neuropathy, peripheral arterial disease and inflammations [13]. In the case of DFD, peripheral arterial disease and neurological disorders can change the temperature of the lower limb [14]. The studies have reported that temperature variations in the plantar foot regions are because of diabetic foot

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complications [15–21]. Clinically, temperature gradient on the lower limbs is often assessed by gently running the back of the hand from below the knee distally to the toes [13]. Evidently, this method is not sensitive to the subtle temperature changes in different parts of the plantar foot.

The infrared thermography (IRT) is a noncontact, non-invasive and fast technique that allows temperature distributions to be visualised. Further, IRT radiations are harmless, but captures only the body heat profile [22]. Hence, the uses of IRT have considerably risen over the years particularly to study the diabetic foot related complications [23]. The skin temperature distributions and patterns caused by blood perfusions can be simply observed using IRT. In conditions where limited blood perfuse to the lower limbs due to ischemic, the temperature distributions and patterns will change [23]. In general, an ischemic foot tends to appear cold and conversely a neuropathic foot is often warm [24].

In recent years, several authors have studied the plantar foot temperature variations in diabetic patients using IRT [25]. In previous work by Adam et al. [26,27], *four* types of temperature analysis are proposed to study the diabetic foot. The separate lower limb temperature analysis [28–35] provides only temperature ranges for various study groups and cannot localise the risk areas. In asymmetric temperature analysis [36–49], plantar temperature is compared between the right and left foot. This analysis is unable to determine the risk areas if the same complications exist in both feet and also, partial or whole foot amputee patients have to be excluded from this analysis due to the absence of the plantar foot region used for comparison. In temperature distribution analysis [50–55] each foot is analyzed independently. However, attempts to identify spatial patterns of temperature remains hard because of extensive variations in the thermal pattern and distribution especially among diabetic patients, which complicates the classification process. In addition, the interpretation of plantar foot thermographic patterns may be difficult due to insufficient details and classification techniques on these thermographic patterns. In independent thermal and physical stress analysis [56–63], plantar temperature reaction to the applied external stress are independently assessed and analyzed. The external stress that consists of walking or momentarily immersing the limb into cold or hot water may cause discomfort and inconvenient to the. Hence, there is a need to have consistent accurate algorithm which can effectively detect and analyze the minute thermal variations in the diabetic foot.

This study aims to automatically detect the diabetic foot (with and without neuropathy) using plantar foot thermogram. The diverse thermal variations of the plantar foot are quantitatively analyzed and characterized. First, the plantar foot thermal images are delineated and then warped. The warped grayscale images are decomposed using double density-dual tree-complex wavelet transform (DD-DT-CWT). Thereafter, texture and entropies features are extracted from the coefficients of decomposed images. The separately extracted features of left, right and bilateral foot is subjected to various data reduction techniques and ranked based on *F*-value. Finally, the ranked features are input into the various classifiers to evaluate the classifier performances. The block diagram of the proposed system is presented in Fig. 1.

The findings of this study will benefit the diabetic patients considering that IR thermography has the potential to detect diabetic foot early. The rising occurrence and burden of diabetic foot disease demands an efficient and reliable detection method. Thus, the developed thermography-based CAD system can be an adjunct diabetic foot screening tool in clinics to effectively assist the podiatrists in efficient decision making and diagnosis processes. The early detection of diabetic foot may prevent future complications. Also, this study will help the application of new image processing and artificial intelligence techniques for the detection of diabetic foot. Indeed, the selected features (texture & entropy) are able to capture effectively the subtle pattern variations in the pixels among the diabetic patients.

Table 1
The demographic details of healthy and diabetic (with and without neuropathy) groups (mean ± standard deviation).

	Healthy	Diabetic	
		Non-neuropathy	Neuropathy
Total	51	33	33
Female	27	15	9
Male	24	18	24
Average age (years)	48.41 ± 11.12	56.18 ± 14.71	62.33 ± 10.63
Average body mass index (BMI) (kg/m^2)	23.73 ± 3.32	25.08 ± 5.31	27.84 ± 4.37

2. Materials & methodology

2.1. Study population

In this study, healthy adults and diabetic patients with and without neuropathy classes were considered. Ngee Ann Polytechnic and Singapore General Hospital (SGH) recruited 51 healthy subjects and 66 diabetic patients (33 non-neuropathic and 33 neuropathic) respectively. Except for healthy and diabetic non-neuropathic groups, several patients in the diabetic neuropathic group had toes amputation. The feet data collection were approved by the respective sites Institutional Review Boards (IRBs). The demographic information of healthy and diabetic (with and without neuropathy) groups are shown in Table 1. The participants were briefed about the study before signing the patient consent form.

2.2. Thermogram acquisition

The plantar feet thermograms were acquired in a controlled room with temperature = 20 ± 1 °C and humidity = 55± 5%. The participants are needed to remove footwear, socks, and clean their feet. The participants are then remained seated on the treatment bench for 15 min to achieve thermal equilibrium before taking the thermal image. The plantar feet thermal images were captured using **Thermographic System VarioCAM© hr head 680/30 mm** positioned at 1 m distance from the feet. The captured plantar feet thermograms are converted into grayscale images as shown in Fig. 2(a)–(c) with temperature scale range of 20–34 °C The captured thermal images are stored in ***irbis*** format before converted into ***bmp*** format.

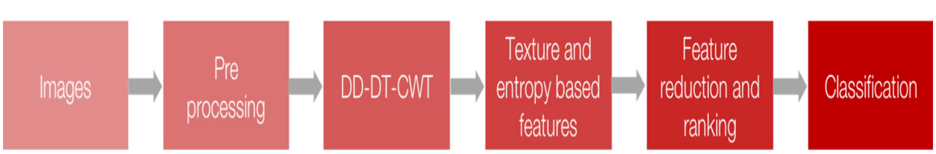

Fig. 1. The block diagram of the proposed methodology using plantar thermal images to detect diabetic foot (with and without neuropathy).