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# Infrared Dermal Thermography on Diabetic Feet Soles to Predict Ulcerations: a Case Study

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## ABSTRACT

Diabetic foot ulceration is a major complication for patients with diabetes mellitus. If not adequately treated, these ulcers may lead to foot infection, and ultimately to lower extremity amputation, which imposes a major burden to society and great loss in health-related quality of life for patients. Early identification and subsequent preventive treatment have proven useful to limit the incidence of foot ulcers and lower extremity amputation. Thus, the development of new diagnosis tools has become an attractive option. The ultimate objective of our project is to develop an intelligent telemedicine monitoring system for frequent examination on patients' feet, to timely detect pre-signs of ulceration.

Inflammation in diabetic feet can be an early and predictive warning sign for ulceration, and temperature has been proven to be a vicarious marker for inflammation. Studies have indicated that infrared dermal thermography of foot soles can be one of the important parameters for assessing the risk of diabetic foot ulceration. This paper covers the feasibility study of using an infrared camera, FLIR SC305, in our setup, to acquire the spatial thermal distribution on the feet soles. With the obtained thermal images, automated detection through image analysis was performed to identify the abnormal increased/decreased temperature and assess the risk for ulceration. The thermography for feet soles of patients with diagnosed diabetic foot complications were acquired before the ordinary foot examinations. Assessment from clinicians and thermography were compared and follow-up measurements were performed to investigate the prediction. A preliminary case study will be presented, indicating that dermal thermography in our proposed setup can be a screening modality to timely detect pre-signs of ulceration.

**Keywords:** Diabetic Foot Ulceration, Pre-Ulceration Detection, Telemedicine, Temperature, Infrared Imaging, Dermal Thermometry

## 1. INTRODUCTION

Diabetes Mellitus (DM) is one of the most common chronic disease worldwide and continues to increase in population and significance. There were 194 million people suffering from DM worldwide in 2004,<sup>1</sup> and this number is expected to grow to 439 million by 2030.<sup>2</sup> Vascular and neurological disorder in lower extremities is one of the common complications with DM. Approximately 15% to 25% of patients with DM eventually develop foot ulcers.<sup>3</sup> If not adequately treated, these ulcers may lead ultimately to total (or partial) lower extremity amputation. Approximately, foot ulceration causes 85% of all lower extremity amputations in patients with DM.<sup>4</sup> The onset of diabetic foot ulcers may be prevented by early identification and subsequent treatment of pre-signs of ulceration, such as callus formation, redness, fissures, and blisters. However, early identification depends on

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frequent risk assessment, which is not always possible. Self-examination is difficult or impossible, due to the consequences of DM, and it is costly and not feasible to do frequent examination by health care professionals.

Thus, any initiative that may overcome these limitations, contribute to automated detection of the early warning signs, and be non-invasive, non-interactive and easy in use should be supported and implemented in diabetic foot care.<sup>5</sup> As to the knowledge of the author, there are four different imaging techniques that are used in detecting these pre-signs of ulceration to predict the diabetic foot ulceration, which are thermal imaging, foot sole scanning, photographic imaging, and hyperspectral imaging.<sup>6</sup> Among the four techniques, foot sole scanning requires patients to press the foot against the scanner, which will cause some unwanted pressure on the foot sole. Thus, a non-contact foot scanner is desirable to obtain a better view of the foot skin.

Pre-signs of ulceration in diabetic foot include redness, increased local skin temperature,<sup>5</sup> thickening of the skin, fissures, blisters and abundant callus formation, all of which are physical features that enable a physician to diagnose the foot and to locate risk areas.<sup>7-9</sup> Increased temperature can be obtained by thermal measurement and the physiological parameters, such as thickening of the skin and the skin spectral properties, can be achieved by hyperspectral image analysis. Besides, 3D surface reconstruction is also essential for detecting the pre-signs, which can reveal the local 3D deformations of the skin surface, and then provide the information about the surface textures. These textures are either caused by geometrical variations of the surface (e.g. papillary lines, fissures, abundant callus) or by radiometric variations (i.e. pigment variations).<sup>6</sup>

The ultimate objective of our project is to develop an intelligent telemedicine monitoring system that can be deployed at the patients' home environment for frequent examination of the patients' feet, to detect pre-signs of ulceration in a timely manner. As the first step, an experimental setup consisting three modalities, which are thermal imaging, hyperspectral imaging and photometric imaging was built.

The study presented in this paper will focus on the preliminary analysis on the acquired thermal images with our setup to show the potential of using thermal imaging to detect the local temperature increase. An IR thermal camera, FLIR SC305, is used to record the temperature distribution of patients' foot soles. The acquired thermal images are then analyzed to detect the abnormalities.

The rest of this paper proceeds as follows: in the next section, an overview of thermal measurement in diabetic foot will be given. The experimental setup and the methodology in thermal image analysis will be presented in Section 3. Results and discussion follow in Section 4. Finally, Section 5 presents the conclusions.

## 2. RELATED WORK

Diabetic foot ulcerations are invariably preceded by inflammation, presence of infection and pain.<sup>10</sup> However, in the early stage of wounds developing, patients with DM can hardly feel pain because of neuropathic sensory loss. On the other hand, inflammation can be easily identified by temperature assessments of the affected foot.<sup>11</sup> Thus, temperature assessment seems to be a useful predictive sign of foot ulceration and subclinical inflammation of the foot.<sup>12</sup>

Researches show that there is a relationship between increased temperature and foot complications in diabetes. Temperature increasing may be detected up to one week before a foot ulceration forms. Foot temperatures vary between patients and depend on ambient temperature and level of activity.<sup>12</sup> Therefore, a standardized reference is required for defining 'increased temperature'. The most common used criterion is as follows: if the temperature difference of the corresponding area of the right and left foot is more than 2.2°C, there is a high risk of infection or ulceration on the diabetic feet.<sup>5,13</sup>

Pilot studies indicate that the incidence of foot ulcerations could be reduced by timely treatment, whereby the lower amputations.<sup>5</sup> The technologies that have been used for temperature assessment to diagnose of foot problems fall in three categories: *a*) dermal infrared (IR) thermometer (local measurement),<sup>5,13</sup> *b*) liquid crystal thermography (LCT),<sup>14,15</sup> and *c*) traditional IR camera systems.<sup>16,17</sup> Among these three categories, only the handheld dermal IR thermometers have been validated by randomized controlled trials for preventing diabetic foot ulceration recurring in the home-based environment.<sup>5,13</sup> However, the demerit of this technology is that the temperature is measured only on specific spots manually, which makes it subjective and impossible to get the temperature distribution of the whole foot. The contact and low-cost LCT has attracted more and more

attention in this area. However, the non-contact traditional IR camera was chosen for our research because of its advantages over LCT as follows. First of all, non-contact of feet is required to prevent un-wanted pressures and the transmission of the pathological organisms.<sup>18</sup> The temperatures of non-contact foot area, such as the medial arch, can be easily measured. Additionally, it is capable of measure the dorsal side of the foot for the future development.

### 3. MATERIALS AND METHODS

An experimental setup, consisting of an IR camera FLIR SC305, was built as shown in Fig. 1. The camera has a resolution of  $320 \times 200$  pixels and is placed at a distance of 860 mm so that it provides a sampling resolution on the foot soles of about 8 pixels per centimeter. A set of six thermal reference elements is mounted in the field-of-view of the thermal camera, above and below the foot positions. These reference elements are heated to different, constant temperatures in the range expected for the foot soles and serve as long-term reference of the absolute temperatures. Within 1 second of acquiring a thermal image their temperatures are measured via built-in calibrated PT1000 resistors are read out by the control software and stored together with the image. Prior to the clinical tests, the uniformity of the thermal camera response was characterized. The minimal temperature difference that can be measured between corresponding locations on the soles of the left and the right foot is  $\pm 0.25\text{K}$  for  $4 \times 4$  pixel areas (circa  $5 \text{ mm} \times 5 \text{ mm}$ ).

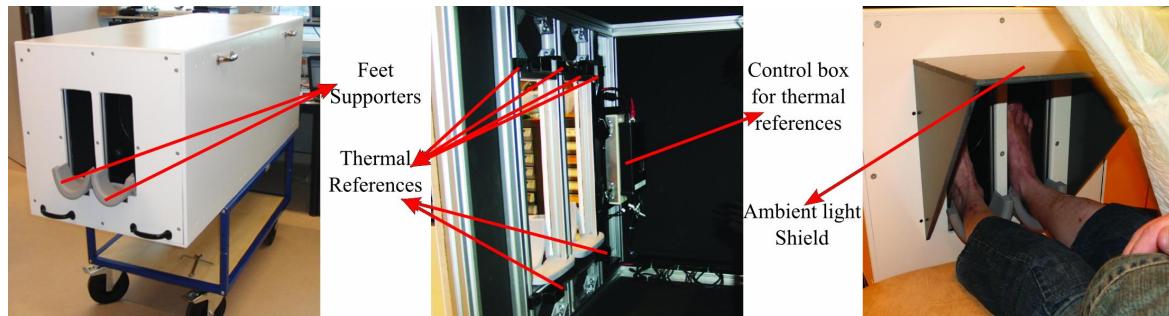


Figure 1: The experimental setup for foot scanning and measurement with it. The blocks on the top and bottom of the images are the thermal references.

Patients were recruited from the multidisciplinary diabetic foot clinic of the Hospital Group Twente, Almelo, the Netherlands. The patients included in this study are all diagnosed with diabetes and showed (pre-signs of) ulceration or have a history of ulceration.

All the patients were asked to remain in a seated position with bare foot for 5 -10 minutes before the measurements. This can help to achieve equilibration with the contrast ambient temperature. The feet are placed into the right position with the help of clinicians. Hospital cloth and black cloth are draped over the shield of the setup and the lower legs to block external light sources and provide a homogeneous background.

For each patient who participated in this project, a live assessment form of the feet soles was filled by clinicians. The live assessment will be used for inspection of the automatic abnormality detection with the thermal images in the post-processing stage.

#### 3.1 Methodology

The acquired thermal images are analysed as shown in Fig. 2 to identify the abnormality. These steps are implemented with MATLAB platform, described as follows:

##### (1) Foot Segmentation

Extract left and right foot from the background in the acquired thermal images.

##### (2) Feet Registration

Register the left and right foot based on the contours of the feet so that corresponding points on left and right foot can be compared.

### (3) Abnormality Detection

Compare the pixel values of the left and right feet to determine whether there is risk of the abnormality .

At this moment, we also added a step for checking whether the resulted segmentation is satisfactory or not. If not (too over segmented or inadequately segmented), the foot contour will be manually labeled to accomplish the segmentation.

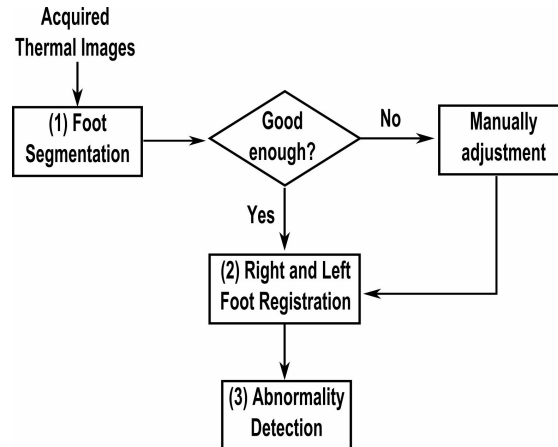


Figure 2: The flowchart of the methodology for thermal image analysis.

### 3.2 Foot Segmentation

Foot segmentation is an important step in the proposed methodology, and presents several challenges. First of all, some patients have feet or parts of the feet with low temperatures, which is close to the ambient temperature (Fig. 3b). Sun et al.<sup>16</sup> indicated that the temperature of the medical arch was the highest and that of the lesser toes was the lowest in healthy and some of the patient population. Thus, for thermal images of such feet, it is difficult to extract the foot area from background, especially for the toes. Second, the radiation from the ankles and legs are visible (Fig. 3c), which also increases the difficulty of segmentation. Besides, these radiation could increase the background temperatures. Although cloth was used to eliminate this affect, the patients always likes to rest their feet onto the supporting bars so the ankles were still visible.

Therefore, it is important to find an appropriate segmentation technique for extracting feet from these thermal images. Kaabouch and colleagues<sup>17</sup> implemented and evaluated five groups of auto-thresholding techniques, which are histogram shape-based methods, clustering-based methods, entropy-based methods, object attribute-based methods and complex genetic algorithms. They found genetic algorithms provided better results than

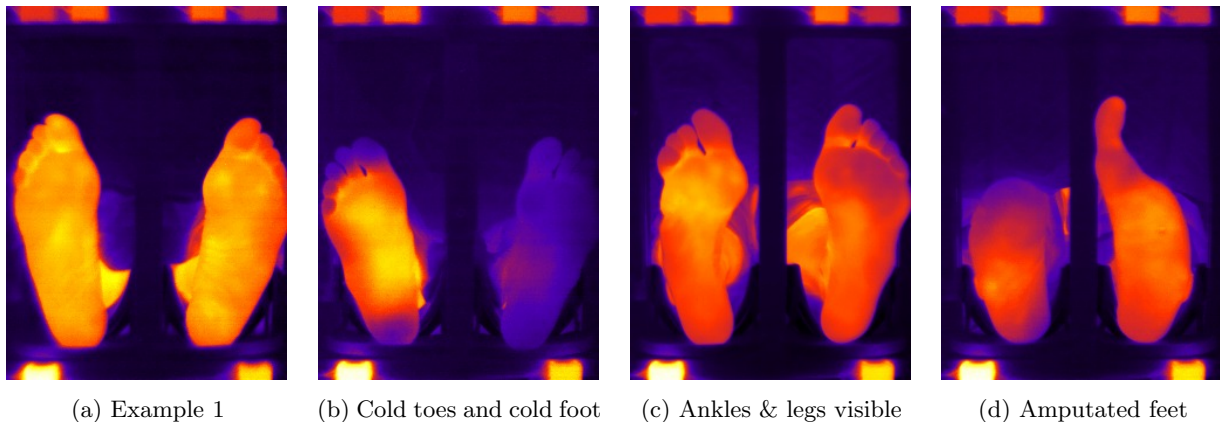


Figure 3: Examples of acquired thermal images.

the other implemented images. We also implemented these methods for our acquired images, yet none of them provides satisfactory results, especially for images like Fig. 3b and Fig. 3c. The reason may be that there is no clear intensity difference between the foot and the surroundings.

In this paper, the segmentation method implemented was active contours without edges (ACWE),<sup>19</sup> which is a region-based method, which will be introduced briefly later.

To make the segmentation easier and eliminate the noise between feet, the images are separated with the help of the bars between the left and right foot. Image segmentation is done separately for each foot. Besides, we also enhance the higher temperatures, before segmentation, with the following equations:

$$I_{inv} = \max(I) - I; \quad I_{en} = I - I_{inv} \quad (1)$$

where  $I$  represents the input image intensities,  $I_{inv}$  is the inverse of the input image intensities, while  $I_{en}$  is the image intensities that has been enhanced.

### 3.2.1 Active Contours Without Edges

Edge detections based on active contour models (ACMs) have been extensively applied for image segmentation. Compared with the conventional edge detection methods, ACM have the following significant advantages: a) The ACMs can allow incorporation of various prior knowledge, such as shape and intensity distribution; b) the ACMs can achieve sub-pixel accuracy of the object boundaries; c) the ACMs can provide smooth and closed contours, which can avoid the post processing in traditional edge detection models.

There are two categories of ACMs, which are edge-based and region-based. The first uses local edge information to guide the contour searching towards the object boundaries, while the other utilizes the image statistical information and has better performance over the edge base ACMs.<sup>20</sup> Nowadays, one of the most popular region-based models is ACWE model. The ACWE model is a simplified piecewise-constant Mumford-Shah model. Let  $\Omega \subset \mathbb{R}^2$  be the image domain and  $I : \Omega \rightarrow \mathbb{R}$  be the given gray level image. The variable  $(x, y)$  in  $I(x, y)$  is a point in  $\Omega$ .  $C = \partial\omega$ , with  $\omega \subset \Omega$  being an open subset. Let  $\Omega_1 = \omega$  (regions outside contour) and  $\Omega_2 = \Omega/\omega$  (regions inside contour), and two unknown constants  $c_1$  and  $c_2$ , which denote the image intensities in  $\Omega_1$  and  $\Omega_2$ , respectively, the contour can be found by minimizing the following energy function:

$$E = \mu L_C(C) + \nu A_{\Omega_2}(C) + \lambda_1 \int_{\Omega_1} |I(x, y) - c_1|^2 dx dy + \lambda_2 \int_{\Omega_2} |I(x, y) - c_2|^2 dx dy \quad (2)$$

where  $\lambda_1, \lambda_2 > 0$ ,  $\mu, \nu \geq 0$  are fixed parameters;  $L_C(C)$  and  $A_{\Omega_2}(C)$  represent the length of the contour and the area of the regions inside the contour, respectively. The last two items in the above equation are called the global data fitting energy.<sup>19</sup>

With level sets,<sup>21</sup> representing the contour  $C$  with zero level set  $C = \{x, y \in \Omega \mid \phi(x, y) = 0\}$ , the solutions obtained by minimizing Eq. 2 is:

$$\begin{cases} c1(\phi) &= \frac{\int_{\Omega} I(x, y) H_{\varepsilon}(\phi(x, y)) dx dy}{\int_{\Omega} H_{\varepsilon}(\phi(x, y)) dx dy} \\ c1(\phi) &= \frac{\int_{\Omega} I(x, y) (1 - H_{\varepsilon}(\phi(x, y))) dx dy}{\int_{\Omega} (1 - H_{\varepsilon}(\phi(x, y))) dx dy} \\ \frac{\partial \phi}{\partial t} &= \delta_{\varepsilon}(\phi) \left[ \mu \operatorname{div} \left( \frac{\nabla \phi}{|\nabla \phi|} \right) - \nu - \lambda_1 (I(x, y) - c_1)^2 + \lambda_2 (I(x, y) - c_2)^2 \right] \end{cases} \quad (3)$$

where  $H_{\varepsilon}(\phi(x, y))$  and  $\delta_{\varepsilon}(\phi)$  are regularized versions of the Heaviside function and the Dirac function, respectively:

$$\begin{aligned} H_{\varepsilon}(\phi) &= \frac{1}{2} \left[ 1 + \frac{2}{\pi} \arctan\left(\frac{\phi}{\varepsilon}\right) \right] \\ \delta_{\varepsilon}(\phi) &= \frac{1}{\phi} \frac{\varepsilon}{\varepsilon^2 + \phi^2} \end{aligned} \quad (4)$$

### 3.3 Left and Right Foot Registration

The abnormality in the proposed method is identified by comparing the temperatures of the corresponding points on the left and right foot. However, the feet in the thermal images are hardly at symmetric position. And there are usually deformations due to DM or amputations. Therefore, the left and right foot need to be registered with each other.

Image registration is a process for determining the correspondence of features between images collected at different times or using different image modalities. The correspondences can be used to change the appearance of the object by rotating, translating and scaling. The image registration techniques fall into two categories, which are rigid and non-rigid methods. When using the rigid method, the registration between the images are assumed to be achieved by rotating and/or translating with respect to each other. On the other hand, nonrigid method assumed that the correspondences can not be achieved without localised scaling of the images, due to biological differences or imaging acquisition or both.<sup>22</sup>

Suppose we have two images  $I_l(x, y)$  and  $I_r(x, y)$ , The goal of the registration for these two images is to find the transformation  $T$  to make

$$I_r(x, y) \simeq I'_l(x, y) = T(I_l(x, y)) \quad (5)$$

For the study, the B-spline grid, non-rigid point-based registration proposed by Klein et. al<sup>23,24</sup> was implemented.

Based on the segmentation done, 300 corresponding points on each contour of left and right feet are extracted, except for the centroid and the furthest points on the heels. Most of the points are located surrounding the heels to avoid the area where deformation most likely happened. All the extracted contour points are used as landmarks to calculated the displacement and the transformation.

### 3.4 Abnormality Detection

Once the registration is done, geometric transformation will be done to right foot to make the pixels on it are corresponded with pixels on the left foot. The spots at risk will be identified simply by subtraction between the corresponding pixel values from the left and right foot. The threshold we use for abnormality detection is: if the temperature difference of the corresponding area of the right and left foot is more than  $2.2^\circ\text{C}$ , there is a high risk of infection or ulceration on the diabetic feet.<sup>5,13</sup> This is the most common and the only criterion which has been clinically validated for determining abnormality on diabetic foot.

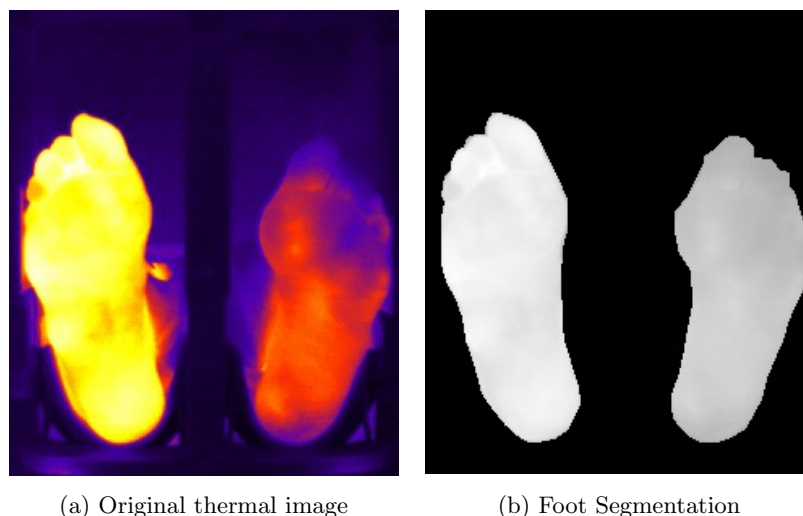
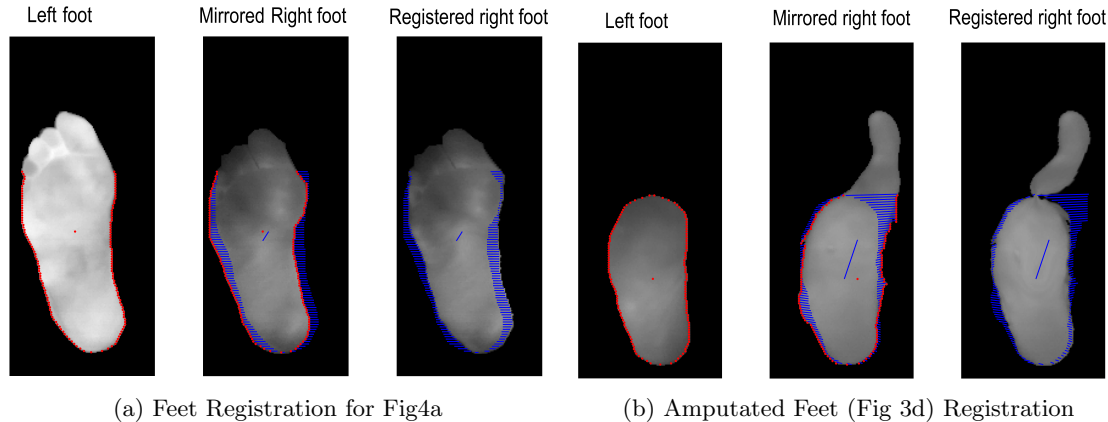


Figure 4: Examples of original thermal images without the thermal references and segmentation results. The left foot was presented in the left of the thermal image.

## 4. RESULTS AND DISCUSSION

An example thermal image (Fig. 4a) and the segmentation result of the example (Fig. 4b) are given. For the thermal images like the left foot in Fig. 4a, where only small part of the ankle are captured and the foot has clear edges from the background, the ACWE model can easily get a satisfactory result. Although the small part of ankles may still be detected, post-processing can easily remove it automatically. However, for images those have the similar temperature distribution as that shown in Fig. 3c (large parts of ankles or legs), and the left feet in Fig. 3b and Fig. 4a (no clear boundaries from the background), some of them (7 among 20 measurements analysed so far) still need the manually segmentation. The segmentation error may result from a intrinsic disadvantages that the algorithm can be easily affected by the initial position of the contours and the noises in the images. To solve this, shape-based segmentation methods might be options, such as Active shape Model and Active Appearance Model, which have advantages over ACWE models in finding contours in noisy images.

The registration results are shown in Fig. 5. We always make the left foot as the static one and try to transform the right foot on to it. As shown in Fig 5b, the B-spline grid, non-rigid point registration method works pretty well, even for foot with large deformation. Thus, we can conclude that this registration technique is suitable to register the feet with whatever shapes, sizes and positions, once the contours are well detected.



(a) Feet Registration for Fig4a

(b) Amputated Feet (Fig 3d) Registration

Figure 5: Examples of segmentation results with different techniques. The red dots represents the landmarks on the feet contours and the blue lines illustrate how the displacement moves.

Examples of possible future clinical application of thermal images are shown in Fig. 6. By calculating the temperature difference between the left and the right foot, taking  $2.2\text{ }^{\circ}\text{C}$  as a clinically relevant difference,<sup>5,13</sup> (pre-)signs of ulceration can be automatically detected. The first example, patient 01 (figure 6a), shows a patient with an infected ulcer on his left foot. This results in a much higher temperature in the infected area, which can be automatically detected by thermal imaging. The second example, patient 02 (figure 6b), is a patient with a diagnosis of an active Charcot foot. This is reflected in the thermal image by the large difference between the left and right foot, more than  $2.2\text{ }^{\circ}\text{C}$  on any part of the feet. Thermal imaging may be used for this patient in the follow-up, to see if the Charcot foot it still active. When the temperature difference between both feet is smaller than  $2.2\text{ }^{\circ}\text{C}$ , the next phase of the treatment can start.<sup>4</sup>

## 5. CONCLUSION AND FUTURE WORK

In this contribution, an experimental setup was build with an IR thermographic camera was built. A methodology was proposed for detecting the abnormality on diabetic foot with the acquired thermal images. The left and right foot was extracted with ACWE model from the background. The model works well so far, although manual adjustment is still needed for some feet with cold toes and visible ankle. The registration between left and right foot, based on foot contours, presents fairly good results, no matter the shapes, locations or positions of the feet. Through the preliminary analysis presented here, we have proven the feasibility that the images acquired



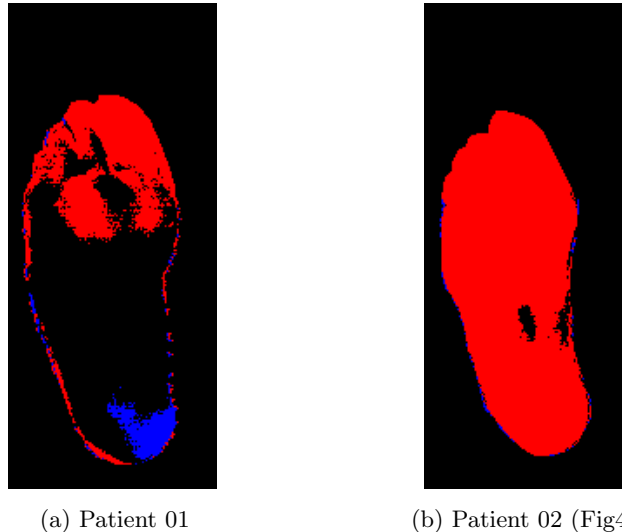


Figure 6: Examples of abnormalities identification results. According to the live assessment done by clinicians, the red part in Fig. 6a is ulceration and redness. Red color means the temperature on the left foot is  $2.2^{\circ}\text{C}$  is higher than that on the right. The inverse status is presented by blue color.

through our experimental setup can detect the (pre-)signs of ulcerations as well as other complications of the diabetic foot, which is associated with temperature changes.

Due the fact the the foot usually has a lower temperature than the other body part, when the other body parts visible in the thermal images, e.g the legs and ankle, the segmentation work for extracting the feet from the background still remains a difficult task. Besides, the low temperature of the toes also increase the segmentation difficulties. In the future, we can try the shape-based model and also enhance the shielding of these radiations to solve the problem.

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