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Experimental modelling of heat generation in porcine tissue to investigate the etiology of diabetic foot ulceration

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Abstract

Diabetic foot ulceration is a major complication of diabetes. A recent systematic review has concluded that an increase in skin temperature is associated with a higher risk of diabetic foot ulceration. However, the mechanism of the rise of foot temperatures is not understood. In this paper, we examine the effect of viscoelastic heating on the foot temperature by experimentally measuring temperature of porcine tissue during cyclic loading. We show that the heat generated in the tissue increases with amplitude and frequency of loading. This viscoelastic heating may contribute to changes in foot tissue temperature.

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Keywords: Diabetic foot ulceration; heat; temperature; modelling; simulation

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1. Introduction

Diabetic foot ulceration is a major complication of diabetes. Approximately 7% of people who have diabetes have foot ulcers [1]. Delay in treatment of foot ulcers may cause infection which results in severe complications like amputations [2] and psychological stress. Early identification of diabetic foot ulcers enables more effective management, improved outcomes and ultimately a better quality of life [3].

The main way in which ulcers are detected is by visual examination of the foot – at-risk patients are asked to examine their foot daily and go to a foot clinic in case there are any problems in the feet [4]. Regular visits to a foot clinic – every month to once in 6 months depending on the risk – are advised [4]. However, self-examination is not very effective due to low compliance, visual and other concomitant health problems due to diabetes and lack of training [5].

Parameters including elevated plantar pressure, blood flow to the foot, peripheral neuropathy, duration of diabetes, foot deformities, history of prior amputation etc. are known to be risk factors for diabetic foot ulceration [6,7]. It has also been

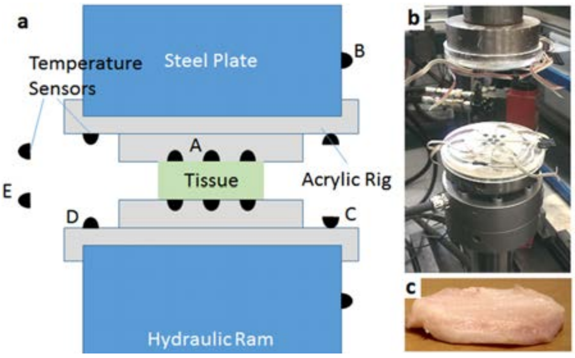

Fig. 1 **a**. The experimental setup that we used to load the porcine tissue (belly pork). The steel plates are a part of the hydraulic dynamic test rig (Instron Mass, USA). 16 temperature sensors (TMP35, Analog Devices) were used to measure the temperatures. 8 temperatures sensors (Sensors A) were used to measure the temperatures of the top and bottom of the tissue. Two sensors (D) measured the temperature of the acrylic plate. Two sensors (B) measured the temperature of the steel plates. The ambient air temperature was measured near the tissue by two sensors (C) and far away from the tissue by two sensors (E). **b.** The Instron hydraulic testing rig along with the acrylic plates having the temperature sensors to measure tissue temperatures. **c**. A tissue disc used for testing.

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suggested that the temperature of the foot may be a marker for ulceration. A difference of 2^0C or more between the same locations of the two feet is a predictor of ulceration in the foot with the higher temperature [8].

We have been investigating how the temperature of the foot changes as healthy people walk using an in shoe temperature measurement device with a view to improving the scientific understanding of the etiology of diabetic foot ulceration. The study found that the temperature of the foot could increase by up to 10^0C while walking in healthy participants [9,10]. In people with diabetes impaired circulation is likely to reduce the ability to regulate temperature.

There is no information concerning the mechanisms of rise of foot temperatures even in healthy participants. Our hypothesis is that foot circulation, muscle activity and viscoelastic heating affect foot temperature. In this paper, we examine the effect of viscoelastic heating by experimentally measuring the temperature of porcine tissue during cyclical normal loading (as an animal model for human plantar tissue [11]).

2. Methods

2.1. Experimental Method

Porcine tissue samples - 'belly pork' – were bought at the local butchers and cut into discs of 30 mm diameter using a circular punch. They were used the same day when they were bought (the tissue was used less than 2 days after slaughter). The tissue was cut such that it had skin and fat only. We removed the muscle tissue as much as possible (see Fig. 1c). The thickness of the tissue was variable – between 3.6-9.6 mm, which reduced to 3.5-8.5 mm after loading.

The tissue discs were loaded cyclically, using a dynamic hydraulic testing rig which was controlled using Labtronic 8800 controller (Instron Mass, USA), for a period of one hour. The discs were compressed between two flat steel plates at five different frequencies (0.5, 1, 1.5, 2 and 2.5 Hz) and three different load amplitudes (200, 500 and 750 N). There are 15 amplitude/frequency conditions which were run 3 times to give 45 trials.

A total of 16 temperature sensors (TMP35, low voltage, precision centigrade temperature sensors from Analog Devices) were used to monitor the temperature of the tissue and the ambient environment (see Fig. 1). Eight sensors embedded in an acryclic base monitored the temperature of the bottom and top surface of the tissue – four for each surface. The remaining eight sensors monitored the environment – two sensors monitored the temperature of the top and bottom acrylic plates, two the top and bottom steel plates, and four sensors measured the air temperatures near the tissue and far from the tissue.

The temperature data was recorded using a myRIO – a reconfigurable data acquisition device from National Instruments – at a sampling frequency of 100 Hz and stored in a USB memory drive. The temperature data and the mechanical data (recorded by the Instron software) were exported and analyzed in MATLAB software (Mathworks Ltd.).

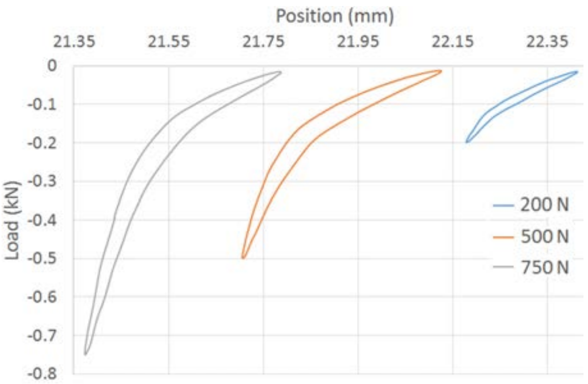

Fig. 2 One cycle of compression and relaxation for different amplitudes of loading showing the hysteresis and, hence, mechanical energy lost in the tissue. The curves are shown for loading while the tissue was loaded at a frequency of 1 Hz. The position is measured as the separation between the top and bottom steel plates.

2.2. Mechanical Load Analysis

Each cycle of compression and relaxation during cyclic loading produces a hysteresis curve (see Fig. 2). The area between the curves shows us the mechanical energy that is lost in the tissue per cycle. We can calculate the heat generated in the tissue per cycle, if we assume that all this mechanical energy is converted to heat. Using the Instron software (Wavematrix 1.8) we recorded the hysteresis curves for the last 1000 cycles of the loading test. The position and the load data were recorded at a sampling rate of 100 Hz. Average heat generated was calculated, from these 1000 cycles, for each experimental run. The average heat generated was normalized for volume of the sample.

2.3. Temperature Measurement Analysis

The tissue temperature was calculated as the average of the sensors embedded in the acrylic to measure the top and bottom surface temperatures of the tissue (sensors A in Fig. 1A). The ambient temperature was the average of the two sensors measuring the air temperature near the tissue (sensors C in Fig. 1A).

3. Results

3.1. Mechanical Loading

In Fig. 2, we show a plot of one cycle of loading and unloading for the three different loads (200, 500, 750 N) at 1 Hz.

The average heat generated per unit volume (in μJ/s/mm^3) during 1 hour of cyclic loading at different amplitudes and frequencies are shown in Fig. 3. It can be observed that the heat generated increases with increasing load amplitude and frequency.