ORIGINAL PAPER

TEMPERATURE DISTRIBUTION ON CENTERS OF INFLAMMATION AT ANKLE FRACTURES

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Abstract

Shortly after the injury process, a swelling of the soft skin tissue in the fracture area is formed, often preventing an immediate operation of the fracture. Our work aims for reducing the swelling and to accelerate the swelling decline. This is achieved by considering the spatial distribution of inflammation and applying mild local hyperthermia. Therefore it is necessary to investigate how the inflammation has spread out nearby the fracture tissue. In order to locate the focus of inflammation, a time-dependent monitoring with a temperature sensor mat is necessary. Temperature sensors should be arranged in a netlike style in order to measure a skin area as large as possible under the support bandage. The spatially optimal necessary distance between the sensors is determined by analyzing and evaluating temperature gradients on infrared images of ankle fractures.

Keywords*: hypothermia, infrared imaging, quantization, reduction of swelling, size of shoem, temperature sensors*

Introduction

Problem: Fracture swellings

Ankle and wrist fractures are among the most common injuries in traumatology. They are classified as extremity fractures, which have the highest incidence (80 %) in relation to the totality of all fractures [3]. Shortly after the injury process, a swelling of the soft skin tissue in the fracture area is formed. In addition to local heating of the skin temperature, swellings indicate an inflammation after Celsus and Galen [10].

Due to this distinctive swelling, an operation of the fracture cannot be done immediately. The reduction of the swelling varies, taking 7 to 14 days in general [3]. Increased treatment costs, longer times of work absence and pain periods for the patients are the consequence of the delayed surgery.

Solution: Physiological adapted cooling

By applying mild local hypothermia under the support bandage, swellings around fracture areas can be reduced and their increase prevented. Previous systems for the reduction of the swelling by means of hypothermia are based on hydraulic systems with ice cube cooling or fixed, not individually adapted temperatures [1,2]. However, no physiologically adapted cooling can take place. Therefore we want to create a system with adaptive cooling that reacts to the physiological characteristics of the thermoregulation of the human. This requires knowing how the inflammation has spread out nearby the fracture tissue, which so far has not been investigated.

Requirement: Temperature sensor mat

Conventional temperature measurement methods, such as the use of infrared cameras, are not usable because, for example, the support bandage prevents the measurement of inflammation due to its low thermal conductivity. It would have to be removed in order to carry out a measurement. Instead, a temperature sensor mat for use under the support bandage is required. By analyzing infrared images of ankle fractures, the spatially optimal necessary distance of the temperature sensors is determined in order to realize a targeted temperature control.

State of the art

Previous researches in the field of the detection of centers of inflammation with infrared images have been related to temperature changes of individual inflamed body or skin areas during therapy [13] or have been used to diagnose various disease symptoms [11,12]. A temperature sensor mat for long-term use on the patient has not yet been designed in this way.

To the best of our knowledge, our work investigates for the first the spatial distribution of any inflammation by using a novel temperature sensor mat [8,9]. This enables us to apply targeted cooling and, thus, significantly reduce the swelling.

Contributions

The contributions of this paper are to provide an analysis about the distribution of the temperature in the area of an ankle fracture and the optimal distance between temperature sensors on an associated temperature sensor mat. This allows the development of a temperature sensor mat with optimally arranged sensors relating to possible inflammation spots at fracture areas.

Materials and methods

Inflammation reaction and swelling reduction

If human tissue is injured, the body tries to remove toxins and pathogens from the affected tissue cells with an immune reaction and to create conditions for a repair process. Regarded locally this is called an inflammatory reaction. It is characterized by the typical five inflammatory characteristics redness, warming, swelling, pain and limited function [7]. The temperature rise of the injured tissue is caused by increased metabolic activity and amounts approximately 2 to 5°C [14]. On the basis of the increased temperature, a possible swelling can be concluded.

In order to reduce the swelling and to accelerate the swelling decline, we analyzed the effect of mild local hypothermia (tissue cooling) first. A temperature decrease of 10 K results a reduction of the metabolic rate of about 50 % [4]. Through the resulting reduced energy consumption and the associated decrease of the oxygen demand for the metabolism in the fracture area, there is an adaption to the posttraumatic reduced local oxygen supply in the tissue, which is due to the bleeding in the fracture area. The local hypothermia reduces the metabolism as well as the blood circulation and leads to a decrease of the posttraumatic swelling or prevents their formation by inhibiting the local inflammatory response. Thereby the physician is able to carry out the operation contemporarily. Through an extracorporeal targeted regulation of the temperature at the fracture area after the operation, the self-healing powers of the body can be exploited in order to run an extenuated inflammatory response in the corresponding tissue consciously.

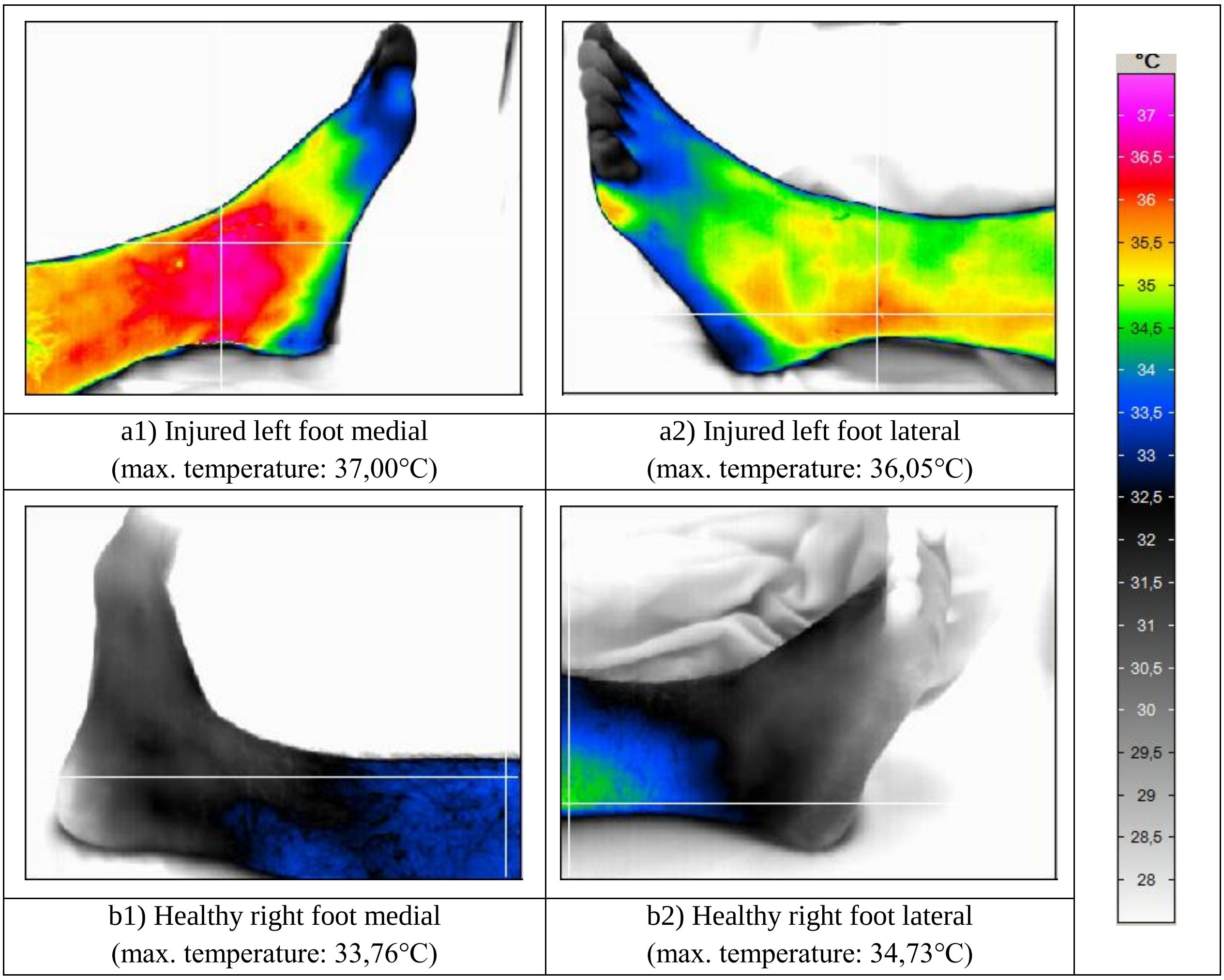
Planning of the temperature sensor mat

In order to insert the hypothermia, the local distribution of the inflammation at the fracture site must be known. A temperature sensor mat adjusted to the anatomy should be used enabling a continuous, plane measuring process. The temperature sensors are arranged in a network structure, allowing the microcontroller to detect the center of the inflammation. Following the definition in [14], inflammations exist when the skin temperature has a difference of 2 K to the temperature of the surrounding skin tissue.

For development of such temperature sensor mats few parameters needs to be determined, for example the number of necessary sensors. This is done by determining the spatially optimal necessary distance between two temperature sensors by considering the gradient of the temperature distribution at fracture sites.

Recording infrared pictures

Therefore we evaluate pictures with an infrared camera of the type VarioCAM in the software IRIBIS 3.0 professional. The camera has a temperature resolution of < 0.05 K between 0 and 100°C in the spectral range of wavelengths from 7.5 to 14 µm [5]. The analysis is executed at the fracture with the largest temperature gradient from the totality of all the available infrared images from ankle fractures. Figure 1 a1) and a2) show pictures of a Pronation-Eversion Fracture Stage IV according to Lauge-Hansen (PE IV) [6] at the left foot on the third postoperative day from two different perspectives. The CRP value of the patient, a nonspecific inflammatory parameter, had an amount of 19.6 mg/l on the second postoperative day, which is 9.6 mg/l higher than the normal value of a healthy adult. For comparison in Figure 1 b1) and b2) pictures of the healthy right foot of the same patient in the same color scale with the name “Weiß / Schwarz / VarioCAM” are presented. A white reticle illustrates the pixel with the maximum temperature in the respective area (Pixel 0). The pictures are taken at a room temperature of 25°C. Since the tested patients were not affected in any way by the infrared recordings in their healing process or their person, all standards of ethical conduct of research were respected. Recordings were only performed with permission of the patient. The data material has been encrypted.



a1) Injured left foot medial (max. temperature: 37,00°C)

a2) Injured left foot lateral (max. temperature: 36,05°C)

b1) Healthy right foot medial (max. temperature: 33,76°C)

b2) Healthy right foot lateral (max. temperature: 34,73°C)

Figure 1 - Infrared images of both feet of a patient with a left-sided PE IV fracture

Division with measurement lines for evaluation

For evaluation of the most pronounced temperature profile on the inner side of the injured foot, straight lines with the designations L1 to L12 are arranged clockwise at an offset of 30° starting from the pixel with the maximum temperature. Figure 2 shows this arrangement on a color scale display with a distance of 0.25 K between the different colors. Any temperatures below 32°C are blackened because the Region of Interest (ROI) is located only on the skin surface near the fracture site. A strong temperature drop takes place whenever the line leaves the pixels belonging to the skin surface and enters the region with the pixels of the ambient temperature. At this point the evaluation is cancelled because no changes in the temperature occur.

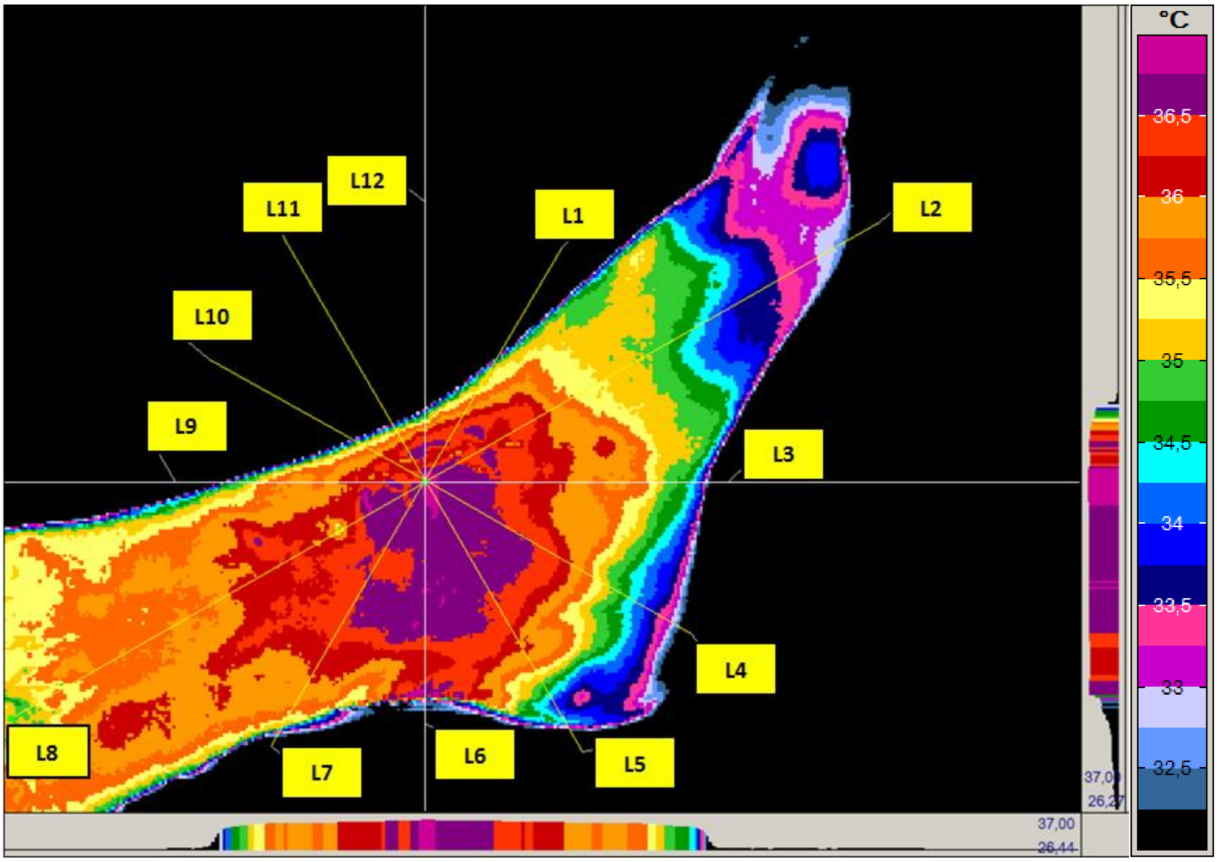


Figure 1 - Colored gradation of the left-sided PE IV fracture medial

Results

Quantization of measurement lines

According to [14], a clarification of inflammation can only be detected by a temperature differences of 2 K, therefore the temperature curves are quantized with a quantization level of Δ = 1 K. Thus, more accurate information can be obtained because several quantization levels can be conducted respectively for two quantization step length over the temperature difference of 2 K (next higher quantization level and considered level and next lower quantization level and considered level). The assignment of the quantization is carried out in Eq. 1.

$$Q(x)=\mathrm{sgn}(x)\cdot\Delta\cdot\lfloor |x|/\Delta \rfloor \quad (1)$$

The infrared images in figure 1 and 2 are pictures of three-dimensional bodies on two-dimensional representations. Therefore an analysis of the spatial temperature distribution is only useful on nearly planar regions of the skin, because this ensures an approximately constant real spatial distance between consecutive pixels on the examined tissue. Because the lines L1 and L10 to L12 run on strongly to the projection plane vertically sloping skin areas, they are not considered in the evaluation. The quantized surface temperature profiles of the lines L2 to L9 are shown in Figure 3. The distance of the considered point to the point with the maximum temperature is represented on the x-axis in pixels.

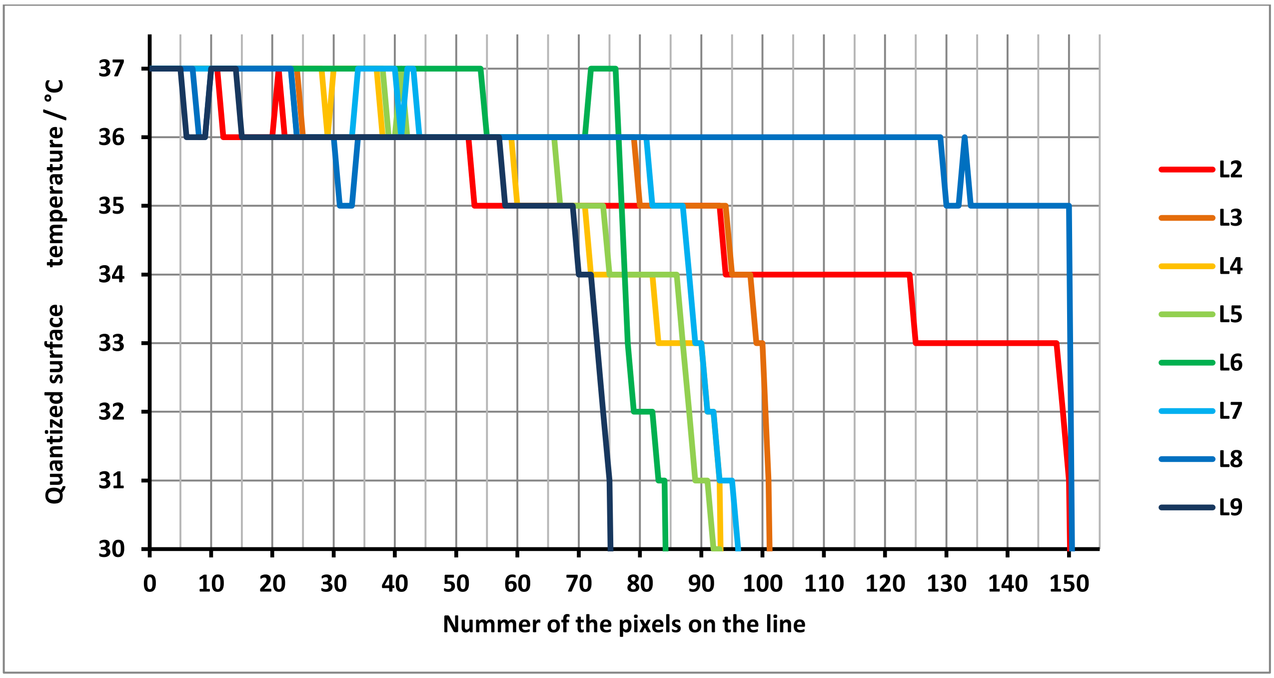


Figure 3 - Temperature profile of the quantized surface temperature with Δ=1 K of the left-sided PE IV fracture medial starting on the pixel with the maximum temperature

Evaluation of the quantized curves

By evaluating the quantized curves, the following conclusions can be drawn:

- Short-term temperature fluctuations that do not exceed a length of 5 px are neglected.
- In order to take the non-planar course of the skin surface nearby the foot edge in the projection into account, the evaluation is carried out only up to a distance of 10 px to the edge of the ROI. Characteristic value-continuous curves, which are not completely shortened through this determination, are neglected.

Looking at the lines L2 to L9, the shortest value-continuous quantization step length can be found over a temperature gradient of 2 K on line L4 over the range of 34°C and 35°C with a length of 23 px. The largest quantization step length over 2 K with a length of 134 px is reached on line L8 over the range of 36°C and 37°C. On average the quantization step lengths over 2 K show lengths of 60 px.

Spatially optimal necessary distance of the sensors

Obviously, the sensor distance is derived from the temperature gradients. For this a conversion of the picture length in px to a person-specific length in mm is necessary, which is achieved by a comparison with the foot length of the patient. The patient has a shoe size SG of 44, which corresponds to a real foot length l_foot of about 27.8 cm according to Eq. 2 referred to the Paris point.

$$SG \approx (l\_foot + 1{,}5) \cdot 1{,}5 \qquad (2)$$

A straight line projected on this foot length with a number of pixels of approximately 258 px indicates a conversion factor of about 1.078 mm/px. A minimum required distance between two temperature sensors amounts 24.794 mm, or about 25 mm, based on a minimum quantization step length of 23 px. If a spatial to the shoe size equally distributed inflammation is assumed at SG≈39 and SG≈30, proportional to SG=44 minimum necessary distances of 22 mm and 17 mm can be presumed.

Discussions

Obviously, the preparation of a temperature sensor mat requires the knowledge about anatomical specificities in the ankle and forefoot area. In accordance with [9], a sensor distance among each other of approx. 23 mm and a distance of approx. 20 mm to the location of a heat sink must be maintained. This makes it possible to develop a temperature sensor mat which is sensibly adapted to the physiological and therapeutic preoperative environment and which has not yet been available on the market for such applications. The temperature sensor mat can be worn under the support band and allows a temporal localization of the focus of inflammation. Thus, the support bandage does not have to be removed in order to recognize the state of the inflammation to know when an operation could be carried out. The presented results can be applied in the fields of orthopedics and accident surgery to design temperature sensor mats for real-time monitoring.

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