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Soraia Carvalho and Ana I. Pereira

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Characterization of Feet Temperature

Soraia Carvalho* and Ana I. Pereira*,†

*Polytechnic Institute of Bragança, Portugal

†ALGORITMI, University of Minho, Portugal

Abstract. In this work it was studied the problem of finding the best approximation to characterize the feet temperature distribution. For this study it was considered the nonlinear optimization, specifically the pattern search method for local optimization and the genetic algorithm method for global optimization. Using these nonlinear optimization methods we were capable to identify the function that fits the data obtained through thermographic images.

Keywords: Nonlinear Optimization. Temperature Distribution. Global optimization.

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INTRODUCTION

Mathematical modeling has been used for the study, analysis and understanding of many problems and real phenomena in various areas such as engineering, economics, medicine, among the others.

In this study, it was used thermal plantar images to support a mathematical model for foot temperature distribution. It was used the nonlinear optimization technique to minimize the square error between the mathematical modeling and the real temperature distribution. The images were obtained by a thermal camera and then applied image processing techniques using the Matlab software and, finally, it was obtained the temperature matrix.

The main idea of this work is to characterize the behavior of the temperature distribution in the healthy foot and in the diabetic foot, and also, verify if there exists differences in the temperature distribution between two types of foot (with and without pathology).

The paper is organized as follows. Section 2 describes the materials and methods used in this study. Section 3 provides some numerical results and the last section presents some conclusions and ideas for future work.

MATERIALS AND METHODS

Protocol

In this study we have images of healthy and diabetic feet. The healthy feet images were recruited from Polytechnic Institute of Bragança. The diabetic feet images were obtained in old people's home Santa Casa da Misericórdia, at Bragança.

The images were collected by a thermal camera (FLIR 365) positioned at a fixed distance of one meter of the patient's feet.



FIGURE 1. Isolation of the feet temperature.

The subjects were guided to keep resting supine position without shoes or socks for ten minutes, before measurement, to stabilize the feet temperature. A rigid foam plate was placed over the ankles to isolate the temperature of feet from the body of the volunteer, as it can be seen in the Fig. 1. The total time of data acquisition process did not exceed fifteen minutes. For more details, please see [1, 2, 3, 4].

Infrared thermography is a technique that aims to measure, in real time, the temperature variation of a specific body location. In our case, this location is the feet. The obtained image has a color variation taking into account the temperature of the skin of the feet. It is through image processing techniques that it is obtained an image with good color contrast [5].

The next figure will demonstrate the difference between the healthy foot and the diabetic foot, represented in thermal images. The diabetic foot and foot ulcers are serious threats to patients and must always be treated. So, this study has the intention to characterize the diabetic foot in order to have a early diagnostic [6].

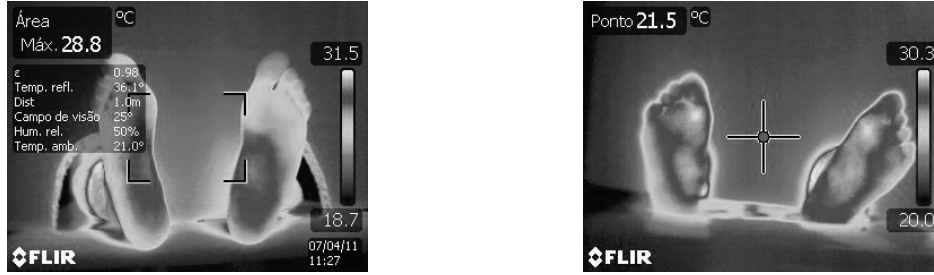


FIGURE 2. Healthy (on the left side) and Diabetic feet (on the right side).

As it can be seen in the Fig. 2, there are a range of colors to represent the feet temperature distribution. In our case, a hot spot color (the clearest spot), corresponds to a high temperature at that location. As the temperature decreases, the spot color will be closer to a cold color (the darkest spot). The objective of this study is to find the best approximation for the data obtained in the matrix of the feet temperature distribution.

Method

Consider the plantar image, l , obtained using a thermographic machine. Each thermographic image, l , was saved in the Matlab software computer, through a matrix temperature, t_{ij} , with size $M^l \times N^l$. For each image l , it was analyzed six different regions presented in the Fig. 3.

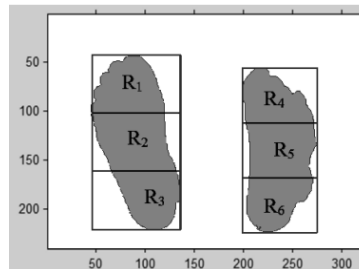


FIGURE 3. Feet regions.

For each region, R_k^l , for $k = 1, \dots, 6$, it was obtained the matrix data with temperature distribution with size $M_k^l \times N_k^l$.

In this study, it was considered five nonlinear functions to characterize the matrix data:

- $f_1(x, i, j) = x_1 \sin^2(x_2 i) + x_3 \cos^2(x_4 j) + x_5 + x_6 \sin(x_7 i) + x_8 \cos(x_9 j)$;
- $f_2(x, i, j) = x_1 \sin^2(x_2 i + x_3 j) + x_4 \cos^2(x_5 i + x_6 j) + x_7$;
- $f_3(x, i, j) = x_1 \sin(x_2 i + x_3 j) + x_4 \cos(x_5 i + x_6 j) + x_7$;
- $f_4(x, i, j) = x_1 \sin(x_2 i) + x_3 \sin(x_4 j) + x_5 \cos(x_6 i) + x_7 \sin(x_8 j) + x_9$;

$$\bullet f_5(x, i, j) = x_1 \sin^2(x_2 i + x_3 j + x_4) + x_5 \cos^2(x_6 i + x_7 j + x_8) + x_9 + x_{10} \sin(x_{11} i + x_{12} j + x_{13}) + x_{14} \cos(x_{15} i + x_{16} j + x_{17}) + x_{18}.$$

The main objective of this work is to identify what function is the best approximation for each region R_k^l , for $k = 1, \dots, 6$. For that, we need to solve, for each function f_w , for $w = 1, \dots, 5$, the following nonlinear unconstrained problem

$$\min \sum_{i=1}^{M_k^l} \sum_{j=1}^{N_k^l} (t_{ij} - f_w(x, i, j))^2 \quad (1)$$

where t_{ij} is the temperature matrix coefficient, (i, j) represent the pixels positions, M_k^l and N_k^l is the matrix dimensions (rows and columns, respectively) associated to the region R_k^l , for $k = 1, \dots, 6$ and $l = 1, \dots, 6$.

To solve the nonlinear optimization problem it was used the local method pattern search (PS) and for the global methods, genetic algorithm (GA) and hybrid genetic algorithm (HGA).

The Pattern Search method (PS) is a direct method that finds a minimum of the unconstrained optimization problem, where the objective function is not necessarily differentiable [7, 8].

The genetic algorithm (GA) is based on a technique of random search that has the aim of finding the global solution. In this case, it was tested the simple version of the genetic algorithm and the genetic algorithm combined with a local search, known as hybrid genetic algorithm (HGA) [9].

NUMERICAL RESULTS

The numerical results were obtained using Intel(R) Core(TM) i7-3517U CPU 1.90GHz with 8.0 GB of RAM.

For this study, it was used three healthy feet images and three diabetic feet images. It was used a random vector as a initial point and each optimization problem was solved ten times.

The following table presents the numerical results, for the local method pattern search (PS) and for the global methods, genetic algorithm (GA) and hybrid genetic algorithm (HGA). It was used the predefined functions in the global optimization toolbox of the matlab software to solve the optimizations problems.

The table presents the average of the best solution obtained for each region and each function.

As we can see, the best mathematical model in studied was the function f_5 , since the best solution is near of zero.

The method that obtain better results was the hybrid genetic algorithm method, however for the function f_1 , the best approximations were always obtained by pattern search method.

For the mathematical models f_1, f_2, f_3 and f_4 there isn't a significant difference in the best solution when compare the data obtained from the healthy and diabetic foot. When analyzed the numerical results obtained with function f_5 , it is possible to conclude that exists significant differences, in some regions, as for example R_1, R_5 and R_6 .

CONCLUSIONS AND FUTURE WORK

In this work it was analyzed some thermal plantar images in order to define a mathematical model for the feet temperature distribution. It was used the nonlinear optimization technique to minimize the square error between the mathematical modeling and the real temperature distribution.

The main conclusion of this work is that the f_5 function approximates the numerical data in a better way. When compared the healthy feet with the diabetic ones, we can see that there are some differences for some feet regions.

As future work it should be tested other mathematical models and nonlinear optimization techniques. Testing other variants of the f_5 function can be another idea for getting better results. This study should be extended by using more thermographic images of healthy and diabetic feet. This study can be also expanded to patients with other types of diseases that affect directly their feet.

TABLE 1. Average of the best solution.

Region	Function	Healthy feet			Diabetic feet		
		Local	Global		Local	Global	
		PS	GA	HGA	PS	GA	HGA
R_1	f_1	4.2E2	2.4E4	1.3E3	4.2E2	2.4E4	1.6E3
	f_2	1.3E3	3.2E4	2.5E2	7.6E2	3.2E4	2.5E2
	f_3	1.6E3	3.6E4	2.0E2	1.4E3	3.4E4	3.4E2
	f_4	7.0E2	2.7E4	6.6E2	7.3E2	2.6E4	8.1E2
	f_5	3.0E1	2.2E4	2.4E1	1.5E1	2.2E4	5.0E0
R_2	f_1	4.0E2	2.2E4	1.2E3	4.0E2	2.4E4	2.1E3
	f_2	4.8E2	3.2E4	2.0E2	8.5E2	3.1E4	2.0E2
	f_3	6.0E2	3.5E4	5.5E2	1.2E3	3.6E4	1.9E2
	f_4	6.7E2	2.4E4	5.3E2	7.1E2	2.4E4	8.7E2
	f_5	1.3E1	2.3E4	0.4E0	6.7E1	2.3E4	1.3E1
R_3	f_1	3.8E2	2.3E4	1.1E3	3.7E2	2.5E4	1.5E3
	f_2	5.6E2	3.2E4	2.0E2	9.3E2	3.2E4	2.0E2
	f_3	5.7E2	3.6E4	1.7E2	8.2e2	3.6E4	1.8E2
	f_4	6.4E2	2.6E4	9.2E2	8.3E2	2.6E4	9.1E2
	f_5	5.3E1	2.4E4	1.1E0	5.3E1	2.3E4	6.3E0
R_4	f_1	3.5E2	2.4E4	1.0E3	4.4E2	2.3E4	1.7E3
	f_2	7.1E2	3.1E4	1.8E2	1.2E3	3.3E4	1.8E2
	f_3	4.8E2	3.8E4	2.5E2	1.4E3	3.6E4	3.3E2
	f_4	8.0E2	2.5E4	4.9E2	6.3E2	2.6E4	5.3E2
	f_5	4.3E1	2.3E4	0.5E0	3.2E1	2.2E4	4.7E0
R_5	f_1	3.3E2	2.4E4	1.3E3	3.3E2	2.5E4	1.3E3
	f_2	1.0E3	3.1E4	1.8E2	1.1E3	3.2E4	1.7E2
	f_3	6.3E2	3.6E4	3.1E2	9.2E2	3.6E4	3.0E2
	f_4	5.7E2	2.5E4	4.7E2	5.7E2	2.6E4	4.5E2
	f_5	2.7E0	1.8E4	3.0E-4	1.1E2	2.2E4	1.4E1
R_6	f_1	3.0E2	2.3E4	6.5E2	3.0E2	2.5E4	1.0E3
	f_2	6.4E2	3.4E4	1.6E2	9.6E2	3.2E4	1.6E2
	f_3	9.3E2	3.9E4	1.5E2	4.7E2	3.8E4	1.5E2
	f_4	5.4E2	2.5E4	6.0E2	6.9E3	2.5E4	4.8E2
	f_5	9.5E1	2.3E4	5.7E-6	1.4E2	2.4E4	2.7E1

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