Thermal Imaging-Based Muscular Activity in the Biomechanical Study of Surgeons

Ramon Sancibrian[1(✉)], Maria C. Gutierrez-Diez[2], Carlos Redondo-Figuero[3],
Esther G. Sarabia[4], Maria A. Benito-Gonzalez[5], and Jose C. Manuel-Palazuelos[6]

[1] Department of Structural and Mechanical Engineering,
University of Cantabria, Santander, Spain
sancibrr@unican.es
[2] Department of Medicine and Psychiatry, University of Cantabria, Santander, Spain
mariacruz.gutierrez@unican.es
[3] Department of Medical and Surgical Sciences, University of Cantabria, Santander, Spain
carlos.redondo@unican.es
[4] Electronic Technology and Automatic Systems Department,
University of Cantabria, Santander, Spain
esther.gonzalezs@unican.es
[5] Department of Nursery, Marques de Valdecilla University Hospital, Santander, Spain
abenito@hvvaldecilla.es
[6] Surgical Unit of the Valdecilla Virtual Hospital, Santander, Spain
jcpalazuelos@hvvaldecilla.es

Abstract. The use of minimally invasive surgery has introduced many modifications in surgical procedures. Despite the advantages that this kind of surgery provides, surgeons have to confront many ergonomic problems during their interventions. In fact, the poor ergonomic characteristics of the workplace reduce the efficiency of the interventions and produce undesirable effects such as physical fatigue or musculoskeletal injuries. Electromyography has been used traditionally for measurement of the muscular effort in the workplace. However, in recent studies thermal imaging has been highlighted as a valuable alternative in the determination of muscular activity. One of the main advantages of using thermal imaging is that there is no necessary to foresee the muscular groups activated in the performance of surgery. In this paper thermal imaging is used to evaluate the muscular effort of surgeons and the results are compared with electromyography. The paper shows the features of this technique and the relationship with electromyography.

Keywords: Muscular effort · Electromyography · Thermal imaging · Ergonomics · Biomechanics

1 Introduction

The use of minimally invasive surgery (MIS) procedures has led to a great advance in the performance of surgical interventions. Twenty years since the first use of these surgical techniques, a retrospective view shows several advantages for patients.

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Indeed, they need less recovery time, their risk of infections is reduced and there are aesthetic benefits [1, 2]. However, this kind of surgery has significantly changed the working life of surgeons [3, 4]. In fact, from the perspective of the surgeon MIS does not only imply adaptation to new technologies but also involves important restrictions on how they perform their work. The biomechanics of surgeons reveals that laparoscopic surgery strongly restricts the degrees of freedom of forearms, wrist and hands [5, 6]. Surgeons cannot move freely as they do in open surgery because they work with special instruments which limit the access to the patient's organs obliging them to adopt awkward postures. The literature shows that several factors influence these ergonomic deficiencies [7, 8]. For instance, the layout of the surgical room plays an important role because it determines the range of motion of the surgical team. However, the main issues influencing the ergonomic features of the workplace can be focused on three main factors: the height of the worktable, the position of the monitors [3] and the design of the handles of the surgical instruments [5]. Manufacturers of surgical instruments try to design the best ergonomic handles for their surgical instruments. Nevertheless, the design of the handles has to accommodate many constraints making it difficult to find satisfactory solutions.

Due to the long duration of surgical interventions, the lack of ergonomic characteristics produces physical fatigue in the surgeon. This fact not only has negative effects on the surgeon but also on the patient. Indeed, considering the long duration of surgical interventions, a tired surgeon is more likely to make mistakes. In the long term, the poor ergonomics produces injuries and musculoskeletal disorders (MSDs), reducing the capacity and efficiency of the surgeons [9, 10]. In order to avoid all these problems, it is necessary to develop accurate methodologies to assess the ergonomic features of new designs.

Surface electromyography (sEMG) is considered the best technology to evaluate the muscular effort in surgeons [11, 12]. This is not an invasive procedure because the electrodes are situated on the skin [13, 14]. However, cables are always present to transport the signal from the surgeon's body to the analyzer. The presence of cables is uncomfortable for the surgeons and could change the way in which they work during the tests. On the other hand, the location of the sEMG electrodes needs to be foreseen before making the measurements [15]. In other words, the analyst should know which muscles will be involved in the performance of the work before carrying out the test. In this way they can locate the electrodes on the correct muscular group to collect the data. Those muscles which are not considered important would not be measured. Obviously, this fact could lead to overlooking important muscular activity which has not been foreseen.

The technological evolution of infrared (IR) technology has provided an important tool for ergonomic research [16, 17]. Thermal imaging provides accurate information about the variation in temperature on the skin surface. The increase in the muscle temperature is due to the heat production in the metabolic process that takes place during the dynamic effort [18–20]. Thus, the modification of the temperature can be correlated with the muscular activity and therefore used to obtain information about the effort necessary to complete surgical tasks [21].

This research work delves into the use of thermal imaging for the determination of the muscular activity in surgeons. The objective is to propose an alternative to EMG in the measurement of the muscular effort during the performance of surgery. Using the results obtained from the tests, this paper compares the two technologies and determines the influence and relationship of the muscular effort on temperature.

2 Materials and Methods

2.1 Participants and Inclusion Criteria

Ten surgeons (6 males and 4 females) volunteered to participate in the experiment, which was carried out in the Laboratory of Human Factors and Ergonomics of the Valdecilla Virtual Hospital in Santander, Spain. The age of the participants ranged from 25 to 35 years old and their experience in surgery was from 1 to 5 years. All participants were healthy and they did not mention any musculoskeletal disorder. Pregnant and left-handed surgeons were excluded from the experiment. The survey was approved by the Institutional Review Board (IRB) of Cantabria. The participants were informed about the objective and conditions of the experiment and all of them gave their informed consent before starting the tests.

2.2 Design of the Tests

The experiment consists of two tasks which were carried out by each volunteer taking part in the survey. The first task (T1) was a controlled test in which the forearm muscles of the surgeon were fatigued. The main objective of this test is to monitor all parameters and to know when exactly the participant is fatigued. For this, a handgrip is used and the participant is requested to exert dynamic hand contractions until the forearm muscles are exhausted. The duration of the controlled test depends on the volunteer's strength but in all cases was around one minute or less. The second part of the experiment is a surgical task (T2) where the surgeon has to perform an activity during twelve minutes in an endotrainer (see Fig. 1). The objective is to simulate the actual conditions in an operating room reproducing the movements of the forearm, wrist and hand. The design of the tests pays special attention to the muscular effort necessary to complete the tasks. The surgical activity was designed to activate the forearm muscles in a similar way to that used in real surgical operations.

All participants stood on a height-adjustable platform which was used to obtain an angle of 110 degrees between the arm and forearm. In this way, the effect of the position of the forearm did not have influence on the results of the experiment.

During the tests the EMG values and infrared imaging were recorded. In order to avoid the influence of room temperature on the results of the experiment, the environmental conditions of the laboratory were controlled during the performance of the test and the temperature was constant at 24.5 °C (±3 %). The participants rested in the laboratory for at least 15 min before starting the tests in order to acclimatize them to the laboratory conditions.

Fig. 1. Participant performing the surgical task (T2).

2.3 Measuring EMG

The EMG signal was registered with surface electrodes (B&L Engineering, USA). The electrodes were located on the skin to measure the activity of the muscular groups which are the extensor digitorum and flexor carpi radialis. The analysis of EMG was carried out with Matlab$^{\text{TM}}$, R2014b (Mathwork, USA). A passband filter was applied to the raw signal to obtain the information in the frequency range from 20 Hz to 250 Hz. A notch filter was applied to the electromyograms in order to remove the spike signal generated at 50 Hz from electrical noise.

The analysis of the EMG signal involves the parameters commonly used in investigating muscle activity. However, it is necessary to consider that in the case of the surgeon's work, the dynamic contraction of the muscles is more important than sustained contraction [22]. Normally, time-domain and frequency domain are used to obtain EMG information. Parameters such as root mean square (RMS) and zero crossing per second are commonly used in the time-domain. RMS (%) was used to obtain the force exerted by means of the comparison with the maximum voluntary contraction (MVC). However, time-domain parameters are normally used for the determination of the force exerted during the activity [23]. On the other hand, the frequency-domain is used to obtain information about muscle fatigue because it is related with the reduction of muscular activity when the surgeon becomes tired. Several parameters are defined in the literature for the study of muscular fatigue in the frequency-domain but two of them can be highlighted as the most important. They are the median frequency (MDF) and the mean frequency (MNF) [24].

In this work MDF and MNF are processed from EMG signals which were recorded from the forearms of the surgeons. The MDF parameter can be defined as the frequency value which divides the power spectrum into two equal regions. It is expressed as follows,

$$\sum\nolimits_{j=1}^{m} P_j = \sum\nolimits_{j=m}^{N} P_j = \frac{1}{2}\sum\nolimits_{j=1}^{m} P_j \quad (1)$$

Where N is the size of frequency bin, P_j is the power spectrum for the jth value of the frequency, and the parameter m, once obtained, is the value MDF. On the other hand, the MNF is the average frequency that can be computed as follows,

$$MNF = \frac{\sum_{j=1}^{N} f_j P_j}{\sum_{j=1}^{N} P_j} \tag{2}$$

where f_j is the frequency at j.

During the tests the raw EMG signal was recorded and filtered. The analysis of the signal requires the RMS values to be obtained in order to calculate the magnitude of the force applied during the test. The muscular fatigue is obtained using the Fast Fourier Transform (FFT) in the standard way but applied consecutively in windows over the whole signal. In order to avoid the leakage problem, Hanning was applied to the Short-time Fourier Transform (STFT). The result of the sliding window technique is the variation of MDF and MNF with time. The slopes of the regression lines for MDF and MNF values are used as a fatigue index (FI).

2.4 Measuring Thermal Parameters

An IR camera (ThermalCAM® B2, Flir$^{\text{TM}}$, Sweden) was used to measure the temperature distribution and variation of muscles. The spectral range is 7.5 to 13 μm, the type of detector was focal plane array (FPA) uncooled microbolometer and the resolution was 320 × 240 pixels. The temperature range was from −20 °C to +100 °C. The sensitivity of the camera was less than 0.1 °C. The emissivity of the human body surface was selected as 0.98.

The IR camera was located in front of the forearm of the participant and separated 0.5 m from the body's surface as is shown in Fig. 1. Thermograms were taken at different instants of the experiments in order to obtain the temperature variation. The measurement of temperature consisted of identifying the hottest zones of the forearm during the evolution of the tests. For this, an algorithm was developed to analyze the increment of temperature in each pixel of the forearm. That is,

$$\Delta T_i = T_{ki} - T_{0i}; \quad i = 1, 2, \ldots np \tag{3}$$

where np stands for the total number of pixels and T_{ki} and T_{0i} are temperatures obtained in the instant k and at the beginning the task, respectively. The maximum value given by Eq. (3) gives the maximum increment of temperature along the forearm. The algorithm also identifies which is the hottest zone and relates it to the muscular group affected by the increment in temperature.

3 Results

3.1 Demographic Results

The demographic characteristics of the participants who took part in the experiment are presented in Table 1. Except the weight, there are no significant differences between

Table 1. Mean and standard deviation of the demographic values of the participants

	Age (years)	Height (m)	Weight (kg)	Forearm length (cm)	Hand size (cm)	Skinfold (mm)
Male	28.2 (3.71)	1.8 (0.06)	81.2 (15.92)	26.8 (2.15)	22.8 (0.12)	4.8 (0.69)
Female	24.8 (4.07)	1.6 (0.07)	61.4 (13.46)	25.2 (2.19)	20.1 (0.13)	4.9 (0.92)
Group	26.5 (4.10)	1.7 (0.10)	71.3 (17.45)	26.0 (2.24)	21.4 (0.18)	4.8 (0.78)

male and female variables. The results shown in this table could be useful to be compared with other demographic data from other countries.

3.2 EMG Results

The measurements obtained from the EMG electrodes were recorded for each participant in the two tasks in the experiment. An example of EMG graphical results obtained during the first task is given in Fig. 2. In this case the participant was exhausted after 40 s of using the handgrip. Figure 2a and b shows the raw and filtered signal, respectively. Figure 2c shows the values of the MNF during the task and Fig. 2d displays the evolution of the MDF. In these figures the lines depict the linear regression of the MNF and MDF, which indicate the fatigue of the participant. The negative slopes of Fig. 2c and d shows that in both cases, (MNF and MDF) the effect of physical fatigue is reflected from the beginning of the experiment to the end.

Finally, Fig. 2e gives the spectrogram showing how the spectrum of frequencies varies with time. It is expected that when the participant becomes tired the range of frequencies is reduced as well as the amplitude of the signal. In the spectrogram, it is clear that this happens in the last eight seconds where the intensity of the predominant frequencies decreases.

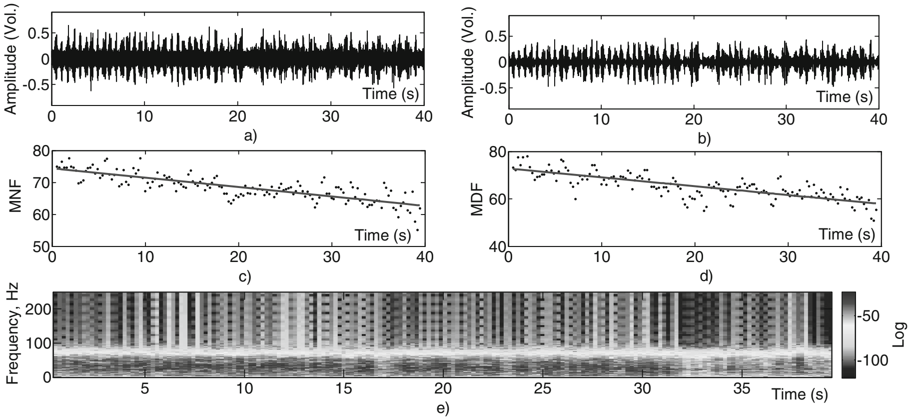

Fig. 2. EMG data collection recorded from the task (T1).

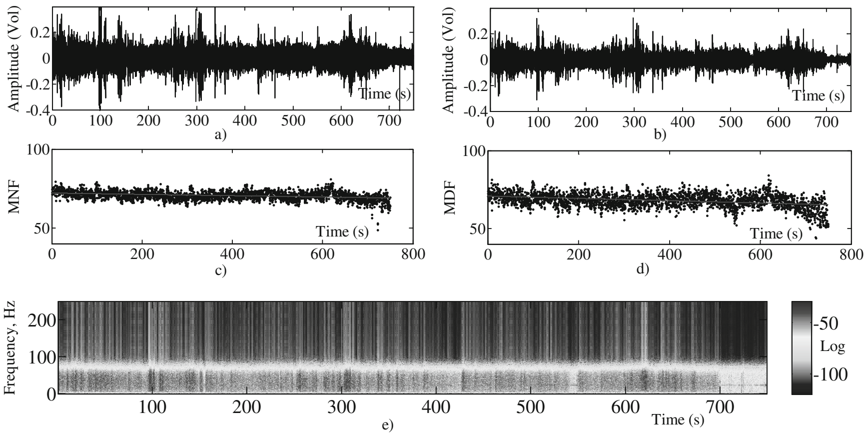

Fig. 3. EMG data collection obtained from one participant during the surgical task (T2).

Figure 3 shows the same results as Fig. 2, but in this case they correspond to the surgical task (T2). As is expected the slope of the regression lines is negative but with lower intensity than in the first task. That means that the physical fatigue of the participant is less because the surgical task requires less muscular effort to be completed. The comparison of Fig. 3c and d shows that the dispersion of the MNF values is lower than MDF, and this behavior is found in all participants. The spectrogram also shows that the variation of the frequencies involved in the task is lower. The RMS (%) values are measured as a percentage of the MVC in order to obtain relative values with respect to the maximum effort exerted by each participant. The values of MNF and MDF are shown using the slope of the regression lines. In this way the more fatigued a participant is, the more negative the index obtained. Indeed, in the last 100 s the amplitude of the frequencies involved is strongly diminished.

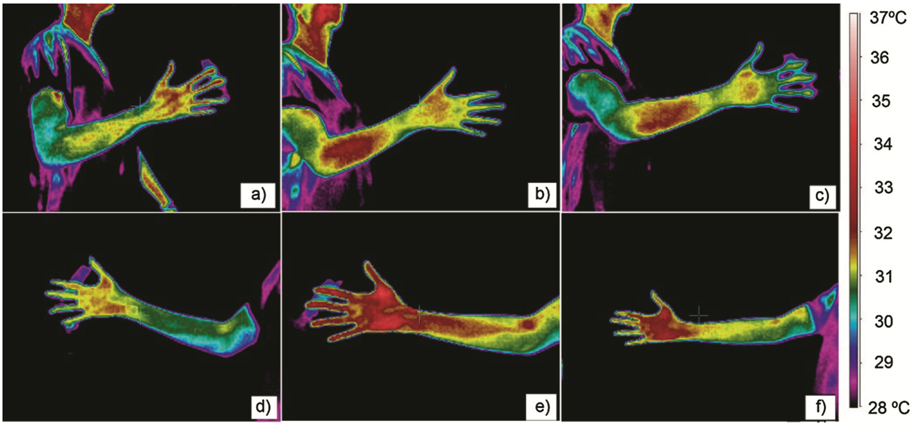

Fig. 4. Thermographs obtained at the beginning and end of the tasks.

3.3 Thermal Imaging Results

Before beginning the experiment thermal images of the dorsal and ventral forearm were taken in order to obtain a temperature reference for each participant. After the first and second task thermal images were taken again and they were used to evaluate the muscular activity by means of the variation in temperature and its distribution along the forearm. An example of thermal images obtained from one of the participants is shown in Fig. 4.

All thermograms in Fig. 4 shows the thermal changes in the forearm of the participant. In this figure thermographs 4a and d were taken after the rest period of the participant, just before starting the first task. Figure 4b and e were taken immediately after finishing the first task. Finally, Fig. 4c and d corresponds to the temperature distribution of the participant after the surgical task.

The heat generated in the first task provides a wide zone in the extensor digitorum and flexor digitorum where the temperature has been increased due to the muscular activity. The images in Fig. 4c and f clearly shows an increment of the temperature in the performance of the surgical task, but in this case it is less important than in the first task.

Table 2. Pearson's correlation and significance between EMG and fatigue index (FI).

Parameters		T1		T2	
		Correlation	*p* - value	Correlation	*p* - value
Dorsal	RMS	0.9669	0.0407	0.7893	0.0066
	MNF	−0.4986	0.1424	−0.5000	0.1411
	MDF	−0.8401	0.0023	−0.7568	0.0113
Ventral	RMS	0.8006	0.0054	0.8844	0.0007
	MNF	−0.4985	0.1425	−0.2807	0.4321
	MDF	−0.2313	0.5202	−0.1500	0.6791

3.4 Correlation Between Thermal Parameters and EMG

In the next paragraphs the outcome of the first and second test are graphically shown together with the linear regression, Pearson's correlation and statistical significance, p. Significant relationship was considered when $p < 0.05$.

Figure 5 shows the results obtained in comparing EMG and thermal parameters for the dorsal part of the forearm and Table 2 shows the Pearson's correlation and significance. Figure 5a and c shows the relationship between temperature and the RMS (%) obtained from the EMG readings. The Pearson's correlations for these values are 0.9669 and 0.7893, respectively, which are significant ($p < 0.05$). However, MNF and MDF show different results (see Fig. 5b and d). Indeed, the MNF correlation with temperature is not significant whereas MDF shows a good correlation with a p value of 0.0023.

Figure 6 shows the relationship of the EMG and temperature in the ventral part of the forearm. In this case, again the relationship of RMS values with temperature presents a good correlation which is significant. However, MNF and MDF show poor correlation and significance.

4 Discussion

This paper shows that the muscular effort in the forearm of surgeons performing laparoscopic surgery generates thermal effects on the skin. Thus, by means of infrared imaging, it is possible to monitor the changing temperature during the working hours. Furthermore, the statistical analysis showed that there is a significant correlation between temperature and muscular activity in the forearm.

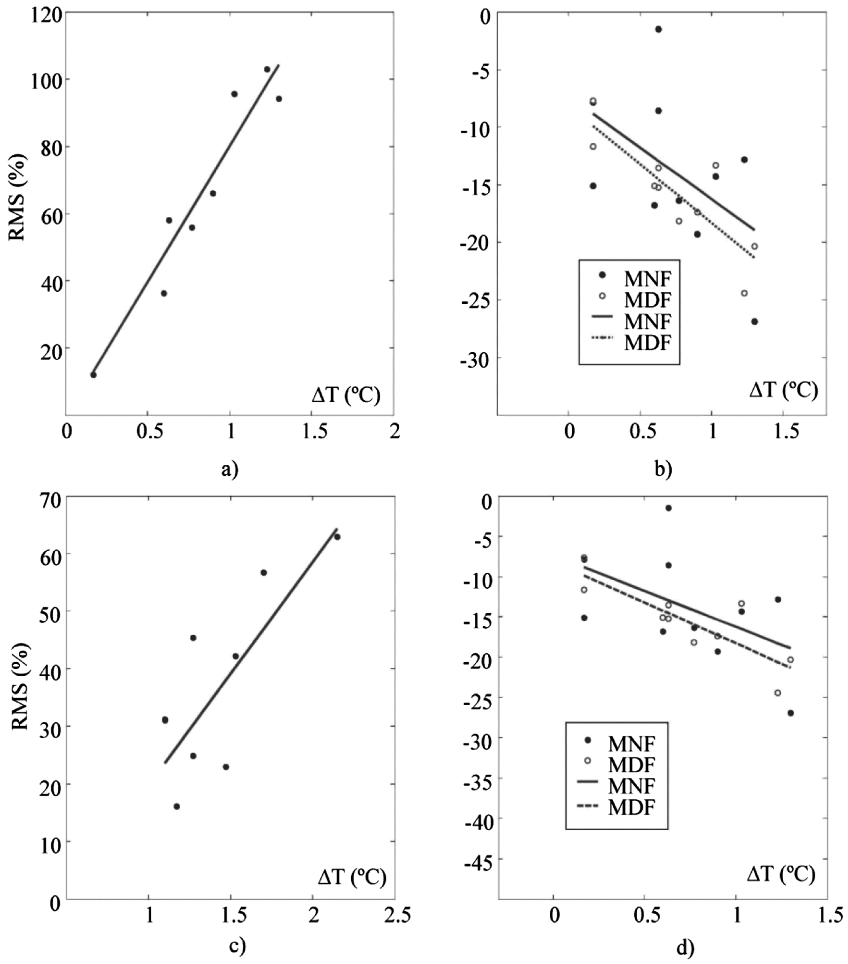

Fig. 5. Relationship between temperature and EMG parameters in the dorsal part of the forearm.

The thermographs show that the temperature is clearly increased in the muscular groups with more activity during the tests. However, the Pearson's correlation is only significant when temperature and RMS values obtained from EMG are compared. In fact, the results obtained do not permit a clear relationship to be established between temperature and muscle fatigue. In other words, the temperature is related with the instant effort but not with the cumulative effort.

In this study MNF and MDF have been used as the references in the measurement of muscle fatigue obtained from EMG. However, it is necessary to take into account that the accuracy of these indexes is not always reliable and many authors recognize the lack of precision under certain circumstances [12, 14]. More research is necessary in order to find a significant correlation of the thermal readings and muscular fatigue.

The dispersion of the results obtained is important in all cases and it may be due to several factors. Differences in vasculature, skin characteristics, subcutaneous fat and muscular strength may explain these findings. Subcutaneous fat would allow the heat

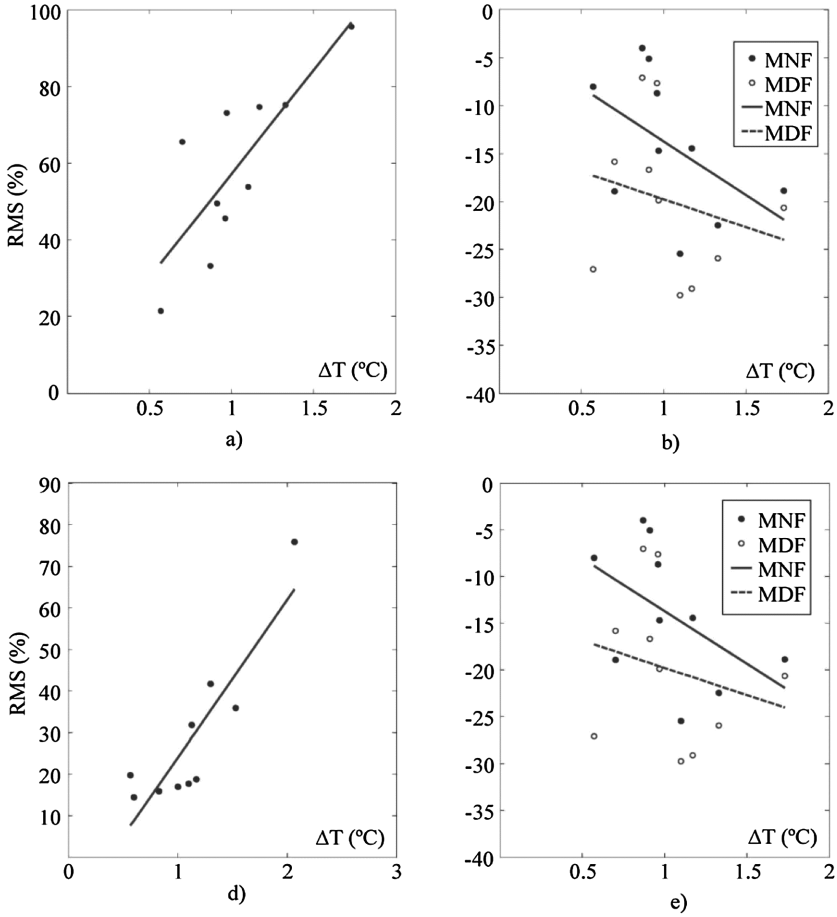

Fig. 6. Relationship between temperature and EMG parameters in the ventral part of the forearm.

transmission to be reduced because fat acts as a thermal insulator in the human body. The results obtained in this study were compared with the skinfold values obtained from each participant. However, these results were not significant because the sample size was not large enough. Further research is necessary about how subcutaneous fat influences the increment of temperature due to the muscular effort.

Qualitative information obtained from thermal imaging can be useful for the identification of muscular groups taking part in the surgical work. However, it is clear that further research is necessary to explore the possibilities of using thermal imaging as a quantitative technique for the assessment of muscular activity. For example, it would be interesting to use spectral analysis in the data obtained from the thermal outcomes. This information could be correlated with the spectral analysis obtained from EMG data.

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