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An application of a dynamic thermography for studying a relation between thermal and mechanical activities of a skeletal muscle during a static load

Abstract

A thermal distribution provides useful information of physiological and pathological processes. However, only a static thermography was applied in the most of medical studies. This paper shows an example of application of a dynamic thermography to study a physiological activity of a skeletal muscle. The goal of the presented work was to study a putative relationship between mechanical and thermal activity of the quadriceps during a static submaximal load. During a strain a dynamic temperature distribution on a thigh surface and a force moment of a knee erector were registered. The performed analysis used a time-dependent mean temperature, a time-dependent standard deviation and an impulse of a force moment. Moreover, we analyzed of autocorrelation functions to compare the dynamics of these parameters. Finally, we showed the nonlinear, statistically significant relationship between spatial-temporal variability of temperature and the force developing by a concentrative contracted quadriceps. A possible biological interpretation of the identified relation is also proposed taking the described mathematical model of muscle heat transfer into account.

Keywords: dynamic thermography, physical exercises, muscle contraction, muscle force, impulse of a force moment.

1. Introduction

A thermography is a noninvasive technique allowing to visualize a spatial temperature distribution measured on an object's surface. These temperature distributions provide useful information about a material structure as well as physical phenomena occurring in the studied objects.

For many years thermography is applied in technique and medicine apart from evident military implementation for object visualization in dark or smog environments. For example, it is used to investigate draughtiness of doors or windows, heat exchanges in electronic circuits or to study mechanical strains of some exploitative parts of machines and robots [1].

The most studied areas of medicine where the thermography is employed are dermatology, gynecology and sexology, diabetics, dentistry orthopedics or rehabilitation and sport medicine. Thermographical images allow to control effectiveness of ozone therapy of patients with systematic sclerosis [2]. Zhu et al, showed in 1990 that IR thermography was superior to subjective burn wound assessment [3]. Recent works by Medina-Preciado et al. showed significant difference in the thermal pattern of superficial skin and deep skin burn wounds, which are especially difficult to assess clinically [4]. Moreover, a thermography was successfully applied for detection of a skin cancer (e.g. melanoma), allergic skin malformations or ulcers [5, 6].

The most studied application of a thermography in reproductive medicine is detection of a breast cancer. However, the obtain results are still poor. De Jesus Guirro *et al.* showed that the area under the receiver operating characteristic (ROC) curve for detection of a breast cancer basing on the thermography was between 0.57 and 0.75 leading to low and moderate predictive accuracy [7]. Jo and Kim compared the abdominal skin temperature between fertile and infertile women by an infrared thermography. They evaluated the value of the difference between the temperature of the mild abdomen and the temperature of the ventral upper arm in the groups of fertile and infertile women. Their results indicated that this value was significantly lower for the infertile women[7]. The same authors used a thermography to prove a strong positive correlation between BMI and the scrotal temperature in men. It can disturb a spermatogenesis [8].

A thermography seems to be a useful measuring tool in sexological pure studies. There are several papers revealing its application investigation of genital or full body responses to different sexual stimuli under different psychophysiological conditions, for example in [10]. In spite of actually a thermography is applied only in scientific researches on human sexuality, it has a putative role in clinical settings, for example to monitor effects of a sexual rehabilitation of persons with spinal cord injuries.

The discussed measuring technique is helpful in diabetics and angiology. Balbinot LF *et al.* indicated that the active thermography, i.e. monitoring of a skin response to a cold stress can diagnose a neuropathy with the sensitivity equaled to 83% [11]. Traditionally, a thermography is dedicated to diagnose a diabetic foot or Raynauld syndrome[12,13].

The interesting example of the active thermography in dentistry was provided by Matsushita-Tokugawa *et al.* They used a vibrothermography for detection of teeth micro-cracks as a thermal response of a tooth to ultrasonic vibrations. Microcracks with a width of 4 to 35.5 μm were detected with this method [14].

A passive (mainly) as well as active thermography is widely exploited in orthopedic, physiotherapy and sport medicine, for example to detect an anterior cruciate ligament rupture, observe muscles activities during exercises or different sport disciplines [15].

Summarizing, we note that the most of medical studies used a static and passive thermography. Therefore, the analysis of the obtained results usually led to qualitative comparison of thermal images registered in good health persons and ill patients or images registered before and after exercises. Quantitative comparisons were limited to the average temperatures computed for a given image. Such methods disable to investigate a biological mechanism leading to increasing or decreasing of the temperatures. Particularly, according to our best there is lack of researches describing a relation between a mechanical and a thermal activity of a skeletal muscle. It seems that knowledge about this relation is important and needed to optimize sport trainings and rehabilitative exercises.

Therefore, the goal of our work was to study a putative relationship between mechanical and thermal activity of the quadriceps during a static submaximal load.

2. Physiological processes influencing on heat production by skeletal muscles

According to the biophysical model proposed by Gonzalez-Alonso *et al.* there are several physiological phenomena which play a role in heat production by a skeletal muscle during loading [16].

Rate of heat storage in active muscles

This rate is described by the following equation [16]:

$$\frac{dQ_m(t)}{dt} = mc_m \frac{dT_m(t)}{dt}, \tag{1}$$

where Q_m is a stored heat in muscles, T_m is a temperature of an active muscle measured before and during a contraction, m is a muscle mass and c_m is its specific heat equaled to the value c_m=3590 $\mathrm{Jkg^{-1}{}^{\circ}C^{-1}}$.

Rate of heat removal by the blood

This heat is modeled by the following formula [16]:

$$\frac{dQ_b(t)}{dt} = m_b c_b \frac{d}{dt}\left[T_a(t) - T_v(t)\right], \tag{2}$$

where Q_b is heat transported out of a muscle by the blood stream. T_a, T_v are blood temperatures of the inflow (arterial) and outflow (venous) part of a blood. The m_b is a mass of a total blood flowing through a thigh and c_b=3801 $\mathrm{Jkg^{-1}{}^{\circ}C^{-1}}$ is the specific heat of the blood.

Rate of heat loss from the thigh muscle to the thigh skin

Heat is also lost by a conductive process which transfers this heat from the muscle tissue to the skin. This process is described in the following manner [16]:

$$\frac{dQ_{m-s}(t)}{dt} = k_m \frac{\left[T_s(t) - T_m(t)\right]}{L} S, \tag{3}$$

where Q_{m-s} is the fraction of muscle heat lost by a conductance during a muscle contraction, T_m, T_s denote temperature of the muscle and skin layers, respectively. k_m is a thermal conductivity of a human muscle tissue k_m=4.8 $\mathrm{Js^{-1}{}^{\circ}C^{-1}}$ and L≈3 cm is the mean distance of this conduction, S is the cross-section area of the muscle parallel to the skin surface.

Rate of heat loss through the thigh skin

This heat rate is defined analogously as the previous formula [16]:

$$\frac{dQ_{s-e}(t)}{dt} = \rho_b c_b \frac{dV_b}{dt}\left(T_a(t) - T_s(t)\right) \tag{4}$$

where Q_{s-e} is the rate of heat transferred through the skin to the patient's environment, T_a, T_s are the temperatures of the an arterial blood and a skin, dV_b/dt = 0.005 $\mathrm{ls^{-1}}$ is the estimated velocity of the thigh skin blood flow, and blood density ρ_b equals to 1.053 $\mathrm{g/cm^3}$.

Rate of heat loss by the lymph flow

Heat is also removed from a muscle tissue by the lymph. This process can be also described similarly [16], i.e.:

$$\frac{dQ_L(t)}{dt} = \rho_L c_L \frac{dV_L}{dt}\left(T_a(t) - T_L\right). \tag{5}$$

Then, Q_L denotes a heat fraction removed from the muscle by the lymph, T_a, T_L are the temperatures of the arterial blood and the lymph, dV_L/dt = 0.003 $\mathrm{ls^{-1}}$ is the estimated velocity of the lymph flow and is the specific heat of the lymph ($c_L\rho_L$=3930 $\mathrm{Jl^{-1}{}^{\circ}C^{-1}}$ and ρ_L≈1 $\mathrm{g/cm^3}$).

Summarizing of the heat transfer model

The described model has the linear form. The total energy turnover can be expressed by sum of the equations (1)-(5) and the mechanical muscle power output.

Although there is a linear model it well explains the physiological processes influencing on heat production by a skeletal muscle. Indeed, these relations are nonlinear. Moreover, this model shows that a measured temperature depends also on blood and lymph flow so this temperature immediately depends on a heart rate, a blood pressure varied during muscle contraction. Therefore, a relation between a muscle force and its temperature can be confounded by many factors so it must be evaluated experimentally.

3. Materials and methods

To identify a relation between a temperature dynamic of a thigh and a force of knee erectors we performed the experiments described below. The scheme of the laboratory stand is presented in the Fig.1.

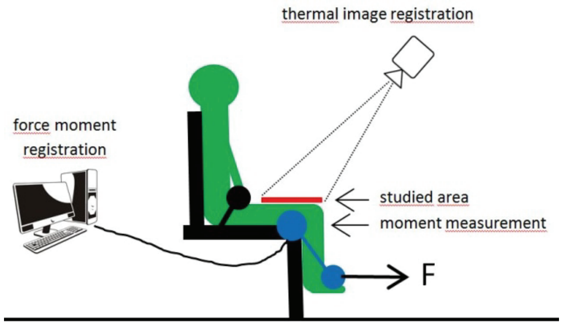

Fig. 1. The scheme of the laboratory stand used for measuring moments of forces generated by lower limbs

The experiments were consisted of the following steps:

1. A person took the laboratory armchair. The sizes of this armchair were adapted for the person ensuring right angles in hip and knee joints. The trunk and legs were stabilized by the mechanical stabilizers.
2. The sensor measuring the force moments was placed distally on the tibia higher than the ankle join. The thermographic camera was placed 1 meter away from the studied thigh and focused individually.
3. After the above settings a person was relaxed for 30 seconds.
4. A person received the instruction to kick and keep in a submaximal tone his/her knee erectors for 30 seconds. Then, the moment of a force and the dynamic of temperature distribution were measured.
5. The dynamic of temperature distribution was still measured after muscle relaxation of the tension for 3 minutes.

Therefore, we were able to observe time-varying and space-varying changes of a temperature distribution on the thigh surface during a concentrive strain of the quadriceps muscle together with a force moment under a static load. The temperature distributions were measured by the FLIR camera, model E40 with 30 frames per a second. The laboratory stand and software for force moments measuring was produced by the Jba Zbigniew Staniak Company. The sample frequency of a force moment was 50 Hz.

In this way 17 women and 16 men were studied. Their age was 19-26 years. All were healthy students of physiotherapy. 28 of them were physically active at least one day every week.

Finding of a relation between a muscle temperature and its mechanical force requires a parameterization method of the registered thermal images and the time-varying values of force moments. For this purpose we manually marked an area of a quadriceps muscle on the thermal images for a given person.

Because we use a dynamic thermography, a thermal image being a temperature distribution can be represented as $T(x,y,k)$ for $x,y\in$ROI and k^{th} frames.

Although there are many parameterization methods of images we have chosen the simplest ways to ensure easy biological interpretation of the obtained results. Thus, we used two parameters: the spatial mean temperature and the spatial standard deviation.

The spatial mean temperature of a ROI consisted of $N\times M$ pixels computed for every k=1,…K frames.

$$\mu(k) = \frac{1}{NM}\sum_{i=1}^{N}\sum_{j=1}^{M} T\left(x_i, y_j, k\right) \tag{6}$$

The spatial standard deviation of the temperature belonging to the ROI:

$$\sigma(k)=\sqrt{\frac{\sum_{i=1}^{N}\sum_{j=1}^{M}\left(T(x_i,y_j,k)-\mu(k)\right)^2}{NM}} \tag{7}$$

The value of $\sigma(k)$ may be interpreted as variation of myocytes activating during a static load.

For parameterization on time-dependent moment of a force M_F we proposed the impulse of this moment defined as:

$$I_M=\int_0^{t_k} M_F(t)\,dt \tag{8}$$

Integration was performed numerically using the trapezoidal method. Moreover, we estimated the autocorrelation of these parameters to show similarity of their dynamics.

The above introduced parameters were computed for all persons. Next, the Spearman correlation coefficient was estimated to identify an association between a force and thermal activity of the quadriceps muscle.

The following software was used. ROI marking and image parameters computing were done using Flir Tools 4.2 and ResearchIR max 4.30. The ROI were determined manually for every patient in the manner ensuring their independence on small thigh movements. The further analysis was performed with the help of Matlab 2016b.

4. Results

Fig. 2 shows the temperature distributions obtained for two drawn persons before a strain and during loading. The changes in temperature ranges are well seen.

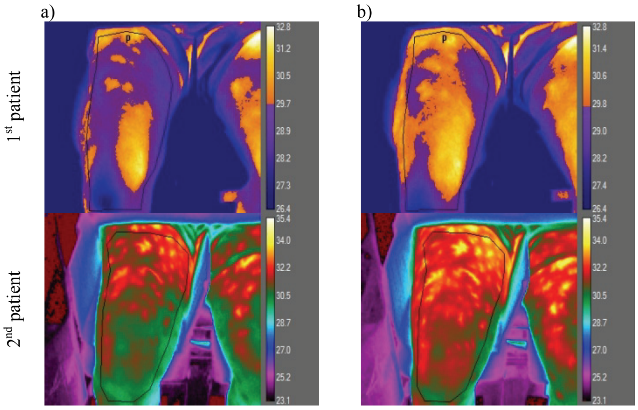

Fig. 2. The temperature distributions obtained for drawn two patients a) during loading b) after a strain

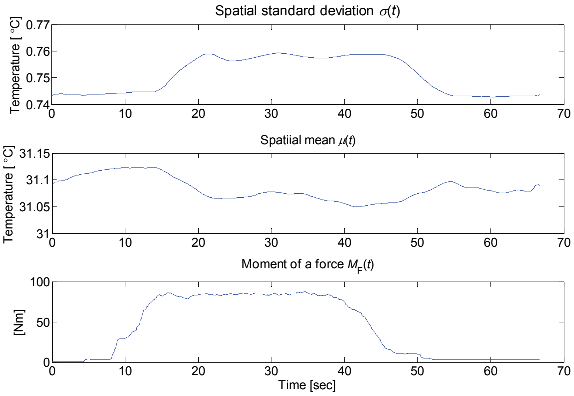

Fig. 3. The time varying temperature parameters and the force moment for the averaged studied person

To better show the main trends of the analyzed process we average the time-course of the means, standard deviations and force moments over 35 persons. Figure 3 presents obtained trends. The measurements uncertainties estimated by a standard errors computed for 35 persons were in the following ranges:

- for the spatial standard deviation $SE\in[0.19; 0.21]$
- for the spatial mean $SE\in[1.03; 1.12]$
- for the moment of a force $SE\in[3.12; 8.45]$

where SE means the standard error of the measurements.

We can observe a delay between starting of the force and the thermal reaction of the quadriceps muscle. Its tension was associated with significant increasing of the spatial deviation of the temperature and decreasing of the mean.

The estimated autocorrelation is seen in the Fig. 4. These functions were computed only for the time period equaled to the active phase of the muscle work. The analysis of this graph suggests that all three processes have very similar dynamics. Moreover, the shapes of autocorrelations resemble quasi linear processes.

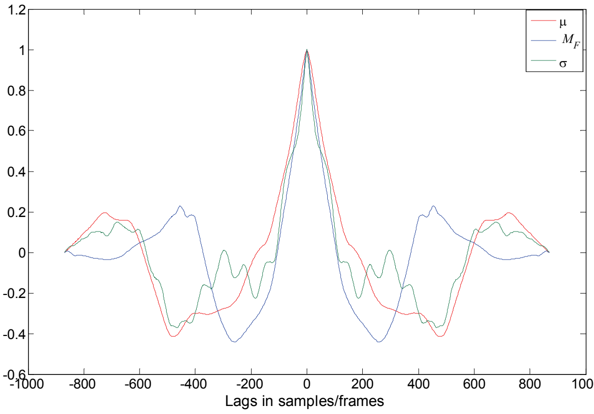

Fig. 4. The autocorrelations of persons averaged parameters $\mu(k), \sigma(k), M_F(k)$

We also identified the nonlinear relation between the impulse of the force moment (8) and the time-variation of the $\sigma(t)$ measured as a standard variation of this parameters, i.e.:

$$\sigma_k\left[\sigma(k)\right]=\frac{1}{K}\sum_{k=1}^{K}\left(\sigma(k)-\bar{\sigma}(k)\right)^2 , \tag{9}$$

where $\bar{\sigma}(k)=\frac{1}{K}\sum_{k=1}^{K}\sigma(k)$ is the time mean of the spatial standard deviation averaged for all frames.

The Spearman's correlation coefficient was R=0.40; p=0.003.. This relation is presented in the Fig. 5.

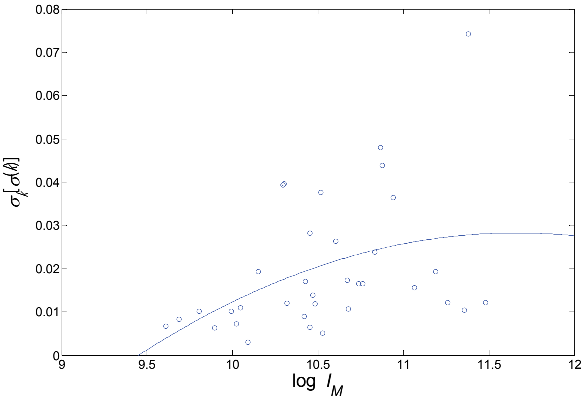

Fig. 5. The nonlinear relationship between the impulse of the force moment and the $\sigma_k\left[\sigma(k)\right]$, eq. (9)

5. Conclusions

According to our best knowledge, there is the first study of a relation between thermal and mechanical activity of a skeletal muscle using a dynamic thermography. The observed increasing of a time variability of the spatial standard deviation of the temperature belonging to the area of the quadriceps muscle suggests a continuous activations of myocytes during a strain. On the other side, we showed that during a static load of a knee erector the measured temperature was decreased. Basing on the equations (1)- (5) we note a pivotal role of a blood and a lymph in hea balance between a quadriceps and its surroundings. Physiological experiments strongly prove that in even 20% of a maximal static load the arterial inflow and the venous blood and lymph outflow approach zeros. At the same time, the Reynolds number reduces. In this situation the heat transferred by a convection between a blood and surrounding also approaches zero according to the equations (4) and (5). Moreover, lack of a blood flow may lead to increase a heat storage in the thigh muscle in compliance with the equation (1). The muscle is not cooled by a blood and a lymph. We suggest that these processes may be responsible for the observed decreasing of the spatial mean measured temperature ($\mu(t)$). Moreover, the fact that spatial mean measured temperature increases after a load confirms our speculation. Then, a turbulent blood flow improves heat transfer to the muscle surroundings. It also agrees with the experimental results obtained by González-Alonso *et al.* [17]. They showed that the limb vascular conductivity increases with blood temperature. Moreover, we confirmed that dynamic of heat balance in a skeletal muscle seemed to be linear on the base of the identified autocorrelations. It corresponds to the model proposed by the same authors [16].

The relationship between a force moment and time-spatial variation of temperature indicates a crucial role of metabolism in myocytes or time-varying switching on/off of particular myocytes. It may prevent muscle fatigue.

The paper presents the first study which shows that a static load characterizes different thermal balance than a dynamic load which may produce a muscle hyperthermia. From the practical point of view hyperthermia estimation by decreased measured temperature can be used in physical efficiency tests.

Further investigations may be performed applying multimodal measurements combining dynamic thermography, EMG and plethysmography.

At the end the performed studies show important usability of dynamic thermography in medicine because it gives more and more information about studied process not only an object.

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