

Changes in electromyographic signals and skin temperature during standardised effort in volleyball players

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Purpose: The state of athletes' muscles is not constant, but it differs depending on the stage of sports training, which is associated with different degrees of muscle fatigue. There is thus a need to find a non-invasive and simple method to assess muscle fatigue. The aim of the study was to determine the relationship between muscle fatigue due to physical effort and changes in skin temperature, measured using a thermographic camera. *Methods:* The study involved 12 volleyball players. The participants were to maintain 70% of peak torque in the joint for as long as possible. We measured peak torque and the time of maintaining 70% of its value (t_{lim}) as well as continuously recording skin temperature and electromyographic (EMG) signals in the region of the belly of the rectus femoris. The measurements were taken twice: before and after a series of squats. *Results:* The study found that t_{lim} decreased when isometric contraction was performed after physical effort. Pre- and post-exercise skin temperature did not differ significantly, however, the increase rates of temperature and the root mean square (RMS) of the EMG signals grew significantly. In most of the players, skin temperature also correlated with the RMS, median frequency (MDF), and mean frequency (MF) of the EMG signals. *Conclusions:* Measuring the time of maintaining submaximal torque during isometric contraction and the slope coefficient for the increase in temperature recorded using a thermographic camera can be a simple, cost-effective, and non-invasive method of assessing fatigue and efficiency decreases in the muscles in volleyball players.

Key words: thermography, temperature variability, volleyball players, electromyographic signals, standardised effort

1. Introduction

Surface electromyography (sEMG, surface EMG) is commonly used in research involving athletes to evaluate muscle activity, function, and fatigue. Electromyographic signals contain information on muscle excitation, that is, on the recruitment of motor units (MUs) which enable the muscle to produce force [25]. Although there is no clear relationship between excitation and active force production, it is possible to draw conclusions concerning muscle activity, based on the RMS values of electromyographic signals. EMG signals are also used to assess muscle fatigue, which is evidenced by a reduction in signal frequency [3], [13], [17], [22]. Research examining EMG signals during

prolonged isometric contraction has shown that with time, there is a reduction in the frequency and an increase in the amplitude of the signal. Researchers are endeavouring to explain this phenomenon using motor unit-based models [7], [10], [20], [26].

Determining the functional state of the muscles is important in training planning and evaluating the state of the musculoskeletal system in athletes. During intense exercise, there is a decrease in muscle efficiency, measured using the ratio of energy expended on the work to the sum of the mechanical energy and heat produced. Krstrup et al. [14], who assessed efficiency based on temperature increases measured with thermistors inserted into the muscles, found that depending on exercise intensity and time, efficiency fell from 70% to even 30%.

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Owing to thermal conductivity, part of the heat produced in the muscle is transferred to the skin. Skin temperature measurements are currently possible thanks to the use of thermographic cameras [8], [15]. When performing such measurements, one needs to consider and control many factors, including ones that are environmental, individual, and technical in nature. This simple and non-invasive method is used to investigate how temperature changes are related to muscle function and performance during effort in athletes. Some studies that have used thermographic cameras have focused on measuring temperature before and after muscle exercise [5], [9], [12], [19], [23]. Such research has shown that in the initial phase of excitation and after intense effort, skin temperature in the region of the muscle falls or is maintained at a constant level. This is a consequence of the physical processes of heat transfer, such as convection, radiation, and evaporation, as well as the thermoregulation processes in the body. Studies carried out with the use of thermographic cameras [2], [4], [14], [16], [18], [21] have found that temperature increases during exercise after the initial phase of excitation.

Of practical importance in research into the motor capacities of volleyball players are measurements of muscle strength both in isokinetic [1], [6] and isometric [11], [24] conditions. The specificity of competitive volleyball requires that particular muscle groups work effectively and have the capacity to perform long-lasting effort. That is why, when assessing their function, one should also take into account fatigue and decreases in efficiency.

The aim of the current study was to explore the relationship between muscle fatigue and excitation and temperature, measured using a thermographic camera in standardised effort in volleyball players. The objectives were to:

- 1) determine the relationship between peak torque (M_{\max}) and the time of maintaining 70% of this value (t_{lim}) in volleyball players;
- 2) analyse the correlations between changes in temperature and the RMS, MDF, and MF values of the EMG signals;
- 3) examine the effect of physical exercise performed before the isometric contraction test on the time of maintaining 70% of peak torque and changes in skin temperature as well as the RMS, MDF, and MF parameters.

The first objective was related to the fact that the biomechanical assessment of athletes' muscles should not be restricted only to the measurement of peak torque since in sport disciplines involving long-lasting effort an equally important role is played by endurance,

that is the capacity to maintain a high level of torque. We hypothesised that there is a negative correlation between M_{\max} and endurance, which was determined using t_{lim} . The second objective came from our intention to confirm that there is a correlation between changes in skin temperature and the parameters of EMG signals, in which case measurements of this temperature using a thermographic camera could be used as an alternative for EMG methods in assessing muscle function. The final objective stemmed from the fact that determining changes in t_{lim} and the curves of the thermographic and electromyographic signals after a series of physical exercises could be used to evaluate muscle fatigue.

2. Materials and methods

2.1. Subjects

12 volleyball players (age: 21.0 ± 2.2 years; height: 190.7 ± 4.3 cm; body mass: 86.1 ± 6.7 kg; BMI 24.0 ± 1.6) with approximately six years of training experience on average participated in the research. They were healthy and did not complain about muscle pain. They had not sustained any injuries and had not had any interruptions in their training over the past year. They participated in the study on a voluntary basis and were informed about the research procedure and aim. The study was approved by the Research Ethics Committee of the Józef Piłsudski University of Physical Education in Warsaw.

2.2. Measurements

Before the experiment, the subjects performed a standard warm-up under the supervision of the coach. Following the warm-up, the peak torque of the knee extensors was measured. The time of the measurement of peak torque was 5.2 ± 2.2 s. The measurements were carried out on an LR2-P (JBA Zb. Staniak, Poland) measuring station. The results of the measurement were used to determine individual loads that constituted 70% of the maximal load.

After 1 minute of rest, the subjects were to develop and maintain 70% of peak torque. During the test, electromyographic signals were acquired continuously, and the thigh surface was recorded using a thermographic camera. The test was terminated when there was a decrease in torque below the designated value. Then, the

subjects completed three series of 10 squats, after which the test described above again was repeated.

2.3. Recording and analysis of electromyographic signals

We monitored neuromuscular activity in the right rectus femoris muscle. Electromyographic signals were recorded with the Noraxon TeleMyo 2400 system. We used Noraxon Ag/AgCl Dual Electrodes (with a 1-cm diameter and an inter-electrode distance of 2 cm). The electrodes were connected to a distributed temperature sensor (DTS), which is where the reference electrode was. Before the electrodes were attached, the skin was shaved, washed, and cleaned with alcohol. Skin impedance was 2 k Ω . The electrodes were placed on the muscle belly parallel to its orientation, and the DTS was positioned next to the electrodes. The EMG signals were recorded with a sampling frequency of 1500 Hz and 16-bit resolution. The signals were analysed using MyoResearch XP Master Edition software (v. 1.08.27). Standard Amplitude, Average Activation, and Frequency Fatigue Reports were used in the analysis.

2.4. Recording and analysis of thermographic data

Thermographic images were recorded directly onto a computer, using a Flir E60 thermographic camera (Flir, Wilsonville, Oregon, USA) with an infrared resolution of 320 \times 240 pixels and thermal sensitivity of 0.05 $^{\circ}$ C. Data were collected continuously at a rate of 30 frames per second. The subject was in a sitting position, and the camera was placed perpendicular to the surface of the right thigh, 1 m above it.

The temperature in the room was 23 $^{\circ}$ C \pm 0.5 $^{\circ}$ C, humidity was 60% \pm 3%, and the emissivity factor was 0.98.

The recordings from the thermographic camera were analysed using FLIR ResearchIR software v. 4.40.7.26. Maximal temperature was recorded within the EMG signal ellipses. We decided to measure the changes in maximal temperature in order to avoid errors resulting from discrepancies in the selection of measurement points. At different moments in time, the heat transferred to the external layers of the skin can cause increases in temperature in other regions of the skin. During all of the measurements, the maximal temperature index was within the ellipse surrounding the electrodes (Fig. 1).

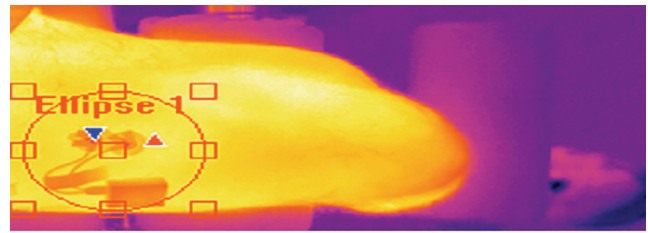


Fig. 1. Recording and analysis of changes in temperature in time. Red arrow indicates maximal temperature

2.5. Analysis and statistics

The following values were calculated:

- 1) peak torque (M_{\max});
- 2) time of maintaining 70% of peak torque (t_{lim}) pre- and post-exercise;
- 3) changes in temperature (T) as well as the RMS, MDF, and MF values of the electromyographic signals (EMG signals and temperature variations were analysed in 1-s intervals);
- 4) decreases in temperature (dT/time), RMS ($d\text{RMS}/\text{time}$), mean frequency ($d\text{MF}/\text{time}$), and median frequency ($d\text{MDF}/\text{time}$) pre- and post-exercise (frequency reductions were determined using Frequency Fatigue Reports, and changes in RMS and temperature were established based on scatter plots).

All statistical analyses were made using Statistica software v. 13.3. Normality of distribution was assessed with the Shapiro–Wilk W -test. The significance of the differences between means was evaluated using student's t -test if data distribution was normal, and using the non-parametric Wilcoxon signed-rank test if the data were normally distributed. Correlations were determined by calculating Pearson coefficients for normally distributed data and Spearman's coefficients for non-normally distributed data.

3. Results

Figures 2 and 3 show the values of peak torque (M_{\max}), the time of maintaining 70% of this value (t_{lim}), and the relationship between these values after the exercise which preceded the isometric test and before the exercise for particular volleyball players.

A negative correlation was found between the time of maintaining 70% of maximal voluntary contraction (MVC) and M_{\max} values. The coefficients were -0.82 pre-exercise and -0.62 post-exercise. The greater peak torque, the shorter t_{lim} (Fig. 4).

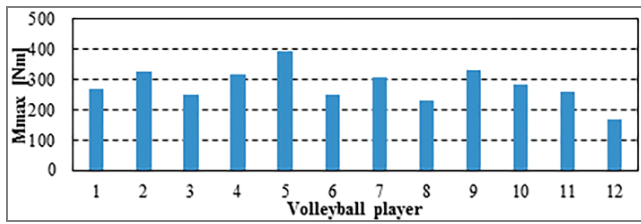


Fig. 2. Peak torque values in respective players

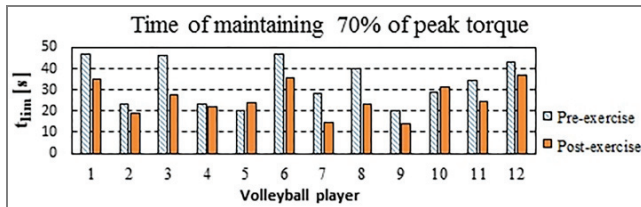


Fig. 3. Time of maintaining 70% of peak torque (t_{lim}) pre- and post-exercise

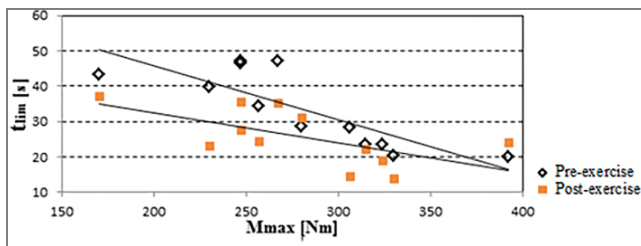


Fig. 4. Relationship between time of maintaining 70% of MVC (t_{lim}) and peak torque value (M_{max})

Mean t_{lim} was significantly lower post-exercise than pre-exercise ($p < 0.003$). This leads to the conclusion that measuring the time of maintaining high torque during isometric contraction can be a simple and reliable indicator of muscle endurance.

In order to establish the impact of the exercise performed before the isometric test, we determined muscle temperature pre- and post-exercise in the first and last second of the test. Figure 5 shows the changes in temperature in a selected subject pre- and post-exercise, in charts A and B, respectively. For comparison purposes, the same time scale was used in both charts.

Mean and standard deviation values obtained in these measurements are shown in Fig. 6, whereas the results of the comparative analysis of differences between means conducted using student's t -test (the distributions were normal) are given in Table 1.

Mean skin temperature T_1 did not increase after the series of squats ($p = 0.825$), but the differences in temperature between the first and last second of maintaining 70% of MVC were significant. Skin temperature was thus unaffected by the preceding effort

related to performing a series of squats, but by maintaining 70% of peak torque. However, the increases in temperature ΔT ($T_E - T_1$) were significantly higher after than before the exercise. This means that the rate of temperature increase grew post-exercise.

In most of the subjects, temperature and RMS values increased during maintaining 70% of M_{max} , whereas frequency had a tendency to decrease. Correlations between temperature, time, and RMS, MDF, and MF values are shown in Table 2. Shaded cells indicate significant correlations.

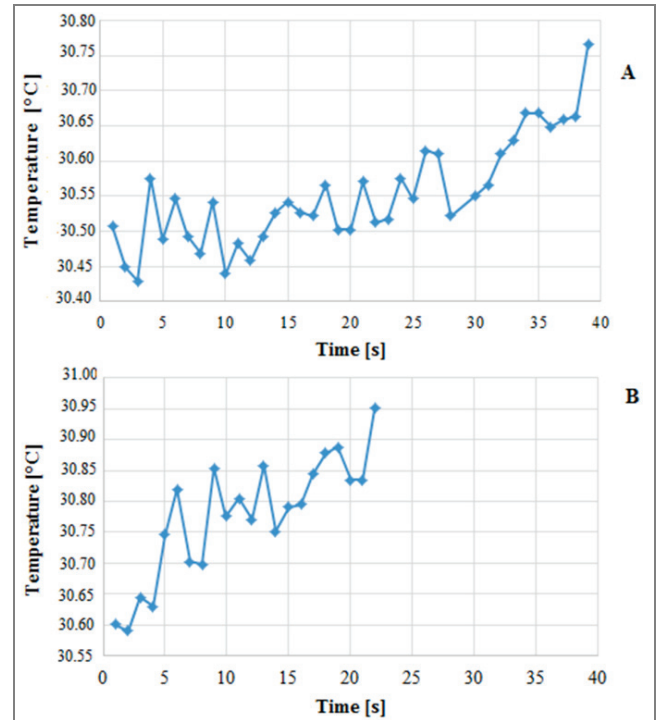


Fig. 5. Changes in temperature pre- (A) and post-exercise (B) in a selected subject

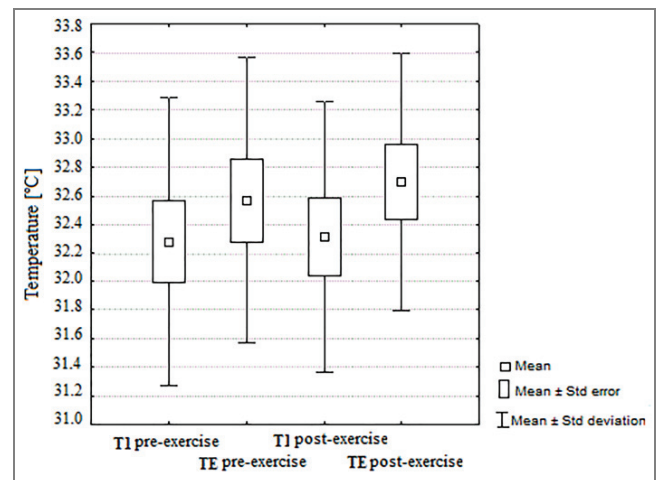


Fig. 6. Means and standard deviations for skin temperature in the first (T_1) and last (T_E) second of maintaining 70% of MVC pre- and post-exercise

Table 1. Statistical significance of differences in mean temperature in the first (T1) and last (TE) second of maintaining 70% of MVC pre- and post-exercise

| | | | |
|--|---|---|--|
| T_1 pre-exercise vs. T_1 post-exercise | T_1 pre-exercise vs. T_E pre-exercise | T_1 post-exercise vs. T_E post-exercise | $\Delta T (T_E - T_1)$ pre-exercise vs. $\Delta T (T_E - T_1)$ post-exercise |
| $p = 0.825$ | $p < 0.001$ | $p < 0.001$ | $p < 0.05$ |

Table 2. Spearman’s correlation coefficients between temperature (T), time, and RMS, MDF, and MF values of EMG signals. Shaded cells indicate significant correlations at $p \leq 0.05$

| Subject no. | Pre-exercise | | | | Post-exercise | | | |
|-------------|---------------|---------------|---------------|---------------|---------------|--------------|---------------|---------------|
| | T, time | T, RMS | T, MDF | T, MF | T, time | T, RMS | T, MDF | T, MF |
| 1 | 0.485 | 0.296 | -0.332 | -0.408 | 0.730 | 0.479 | -0.697 | -0.748 |
| 2 | -0.287 | 0.216 | 0.297 | 0.302 | -0.222 | 0.017 | 0.109 | 0.143 |
| 3 | 0.656 | 0.484 | -0.632 | -0.672 | 0.638 | 0.360 | -0.234 | -0.375 |
| 4 | 0.171 | 0.284 | -0.366 | -0.025 | 0.916 | 0.865 | -0.171 | -0.267 |
| 5 | 0.607 | 0.139 | -0.343 | -0.470 | 0.930 | 0.489 | -0.755 | -0.875 |
| 6 | 0.624 | 0.057 | -0.603 | -0.636 | 0.931 | 0.298 | -0.714 | -0.873 |
| 7 | 0.605 | 0.665 | -0.274 | -0.373 | 0.509 | 0.077 | -0.271 | -0.287 |
| 8 | 0.735 | 0.259 | 0.680 | -0.723 | 0.760 | 0.626 | -0.394 | -0.510 |
| 9 | 0.295 | 0.314 | -0.138 | -0.084 | 0.883 | 0.801 | -0.685 | -0.624 |
| 10 | 0.689 | 0.436 | -0.378 | -0.408 | 0.825 | 0.560 | -0.135 | 0.209 |
| 11 | 0.529 | 0.243 | -0.646 | -0.499 | 0.814 | 0.766 | -0.635 | -0.595 |
| 12 | -0.582 | -0.460 | 0.273 | 0.398 | -0.339 | -0.245 | -0.030 | 0.166 |

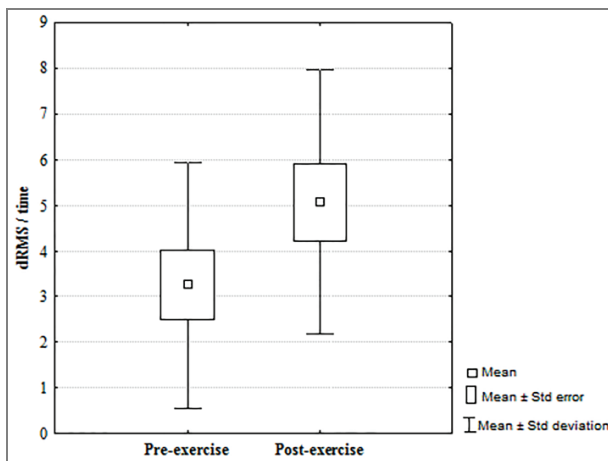


Fig. 7. Means and standard deviations for RMS slope coefficients pre- and post-exercise

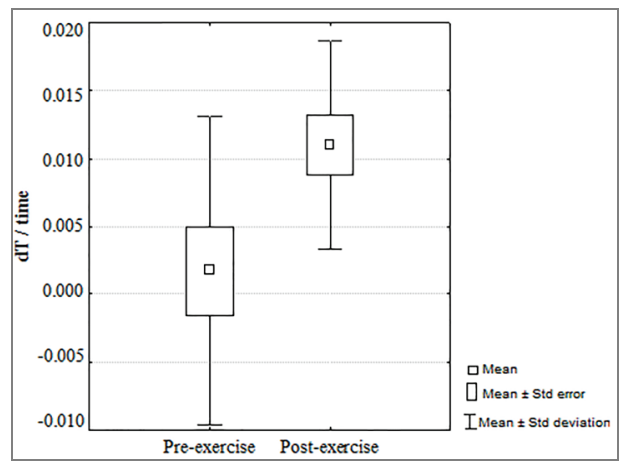


Fig. 8. Means and standard deviations for temperature slope coefficients pre- and post-exercise

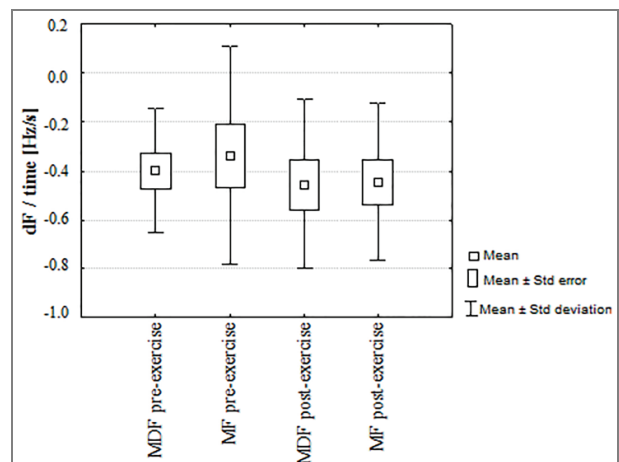


Fig. 9. Means and standard deviations for median (MDF) and mean (MF) slope coefficients pre- and post-exercise

As is visible in Table 2, there was a significant increase in temperature over time in 8 subjects pre-exercise and in 10 subjects post-exercise. In most volleyball players, the temperature changes correlated positively with RMS values and negatively with the frequency of the electromyographic signal. When the isometric test was preceded by exercise, temperature correlated with the RMS value in a greater number of subjects, which is probably related to the fact that after the exercise, there was a decrease in muscle efficiency, that is the ratio of the mechanical energy of the contraction to total energy. Thus, for a constant level of muscle force to be maintained, this decrease needed to be compensated for by an increase in muscle excitation.

To answer the question regarding the impact of exercise performed before the test involving maintaining constant torque, we examined the rate of the changes in temperature, RMS, MDF, and MF. For the MDF and MF values, the changes were determined with the use of the Frequency Fatigue Report, whereas for temperature and the RMS value, they were calculated using scatter plots in Statistica. The mean results are illustrated in Figs. 7–9.

Since data distribution was normal, the significance of the differences between means was examined using student's *t*-test (Table 3). After the effort, there was a significant rise in the temperature increase rate and the RMS value, however, the difference for the frequency reduction rate was not statistically significant.

Table 3. Significance of differences between mean slope coefficients for the changes in temperature as well as RMS, MF and MDF pre- and post-exercise

| dT/time [°C/s] | $d\text{RMS}/\text{time}$ [μV/s] | $d\text{MDF}/\text{time}$ [Hz/s] | $d\text{MF}/\text{time}$ [Hz/s] |
|----------------------------|-------------------------------------|-------------------------------------|------------------------------------|
| 0.005 | 0.019 | 0.937 | 0.875 |

The results can be summed up as follows:

- 1) The time of maintaining 70% of peak torque (t_{lim}) correlated negatively with peak torque (M_{max}).
- 2) t_{lim} was significantly lower when the isometric test was preceded with exercise than when it was not preceded by it.
- 3) After exercise, there was a significant rise in the increase rates of temperature and the RMS value of the signal.
- 4) In the majority of subjects, temperature measured using a thermographic camera correlated positively with RMS and negatively with the frequency of the EMG signal.

- 5) The reduction in the frequency of the EMG signal was compensated for by an increase in muscle excitation, which is evidenced by the increase in the RMS value.

4. Discussion

The aim of the current study was to determine the relationship between changes in temperature measured by means of a thermographic camera and the values and frequencies of the EMG signal during isometric contraction, as well to investigate the impact of fatigue on these parameters and on the time of maintaining a constant high level of torque. The tests were carried out with a submaximal load equal to 70% of the peak torque value. Bartuzi et al. [2] carried out measurements with a thermographic camera during isometric contraction in a group of ten students performing exercise of low intensity, that is 5, 15, and 30% of maximal voluntary contraction. The electromyographic signals were collected from the biceps brachii and temperature was recorded from the skin over the muscle. Temperature was found to correlate with RMS, mean frequency, and median frequency values. In the current study, such correlation was observed for intense exercise for the rectus femoris. The dynamic measurements of the temperature of the quadriceps muscles during ergometer exercise taken by Krustup et al. [14] showed a linear increase in temperature in time as well. In their research, temperature was measured directly in the muscle by means of thermistors inserted using venflons. An increase in temperature in the biceps brachii during intense exercise was also recorded using a thermographic camera by Neves et al. [18]. These authors noted a decrease in temperature in the initial phase of the exercise and then a gradual increase in temperature, which depended on fatfold thickness.

In the current study, atypical changes in the form of decreases in temperature were observed in two players (number 2 and 12). The reason for the exceptions to the overall trend could be the activation of deep motor units. Vigotsky et al. [25] found that the results of the measurements of EMG amplitudes can differ considerably if deep motor units are recruited. This can also influence the transfer of heat generated in the muscle to the skin.

In the current study, after the effort performed during the series of squats, the rate of temperature increase in time was significantly greater than before the exercise ($p < 0.005$). The RMS increase rate was also signifi-

cantly higher post-exercise ($p < 0.05$), whereas differences in frequency reduction were non-significant. In order to maintain a high level of force, trained volleyball players most likely compensate for reductions in frequency by increasing muscle excitation.

Thermographic measurements can be competitive in relation to electromyographic ones in assessing muscle fatigue and efficiency in athletes as long as factors that can lead to errors are considered. It is extremely important to maintain comparable conditions during measurement (temperature, humidity, distance from the camera, emissivity settings, and the elimination of the impact of heat and light sources). The skin from which the measurements are taken should not be injured or inflamed. In electromyographic studies, errors can be due to inadequate cleaning of the skin, excessive bioimpedance, or inaccurate placement of the electrodes.

The strengths of the current study include the standardisation of the measurement conditions and the determination of parameters that are significant for the assessment of muscle function, which are the slope coefficient for temperature changes and the time of maintaining 70% of peak torque. Although the measurements were carried out only in volleyball players, it can be surmised that the mechanisms of decreases in muscle efficiency are similar in athletes from other disciplines as well as in non-athletes.

5. Conclusions

Based on the findings of the study, we recommend simple, low-cost, and non-invasive tests for assessing the level of muscle fatigue and the decrease in muscle efficiency in volleyball players consisting of the measurement of the time of maintaining high torque in isometric contraction and of the slope coefficient for the increase in temperature recorded using a thermographic camera.

In our opinion, the non-invasiveness of such measurements is their greatest advantage, compared to sEMG which requires direct contact with the subject's skin.

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