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The Influence of Fatigue on Muscle Temperature

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The aim of the study was to investigate the possibility of using infrared (IR) thermography for assessing muscle fatigue during low effort. Three tests at constant levels of load 5, 15 and 30% of maximum voluntary contraction (MVC) lasting 5 min each were performed on a group of 10 men. Temperature and electromyographic (EMG) signal were registered from biceps brachii (BB). Analysis focused on the influence of load on the values and changes in time of muscle temperature. Correlations between temperature and EMG parameters (RMS, MPF and MF) were also analysed. Constant load sustained during the tests resulted in an increase in the temperature of BB. There were statistically significant correlations between temperature and EMG parameters for most subjects. Results of the study suggest that IR thermography can be an alternative or supplementary method for assessing muscle fatigue at low levels of contraction.

EMG muscle fatigue muscle temperature biceps brachii

1. INTRODUCTION

Muscle fatigue related to excessive muscle load can become the source of complaints associated with the musculoskeletal system [1, 2]. This means that reducing fatigue in working conditions can result in a decrease in the number of musculoskeletal complaints. Thus, methods and algorithms for assessing muscle fatigue are important.

Since the 1980s, electromyography (EMG) has been the leading technique in assessing muscle fatigue. This method makes it possible to estimate fatigue on the basis of the electrical signal registered from muscles during their activation [3, 4, 5, 6, 7, 8, 9, 10, 11, 12]. The registration of an electrical signal with surface electrodes is commonly used to assess muscle load and fatigue during occupational tasks [13, 14, 15, 16, 17]. Numerous studies indicate the relationship between the amplitude of the EMG signal and the force developed by muscles [18, 19, 20, 21]. Moreover, many studies confirm the influence of the level of muscle load on the values of the parameters characterizing the power spectrum of the EMG signal [6, 7, 8, 9, 10] and indicating muscle fatigue. Thus, it can be assumed that EMG is a method suitable for assessing muscle fatigue. However, surface EMG, in addition to its numerous advantages, has its limitations, especially at low levels of muscle contraction [5, 21, 22]. The load and alleged fatigue at a very low level of muscle load is still under dispute. According to Rohmert, force at a

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low level, such as 10% of maximum voluntary contraction (MVC), can be exerted continuously [23]. However, other studies indicate musculoskeletal disorders in muscles (e.g., trapezius) loaded at a very low level with continuous work [24]. Studies also suggest that some phenomena, which lead to muscle myalgia, occur even at low levels of muscle contraction [25, 26]. Invasive experiments, with biochemical indicators (CrP, ATP, ADP) show changes in time of load even at levels under 10% MVC [25]. The results indicate that low-level effort causes changes in blood pressure, heart rate and blood flow [27, 28, 29]. Moreover, studies with the use of surface EMG show fatigue at levels of muscle contraction as low as 8% MVC [26]. This suggests that especially low levels of load of the musculoskeletal system require further study.

The effect of an increase in muscle temperature due to heat production in metabolic processes is commonly considered during tests on high dynamic effort [30]. Research on muscle temperature mainly concerns issues associated with analysing the influence of initial muscle temperature or environment temperature on force and muscle fatigue [20, 31, 32, 33, 34] or the influence of the type of activities on joint temperature [30]. Becher, Springer, Feil, et al. suggest that changes in the temperature of joints are associated with the type of activities [30]. Significantly fewer studies are dedicated to temperature changes in single muscles as a result of static muscle effort at low levels of load [35].

Thanks to technological development, there are new methods of assessing fatigue, which can be used in improving occupational safety and health. In recent years, infrared (IR) thermography has been widely used in various fields of life. On the basis of their studies on the anterior deltoid muscle during static exertion, Bertmaring, Babski-Reeves and Nussbaum reported that IR thermography had capabilities to detect work-related musculoskeletal disorders [35]. They also suggested that results obtained with IR thermography were sensitive to change in a factor like shoulder posture. An advantage of IR thermography is the possibility of contactless temperature measurement with sensitivity of 0.08 °C. Therefore, the aim of the study was to investigate the possibility of using IR thermography in assessing muscle fatigue during muscle effort at a constant load under 30% MVC. The hypothesis is that during static load of up to 30% MVC, an increase in muscle temperature can be an indicator of muscle fatigue. To verify this hypothesis, a study was conducted in healthy men doing static elbow flexion at 30, 15 and 5% MVC. IR thermography and surface EMG were used.

2. METHODS

2.1. Subjects

All 10 male subjects were students at the University of Physical Education, Warsaw, Poland. The group was homogeneous in terms of age, body weight and body height. The means (*SD*) for the subjects' age, body weight and height were 23 years (0.67), 78.8 kg (5.71) and 185.2 cm (3.29), respectively. They were all healthy and had no musculoskeletal complaints. Each subject read and signed an informed consent form prior to the study. The protocol of the study was approved by the local ethics committee.

2.2. Examined Muscle

The subjects maintained static body posture and a constant level of exerted force during the tests. This provided isometric conditions for measuring the temperature and the EMG signal from the short head of biceps brachii (BB) of the right upper limb.

2.3. Protocol

The environmental temperature in the laboratory during the tests was constant at 24.9 °C (±4%). Before the measurements, the subjects were in the laboratory for at least 15 min to acclimatize. During the measurements, they were standing upright, with their right upper limb flexed in the elbow at 90° (Figure 1). The flexion angle of the shoulder was also 90°. The subject's task was to maintain elbow flexion against resistance.

The measurements had two stages. The first one consisted of registering the EMG signal and the external force at maximum effort (MVC). In one measurement, the subjects exerted force twice, the greater effort was chosen as MVC. The measurement at maximum effort took 10 s.

The second stage was done for the same body posture as in the first stage. Muscle temperature and the EMG signal were recorded while the subject maintained constant force during tests at 30, 15 and 5% MVC. The distance between the IR camera and the arm was 0.6 m. Duration of effort in the three tests was up to 5 min, which was based on maximum endurance time obtained in other studies [36, 37, 38]. According to those studies, maximum endurance time is 70–300 s, depending on anthropometric characteristics, physical activity and age. The subjects were allowed to stop maintaining the load when exhausted or experiencing pain. If the value of external force fell by at least 10% of the set level for at least 3 consecutive seconds, the measurement was terminated. All measurements were sequenced and occurred at determined time intervals. The experiment was designed in this way to obtain, in a relatively short time, the influence of fatigue not only at the level of 30% MVC, but also at lower levels of load (5 and 15% MVC). It was assumed that the initial relatively high level of load (30% MVC) would cause fatigue in BB and then subsequent load even at the lower levels would lead to fatigue faster. Thus, the first test involved maintaining constant force of the muscles of the right upper limb at 30% MVC. Then, tests were done at 15 and 5% MVC. There was a 15-min break for recovery between tests.

2.4. Equipment

2.4.1. Measuring temperature of BB

An IR camera (ThermaCAM SC2000; FLIR Systems, Sweden) was used to measure muscle temperature. It had a focal plane array (FPA) of uncooled microbolometer detectors that gave a resolution of 320 × 240 pixels. The spectral range of matrix detectors was 7.5–13 µm. The measured temperature range for objects was from –40 to 2000 °C. The tests were performed in one measuring range, namely, from –40 to 120 °C.

The sensitivity of the IR camera was under 0.08 °C. Due to the high emissivity of the surface of a human body (0.98) and precisely measured environmental temperature during tests, the measurements were very precise (0.2 °C). The precision of determining a temperature increase was ~0.1 °C. The camera supported a 14-bit digital recording with full dynamics. The image in the camera was refreshed at the frequency of

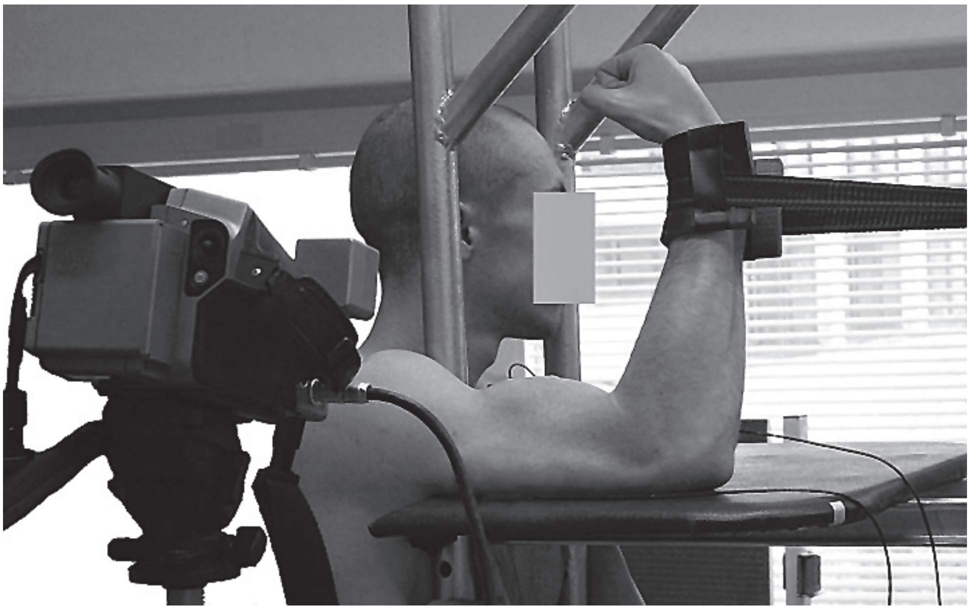

Figure 1. Posture during measurements.

50 Hz. During tests, the registration frequency of thermograms was 1 s.

Thermogram sequences were registered and analysed with ThermaCam Researcher 2001 software (FLIR Systems, Sweden). Each thermogram contained digital information on the temperature values for each of the 76 800 pixels (320 × 240). Special colour palettes, where values of temperature were assigned colours, provided a temperature image of the surface of an object conveniently and legibly. Figure 2 shows sample thermograms of the skin surface over BB at the beginning and at the end of a measurement for 30% MVC.

2.4.2. Measuring force

The levels of load (30, 15 and 5% MVC) were determined on the basis of the value of external force measured with a dynamometer. A dynamometer in conjunction with a transducer makes it possible to convert force to an electrical signal and to present the change in the values of force during a test. CPS version 2.0 software (JBA Zbigniew Staniak, Poland) was used to visualize and measure the force. In this way force was observed and could be exerted at a constant level.

2.4.3. Measuring EMG

The EMG signal was registered with surface electrodes (Ambu Blue Sensor P, Denmark). Interelectrode distance was 20 mm. Before the electrodes were fixed, the skin was prepared (shaved and disinfected with an alcohol). The electrodes were located on the skin in accordance with the SENIAM guidelines and Perotto [41]. They were located on a line between the medial acromion and the fossa cubit at one third from the fossa cubit. Three electrodes registered the EMG signal; two active ones along muscle fibres, on the line between the acromion and the fossa cubit, and a third, reference one. Contact material of the sensor was Ag/AgCl, sensor area was 13.2 mm^2. Resistance between the skin and an electrode was under 2 kΩ.

ME4000P (Mega Electronics, Finland) apparatus measured and registered the raw EMG signal. The input impedance of ME4000P was 10 GΩ, common mode rejection ratio (CMRR) was 110 dB and the signal to noise ratio –75 dB. EMG amplification was 1000. The bandwidth of the apparatus was 8–500 Hz (–3 dB, Butterworth filter). The registered EMG signal was sampled at the frequency of 2 kHz.

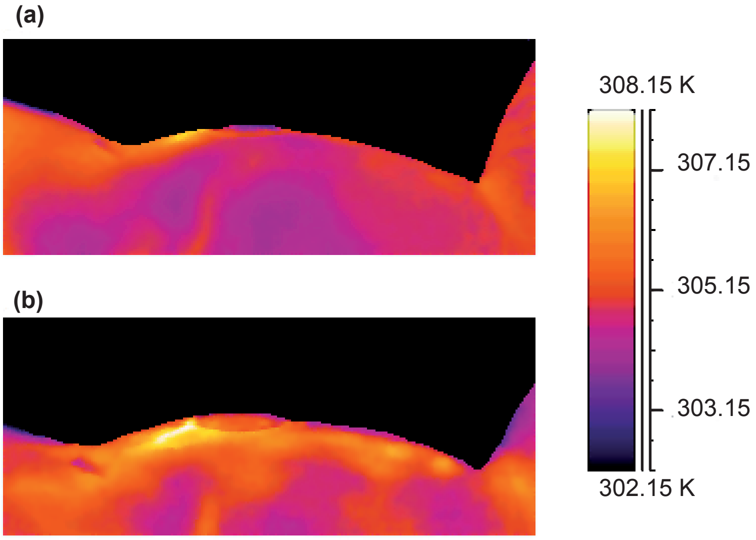

Figure 2. A sample thermogram of the surface of the skin over biceps brachii (a) at the beginning and (b) at the end of a measurement at 30% MVC. *Notes*. For clarity, background items, not associated with the subject, were removed from the thermograms; MVC—maximal voluntary contraction.

2.5. Analysis

This analysis aimed to (a) determine the influence of the level of load on the values of muscle temperature and the values of the EMG parameters and (b) analyse the relationship between muscle temperature and the EMG parameters during the load.

The analysis concerned values of the EMG parameters commonly used in investigating muscle fatigue (root-mean-square, RMS; mean power frequency, MPF; and median frequency, MF) and muscle temperature (T). The analysis of the EMG signal was carried out with Matlab R2009a software (MathWorks[1], USA). Temperature was analysed on the basis of fragments of thermograms corresponding to fragments of the skin in the immediate vicinity of the EMG electrodes.

During tests at three levels of muscle force (30, 15 and 5% MVC), temperature (T) of BB was recorded with the time resolution of 1 s. The EMG signal was divided into windows also with 1-s intervals (1 s, 2000 samples, boxcar window). This means that 300 values of each parameter (T, RMS, MPF and MF) were obtained from a 5-min test.

RMS expresses the relative value obtained as a result of dividing the amplitude of the EMG signal from measurements in separate tests (at 30, 15 and 5% MVC) by the value of the amplitude the measurement at MVC.

Parameters corresponding to the beginning of the tests (bT, bRMS, bMPF and bMF) were determined by averaging the values for individual parameters (T, RMS, MPF and MF) from the first 5 s of each test. The differences between the three levels of load (5, 15 and 30% MVC) were analysed on the basis of parameters bT, bRMS, bMPF and bMF.

The relationships between the values of the EMG parameters (RMS, MPF and MF) and muscle temperature (T) for subsequent values of the parameters during load were also analysed. The analysis also aimed to investigate the influence of the level of load on changes in the temperature of BB (DT) during the tests. Parameter DT was calculated as the difference between the temperature read from the last thermogram and the temperature read from the first thermogram of each test.

2.6. Statistical Analysis

To determine the influence of the level of load on temperature (bT) and parameters bRMS, bMPF and bMF (related to the beginning of tests), an analysis of variance (ANOVA) was done for each parameter. The first stage of ANOVA included Levene's test, which confirmed the hypothesis of variance homogeneity for bT, bMPF and bMF. The hypothesis was rejected for bRMS. Parametric ANOVA was used for parameters with variance homogeneity (bT, bMPF and bMF), whereas a nonparametric Kruskal–Wallis test was used for bRMS.

Spearman correlation between the values of the temperature of BB and the values of RMS, MPF and MF obtained in consecutive moments of the test, was analysed to assess the relationship between the values of the EMG parameters and the temperature of BB registered during the load.

The influence of long-term load on the changes in the temperature of BB was expressed with DT. As Levene's test did not confirm the hypothesis of variance homogeneity for DT, a nonparametric Kruskal–Wallis test was used. The test evaluated the differences in DT between the levels of load. The analysis was done with Statistica 9.0 (StatSoft[2], USA), $\alpha = .05$ was accepted.

3. RESULTS

Figure 3 presents the mean values of the temperature of the skin over BB (bT) registered at the beginning of tests at three levels of load (5, 15 and 30% MVC).

Table 1 shows the results of an analysis focused on the influence of the level of muscle contraction on the parameters obtained at the beginning of a test. Those results show a statistically

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[1] http://www.mathworks.com
[2] http://statsoft.com

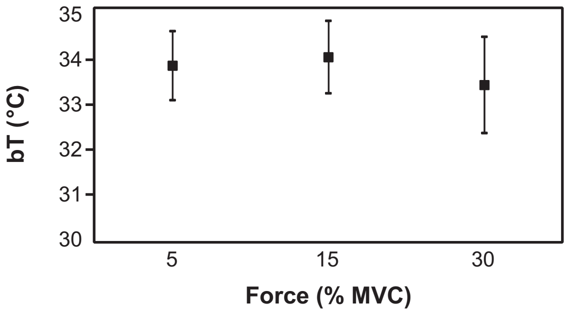

Figure 3. Mean values and standard deviations for the temperature of the skin over biceps brachii at the beginning of a measurement (bT) during muscle activation at 5, 15 and 30% MVC. *Notes.* MVC—maximal voluntary contraction.

TABLE 1. The Influence of the Level of Load (5, 15 and 30% MVC) on the Values of the Parameters at the Beginning of a Test

Parameter	F	p
bT[a]	1.27	.2973
bRMS[b]	**21.37**	**.0001**
bMPF[a]	**6.28**	**.0057**
bMF[a]	0.12	.8840

Notes. Bold indicates significance at $p < .05$; MVC—maximal voluntary contraction; a—result of analysis of variance (ANOVA), b—result of the Kruskal–Wallis test.

significant influence of the level of load on the amplitude of the EMG signal (bRMS) and mean frequency (bMPF) corresponding to the beginning of the tests. However, there was no statistically significant influence of the level of load on bT and bMF.

Spearman correlation between the values of T and the values of RMS, MPF and MF obtained in subsequent moments of the tests, for all tested

TABLE 2. Spearman Correlation Between the Temperature of Biceps Brachii and Parameter RMS for 3 Levels of Load for All Subjects

	5% MVC		15% MVC		30% MVC	
Subject	*R*	*p*	*R*	*p*	*R*	*p*
1	**.21**	**.0024**	–.07	.3256	**.45**	**.0001**
2	**.86**	**.0001**	**.40**	**.0001**	**.74**	**.0001**
3	**–.33**	**.0001**	**.30**	**.0001**	**.87**	**.0001**
4	**.31**	**.0001**	**.24**	**.0001**	**.28**	**.0001**
5	**.40**	**.0001**	**.85**	**.0001**	**.90**	**.0001**
6	**.33**	**.0001**	**.69**	**.0001**	–.07	.2467
7	**.60**	**.0001**	**.59**	**.0001**	**.90**	**.0001**
8	**–.49**	**.0001**	–.08	.2050	**.43**	**.0001**
9	**–.50**	**.0001**	**.20**	**.0011**	**.90**	**.0001**
10	.03	.6780	**.56**	**.0001**	**–.41**	**.0001**

Notes. Bold indicates significance at $p < .05$; RMS—root-mean-square; MVC—maximal voluntary contraction.

TABLE 3. Spearman Correlation Between the Temperature of Biceps Brachii and Parameter MPF for 3 Levels of Load for All Subjects

	5% MVC		15% MVC		30% MVC	
Subject	*R*	*p*	*R*	*p*	*R*	*p*
1	**.14**	**.0418**	–.13	.0575	**–.43**	**.0001**
2	**–.79**	**.0001**	**–.29**	**.0001**	**–.57**	**.0001**
3	**–.11**	**.1090**	–.02	.7335	**–.42**	**.0001**
4	**–.26**	**.0001**	**.29**	**.0001**	–.04	.5676
5	**–.39**	**.0001**	**–.62**	**.0001**	**–.58**	**.0001**
6	**–.20**	**.0008**	**–.26**	**.0001**	.04	.4833
7	**–.22**	**.0002**	**–.23**	**.0001**	**–.37**	**.0001**
8	**.23**	**.0002**	.04	.5179	**–.28**	**.0001**
9	–.08	.1493	–.11	.0950	**–.40**	**.0001**
10	**.15**	**.0170**	–.02	.7785	**.15**	**.0294**

Notes. Bold indicates significance at $p < .05$; MPF—mean power frequency; MVC—maximal voluntary contraction.

TABLE 4. Spearman Correlation Between the Temperature of Biceps Brachii and Parameter MF for 3 Levels of Load for All Subjects

	5% MVC		15% MVC		30% MVC	
Subject	***R***	***p***	***R***	***p***	***R***	***p***
1	**.20**	**.0035**	**–.19**	**.0037**	**–.56**	**.0001**
2	**–.26**	**.0001**	**–.33**	**.0001**	**–.91**	**.0001**
3	**–.18**	**.0081**	**.21**	**.0007**	**–.69**	**.0001**
4	**.18**	**.0021**	**.70**	**.0001**	–.12	.0690
5	**–.50**	**.0001**	**–.48**	**.0001**	**–.66**	**.0001**
6	–.05	.3951	**–.41**	**.0001**	**.12**	**.0455**
7	**–.14**	**.0161**	**–.29**	**.0001**	**–.78**	**.0001**
8	**–.17**	**.0036**	.08	.1952	**–.29**	**.0001**
9	**–.21**	**.0002**	**–.18**	**.0037**	**–.81**	**.0001**
10	**.29**	**.0001**	–.04	.6194	**.38**	**.0001**

Notes. Bold indicates significance at $p < .05$; MF—median frequency; MVC—maximal voluntary contraction.

subjects, was analysed to assess the relationship between changes in the EMG parameters and changes in the temperature of BB during the load. Table 2 shows correlation coefficients and probability for parameters T and RMS; Tables 3–4 show the same for MPF and MF, respectively.

The correlations between the values of the temperature of BB and the EMG parameters for all three levels of load (5, 15 and 30% MVC) were statistically significant for most subjects (Tables 2–4).

Constant load sustained during the tests resulted in an increase in BB temperature, which is quantitatively expressed with parameter DT. Values of this parameter differ in tests (Figure 4).

The result of the Kruskal–Wallis test (value 12.1, $p = .0024$) indicated that the level of load had a statistically significant influence on the value of DT, which indicates an increase in muscle temperature during the load. The analysis showed significant differences in the values of DT in tests at 5 and 30% MVC.

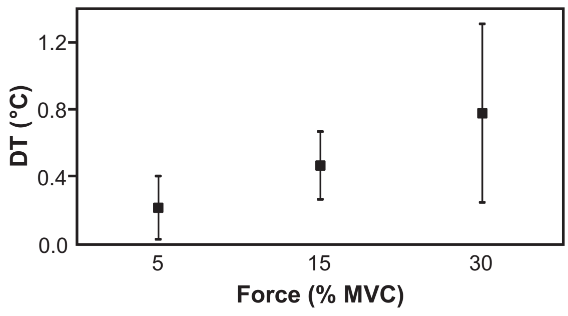

Figure 4. Mean values and standard deviations for parameter DT from biceps brachii during muscle activation at 5, 15 and 30% MVC.
Notes. MVC—maximal voluntary contraction.

4. DISCUSSION

The statistical analysis showed that the level of load itself did not affect the values of the temperature of BB. At the same time, the level of load developed by the muscle unequivocally affected the values of the EMG parameters (bRMS and bMPF). The greater the external force, the greater the values of bRMS (corresponding to the beginning of the tests) and the lower the values of bMPF. Those results confirmed previous research showing similar relationships [7, 8, 9, 10, 20, 21].

The statistical analysis also showed that changes over time in the values of all analysed EMG parameters (RMS, MPF and MF) were correlated with changes in the temperature of BB (T). The increase in muscle temperature was expressed quantitatively with parameter DT; and muscle fatigue was probably responsible for that increase. During tests at higher levels of muscle contraction, parameter DT increased its value to a greater extent. The trend of a greater increase in muscle temperature at a higher levels of muscle contraction may result from the fact that at a higher load of BB, fatigue was greater. Other researchers reported an increase in temperature during physical effort. Becher et al. did not observe any significant influence of the level of load on the temperature in joints registered at the beginning of a measurement [30]. However, they noticed that the larger the force exerted during tests, the greater the changes in the temperature in the joints over time. This means that the level of load affects the changes in the temperature in the joints, which is a result of fatigue.

Bertmaring et al. suggested that results obtained with IR thermography were sensitive to fatigue of the musculoskeletal system; however, various factors such as blood flow or muscle heating could affect the skin surface temperature [35]. The results of other studies also indicate that muscle effort causes changes in blood flow [27, 28, 29]. The changes in temperature on the surface of the skin, observed in the present study, may result not only from muscle heating but also from other factors such as blood flow. However, it should be noted that changes in muscle temperature were strongly correlated with the values of the EMG parameters, which are commonly used as indicators of muscle fatigue. This suggests that muscle fatigue significantly influenced temperature changes observed in this study.

The influence of the force fluctuation on the EMG parameters, especially at low levels of load, may interfere with assessing muscle fatigue [42]. The results of the tests in studies presented in this paper indicate that changes in muscle temperature are sensitive to sustained constant load at low levels of the external force. Thus, IR thermography may be an alternative method to EMG in assessing muscle fatigue, also where muscle load is maintained at low levels. This study demonstrated that the temperature at the beginning of the tests (bT) was insensitive to changes in the level of load. This indicates an additional advantage of IR thermography in assessing muscle fatigue, i.e., its insensitivity to short changes in the level of load.

However, in this study there were some limitations resulting from using IR thermography as a method for assessing muscle fatigue. Because of the influence of the environmental temperature on the temperature of the skin above the studied muscle, it was necessary to maintain constant environmental temperature. This study was done on a muscle that was not covered with clothes. If the study were done on a muscle covered with clothes, the increase in the temperature of the skin above the muscle would probably be greater; however, it would have been difficult to measure it with IR thermography. This limitation makes it difficult to use this method at workstations with unstable environmental temperature and ones that require full-body clothing. Body posture maintained in the test differs from postures that are common in working conditions, which is also a limitation.

Another limitation resulting from the system of recording temperature is the fact that the tests did not consider the influence of the subcutaneous layer. The fatty tissue layer could affect the temperature differences between the studied muscle and the skin on the surface as well as values of the EMG parameters [35, 43, 44, 45]. Like in the case of the EMG parameters, the influence of the subcutaneous layer on the recorded temperature is difficult to predict in IR thermography. This seems to be a significant problem, considering that the temperature is recorded from the skin surface, i.e., with the mediation of the fatty tissue located between the skin and the muscle. De Ruiter and De Haan recorded skin temperature with a thermocouple placed over the muscle; they calculated temperature inside the muscle from the measured skin temperature with the linear relationship between skin and muscle temperature [32]. In the present study, the temperature of the skin above BB was analysed excluding the influence of the mediation of the fatty tissue located between the skin and the muscle. The influence of fatty tissue on the analysed parameters was minimized by carrying out the tests with subjects with proper values of the body mass index (BMI) (22.96 ± 1.36). It was assumed that the changes in the analysed parameters in the study mainly resulted from processes associated with muscle fatigue; the influence of other factors, such as fatty tissue or blood flow, was ignored.

With the adopted sequence of individual tests (30, 15 and 5% MVC), the changes in the values of the parameters in the last test (5% MVC) could result from cumulative fatigue, which can also be a limitation. However, the 15-min breaks between the tests made it possible for muscles to regenerate, thus minimizing cumulative fatigue.

Changes in muscle temperature are associated with changes in the EMG parameters commonly accepted as indicators of muscle fatigue. It was demonstrated that sustaining constant load at a muscle contraction level up to 30% MVC affected muscle temperature. An increase in the temperature of BB during the load, is correlated with an increase in RMS and a decrease in MPF and MF of the EMG signal resulting from growing muscle fatigue.

5. CONCLUSIONS

IR thermography can supplement surface EMG in assessing muscle fatigue. A combination of those two methods makes it possible to obtain more comprehensive information regarding the processes related to muscle fatigue. Fatigue indicators based on the increase in muscle temperature might be very useful not only in the laboratory, but also at work. The results of this study help develop more specific indicators of muscle fatigue based on IR thermography.

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