Could Thermal Imaging Supplement Surface Electromyography Measurements for Skeletal Muscles?

Bartłomiej Zagrodny, Wiktoria Wojnicz, Michał Ludwicki, and Jan Awrejcewicz

***Abstract*— 1) *Background:* The aim of this study is to present the results of experiments in which surface electromyography (sEMG) and thermal imaging were used to assess the muscle activation during gait and to verify the hypothesis that there is a relationship in the case of low fatigue level between sEMG-measured muscle activation, assessed in the frequency domain, and thermal factors calculated as minimum, maximum, kurtosis, mean, median, and mode from the area of interest. 2) *Methods:* Comparison of activity calculated from the recorded sEMG data for** *rectus femoris* **(RF),** *biceps femoris, tibialis anterior, and gastrocnemius medialis* **(GM) with thermal data obtained from the infrared vision. 3) *Results:* Data of 14 healthy volunteers obtained during 10 min of treadmill gait are presented and analyzed. The analysis revealed statistically significant linear correlations for RF (five moderate relationships) and GM (one good relationship) and moderate nonlinear correlations for all examined muscles. Also, a detailed protocol for precise, repeatable thermal examination is presented. 4) *Conclusions:* Estimated moderate linear and nonlinear correlations between thermal and electromyographic parameters are found for low level of muscle fatigue, which suggests that the presented method is useful in the analysis of muscle activation with the use of a thermal imaging as a complement to sEMG.**

***Index Terms*— Electromyography, muscle activity, muscle fatigue, thermal imaging.**

I. Introduction

Surface electromyography (sEMG) is used to assess the muscle activity [1] during movement, also in the case of gait analysis [2]–[5] and different daily activities [6]. However, the sEMG results used in the individual biomechanical study depend on the method of signal processing, examiner's experience [7], electrodes' placement, sEMG device, skin preparation, and other factors [8]. Thus, a standardization of the examination procedure is a crucial factor of sEMG data collecting. [9], [10] and processing [7], [11]. Quantitative information based on sEMG analysis of the activation of skeletal muscles can give an insight into their fatigue level [12]. For this purpose, the muscle fatigue criterion can be defined by changes observed in EMG frequency range 20–450 Hz, e.g., the median frequency (MF), mean power frequency (MPF) [13], or MPF obtained using a wavelet transform (where wavelet function of the Daubechies family (CMPFdb5) is used in [14]) or functions in the time domain, such as the rms or integrated EMG. It is worth noting that some contemporary researches reveal time dependence in the case of sEMG for the same exercises in unchanged conditions [15] which may be an additional reason for the variability of the results over time. Barry and Cole [16] suggest that signal generated by the muscles at the resonant frequency during contraction can be used to determine changes of muscle stiffness changes in case of isometric contractions, what implies that this method could also be useful to monitor the muscle fatigue.

Wearable sensor systems are also used in remote monitoring of biomedical signals (e.g., EMG). To analyze these signals, a series of contaminants (measurement, instrumentation, and interference artifacts) should be removed. This could be done by applying sophisticated methods of classification and regression, e.g., one-class support vector machine [17] and adaptive neuro-fuzzy inference system (ANFIS) that uses an artificial neural network (ANN) and a chosen fuzzy interference system [18].

The beginning of modern thermography starts in the 30s of the 20th century [19]. The predecessors of modern forward-looking Infrared (FLIR) systems were born in the late 50s. From the early 60s, the first use of the infrared technique to perform the nondestructive testing in civil application took place [20]. Nowadays this technique is widely used in many fields, like medicine, biomechanics, architecture, detection of gases, and humid areas, testing of electrical circuits, and military purposes. One of the utilitarian uses is the application of infrared technique to identify symptoms of diseases like SARS, MERS, or COVID [21], [22]. With respect to the human beings, the infrared emissions of the human skin at 27 °C is located in the range of 2–20 μm of the wavelength, with peaks around 10 μm [20]. The emissivity of the Caucasian race is assumed as 0.97–0.98, depending on the publications [20] and [23]. Examining a musculoskeletal system with the use of thermal imaging equipment is based

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on the phenomena that any muscle contraction affects the change in its temperature. It is assumed that human skeletal muscles have mechanical efficiency in the 30%–65% range and its change in exercise time is also noted (from higher to lower) [24] due to increased energy dissipation in the form of heat. Increased skin temperature in the region of active muscles and change in the overall body temperature can be identified using thermal imaging camera [23], [25]–[28]. On this basis, muscle activity during the whole experiment and symmetry of muscle work can be observed. It is worth noting that one of the problems with the assessment of muscle activity based on thermal imaging is a decrease in skin temperature caused by vasoconstriction during the initial exercise time [29], thermoregulation, and sweating of the human body [23] even in the case of low workload exercise like walking at comfort speed without additional load [26], [30]–[33].

Unlike sEMG, thermal imaging is a noncontact technique which can be considered as its greatest advantage. More accurate and cheaper infrared cameras make this method popular in medicine [34] in clinical use and biomechanics [23], [35]–[37]. However, some restrictions in preparation and examination are mandatory [26], [33], [37]. To assess the muscle activation level, the following parameters are calculated: the mean temperature values from selected areas [23], [25], [26], [31], [33], [38], [39], maximum [39], [40], median, and kurtosis [41] of temperature distribution.

There are only a few studies in the literature that are strictly devoted to experiments on the relationship between sEMG parameters defined in the time or frequency domain and thermal analysis. In [37], the research was carried out in the case of incremental workload cycling. Researchers were unable to report specific parameters that can correlate thermal and sEMG parameters in the case of an incremental workload cycle exercise to exhaustion. In their experiment, ten physically active participants were examined. The sEMG signals were recorded from rectus femoris (RF), vastus lateralis, biceps femoris (BF), and gastrocnemius medialis (GM). Thermal images were analyzed before, immediately after and 10 min after finishing the exercise at the aforementioned body regions. In the case of vastus lateralis, an inverse relationship between skin temperature and sEMG was found, but in the case of BF and GM, no changes in temperature after the test were reported. However, these conclusions contrast with the result published in the next two cited studies [14], [42]. In [14], contractions of the upper limb in isometric condition were considered. Ten volunteers were tested and it was proved that for 5%, 15%, and 30% of maximum voluntary contraction (MVC), the rms and MPF parameters were correlated ($p < 0.05$) with changes in skin temperature for biceps brachii. The study by Ridzuan *et al.* [42] presented the results for the lower limb running speed of 10 km/h and the period of 30 min. However, the experiment was carried out for only five participants. The results are questionable because the authors used an air conditioner during the experiment and did not determine the distance between the thermal imaging camera and the examined person. However, the authors suggest that the sEMG MF may be related to the average temperature, but this assumption was made on the results of linear approximation and Pearson correlation coefficient. The study by Kuniszyk-Jóźkowiak *et al.* [43] considered a static test for the RF with muscle at relatively high level of contraction −70% of the MVC. The article by Ali *et al.* [34] revealed a statistically significant difference in EMG amplitude of the GM in case of extensive cooling of the muscles (20 min in 10 °C water). A decreased maximum force of the tibialis anterior (TA) was also revealed. Leg cooling resulted in approximately 15.7 °C drop of skin temperature. The article by Coletta *et al.* [44] revealed that raised core and skin temperature causes shifts of the sEMG signal toward higher frequencies during the force task. According to authors, the higher core temperature, as a thermal stress, influences neuromuscular response, whereas skin temperature has a minimal influence on the submaximal task. The main conclusion is that temperature has a task-dependent impact on neuromuscular responses.

Daud *et al.* [45] presented the results of the study that aimed to determine whether the skin temperature above the muscle is related to the sEMG signals of these muscles. The authors stated that "there exist strong correlations of muscle contractions of upper extremities and heat that is being generated during the activities as exhibited by the EMG recordings and thermal images."

In the literature, it can be found that temperature differences below 1 °C are often considered (see studies [23], [26], [29], [30], [38], [39]). In the case where the experiment is carried out under controlled conditions, the thermal results can be considered as significant [36], [46]. For more energetic exercises, the results can be found in works [38], [42], and [43]. It should also be emphasized that the tests were carried out using a motorized treadmill, which affects the gait parameters [47], that may have an influence on the way of firing and activation of lower limb muscles and the stabilization method. Nevertheless, the treadmill is commonly used in gait tests, especially in longer periods under controlled laboratory conditions.

In all published studies dealing with a problem of correlation between the thermal and sEMG results, no analysis was devoted to the low level activity. Most publications are devoted to activities that can cause high level of muscle fatigue resulting in a higher level of changes in sEMG and thermal parameters. That is why the motivation of this study was to consider normal daily activity by assuming that muscle activation (activation) is identified by using sEMG and muscle activity (activity) can be detected by using thermovision. The aim of the study was to verify a hypothesis that there exist statistical relationships between muscle activation factors and thermal factors for low level of muscle activity. The scope of this study was to establish linear and nonlinear relationships between sEMG parameters and thermal parameters. Based on the cited literature (see [8], [9], [48]), it is assumed that muscle activation can be estimated as the sEMG mean and MF factors (parameters). From the physiology point of view, a manifestation of fatigue phenomenon in muscle fibers is a drop of their contraction properties, i.e., diminish of higher frequencies of muscle fibers contraction [1], [49], [50]. Due to this reason, we identified muscle fatigue by calculating the difference of the sEMG mean and MF at the beginning and the end of tested time interval.

Thermal factors were evaluated as changes (at the beginning and the end of tested time interval) in the minimum, maximum, mean, median, kurtosis, and mode temperature of the skin areas above the tested active muscles. The reason of this decision is the fact that muscle activation changes its temperature due to relatively low mechanical efficiency and due to energy dissipation, i.e., this implies a change in skin temperature.

II. Materials and Methods

Seventeen healthy male volunteers were taken apart; however, one of them was not familiar with treadmill gait and measurements of one of the participants were excluded due to technical problems; also for further analysis, one of the volunteers was used as a control subject to ensure that the laboratory conditions do not affect the results. Finally, 14 sets of measurements were considered for the sEMG-thermal correlations. All volunteers were students. None of the participants declared any kind of cardiovascular or pulmonary problems, none of them took cardiovascular medication, and none had problems with motor system or postural stability. All volunteers provided written informed consent in accordance with procedures approved by the Committee of Research Ethics with Human participation at Gdansk University of Technology.

Inclusion criteria for volunteers were as follows: male, age 20–25 years, and body core temperature < 37 °C. An exclusion criterion encompassed problems with postural stability, neurological problems, cardiovascular drugs treatment, leg length difference greater than 0.5 cm, failure to comply with the preparation rules of thermal imaging examination, skin inflammation, and visible “hot spots” on the body in IR. All participants passed Romberg test.

Basic anthropometric measurements were made for each participant (see Table I): body mass and height with medical scale with a stadiometer (WPT Radwag, Poland) and body fat estimation with a Harpenden skinfold caliper (Baty, U.K.) with a dedicated software according to the Jackson/Pollock four-site measurements method. Data of the volunteer who served as a control are marked as CONTROL [51].

Noraxon MyoTrace 400 system (four channels, 1000 Hz of sampling frequency) was used to measure the sEMG signals. This Noraxon system transmits the results to the PC by using wireless method and can simultaneously collect data from four channels [Fig. 1(a)]. Each channel is connected through the wire with a preamplifier to the double electrode (working in different schemes of measurement). The first channel has an additional third electrode that is a reference (ground) [Fig. 1(b)]. To eliminate the interfering signals, each preamplifier has common mode rejection ratio (CMRR) that exceeds 100 dB. Also, each EMG channel is bandpass antialias filtered in the range from 6 to 500 Hz and amplitude range [-5000; 5000] μV. Analog-to-digital transformation uses a 12-bit resolution. The MyoResearch XP Clinical Edition software was used to postprocess sEMG data, i.e., to rectify and smooth data by using the implemented root-mean-square algorithm with 100-ms window. Postprocessed sEMG data were used to calculate the sEMG mean and MF factors by using MATLAB software.

TABLE I
Anthropometric Data of Volunteers

volunteer	age [years]	weight [kg]	height [cm]	fat amount [%]
1	21.0	58.3	179.0	7.5
2	21.0	84.3	179.5	16.5
3	21.0	90.6	182.0	21.0
4	20.0	69.0	169.5	17.0
5	21.0	77.6	188.0	17.0
6	20.0	74.5	173.0	10.0
7	24.0	72.2	177.5	12.6
8	21.0	69.7	176.5	22.3
9	21.0	81.0	191.0	12.0
10	22.0	82.5	180.0	24.7
11	21.0	88.0	187.5	13.5
12	24.0	70.5	173.5	16.5
13	21.0	75.0	182.5	10.0
14	24.0	77.3	187.5	14.3
AVERAGE	21.6	76.5	180.5	15.3
SD	1.4	8.5	6.4	4.9
CONTROL	23.0	89.0	187.0	12.0

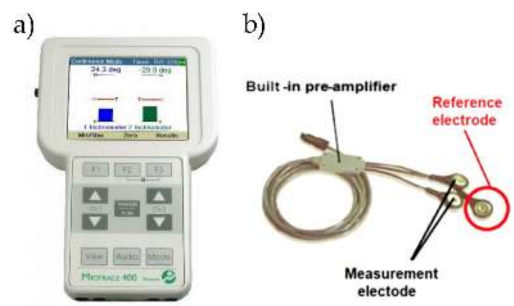

Fig. 1. (a) Noraxon measurement gauge. (b) Electrode [50].

Noraxon dedicated dual-EMG disposable electrodes (with 9-mm diameter of each electrode area) were placed according to the SENIAM recommendations [8] on the following muscle bellies of both legs.

1) *gastrocnemius medialis* (GM),
2) *biceps femoris, long head* (BF),
3) *tibialis anterior* (TA),
4) *rectus femoris* (RF).

The skin was prepared for placing the electrode by shaving and cleaning with an abrasive medical swab, poured with alcohol (Skinsept PUR, Ecolab Deutschland GmbH) (in the area where the electrode was placed). A reference electrode was placed on the malleolus medialis. All electrodes and cables were protected with an adhesive medical tape (Micropore 3M, USA), to reduce the motion artifacts.

For thermographic analysis, an NEC-Avio R300SR-S (NEC, Japan) thermal imaging camera with an FPA-type sensor, spectral range 8–14 μm, NETD 0.08K was used. All thermal images (in the form of panoramic images) were taken in pairs about 3 m from the front and back of the man standing in the anatomical position. There was no high temperature or objects with high reflectance in the laboratory during the experiment. The ambient temperature was set in the range

TABLE II
REQUIREMENTS FOR PREPARATION FOR THERMOGRAPHIC MEASUREMENTS

Time (minimum) before the experiment	**Action**
5 days	Do not sunbath.
2 days (48h)	Do not use: creams, powders, perfumes, deodorants and antiperspirants. Avoid: physical exercise, intensive physical activity, massage, electrical stimulation of muscles/nerves, ultrasound examination, acupuncture, warm or cold compresses, etc.
1 day (24h)	Remove hair from the tested area, preferably with a trimmer instead of a razor. Do not consume any type of alcohol.
12h	Last bath; preferably a short shower in lukewarm water without detergents; 2-3 days before the test a similar method of bathing is recommended. Do not use tight clothing items.
4h	Avoid physical exertion (quick gait, running, going up the stairs to higher floors, exercises). Do not consume beverages containing caffeine (including strong tea), hot or cold drinks.
2h	Do not eat.

of 21 °C–24 °C (the volunteer could decide about its value before the experiment), and the humidity was in the range of 30%–45% RH. It is worth noting that both parameters were monitored during each experiment, stored, and used in further analysis. Convection and advection in the laboratory were minimized. Each participant had 30 min for thermal adaptation. The skin emissivity was set to 0.98. In each case, the skin was tattoo free and no inflammatory or other types of dermatological or vascular problems were detected. For a more accurate thermographic assessment of skin temperature, a few days prior to the experiment, the volunteers were asked to meet the requirements described in Table II; the presented protocol is based on the requirements of the International Association of Certified Thermographers (IACT), American Academy of Thermology, European Association of Thermology, and publications [36] and [46]. Suggestions from the study by Moreira *et al*. [46] were also taken into consideration and all mentioned conditions were fulfilled. All restrictions were supplemented with additional restrictions, based on the authors' experience. Temperature measurement was performed by means of dedicated IR camera software that helps to properly select the area of interest and to export a raw temperature data to MATLAB-compatible file.

The test procedure consisted of thermal imaging and sEMG measurement at the beginning and end of walking on a self-propelled treadmill. Subjects were asked to walk for 10 min with a constant speed of 4.5 km/h. They were asked to walk naturally, without holding treadmill handles, to minimize the external disturbance. All of them were familiar with treadmill walking. This gait speed can be considered as a low-level fatigue exercise that causes low level of muscle activation [26]. Natural speed was also chosen to avoid extensive sweating, what could influence thermal measurements [34].

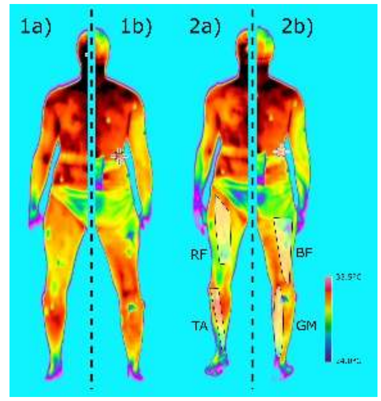

Fig. 2. Differences in the whole body temperature distribution—an example of a thermal image, (1) before exercise and (2) after exercise. (a) Front. (b) Back. The areas of the muscles' temperature measurement are marked: GM—gastrocnemius medialis, BF—biceps femoris (long head), TA—tibialis anterior, and RF—rectus femoris (similar to [34]).

Just before and immediately after the walk (approximately in 30-s delay caused by moving of the volunteer in front of the thermal imaging camera), thermal images of the whole body (anterior and posterior sides) were taken. In addition, the sEMG signals were recorded during the entire experiment; for further analysis, the first minute and last minute of recording the signal were selected. A sample set of thermal images is shown in Fig. 2. All thermal parameters were calculated from the areas of interest (similar to [34]) which were marked in the software dedicated to the IR camera, then the data were exported, and further analysis was performed in MATLAB.

Moreover, level of pulse and oxidation was monitored before and after the experiment. The pulse changed from 65 to 75 bps (the average for all volunteers). The average value of blood oxidation did not change.

A volunteer treated as a control was only asked to perform a quiet standing in a comfortable position and perform slow gait for the same time duration as described in the experimental procedure. All thermal measurements were done in his case in the same manner as for any other participant.

The statistical calculations had been done in STATISTICA 13.1 and MATLAB. The threshold of p-value was established as 0.1 for linear regression and 0.05 for nonlinear regression [31]. Using the Shapiro–Wilk test, the normality of all analyzed factors was checked: temperature ones (Δ minimum—Thermo-ΔMin, Δ maximum—Thermo-ΔMax, Δ kurtosis—Thermo-ΔKurtosis, Δ mean—Thermo-ΔMean, Δ median—Thermo-ΔMedian, and Δ mode—Thermo-ΔMode) and sEMG frequency ones (Δ mean frequency—ΔMeanFreq, ΔMF—ΔMedianFreq). It was assumed that the difference (Δ) is the change between the end and beginning of the experiment.

III. RESULTS

Samples of thermal images of the whole body are presented in Fig. 2. Also, the areas, where the muscles' temperature was analyzed, were marked.

The average temperature difference of the front and back of the volunteer's body between the end and beginning of

TABLE III
AVERAGE TEMPERATURE MEASUREMENTS [°C] FOR MUSCLES: BF, GM, RF, AND TA. 1—BEGINNING. 2—END OF THE EXPERIMENT

	Min [°C]	Max [°C]	Kurtosis [-]	Mean [°C]	Median [°C]	Mode [°C]
1 BF	27.77	31.80	0.84	30.25	30.36	30.64
1 GM	26.45	32.10	5.26	30.72	30.86	30.96
1 RF	27.81	31.64	3.83	30.50	30.58	30.70
1 TA	28.06	32.95	0.49	31.39	31.51	31.80
2 BF	27.71	32.37	1.33	30.49	30.54	30.52
2 GM	26.48	32.35	3.88	30.70	30.85	30.86
2 RF	27.86	31.74	1.23	30.43	30.54	30.71
2 TA	28.20	32.95	-0.61	31.14	31.28	31.37
SD	0.68	0.52	2.03	0.38	0.40	0.43

the experiment was calculated. The results from frontal view are as follows: $T_{\text{min}} = 0.01$ °C, $T_{\text{max}} = 0.19$ °C, Kurtosis $= -0.56$, $T_{\text{mean}} = -0.56$ °C, $T_{\text{median}} = -1.29$ °C, and $T_{\text{mode}} = -1.17$ °C, while from the back view $T_{\text{min}} = 0.01$ °C, $T_{\text{max}} = 0.58$ °C, Kurtosis $= -0.30$, $T_{\text{mean}} = -0.45$ °C, $T_{\text{median}} = -0.72$ °C, and $T_{\text{mode}} = -1.19$ °C.

Detailed measurements (the mean values) of temperature factors of the examined muscles [BF, GM, RF and TA] before and after exercise are presented in Table III. The highest difference obtained in the case of kurtosis for RF reached -2.61 °C, and the smallest was obtained for the maximum mode temperature for the TA muscle. In general, the lowest temperature of 26.45 °C was reached by the GM muscle, and the highest, during the entire experiment, did not exceed 32.95 °C in the case of the TA muscle.

Table IV shows the average differences in the mean and median values of the sEMG signal of these muscles compared to thermal parameters—calculated as the difference between the temperatures of selected areas before and after exercise. Regarding the sEMG signals, the analysis shows that the average decrease in the mean and median values is 3.28 and 4.01 Hz, respectively (the average changes calculated for all muscles examined).

According to the tests performed, all factors of RF, BF, and GM have normal distribution. The TA frequency factors ΔMedianFreq do not have a normal distribution, but the other factors of this muscle have normal distribution.

According to the authors' hypothesis, the relationships between temperature factors and frequency factors were determined by using: 1) the linear regression and 2) nonlinear regression. All graphical presentations of raw data and linear and nonlinear relationships are given in Tables S1–S4 (See the supplementary material).

Linear regression was found between factors with normal distribution using the Pearson's correlation coefficient r and the determination coefficient r^2. On the other hand, the statistical relationship between factors with nonnormal distribution or when one of the two considered factors was not normal was discovered by using the Spearman coefficient $r*$. In attempting to classify the strength of statistical relationship, the following ranges were adopted: (0; 0.25]—weak, (0.25; 0.5]—fair, (0.5; 0.75]—moderate, and (0.75; 1]—good. Analyzing the results of linear correlation (Table V and Table S5 in supplementary material), it was found as follows.

1) Between the results for thermal and frequency factors of RF, there are the following statistically significant relationships.
   a) negative moderate relationship between ΔMeanFreq and Thermo-ΔMean ($r = -0.58$, $r^2 = 0.33$, $p = -0.04$);
   b) negative moderate relationship between ΔMeanFreq and Thermo-ΔMax ($r = -0.62$, $r^2 = 0.39$, $p = 0.02$);
   c) negative fair relationship between ΔMedianFreq and Thermo-ΔMean ($r = -0.49$, $r^2 = 0.24$, $p = 0.09$);
   d) negative moderate relationship between ΔMedianFreq and Thermo-ΔMax ($r = -0.54$, $r^2 = 0.29$, $p = 0.05$);
   e) negative moderate relationship between ΔMeanFreq and Thermo-ΔMedian ($r = -0.56$, $r^2 = 0.31$, $p = 0.05$).
2) There is no statistically significant relationship between the results for thermal and frequency factors of TA and BF.
3) Between the results for thermal and frequency factors of GM, there is one statistically significant positive good relationship between Δ MedianFreq and Thermo-ΔMin temperature ($r = 0.76$, $r^2 = 0.58$, $p = 0.01$).

Nonlinear regression was performed by using the polynomial regression method. The results of nonlinear regression are given in Table VI and described by the determination coefficient R^2, correlation coefficient R^* calculated between the measured thermal factor and predicted thermal factor (i.e., estimated by using nonlinear relationship), statistically significant threshold p, and the power of polynomial regression. It is worth emphasizing that this power was established on the base of assumption that it should be the lowest degree, which allows obtaining statistically significant nonlinear regression. Considering the obtained results of nonlinear correlation, we found as follows.

1) ΔMeanFreq versus Thermo-ΔMin relations were statistically significant in all tested muscles, and with respect to the R^2 value and R^* value, the best fitting was found for TA.
2) ΔMeanFreq versus Thermo-ΔMax relation was statistically significant in BF, GM, and RF, and with respect to the R^2 value and R^* value, the best fitting was found for RF.
3) ΔMeanFreq versus Thermo-ΔKurtosis relation was statistically significant in GM and TA, and with respect to the R^2 value and R^* value, the best fitting was found for TA.
4) ΔMeanFreq versus Thermo-ΔMean relation was statistically significant in BF and RF, and with respect to the R^2 value and R^* value, the best fitting was found for BF.
5) ΔMeanFreq versus Thermo-ΔMedian relation was statistically significant in BF, GM, and RF, and with respect to the R^2 value and R^* value, the best fitting was found for BF.

TABLE IV

AVERAGE sEMG MEAN AND MEDIAN VALUES DIFFERENCES OF BF, GM, RF, AND TA BETWEEN THE END AND THE BEGINNING OF THE EXPERIMENT IN COMPARISON WITH THERMAL PARAMETERS

	EMG		Thermal imaging					
	ΔMeanFreq [Hz]	ΔMedianFreq [Hz]	ΔMin [°C]	ΔMax [°C]	ΔKurtosis [-]	ΔMean [°C]	ΔMedian [°C]	ΔMode [°C]
RF	-5.29	-8.67	0.05	0.09	-2.61	-0.07	-0.04	-0.66
TA	-5.09	-5.59	0.13	0.01	-1.09	-0.25	-0.23	0.37
BF	-2.02	-1.02	0.06	0.51	0.51	0.21	0.18	-0.12
GM	-0.72	-0.75	-0.38	0.16	1.13	-0.04	-0.06	0.07
average	-3.28	-4.01	-0.03	0.19	-0.51	-0.04	-0.04	-0.08
SD	2.27	3.82	0.23	0.26	1.68	0.19	0.17	0.43

TABLE V

STATISTICAL RELATIONSHIPS BETWEEN THERMAL AND MYOGRAPHICAL PARAMETERS FOR MUSCLES: BF, GM, RF, AND TA

Relation	Muscle	r or r^*	p	Normality test (p = 0.05)	r^2
sEMG ΔMean Freq vs Thermo-ΔMean	RF	*-0.5771*	*0.0389*	*norm*	*0.33301*
	TA	-0.1705	0.5775	norm	0.02908
	BF	0.1081	0.7252	norm	0.01169
	GM	0.2346	0.4404	norm	0.05505
sEMG ΔMean Freq vs Thermo-ΔMin	RF	-0.2616	0.3880	norm	0.06843
	TA	0.1912	0.5314	norm	0.03657
	BF	0.2343	0.4409	norm	0.05492
	GM	0.3870	0.1915	norm	0.14974
sEMG ΔMean Freq vs Thermo-ΔMax	RF	*-0.6251*	*0.0223*	*norm*	*0.3908*
	TA	-0.2747	0.3637	norm	0.07548
	BF	0.2279	0.4539	norm	0.05195
	GM	0.1512	0.6219	norm	0.02287
sEMG ΔMedian Freq vs Thermo-ΔMean	RF	*-0.4878*	*0.0909*	*norm*	*0.23791*
	TA	-0.1209	0.6941	non-norm.	-
	BF	0.1208	0.6943	norm	0.01458
	GM	0.0225	0.9420	norm	0.0005
sEMG ΔMedian Freq vs Thermo-ΔMin	RF	-0.1343	0.6618	norm	0.01804
	TA	0.3626	0.2233	non-norm.	-
	BF	0.1270	0.6792	norm	0.01614
	GM	*0.7632*	*0.0024*	*norm*	*0.58254*
sEMG ΔMedian Freq vs Thermo-ΔMax	RF	*-0.5446*	*0.0543*	*norm*	*0.29657*
	TA	-0.1238	0.6870	non-norm.	-
	BF	0.2247	0.4605	norm	0.0505
	GM	-0.0784	0.7992	norm	0.00614

6) ΔMeanFreq versus Thermo-ΔMode relation was statistically significant in all muscles, with respect to the R^2, the best fitting was found for GM, and with regard to the R^* value, the best fitting was found for BF.
7) ΔMedianFreq versus Thermo-ΔMin relation was statistically significant in GM, RF, and TA, and with respect to the R^2 and R^* value, the best fitting was found for GM.
8) ΔMedianFreq versus Thermo-ΔMax relation was statistically significant in all the tested muscles, with respect to the R^2 value, the best fitting was for BF, and with regard to the R^* value, the best fitting was found for BF and RF.
9) ΔMedianFreq versus Thermo-ΔKurtosis relation was statistically significant GM, RF, and TA, and with respect to the R^2 value and R^* value, the best fitting was found for GM.
10) ΔMedianFreq versus Thermo-ΔMean relation was statistically significant in all the tested muscles, with respect to the R^2 value, the best fitting was for GM, and with regard to the R^* value, the best fitting was found for BF and RF.
11) ΔMedianFreq versus Thermo-ΔMedian relation was statistically significant in all the tested muscles, and with respect to the R^2 value and R^* value, the best fitting was found for BF.
12) ΔMedianFreq versus Thermo-ΔMode relation was statistically significant in GM, RF, and BF, and with respect to the R^2 value and the R^* value, the best fitting was found for BF.

IV. DISCUSSION

The measured average temperature differences of the front and back of the volunteer's body show that despite low intensity of the exercise, a general decrease in body temperature was observed, the average differences being 0.56 °C and 0.45 °C for the ventral and dorsal sites of the body, respectively. At the same time, the maximum detected temperature increased by about 0.19 °C for the front part and 0.58 °C for the rear part. This fact is consistent with many works regarding changes (even small) in body temperature during different activities, see [23], [26], [29], [31], [34], [38], [39], [52], and work [30] where the authors analyze and take into account temperature changes at the level of 0.05 °C.

Analysis of the volunteer serving as a control showed that conditions in the laboratory did not affect the body surface temperature after thermal adaptation. The difference of the average temperature of the dorsal site and ventral site of the body before and after the experiment was lower than 0.05 °C after the adaptation period. At the same time, the maximal detected temperature increased by 0.02 °C in case of the front part and 0.03 °C for the back.

Considering thermal parameters, positive values are treated as manifestation of clear muscular activity. On the other hand, negative values mean that the activity of the muscle was too low or the phenomenon of skin thermoregulation (sweating) took place.

Analyzing the results of linear regression, the most informative statistically significant relations are revealed by using: 1) the mean thermal factor and max thermal factor (for each factor, two moderate linear relationships were established) and 2) the sEMG MF factor and sEMG mean frequency factor (for each factor, three moderate linear relationships were estimated). For the RF, there are three moderate relationships

TABLE VI

STATISTICAL NONLINEAR RELATIONSHIPS BETWEEN THERMAL AND MIOGRAPHICAL PARAMETERS FOR MUSCLES: BF, GM, RF, AND TA

Relation	BF				GM				RF				TA			
	R^2	R^*	p	degree	R^2	R^*	p	degree	R^2	R^*	p	degree	R^2	R^*	p	degree
Thermo-ΔMin=f(sEMG ΔMeanFreq)	0.374	0.470	0.0264	4	0.457	0.667	0.0112	3	0.614	0.557	0.0015	5	0.642	0.744	0.0010	4
Thermo-ΔMax=f(sEMG ΔMeanFreq)	0.366	0.654	0.0284	4	0.352	0.620	0.0325	6	0.441	0.722	0.0133	4	0.241	0.461	0.0888	3
Thermo-ΔKurtosis=f(sEMG ΔMeanFreq)	n/a	n/a	n/a	n/a	0.338	0.604	0.0372	5	0.278	0.564	0.0643	4	0.557	0.731	0.0034	5
Thermo-ΔMean=f(sEMG ΔMeanFreq)	0.542	0.760	0.0041	3	0.293	0.582	0.0559	5	0.476	0.718	0.0091	3	0.280	0.503	0.0629	5
Thermo-ΔMedian=f(sEMG ΔMeanFreq)	0.523	0.759	0.0052	3	0.426	0.637	0.0156	7	0.443	0.702	0.0130	3	0.265	0.558	0.0717	5
Thermo-ΔMode=f(sEMG ΔMeanFreq)	0.573	0.793	0.0027	5	0.743	0.679	0.0002	3	0.384	0.276	0.0239	2	0.424	0.678	0.0159	5
Thermo-ΔMin=f(sEMG ΔMedianFreq)	0.248	0.536	0.0835	5	0.546	0.770	0.0039	3	0.507	0.745	0.0063	5	0.437	0.593	0.0140	3
Thermo-ΔMax=f(sEMG ΔMedianFreq)	0.613	0.806	0.0016	5	0.470	0.611	0.0097	3	0.600	0.815	0.0019	5	0.358	0.634	0.0307	3
Thermo-ΔKurtosis=f(sEMG ΔMedianFreq)	n/a	n/a	n/a	n/a	0.850	0.806	0.0000	4	0.396	0.671	0.0211	4	0.404	0.656	0.0196	5
Thermo-ΔMean=f(sEMG ΔMedianFreq)	0.517	0.756	0.0056	3	0.643	0.559	0.0010	4	0.520	0.750	0.0054	5	0.401	0.671	0.0202	3
Thermo-ΔMedian=f(sEMG ΔMedianFreq)	0.525	0.765	0.0051	3	0.460	0.516	0.0109	3	0.507	0.742	0.0063	5	0.472	0.722	0.0094	3
Thermo-ΔMode=f(sEMG ΔMedianFreq)	0.491	0.740	0.0077	3	0.446	0.717	0.0126	3	0.415	0.682	0.0175	5	0.270	0.558	0.0687	5

between the sEMG mean frequency parameter and the mean, maximum, and median thermal parameters. For the same muscle, there are two moderate relationships between sEMG MF factor and the mean, maximum thermal factor. For the GM, there is one good relationship between sEMG MF factor and minimum thermal factor. These established moderate relationships approve our hypothesis that chosen thermal parameters can be used to assess the low-level physical activity (normal gait) by assuming linear link between these thermal factors and sEMG factors.

Analyzing the raw data and results of nonlinear regressions between the thermal and sEMG factors, a conclusion about good fitting (prediction) was drawn on the basis of the following assumption: data placed in quarter II (positive thermal and negative sEMG) and quarter III (negative thermal and negative sEMG) show manifestation of the fatigue, whereas data placed in quarter I (positive thermal and positive sEMG) and quarter IV (negative thermal and positive sEMG) show that muscle is in the regeneration process (without fatigue). It is worth emphasizing that each person uses a different motor command program to activate the muscles to perform the motion. That is why this scatter between raw data is observed (due to different biomechanical properties that also influence different thermoregulation processes in the skin over tested muscles). Applying polynomial regression, we revealed the following classifications.

1) ΔMeanFreq versus Thermo-ΔMin relation is treated as good (because all the tested muscles were considered), and it can be described by using polynomial regression with the third power to the fifth power.
2) ΔMeanFreq versus Thermo-ΔMax relation is treated as medium (because only three tested muscles were considered), and it can be described by using polynomial regression with the fourth power to the sixth power.
3) ΔMeanFreq versus Thermo-ΔKurtosis relation is treated as bad (only two tested muscles can be considered), and it can be described by using polynomial regression with the fifth power.
4) ΔMeanFreq versus Thermo-ΔMean relation is treated as bad, and it can be described by using polynomial regression with the third power.
5) ΔMeanFreq versus Thermo-ΔMedian relation is treated as medium, and it can be described by using polynomial regression with the third power to the seventh power.
6) ΔMeanFreq versus Thermo-ΔMode relation is treated as good, and it can be described by using polynomial regression with the second power to the fifth power.
7) ΔMedianFreq versus Thermo-ΔMin relation is treated as medium, and it can be described by using polynomial regression with the third power to the fifth power.
8) ΔMedianFreq versus Thermo-ΔMax relation is treated as good, and it can be described by using polynomial regression with the third power to the fifth power.
9) ΔMedianFreq versus Thermo-ΔKurtosis relation is treated as medium, and it can be described by using polynomial regression with the fourth power to the fifth power.
10) ΔMedianFreq versus Thermo-ΔMean relation is treated as good, and it can be described by using polynomial regression with the third power to the fifth power.
11) ΔMedianFreq versus Thermo-ΔMedian relation is treated as good, and it can be described by using polynomial regression with the third power to the fifth power.
12) ΔMedianFreq versus Thermo-ΔMode relation is treated as medium, and it can be described by using polynomial regression with the third power to the fifth power.

The presented statistical results of the linear correlations are similar to the observations of other authors [23], [25], [26]; however, contrary to all cited studies, in the presented case, the experiment lasted 10 min and there was no excessive sweating in any of the volunteers. Another remark has also been made: for some of them, a higher temperature was observed for semimembranosus and semitendinosus muscles instead of the BF. In one case, instead of RF, a higher temperature was observed for the sartorius muscle (no problems with gait or unnatural limb behavior were observed for any of the volunteers). In general, an average increase in maximum temperature for the area of interest was observed at 0.19 °C and 0.58 °C for ventral and dorsal body sites, respectively. At the same time, the average temperature values decreased to 1.29 °C for the median, to 0.72 °C for the mode, and to 1.17 °C and 1.19 °C for ventral and dorsal sites, respectively.

V. Conclusion

On the basis of the obtained results, we concluded that neuromuscular and thermal phenomena of low-level muscle fatigue (induced by a 10-min physical activity in the form of a treadmill gait) can be detected by assessing sEMG changes and surface temperature changes. The exercise effects, low level of temperature differences (see Section III), and a small change in the sEMG mean and median signals were revealed (Tables V and VI) by estimating two frequency factors (the sEMG mean and MF factors) and six thermal factors (minimum, maximum, mean, kurtosis, median, and mode temperature factors). To reveal the most proper relations, we tested dependences between all thermal factors (parameters) and all frequency factors (parameters). The novelty of our work was to find out statistically significant linear and nonlinear relationships between sEMG factors and thermal factors that can be used to reveal a low-level fatigue in normal daily activity.

In this study, six linear correlations between thermal and myographic parameters are found (Tables IV and V) using a linear regression method. Considering the results in detail, five moderate statistically significant differences were found for the RF. For the other muscles examined, the results were incoherent in the case of low fatigue. This can be explained that changes in the calculated parameters could be related as nonlinear functions.

To study whether some nonlinear correlations exist between universal thermal and myographic parameters, we applied nonlinear regression (polynomial regression) between thermal factors and sEMG factors. The good fitting results were obtained for five relations: ΔMeanFreq versus Thermo-ΔMin relation, ΔMeanFreq versus Thermo-ΔMode, ΔMedianFreq versus Thermo-ΔMax, ΔMedianFreq vs Thermo-ΔMean relation, and ΔMedianFreq versus Thermo-ΔMedian relation. On the other hand, the moderate fitting results were established also for five relations: ΔMeanFreq versus Thermo-ΔMax, ΔMeanFreq versus Thermo-ΔMedian, ΔMedianFreq versus Thermo-ΔMin, ΔMedianFreq versus Thermo-ΔKurtosis, and ΔMedianFreq versus Thermo-ΔMode. Considering the obtained correlation results, we concluded that more relationships were established using nonlinear regression. This means that tested phenomenon (identification of low load fatigue) is complex one and can be identified in practice by using nonlinear regression, especially for a low level and relatively short time of muscle activity, e.g., examining daily activities which do not cause high level of muscle fatigue. The results of thermographic tests may be treated as complement to sEMG studies to obtain more accurate assessment of muscle activity, especially in the case of a limited number of electrodes. However, it should be emphasized that: 1) thermography will not, at this stage of thermal imaging development, replace sEMG testing, due to skin sweating occurring in case of higher temperatures or more vigorous exercises and 2) application of thermal imaging and sEMG testing is limited due to the fact that skin sweating can blemish the results of thermal analysis and cause ungluing of sEMG electrodes.

This study can help to understand the thermal and electromyographical phenomena that occur during gait with moderate speed. Analysis of parameters obtained from sEMG measurements and thermal imaging could be used to predict the state of the considered live object. Thermal imaging could give a whole-body image and detect unpredicted and nonstandard muscle activation caused by overloading and/or disorders. Also, the technique of thermal imaging undergoes constant improvements and becomes, due to technical development and advanced knowledge, more precise. In this light, the presented results can be treated as preliminary study of how to supplement electromyography by the thermal methods in case of muscle examining.

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