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The influence of the run intensity on bioelectrical activity of selected human leg muscles

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The purpose of this work was to investigate the electromyographic (EMG) fatigue representations in muscles of male runners during run at different level of intensity. In this study, the EMG signals for the rectus femoris and biceps femoris (long head) were collected by bipolar electrodes from the left and right lower extremities. EMG measurements were recorded during the run on tartan athletic track. Four professional athletes had to run a 400 m distance with a different intensity. The first distance of 400 m took 90 s; the second, 70 s; the third, 60 s; and the last one was covered with a maximal velocity until exhaustion. Power spectral analysis of EMG signals was carried out to calculate MPF. The results of our study revealed the efforts of different intensity for each muscle individually. The effect of fatigue was observed only in the case of running with the highest velocity. The biggest changes in MPF were observed for BF (23.6%) and RF (19.5%) muscles of the left leg and then for BF (17.5%) and RF (12.5%) ones of the right leg. We supposed that those differences between the right and left legs were mainly due to the curve of the track where those muscles are differently loaded.

Key words: *sEMG, leg muscles, 400 m run, fatigue, MPF*

1. Introduction

Surface electromyography (sEMG) is one of the methods used to investigate the mechanisms of neuromuscular fatigue [1], [2]. Muscle fatigue can be defined as the inability to maintain an appropriate level of force, whose causes may be central (e.g., changes in motor unit recruitment) or peripheral (e.g., changes in the shape and duration of the intracellular action potential, motor unit size and muscle fiber conduction velocity) [3]. Fatigue is mainly due to processes within skeletal muscles rather than the central nervous system [4], [5]. Neural activation compensates for muscular fatigue and maintains force generation during performance. Fatigue in a muscle appears as a result of its intensive activity and is reflected in certain changes of its electromyogram (EMG) signal either in the time (amplitude of EMG signal) or in the frequency domains (MPF, MF) [6]. Changes in the electromyographic activity, i.e., a decrease in the mean power frequency (MPF) [7]–[10] and/or an increase in the EMG amplitude [11]–[13] and/or integrated EMG (iEMG) during standarized voluntary contractions, have frequently been used as indicators of muscle fatigue [1], [14]–[18]. The muscle fatigue is specific to contraction type, the intensity and duration of activity [19], [20]. Therefore, the relationships observed, e.g., in the isometric muscle contraction, are not the same as in the dynamic exercise [21]. Under dynamic conditions, erroneous interpretation of the EMG signals can be a result of muscle

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length, muscle–electrode distance, movement velocity [22], [23] and fatty tissue level [24]. Some authors have found that the frequency based on EMG variables is less dependent on the instantaneous force level of a muscle [25] than amplitude and it is, therefore, more sensitive to fatigue-related changes. In general, it seems that changes in the MPF and amplitude of the EMG signal are more consistent for high-force contractions than for prolonged low-level dynamic contractions [1]. It is suggested that an increase in EMG activity for a given performance and the shift of EMG power spectrum to low frequencies [5] affect short time and high intensity of human performance. One of the causes of signal power spectrum shift toward lower frequencies is an increase in lactates concentration and a decrease in pH [26]. To obtain some indications of muscular fatigue, it is recommended that amplitude measurements (ARV-average rectified value, RMS-root mean square) should be performed along with the simultaneous calculation of spectral parameters (mean and median frequency) [27]. Therefore, based on a previous experience, our aim was to evaluate the effectiveness of estimating fatigue for individual muscles of lower extremities during the run with various intensities.

2. Material and methods

2.1. Subjects

Four professional 400-m male runners took part in this research. They were at an average age of 24 ± 2 years, their average mass was 72 ± 2.2 kg, and height, 177 ± 1.3 cm. The group consisted of the athletes training for the 400 m, best below 49 s (47.66 ± 0.60 s). They participated in a world championship in a senior category at least once. All participants signed written consent form and proper consent was obtained from a local Ethical Committee.

2.2. Procedures

The subjects were instructed to perform tests correctly, and they were allowed to warm up their muscles. Before the measurements were taken, the subjects were asked to participate relatively rested in the test, to avoid highly intensive training directly before the test or a day before. EMG measurements were recorded during the run on the tartan athletic track. The running speed for every 100 m was timed electronically. Three photocells were placed separately on a tripod, 1–1.20 m above the ground, and they could sense the shoulder height of the passing bodies. Three electronic chronometers (Tag Heuer Electronic Timing), which time up to milliseconds, were connected to all three photocells. They timed the runners over every 100 m and should have helped them to obtain a correct intensity in every condition applied in this study. The electronic timing system was specifically adjusted to automatical printing the duration time and the total time achieved over every 100 m. The athletes had to run a 400-m distance with four different intensities. The first distance the subjects ran with a speed that allowed them to cover the distance in 90 seconds, the second – in 70 s, the third – in 60 s and the last one was performed with a maximal speed until exhaustion. During the last measurements the subjects had to obtain the maximum speed as soon as they could and then to maintain this speed during the whole distance. Thirty-minute breaks between measurements were made and the entire procedure was a standard test used by trainer in the training process four times a year. All tests were evaluated at the end of the Competition Preparation phase.

2.3. SEMG recordings

Bipolar surface EMG recordings were obtained from the rectus femoris (RF), and the long heads of biceps femoris (BF) of the right and left thighs were obtained using self-adhesive pairs of disposable Ag/AgCl surface electrodes (Blue Sensor M-00-S, Ambu, Denmark). The raw SEMG signal was recorded at the sampling rate of 1000 Hz, amplified (differential amplifier, CMRR > 130 dB, total gain of 1000) with a bandwidth from 20 to 500 Hz, analog-to-digital converted (14-bit) using a device ME3000P4 (Mega Electronics, Finland). Power spectral analyses of those signals were performed to calculate MPF by a fast Fourier transformation (FFT) technique. The window length was set at 256 ms and a Hamming window was preferred to rectangular windows. Before electrode placement, the skin area was shaved, cleaned with isopropyl alcohol, and abraded with coarse gauze to reduce skin impedance. Furthermore, the electrode placement was confirmed by palpations of muscle bulk during brief maximal isometric contraction. The electrode placement, for minimizing crosstalk, was validated by the method of WINTER et al. [28].

2.4. Statistical analysis and calculations

Data was analysed with Statistica program (StatSoft, Inc. (2005). STATISTICA (data analysis software system), version 7.1. www.statsoft.com). Simple linear regressions were used to obtain coefficients of the slope. The waveform-matching function lowess (Locally Weighted Scatterplot Smoothing) was applied to MPF smoothing.

3. Results

Sample record of the average frequency of the power spectrum of EMG signal, depending on the intensity and time run, is given in figure 1. In this case, the MPF values are shown by the waveform-matching function lowess. Fatigue comparison for individual muscles, depending on the intensity of run, was described by the slopes of the regression lines estimated by the method of least squares.

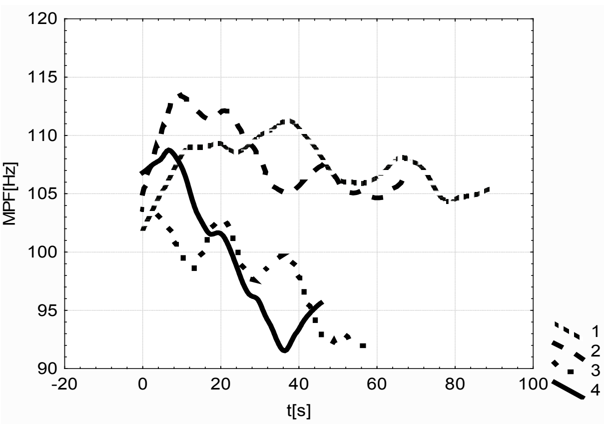

Fig. 1. MPF estimations in time domain collected for BF muscle (an example obtained for one sprinter); 1 – a 90-s run, 2 – a 70-s run, 3 – a 60-s run, 4 – a run with maximal velocity

The values of slope coefficients are presented in table 1. Significant differences between the slopes for the muscles of the left and right limbs were noticed. For both muscles the slopes rose, depending on the velocity of the race. That rise was, however, larger for the left limb. It is worth noting that the differences between the left and right limbs are greater for the RF muscle.

Table 2 presents the coefficients of slope for the regression lines obtained by the approximation of MPF at two intervals: 0 to 25 seconds and 25 seconds to the end of the effort. An example of approximation made for the run with a maximum velocity is presented in figure 2. The extrema between the ranges of run intensity characterize the energy reserve in muscle. A local minimum of MPF values occurred between 18 and 22 seconds.

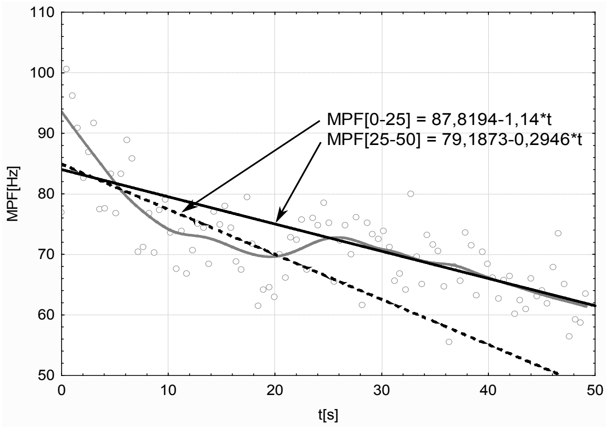

Fig. 2. An example of biceps femoris MPF approximation by the trend line within the ranges from 0 to 25 seconds and from 25 to 50 seconds for the run with the highest velocity (an example obtained for one sprinter)

Extension of the time and intensity of running is associated with a negative slope of the regression lines indicating a steady increase in muscle fatigue. The positive slope was observed in the first time running for all muscles, but only during the run with the lowest intensity. An increase in the slope is linear: a slope increases with the intensity of the race.

The results presented in table 2 testify to a greater muscle fatigue in the left limb. Particularly strong

Table 1. Average values and standard deviations (*SD*) of the regression line slopes computed on the basis of the value of MPF for the run with different intensities: 1 – a 90-s run, 2 – a 70-s run, 3 – a 60-s run, 4 – a run with maximal velocity

Race	RF – right		RF – left		BF – right		BF – left	
	b [Hz·s^{-1}]	SD [Hz·s^{-1}]	b [Hz·s^{-1}]	SD [Hz·s^{-1}]	b [Hz·s^{-1}]	SD [Hz·s^{-1}]	b [Hz·s^{-1}]	SD [Hz·s^{-1}]
1	–0.016	0.002	–0.016	0.074	–0.019	0.009	–0.019	0.002
2	–0.020	0.013	–0.088	0.013	–0.131	0.003	–0.109	0.008
3	–0.113	0.009	–0.181	0.003	–0.150	0.037	–0.205	0.009
4	–0.184	0.016	–0.273	0.020	–0.338	0.095	–0.444	0.090

Table 2. Average (±*SD*) values of slope coefficients computed on the basis of the value of MPF for the run with different intensities occurring within the following ranges of approximation: 0 to 25 s and 25 s to the end of the race; 1 – a 90-s run, 2 – a 70-s run, 3 – a 60-s run, 4 – race with maximal velocity

Race	RF – right		RF – left		BF – right		BF – left	
	0–25 [Hz·s^{-1}]	25 → [Hz·s^{-1}]	0–25 [Hz·s^{-1}]	25 → [Hz·s^{-1}]	0–25 [Hz·s^{-1}]	25 → [Hz·s^{-1}]	0–25 [Hz·s^{-1}]	25 → [Hz·s^{-1}]
1	0.001 ± 0.012	–0.014 ± 0.02	0.003 ± 0.003	–0.044 ± 0.056	0.008 ± 0.02	–0.001 ± 0.001	0.005 ± 0.009	–0.025 ± 0.014
2	–0.019 ± 0.004	–0.017 ± 0.003	–0.003 ± 0.001	–0.133 ± 0.001	–0.009 ± 0.012	–0.153 ± 0.036	–0.02 ± 0.01	–0.019 ± 0.001
3	–0.148 ± 0.007	–0.120 ± 0.003	–0.151 ± 0.016	–0.134 ± 0.06	–0.152 ± 0.014	–0.155 ± 0.041	–0.142 ± 0.015	–0.202 ± 0.026
4	–0.373 ± 0.001	–0.122 ± 0.002	–0.415 ± 0.053	–0.133 ± 0.0115	–0.407 ± 0.025	–0.358 ± 0.0126	–0.53 ± 0.038	–0.368 ± 0.029

effect was observed for the BF muscle. During the run with the highest velocity a 30% difference between the left and the right BF (11% for RF) fatigue (measured as slope coefficients) was observed in the first 25 seconds of the race and it decreased to 3% (9% for RF) after the 25th second of the race.

4. Discussion

Running efficiency needs an optimum combination of the biomechanical variables and external factors [29]. Sprint performance is determined by the ability to accelerate and the ability to maintain velocity at the onset of fatigue. Usually, the 400 meters is known as speed-endurance discipline that demands a capacity to maintain the speed being close to maximum. According to GASTIN [30] a 400-m run belongs to medium anaerobic (mainly lactic) efforts which last about 25–60 seconds. It is important to generate great force/power and to reach high velocity in the block and acceleration phases at the beginning of the sprint run [29]. Research suggests that athletes are not able to maintain the maximal firing frequencies over the entire distance, for example, a 100-m sprint (ATP is resynthesized from PC during about the first 6–7 s of the run). The fatigue is associated with the loss of power output when high-energy sources (PC) depleted. A 400-m run is performed with slightly less speed than 100 m (it depends on the individual tactics), so that during the first 20 s of the run most of the energy comes from the degradation of muscle PC. Thereafter the ability to produce energy from high-energy sources decreases and anaerobic glycolysis plays a significant role in energy production. According to our study this fact causes a decrease in speed. That effect in our study was observed clearly only for the run with the maximum intensity because the ATP and PC reserves were completely exhausted between 0 and 25 seconds. Based on high-velocity running, it can be also hypothesized, that a higher slope of the regression lines in the first 25 seconds (table 2) of the race is the result of the bigger muscle power obtained at the highest rate of ATP resynthesis from PC and glycolysis takes place during the first 10 seconds.

BANGSBO et al. [31] revealed that the contribution of anaerobic processes to energy production is 80% in the first 30 seconds of work, 45% in the period of 60–90 seconds, and 30% in the range from 120 to 190 seconds. Therefore, in the second range, the muscle power decreases and all slopes drop slower. In our research, the local minimum of MPF values occurred (18–22 seconds for all muscles) and MPF significantly decreased, especially in the BF muscles (23.5% for left leg and 17.6% for right leg). BF and RF are both biarticular biphasic muscles. They cooperate in the contact and the support phases, and the time of their activation is longer compared to the duration of the stride cycle when the speed increases [32]. RF is regarded as a direct antagonist muscle to the hamstring. MANN et al. [33] and SIMONSEN et al. [34] have identified two distinct periods of activating the RF as a knee extensor and hip flexor and the BF as a knee flexor and hip extensor. However, RF has a greater contribution to the knee joint, while BF to the hip joint. Forward propulsion is provided mainly by hip flexion (during early and middle swing) and knee extension (during late swing) [35]. The hip extensors are considered as the main muscles that move forward human body [32] (therefore BF is more activated muscles during the running). Fast running is responsible for an increase in the activity of muscles, which may lead to more injuries, first of all in the muscles that are contracting eccentrically (mainly RF and long head of BF) [35]. These muscles (BF, RF) show the earliest signs of fatigue. It has been noticed by many authors, including EDGERTON et al. [36], that the RF is a muscle strongly dominated by type II fibres which according to KOMI and TESCH [37], among others, makes it a fatigable muscle. However, BF shows significantly greater intensive use than RF during both uphill and level running [38]. SLONIGER et al. [38] proved that BF is one of the most activated muscles during horizontal and uphill running, whereas RF shows less activation during uphill running. This might make BF more fatigable, on the basis of decreased MPF values (present in our study), compared to RF. This fact can be caused by more fast-twitch fibers, more eccentric work and smaller muscle cross-section in BF compared to RF. MIZRAHI et.al. [39] found that EMG level of RF is independent of metabolic fatigue (EMG does not change despite the development of metabolic fatigue in level running). It is probably due to greater muscle endurance.

Another important aspect of our study is a greater fatigue of the left limb compared to the right limb during a 400-m run on tartan athletic track. The run at the highest velocity influenced higher fatigue difference for BF (30% vs. 11% for RF) over the first 25 seconds of the race and the fatigue decreased to 3% (9% for RF) over the next 25 seconds of the race. A substantial load on the BF muscle of the left leg is probably a result of running a curve part of the truck. In this case, the inner leg is more loaded during shock-absorption which is caused by more efficient eccentric BF working. Similar effect was also observed for the RF muscle; however, it was not as significant as for the BF muscle. We believe that this effect may be magnified in an indoor athletics arena, where track curves are sharper and more sloping.

The limitations of the protocol will be described before the results are summarized. It can be possible that the dynamic condition of the task studied influences the EMG stationarity. Therefore the EMG validity of the Fourier transformation used to calculate the MPF can be insufficient to obtain correct conclusions. Hence, in this study, the samples were kept as short as possible for the duration of analysis, so that amplitudes of EMG would be relatively constant. It is possible also that the movement of the muscle under the electrodes affects the EMG signals. Therefore, the uncontrolled nature of the dynamic task will serve to reduce the reliability of the protocol [40], [41]. However, numerous previous studies have already demonstrated the hypothesized changes in MPF during dynamic tasks [42]–[44]. Other authors validated the mean frequency as fatigue index during dynamic contractions until exhaustion [44], [45]. However, during low and medium intensity dynamic exercises, some authors did not find any decrease in median frequency [46], [47]. The purpose of the current study was to establish the electromyographic fatigue representations in muscles of subjects during run with different intensity. We found that sEMG frequency-related parameter such as MPF showed good criterion validity with respect to biomechanical fatigue during a 400-m run at the highest velocity (frequency based on EMG variables is sensitive to fatigue-related changes). Nevertheless, it has been suggested that only when a decrease in MPF from the power spectrum significantly exceeds 8% of the initial MPF, it can reliably be identified as localized muscle fatigue [48]. The effect of fatigue at this level was observed only in the case of running with the highest velocity (run until exhaustion). The biggest changes in MPF were observed for BF (23.6%) and RF (19.5%) muscles of the left leg and then for BF (17.5%) and RF (12.5%) of the right leg. Further research requires the phenomenon of the MPF local minimum observed between 18 and 22 seconds. This phenomenon is probably related to the collapse of energy associated with the ATP-PC resynthesis. At that time, the rate of resynthesis from anaerobic glycolysis system is too weak. Therefore, we have an unanswered question: whether a proper training can move in time that minimum of MPF or at least avoid the collapse of ATP-PC resynthesis. The results of our study are characterized by the efforts of different intensity for each muscle individually. They can therefore be used to find muscles of the so-called "weak link" characteristics, which determine the potential of the entire muscle group. Because sEMG allows us to investigate the activation of a single muscle separately during performance, we know that the changes are different in BF and RF of right and left limbs. We suppose that those differences (between the right leg and the left leg) were mainly due to the curve of the track where those muscles were differently loaded.

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