Article

Pre-Olympic Ice-Skaters Training Versus Muscle Fatigability Assessed by sEMG

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Abstract: The aim of this study was to investigate the size of the change in fatigability of gluteus maximus muscles during difficult endurance training in dynamic conditions. The research covered involved eight female athletes of the Polish National Team in short track, which had been prepared to the Olympic Games in PyeongChang. The sEMG system was used to measure fatigue of right and left gluteus maximus muscles, in the modified Biering-Sorensen test. The test was conducted five times during the training: before training, after warmup, and after each of 3 series of the endurance training. Comparing the mean frequency of the surface electromyography power spectrum of the first and the last seconds of the test, statistically significant reduction ($p<0.05$) of the average frequency value of the right muscle from 55.61±7.08 Hz to 48.64±4.48 Hz and left muscle from 58.78±4.98 Hz to 53.18±4.62 Hz was reported. In the conducted Biering-Sorensen test, the value of the muscle signal frequency measured by surface electromyography decreases, which may prove the muscle fatigue. Reductions in the frequency measured in the first and the last second of the test, was higher of the right lower limb. The size of the d Cohen effect in fatigue drops along with subsequent five tests during the training.

Keywords: Muscle fatigue; isometric contraction; gluteus maximus; fatigue effect; short track; fatigue threshold

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1. Introduction

In speed skating, we distinguish two disciplines differing from each other in the track length and skating technique. In short track, the distance of one lap is 111 m, which is less than one third of the skating track on a long track (400m). Such a short distance forces the competitors to go along an oval track with high speed and small turn radiuses. During a race at a distance of 1000 m the short track competitor, when turning, generates twice as large forces as on a long track [1]. In order to obtain the best possible result in short track, the organism of the athlete should be resistant to fatigue. In addition, what also matters are the race tactics, psychological and technical aspects, maximum voluntary contraction force, reaction time and the quality of lower limb muscle coordination [2, 3, 4].

The following tests, in three aspects, focused on the issue of local muscle fatigue in short track female athletes. One of aspects applies to the fatigue of gluteus maximus muscles that extend femoral joint and substantially affect the strength of lower limb bounce off the ice pane. The second aspect applies to determining the level of asymmetry between the right and the left examined muscle, while the final one applies to the size of the fatigue effect.

Currently, winning a competition is affected by many nuances in preparation for start. The muscle fatigue analysis conducted in the research is of great practical importance in the training process, as well as in everyday life. Undertaking physical activity is inseparably associated with fatigue. Fatigue is defined as reduction in muscle capacity to perform work, after prior physical effort [5, 6]. Local muscle fatigue is concentrated mainly on a decrease in contraction force, that is inability

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of the muscle to generate proper capacity [7]. This is an inevitable process, and attempts to reduce it are constantly made.

At present, the literature of the examined phenomenon contains analyses of muscle fatigue and lack of fatigue [8]. Non-invasive methods of determination of fatigue parameters also include surface electromyography (sEMG). Analysis of the sEMG signal frequency of the power spectrum provides useful information concerning local muscle fatigue [9, 10, 11, 12].

In the initial fatigue tests with the use of sEMG, emphasis was put one the importance of static measurement, that is isometric contraction in isolated muscle position [13]. In such measurement, muscle fatigue is reflected by changes in the amplitude and average frequency of the power spectrum of sEMG signal, and average signal frequencies in all muscle groups tested in this way are decreased. In addition, changes in the amplitude and frequency of the signal are correlated as a result of fatigue, if the signal amplitude increases, then the average signal frequency decreases [10, 11, 14]. However, there are also reports where physical effort does not affect reduction in the frequency of sEMG signal [15]. In order to perform a correct measurement during isometric contraction, the sEMG signal should be measured between 0.5 and 2s because only then it gives credible results [16].

Under the influence of the sport training, lactic acid accumulates in muscles which reduces the efficiency of an athlete [17]. It leads to the fatigue effect, which, in the EMG record is shown by reduction in the signal amplitude, which seems to point to the beginning of fatigue [18]. Neto et al. [19], tested fatigue by means of EMG record in two training protocols with different adaptive features (endurance and strength). They demonstrated that training caused reduction in the frequency median for the knee joint extensor muscles in isometric contraction.

To achieve good results in short track, it is necessary for the athlete to generate high driving force, which translates into the speeds achieved on ice - extensor muscles prove decisive in this task [2, 3]. Felser [2] particularizes that the maximum force of lower limb extensors explains 27 % of differences in speeds of short track athletes. In our research, we analysed the work of gluteus maximus muscle whose main function is extending the thigh in the hip joint. This selection of the muscle was due to the suggestion of coaches who wanted to learn about the fatigue ranges of the examined muscles.

Despite efforts, we did not manage to find tests concerning gluteus maximus muscle fatigue in short track athletes using EMG system. Referring to subject of muscle fatigue, it was reported, on the other hand, that athletes going through one-sided curves with high speed, have a tendency to significant asymmetry between local levels of desaturation (reduction in blood saturation with oxygen) in quadriceps femoris muscles of the lower limbs [4]. While passing the curve, on the lower right limb, blood volume decreases in its muscle as a result of its higher load. In the lower left limb, the increase in this parameter is observed. Researchers also demonstrated that during a race, the tissue saturation in the right and left lower limb muscle initially decreases dramatically. In the further course of the race, lower limbs differ from one another. In the right one, the level desaturation is at a relatively permanent level. On the other hand, in the left limb, desaturation gradually returns to the condition from before the race. Finally, significantly various average values of tissue saturation between the two legs during the last lap of a race were detected. Using the EMG system to measure the bioelectric activity of muscles in short track athletes during skating, it was confirmed that activation of muscles differs when skating on a straight line and on the curves, as well as in both lower limbs [3]. Activation of the right lower limb is significantly greater during skating at curves as compared to skating on a straight line. This movement pattern was not observed in the left limb.

It is extremely important for the tests to be as similar as possible to the realities of sports competition. In one of the tests, it was demonstrated that the size of deoxidation of muscles when skating on ice, at the same time in forced lowed body position, was much higher than that observed during the tests on a treadmill [20]. This suggests that the tests should be conducted on ice to obtain the most realistic reflection and understanding of the conditions prevailing in speed skating. In our research, it was not possible due to the static character of the fatigue tests, although the research was conducted during the training. In order to come as close as possible to the ideal conditions, tests were conducted at a skating rink and athletes were tested directly after finishing a series of exercises. The

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tests took place with full uniform and electrodes and EMG sensors were constantly fastened to the athletes throughout the whole training.

Innovation of the tests presented below consisted also in checking how this process is shaped during various training phases. Better understanding of the nature of work and muscle symmetry in sports, examined by sEMG using the example of short track, and may be helpful to coaches, physicians, physical therapists and athletes. Therefore, the purpose of this test was to determine the size of the change in the fatigue of gluteus maximus muscles measured by sEMG in the course of endurance training strongly straining the organism of the athletes. We checked the level of muscle fatigue at the beginning and end of the training and the size of the difference between fatigue of the right and the left gluteus maximus muscle, in spite of a training, based (by definition) on symmetric muscle work.

The first hypothesis of our research is that in the test, mean frequency of power spectrum of the sEMG signal will decrease over 60 s of the modified Biering-Sorensen test and along with the progress of the training. Secondly, owing to the fact that athletes skate always to the left, we expect that the fatigue level will be different for the two lower limbs, and higher in the right limb muscle.

2. Material and methods

2.1. Participants

Tests were performed on eight female athletes of the senior Polish national team in short track who had no medical conditions within the measured muscles and joints that may have an impact on the course and result of the test. It is a young and promising group of athletes aged 18.7 ± 2.9 years, with body height of 162 ± 2.4 cm, and body weight of 57.2 ± 5.9 kg. The research was conducted directly in the period before the Olympic Games in PyeongChang. During this period, the Polish Women's National Short Track Team recorded the greatest development in the history of the Polish short track. These athletes also had repeatedly improved Polish National Records at each of the distances. From year to year, the Polish Team recorded results progress at distances of 500m, 1000m and 1500m. The average group improvement of the result on a distance of 500m was 4%, 1000m - 2.64%, 1500m - 3.75%. Compared to other countries, it was the best result for the last three years before the Olympic Games in PyeongChang. Skaters participated in a large number of international competitions - World Cups, World Championship and European Championship, in which they win medals. The main goal of the training was to qualify the athletes at three distances at the Olympic Games in PyeongChang 2018. The goal has been achieved. Two female athletes competed at the Olympics Games - one at the distance of 500m, the other at three distances. The research was conducted after a weekend break in training to avoid the effect of effort-related fatigue accumulation. The participants were informed about the purpose and the course of tests, and signed a permission to participate in the tests, approved by Bioethical Commission of the Chamber of Physicians in Opole No. 237, in accordance with the guidelines specified in the Declaration of Helsinki on human experimentation. The respondents were asked to refrain from intensive physical exercises in the period of 1 day preceding the test, and not to consume meals and beverages containing caffeine at the interval of 3 hours before the test. The research was conducted in the presence of a coach.

2.2. Procedure

Frequency of the power spectrum of the sEMG signal (reflecting the muscle fatigue level) was examined by means of a sEMG signal in the body position used in the Biering-Sorensen test in isometric contraction conditions. Duration of the test was limited to 60 s, as in the case of Katakura et al. [21]. The test duration was shortened because execution of the trial until the so-called "refusal" could cause excessive strain for the competitors and failure to achieve the training goals. The fatigue tests in isometric contraction over 60 s were also conducted by other authors, modifying the test to their own needs in terms of positions and duration [22, 23, 24]. Analyses took account of changes between the first and the last second of the registered sEMG record. They mainly determined if the EMG variable decreased from the first to last second of Sorensen test. The test protocol contained 5

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series for each of the examined athletes. The first series of tests were held before the training. The next series followed the 15 minutes general warm-up on a track. The last three tests were conducted subsequently after each of 3 series of the endurance training, conducted on ice with full uniform. Each of the three series of endurance training consisted of nine sub-series. The one-minute sub-series consisted of skating on ice with submaximal load and a one-minute break between. The breaks between series in which the test was performed took 8 minutes. After 3 series of endurance training, there was 10 minutes cool down. Research position was placed on the skating rink, and the tests after each of 3 training series, took place immediately after their completion.

2.3. Data collection

The test of bio-electric activity of the right and left gluteus maximus muscle, was conducted by means of electromyograph TeleMyo DTS (NORAXON). Before the test, the place for sticking electrodes was shaved and cleaned using alcohol-soaked cotton to minimize skin impedance. Bipolar electrodes (Ag/AgCl) had a pre-gelled diameter of 10 mm and the inter-electrode distance was 2 cm. Surface electrodes were placed on the muscle venter between the movement point and the tendon attachment, along the longitudinal middle line of the muscle, according to SENIAM methodology [19, 25].

The NORAXON DTS system had the following technical specification: basic noise of the device, below 1 μV RMS, input impedance above 100 Momh, CMR (common signal rejection factor) greater than 100 dB, sampling frequency of 1500 Hz, reinforcement: 500. The raw EMG signals were processed into a root mean square (RMS) with a window of 50 ms. A band pass filter of 20–450 Hz was used together with notch filters at 60 Hz. Processing the signal and EMG analysis were performed using NORAXON MyoResearch -XP 1.07 Master Editionx software.

2.4. Statistical analysis

The statistical analysis was conducted using STATISTICA 12.0 PL software. In order to determine the significance of differences, the Wilcoxon test was used, and the differences were recognized as statistically significant, if the similarity of the examined variables was lower than the assumed significance level $p \leq 0.05$. In order to determine the strength of association between variables the size of the d Cohen effect was calculated. Cohen's d was determined by calculating the mean difference between your two groups, and then dividing the result by the pooled standard deviation.

3. Results

When checking whether it is possible to demonstrate a significant fatigue level in the Biering-Sorensen test, firstly we measured the mean frequency of the power spectrum of both gluteus maximus muscles (GM), in the first and the last second of the test, in all training series, was compared (tab. 1.). The conducted research shows that in the right muscle this difference amounted on average to 6.97 Hz, and in the left - to 5.60 Hz, and in both cases these are statistically significant changes.

Table 1. Values of sEMG signal frequency in gluteus maximus muscles (GM), in the first and the last second of the test.

Variable	Average (Hz)	Minimum (Hz)	Maximum (Hz)	Standard deviation (Hz)
GM right (1 s)	55.61	44.28	75.55	7.08
GM right (60 s)	48.64*	38.31	59.59	4.48
GM left (1 s)	58.78	51.25	77.19	4.98
GM left (60 s)	53.18*	45.63	65.80	4.62

* statistical significance of the changes at the level of $p<0.05$. as compared to the first second of measurement.

By analysing the results of athletes individually, it is possible to note clear reductions in the frequency measured in the first and the last second of the test, however, without explicit

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determination of the left- or the right-sided dominance (fig. 1.). These reductions were statistically significant.

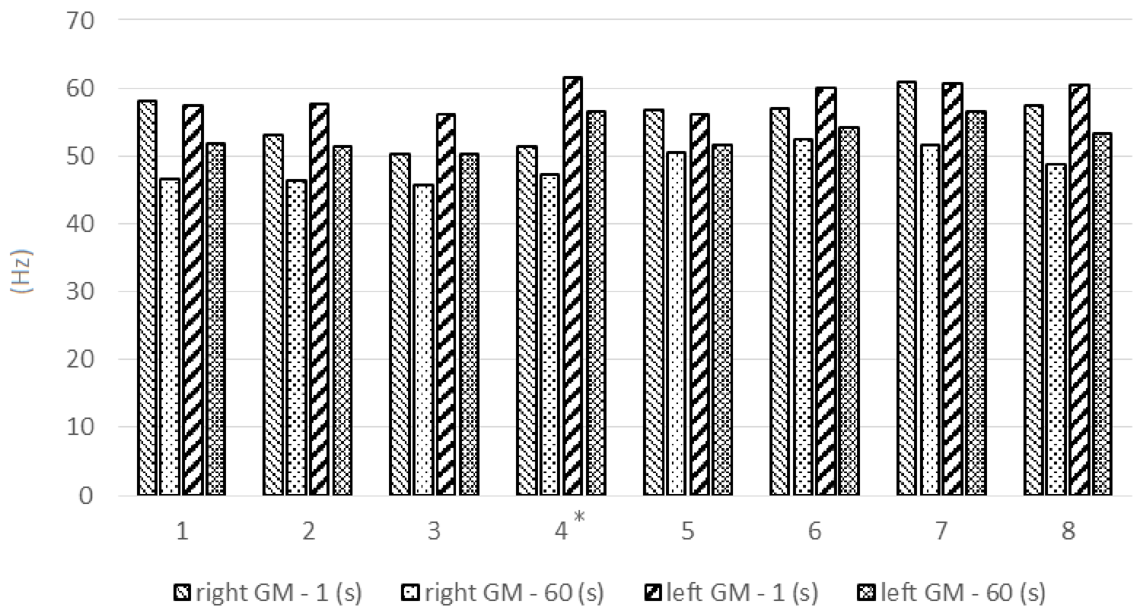

Figure 1. The average value of frequency (Hz) of gluteus maximus muscles of all series, measured at the beginning.

The results presented in Table 2, show the trend of average frequencies of the first and the last seconds, in subsequent test series. Training causes the results of average frequencies to have a decreasing trend. Considering the first second of the test, the average value of frequency in the right muscles decreased by 9.66 Hz, while in the last second it decreased by 1.2 Hz. In the left limb, similarly, the drops by 3.8 Hz and 1 Hz were observed. Significant changes in frequency between series were demonstrated in 1 (s) of right and left GM tests. In the right GM, significant changes occurred between series 1 and 2 where p = 0.05, series 1 and 5, where p = 0.02, series 2 and 5, where p = 0.04, and series 4 and 5, where p = 0.03. In the left GM, significant changes occurred between series 1 and 5, where p = 0.04, and series 3 and 5 where p = 0.04. Significant changes between series measured in 60 (s), did not occur.

Table 2. Average frequencies in gluteus maximus muscles (GM), in the first and the last second of the test, obtained by athletes in subsequent test series.

Variable	1 series (Hz)	2 series (Hz)	3 series (Hz)	4 series (Hz)	5 series (Hz)
GM right (1 s)	60.36	54.86	56.05	56.09	50.70
GM right (60 s)	48.61*	50.45*	47.54*	49.17*	47.42*
GM left (1 s)	59.80	58.97	62.28	56.86	55.97
GM left (60 s)	52.62*	54.55*	54.74*	52.36*	51.62*

* statistical significance of the changes at the level of p<0.05, as compared to the first second of measurement.

Measuring the size of the d Cohen effect, assessing the fatigue between the 1st and 60th s. of the test, it is possible to note a strong effect (value > 0.5) for each series (tab. 3.). The size of the effect drops along with subsequent training series. In the right gluteus maximus muscle, the strongest effect of fatigue is visible in the first series, and the lowest -in the last series. In the left muscle, there is a higher variability of results.

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Table 3. The size of the d Cohen effect of gluteus maximus (GM) muscles fatigue, obtained by athletes in subsequent test series.

Variable	1 series	2 series	3 series	4 series	5 series
GM right (d Cohen effect)	1.73	1.26	1.16	1.10	0.90
GM left (d Cohen effect)	1.79	1.14	1.19	1.16	0.90

4. Discussion

Many aspects concerning fatigue in short track, have not been tested yet, because it is not a very broadly examined sports discipline, and the training process requires enhancements. In order to obtain the best training model, it is necessary to have accurate knowledge of sports requirements specific for this discipline, including individual treatment of each athlete [2]. Conducting such tests is one of the greatest challenges for science in sports. Achievement of the best performance is strictly related to optimization of the training process, and this thesis, concerning the fatigue of gluteus maximus muscles in short track athletes is to contribute to this issue.

Physiological symptoms of muscle fatigue strongly affect their frequency measured by sEMG decreases [26], however, in the opinion of Peach et al. [27], such fatigue measurements cannot be relied upon. In order to avoid an error, we repeated our test in five series. In order to test muscle fatigue using the sEMG system, we paid attention first to the claim by Petrofsky [13] concerning a test during isometric contraction in isolated muscle position conducted in the Biering-Sorensen test. Our tests revealed a decrease in mean frequency of the power spectrum of the EMG signal during the test, as well as in the course of consecutive stages of the training, which is consistent with the tests by Petrofsky [13]. The results of the conducted tests also demonstrated usefulness of EMG in determination of muscle fatigue, which is consistent with the tests by other authors [9, 12, 19, 28]. In addition, we demonstrated that changes in average frequencies measured in the first second, at the beginning and at the end of the test, vary statistically in a substantial way. As a result, the Biering-Sorensen test may be regarded a reasonable tool for testing muscle fatigue, which is suggested by, among others, Champagne et al. [22], Howard et al. [23], Larivière et al. [24]. When the muscle fatigue increases, the number of active motor units decreases and the speed of conductivity of muscle fibres drops [29]. In addition, motor units are stimulated slower and their work becomes more synchronized [5]. All these changes lead to gradual reduction in the muscular work possibility [30].

A tendency of reduction of the average frequency level in the test, was shown also in an individual test of each of the female athletes. In subsequent test series, of the whole group and of each female athlete separately, a decrease in measurements of average frequencies can be noticed during both the first and the last seconds of the whole one-minute test. Both in the right and in the left gluteus maximus muscle, along with the progressing training, the average frequency measurements drop. It can be observed to a larger extent in the case of the beginning of measurements (average frequencies measured from the first second) than those measured at the end of the measurement (in the last second of the test). The fatigue effect is particularly visible in the first series of the measurements, where the differences between the first and the last second are the largest. In the subsequent measurements, this difference is lower (tab. 2). Along with subsequent series, the average frequencies of the first measured second have a decreasing trend to a greater extent than those measured at the end of the measurement, which additionally are similar in each series. On this basis, it can be concluded that in the last second of the measurement, the frequency values reach the fatigue threshold which the organism cannot exceed. Therefore, it is possible to develop the reports of authors [8] who believe that there is an individual variability of muscle features and it is not possible to simply determine the load and time function precisely specifying the muscle fatigue threshold. During examining subsequent series of the training, each female athlete had various frequency thresholds at the beginning and end of the test. The expected decrease in frequency along with each of five series of a straining training does not take place here. The above presumptions are confirmed in analyses of the d Cohen effect size. The first training series [the test before the training) is related to the largest effect of fatigue in both measured muscles 1.73 and 1.79. The fatigue effect in subsequent series is almost two times smaller, reaching the level of 0.90 in both of the examined muscles in the last series of tests. In the right muscle, it decreases systematically in each of the subsequent series, while in the left one a higher fluctuation of results is observed.

Noticing these differences between the sides, it can be stated that fatigue of the muscles of right and left lower limb will differ. Training result was higher changes in frequency in the right muscle, comparing the measurements from the beginning and the end of the training. It would be a confirmation of a generally known trend in short track, involving higher load, and thereby higher fatigue of the right lower limb during skating. This is an effect of its higher load on curves [31]. Our test took place during specialized training, where athletes were skating along a track straining the organism in the aspect of endurance and speed at the same time. The speeds of the female athletes were high, and so were the strains of lower limbs. In the short track athletes, the right lower limb muscles work to a greater extent when skating on the curves on one track lap [4, 31].

Based on the conducted research, we suggest to extend the analysis also to other muscles in the lower limbs, which would give more precise information about muscle fatigue. Using the EMG method for assessment of the gluteus maximus muscle fatigue in short track athletes, high usefulness has been demonstrated.

5. Conclusions

1. The muscle signal frequency measured by sEMG decreases in one-minute Biering-Sorensen test, which may prove the fatigue of muscles.
2. In subsequent series tests, the frequency of 1 second of the measurement has a higher decreasing trend than the measurement of the last second of the measurement.
3. Reductions in the frequency measured in the first and the last second of the test, was higher of the right lower limb.
4. The size of the d Cohen effect in fatigue decreases with subsequent training series.
5. During the consecutive training series, the athletes individually achieve various average values of frequencies at the beginning of the test, without a clear decreasing trend.

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References

1. Rundell KW. Effects of drafting during short-track speed skating. Med Sci Sports Exerc. 1996;28(6):765–71.
2. Felser S. Modeling a performance structure using the example of the sport Short Track. Rostock: University of Rostock; 2012.
3. Felser S, Behrens M, Fischer S, Heise S, Bäumler M, Salomon R, et al. Relationship between strength qualities and short track speed skating performance in young athletes. Scand J Med Sci Sport. 2016;26(2):165–71.
4. Hesford CM, Laing S, Cardinale M, Cooper CE. Effect of race distance on muscle oxygenation in short-track speed skating. Med Sci Sports Exerc. 2013;45(1):83–92.
5. Bigland-Ritchie B, Woods JJ. Changes in muscle contractile properties and neural control during human muscular fatigue. Muscle Nerve. 1984;7(9):691–9.

6. De Luca CJ. Myoelectrical manifestations of localized muscular fatigue in humans. Crit Rev Biomed Eng. 1984;11:251–279.
7. Barry BK, Enoka RM. The neurobiology of muscle fatigue: 15 years later. Integr Comp Biol. 2007;47(4):465–73.
8. Al-Mulla MR, Sepulveda F, Colley M. sEMG Techniques to Detect and Predict Localised Muscle Fatigue. In: Schwartz M, editor. EMG Methods for Evaluating Muscle and Nerve Function. Rijeka: InTech; 2012:157–87.
9. Oskoei MA, Hu H, Gan JQ. Manifestation of fatigue in myoelectric signals of dynamic contractions produced during playing PC games. Conf Proc IEEE Eng Med Biol Soc.2008:315–8.
10. Basmajian J, De Luca CJ. Description and Analysis of the EMG Signal. In: Muscles alive : their functions revealed by electromyography. 1985:65–100.
11. Farina D. Interpretation of the surface electromyogram in dynamic contractions. Vol. 34, Exercise and Sport Sciences Reviews. 2006:121–7.
12. Naik GR, Kumar DK, Wheeler K, Arjunan SP. Estimation of muscle fatigue during cyclic contractions using source separation techniques. In: DICTA 2009 - Digital Image Computing: Techniques and Applications. 2009:217–22.
13. Petrofsky JS. Quantification through the surface EMG of muscle fatigue and recovery during successive isometric contractions. Aviat Sp Environ Med. 1981;52(9):545–50.
14. Calder KM, Stashuk DW, McLean L. Physiological characteristics of motor units in the brachioradialis muscle across fatiguing low-level isometric contractions. J Electromyogr Kinesiol. 2008;18(1):2–15.
15. Arendt-Nielsen L, Mills KR. The relationship between mean power frequency of the EMG spectrum and muscle fibre conduction velocity. Electroencephalogr Clin Neurophysiol. 1985;60(2):130–4.
16. Phinyomark A, Thongpanja S, Hu H, Phukpattaranont P, Limsakul C. The Usefulness of Mean and Median Frequencies in Electromyography Analysis. In: Computational Intelligence in Electromyography Analysis - A Perspective on Current Applications and Future Challenges. InTech; 2012:195–220.
17. Cook SB, Murphy BG, Labarbera KE. Neuromuscular function after a bout of low-load blood flow-restricted exercise. Med Sci Sports Exerc. 2013;45(1):67–74.
18. Merletti R, Parker P. Electromyography : physiology, engineering, and noninvasive applications. IEEE Press; 2004:477–494.
19. Neto GR, Santos HH, Sousa JBC, Júnior ATA, Araújo JP, Aniceto RR, et al. Effects of High-Intensity Blood Flow Restriction Exercise on Muscle Fatigue. J Hum Kinet. 2014;41(1):163–72.
20. Foster C, Rundell K, Snyder AC, Stray-Gundersen J, Kemkers G, Thometz N, et al. Evidence for restricted muscle blood flow during speed skating. Med Sci Sports Exerc. 1999;31(10):1433–40.
21. Katakura M, Duffell LD, Strutton PH, McGregor AH. Effects of a 60 second maximum voluntary isometric contraction on torque production and EMG output of the quadriceps muscle group. Isokinet Exerc Sci. 2011 Jan;19(1):13–22.
22. Champagne A, Descarreaux M, Lafond D. Back and hip extensor muscles fatigue in healthy subjects: Task-dependency effect of two variants of the Sorensen test. Eur Spine J. 2008;17(12):1721–6.
23. Howard J, Granacher U, Behm DG. Trunk extensor fatigue decreases jump height similarly under stable and unstable conditions with experienced jumpers. Eur J Appl Physiol. 2014;115(2):285–94.
24. Larivière C, Gravel D, Arsenault AB, Gagnon D, Loisel P. Muscle recovery from a short fatigue test and consequence on the reliability of EMG indices of fatigue. Eur J Appl Physiol. 2003;89(2):171–6.
25. Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. J Electromyogr Kinesiol. 2000;10(5):361–74.
26. Roy SH, De Luca CJ, Emley M, Oddsson LI, Buijs RJ, Levins J a, et al. Classification of back muscle impairment based on the surface electromyographic signal. J Rehabil Res Dev. 1997;34(4):405–14.
27. Peach JP, Gunning J, McGill SM. Reliability of spectral EMG parameters of healthy back extensors during submaximum isometric fatiguing contractions and recovery. J Electromyogr Kinesiol. 1998;8(6):403–10.
28. Pasquet B, Carpentier A, Duchateau J, Hainaut K. Muscle fatigue during concentric and eccentric contractions. Muscle Nerve. 2000;23(11):1727–35.
29. Farina D, Fattorini L, Felici F, Filligoi G. Nonlinear surface EMG analysis to detect changes of motor unit conduction velocity and synchronization. J Appl Physiol. 2002;93(5):1753–63.
30. Gates DH, Dingwell JB. The effects of neuromuscular fatigue on task performance during repetitive goal-directed movements. Exp Brain Res. 2008;187(4):573–85.

31. Felser S, Behrens M, Fischer S, Baeumler M, Salomon R, Bruhn S. Neuromuscular activation during short-track speed skating in young athletes. Int J Sports Physiol Perform. 2016;11(7):848–54.