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Assessment of muscle load and fatigue with the usage of frequency and time-frequency analysis of the EMG signal

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The aim of the study was to determine the effect of the muscle load and fatigue on the values of the parameters calculated on the basis of the time, frequency (Fourier transform) and time-frequency (wavelet transform) analysis of the EMG signal, for low levels of load.

Fifteen young men took part in the study. The EMG signal was registered from right side biceps brachii (BB) and trapezius (TR) muscles in static conditions, at load 10%, 20% and 30% MVC (maximal voluntary contraction). On the basis of the analysis there were selected parameters sensitive to force (RMS) and parameters sensitive to fatigue but simultaneously insensitive to force (MPF – mean power frequency determined on the basis of Fourier transform, CMPFdb5 – mean power frequency determined on the basis of the wavelet transform).

The results indicate that CMPFdb5 can show similar (muscle BB) or greater (muscle TR) sensitivity to fatigue than MPF. It can suggest that, for low levels of load, the wavelet transform parameters can be more effective in assessing muscle fatigue than the parameters based on the Fourier transform.

The obtained results can allow for a more precise analysis of muscle fatigue at low levels of load. Further analysis for a greater number of muscles activated at low levels of load, with the usage of the parameters tested is desirable.

Key words: *biomechanics, EMG, fatigue, muscle load, wavelet*

1. Introduction

Musculoskeletal disorders are an important work-related problem [1], [2]. The reason for the occurrence of musculoskeletal disorders may be muscle fatigue, associated with prolonged muscle load even at low load levels [3]–[6]. This means that the reduction of the load and fatigue in the working conditions may be an important step in reducing the occurrence of musculoskeletal disorders. A valuable tool for assessment of muscle load and fatigue is non-invasive surface electromyography (EMG) [7]–[10].

There are various methods of the EMG signal analysis. For many years the commonly used indicators of load and fatigue were determined in time or frequency domain on the basis of Fourier transform. The assessment of muscle load in time domain on the basis of the amplitude (RMS – root mean square) of the EMG signal is carried out [11]–[13]. Muscle fatigue, in addition to RMS, can also be visible in the values of the EMG signal power spectrum parameters, such as mean power frequency (MPF) or median frequency (MF). Muscle fatigue causes an increase in RMS and decrease in the values of MF and MPF, which is caused by shifts of the power spectral density (PSD) of the EMG signal towards relatively lower frequencies [14]–[17]. Parameters MPF and MF, determined on the basis of Fourier transform, are commonly used indicators of fatigue, however they have some limitation. This limitation concerns the adopted simplifying assumptions about the stationarity of the signal tested.

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An important problem associated with the analysis of muscle fatigue is the ambiguity of the changes of the EMG signal parameters, particularly at low levels of load [3], [4], [18], [19]. MPF and MF are successfully used to assess fatigue in the case of muscle load at levels above 30% MVC (maximal voluntary contraction). But for smaller loads, there are visible changes in the values of these parameters that may be caused by other factors than muscle fatigue, such as force fluctuation, changing of the muscle length and fatty tissue content [10], [20], [21].

In recent years, time-frequency methods are used in the EMG signal analysis. Authors of many studies indicate that the time-frequency methods provide more accurate results concerning the assessment of muscle load and fatigue than frequency methods [16], [22], [23]. One of the time-frequency methods of the EMG signal analysis is the wavelet transform [24]. The results of research indicate that the time-frequency methods can be used in the analysis of muscle load and fatigue [23], [25]–[27]. In addition, the time-frequency indicators do not require the adoption of simplifying assumptions about the stationarity of a signal [28], [29].

The aim of the study was to determine the effect of the muscle load and fatigue on the values of the parameters calculated on the basis of the time, frequency (Fourier transform) and time-frequency (wavelet transform) analysis of the EMG signal, for low levels of load.

2. Methods and materials

2.1. Participants

A homogeneous group of participants consisted of fifteen young men. Mean (standard deviation) age, body height and weight were, respectively, 21.9 years (1.4); 180.1 cm (3.2); 73.6 kg (3.9). The participants were physically active and they had no musculoskeletal complaints. Each participant read and signed an informed consent form prior to the study. The protocol of the study was approved by the local ethics committee.

2.2. Protocol

The EMG signal was registered from right side biceps brachii (BB) and trapezius (TR) muscles in static conditions, at load 10%, 20% and 30% MVC.

In order to activate the muscles tested the measurement stands were used. BB muscle was activated on USMS stand (Fig. 1) and TR muscle on PSP1 stand (Fig. 2). During activation of BB muscle participants were standing upright, with their right upper limb flexed in the elbow at 90°. The flexion angle of the shoulder was also 90°. The participant's task was to maintain elbow flexion against resistance.

During activation of TR muscle participants were standing upright with straightened upper limbs. They kept in hands the handles attached to the ground. Their task was to lift up arms against resistance.

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

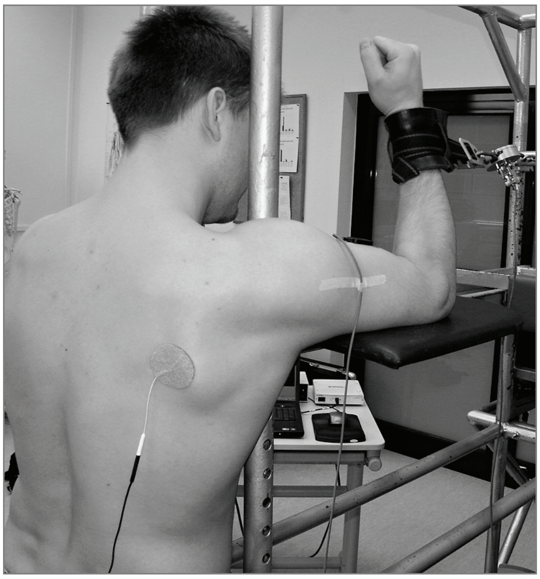

Fig. 1. The activation of BB (biceps brachii) muscle on the USMS stand

The second stage was done for the same body posture as in the first stage. The EMG signals were recorded, while the subject maintained constant force during tests at 10, 20 and 30% MVC. The order of tests for individual subjects was different and determined on the basis of the tables of random numbers.

Measurement of the EMG signal at each level of load lasted up to the fatigue. The criterion of fatigue occurrence was a decrease in the capability of maintaining force, which was displayed on the monitor as a graph, of more than 20% of set level, for at least 2 consecutive seconds. There was a 15 minute break between tests for recovery.

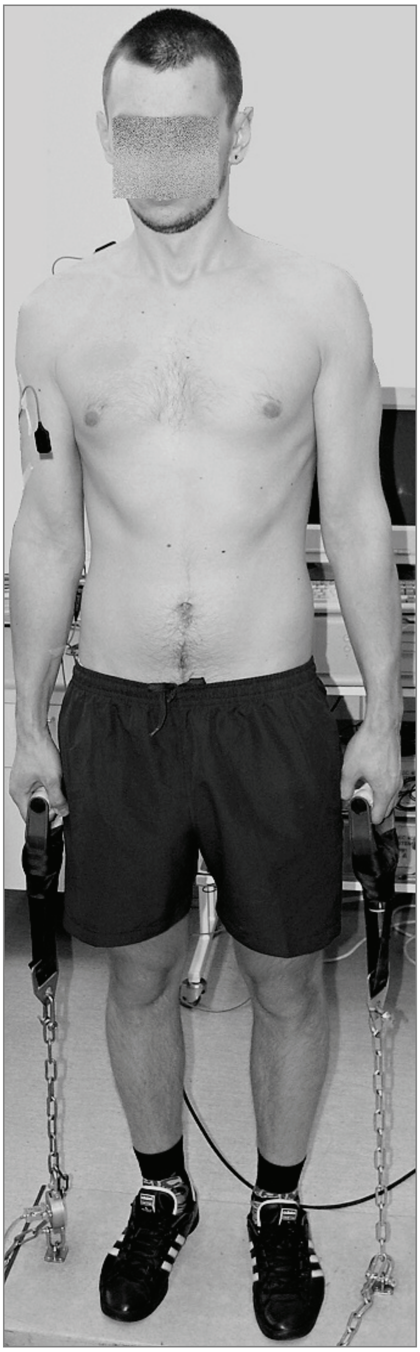

Fig. 2. The activation of TR (trapezius) muscle on the PSP1 stand

2.3. Equipment

2.3.1. Measurements of the EMG signal

Raw EMG signal was measured and registered with a Bagnoli-16 device (Delsys, USA). Data were sampled with a 16-bit DAQCard 6036E A/D card (National Instruments, USA). The signal sampling frequency was 4 kHz. The bandwidth of Bagnoli-16 was 20–450 Hz (±10%), bandwidth roll-off 80 dB/decade, overall noise ≤1.2 μV (RMS, RTI) and EMG amplification 1000. The EMG signal was recorded with EMG Works 3.5 software and double differential surface electrodes DE-3.1 (Delsys, USA). Those electrodes were used to reduce the risk of crosstalk [13], [30]. Contact material of the sensor was 99.9% Ag, contact dimension 10 × 1 mm and contact spacing 10 mm, so the detection area was 200 mm^2 (including both pairs of contacts). Input impedance of the sensor was over $10^{15}\Omega$ //0.2 pF, noise 1.2 μV (RMS, RTI), CMRR-92 dB and preamplifier gain 10.

Before sticking EMG electrodes the skin was shaved and disinfected with a cotton swab soaked in alcohol. The electrodes were also disinfected with alcohol. They were fixed to the skin with a dedicated double-sided adhesive tape. To avoid signal artefacts no gel was used [31]. After affixing the electrodes, participants were asked to relax and to activate the muscles in question to provide a high signal-to-noise ratio [32], [33]. Differences in the amplitude of the EMG signal between the state of activation and relaxation were visually checked. If the difference was not clear, the contact between the skin and the electrode was improved. The electrodes were located on the skin according to the SENIAM guidelines [33], [34] and Perotto [35].

2.3.2. Force measurements

The levels of load (10%, 20% and 30% MVC) were determined on the basis of the values of external force measured with the usage of the dynamometer. The dynamometer in conjunction with a transducer allows converting the applied force to an electrical signal and the presentation of changes in the force values during the test. The software CPSv_2.0 was used to visualise and measure the force. The visualisation of force enabled the subject observation and maintaining the exerted force on a constant level.

2.4. Signal analysis

In order to determine the effect of muscle fatigue on the EMG signal characteristics, the differences in the values of parameters at the end and at the beginning of the tests were analysed. For each participant, each level of load and each muscle tested, fragments of the beginning (B) and the end (E) parts of the EMG signal were chosen. Fragments B concern first two seconds of the load (after stabilization of the EMG signal amplitude) and fragments E correspond to the last two seconds of the load (with stable values of the

EMG amplitude). On the basis of selected fragments the parameters of the EMG signal were determined. The software developed in Matlab (version R2009) was used.

2.4.1. Parameters characterising EMG signal

The parameters which characterize the EMG signal in time, frequency and time-frequency domain were computed. The RMS expresses the relative value obtained as a result of dividing the amplitude of the EMG signal from measurements in separate tests (10%, 20% and 30% MVC) by the value of the amplitude of the measurement at MVC.

MPF parameter was calculated on the basis of the fast Fourier transform (1 s, 4000 samples, Hanning window; 50% overlap). Power spectral density (PSD) was estimated from the Fourier transforms with the Welch method and expressed with periodograms [36]. On the basis of the periodograms MPF parameter was determined in accordance with equation (1).

$$\mathrm{MPF} = \frac{\int_0^\infty f S(f)\,df}{\int_0^\infty S(f)\,df} \tag{1}$$

where $S(f)$ is the value of density function for the frequency f, calculated by FFT.

In order to determine the parameters in time-frequency domain, continuous wavelet transform (CWT) was carried out. Wavelet function from Daubechies family (db5) was used. Wavelet coefficients for 16 scales, representing the EMG signal in the frequency range from 19 Hz to 675 Hz, were calculated. Scales with the following numbers were selected: 6, 7, 9, 11, 13, 16, 20, 25, 31, 38, 47, 58, 69, 81, 95, 109.

Based on CWT, for each of the selected scales, wavelet coefficients were obtained. On the basis of the wavelet coefficients from all scales, the scalograms were obtained. From the scalograms the mean frequency CMPFdb5 was determined [29], [37]

$$\mathrm{CMPFdb5} = \frac{\int_{ls}^{hs} s\,\mathrm{SC}(s)\,ds}{\int_{ls}^{hs} \mathrm{SC}(s)\,ds} \tag{2}$$

where SC is the scalogram, which is equivalent to the periodogram obtained on the basis of the Fourier transform, s is the scale (ls – the lowest scale, hs – the highest scale).

In the analysis the parameters determined in the time, frequency and time-frequency domain were included. In time domain the amplitude RMS was analysed, in frequency domain – parameter MPF and time-frequency domain were represented by the parameter CMPFdb5.

2.4.2. Time normalization

Due to the various levels of load (10%, 20% and 30% MVC) and various endurance of the participants, the duration of the individual EMG signal measurements was different. Fatigue analysis for different levels of load and participants is possible only if the time of load for each of the analysed cases is the same. Therefore, to obtain the values independent of the duration of the measurement, the parameters determined from the end fragments (E) were normalized in time.

To assess fatigue, for all the tests (all levels of load 10%, 20% and 30% MVC, all participants and both muscles) the constant load time (*Tc*) was adopted. In order to normalize the values of the parameters in E fragments, the values of the parameter which would be reached at the time *Tc* were calculated. Therefore, for each parameter, each level of load, each muscle and for each participant, there was determined the equation of the line passing through the following points:

– point B, which is the value of the parameter at the beginning of the load (for this point the adopted time is 0),
– point E, which is the value of the parameter at the end of the load (time *Te*).

On the basis of equation (3), values of the parameter which would be reached at time *Tc* were calculated.

$$\mathrm{EN} = \frac{\mathrm{E} - \mathrm{B}}{Te} \cdot Tc + \mathrm{B}\,. \tag{3}$$

EN expresses normalized value of the specific parameter at the end fragment of load. In the statistical analysis, for each parameter the values corresponding to B and EN were taken into account.

2.4.3. Statistical analysis

In order to determine the influence of the level of load on the EMG signal characteristics, an analysis of variance (ANOVA) was carried out for each parameter calculated from the EMG signal registered in fragment B. The independent variable was muscle force (three levels of load), while the dependent variables were EMG signal parameters (RMS, MPF and CMPFdb5). Statistically significant differences ($p \leq 0.05$) in the values of specified parameter between level of load indicated a sensitivity of this parameter to muscle force. In the cases where the significant differences between the levels of load were obtained, post-hoc analysis using Fisher's test was carried out.

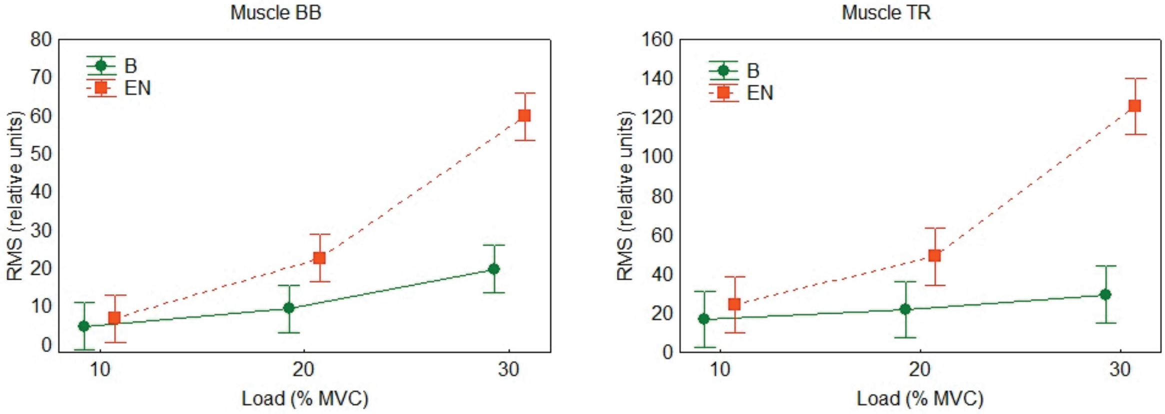

Fig. 3. The mean values and 95% confidence intervals for RMS (root mean square) parameter from the beginning (B) and the end (EN) fragments of BB (biceps brachii) and TR (trapezius) muscles' activation at three levels of load (10, 20 and 30% MVC)

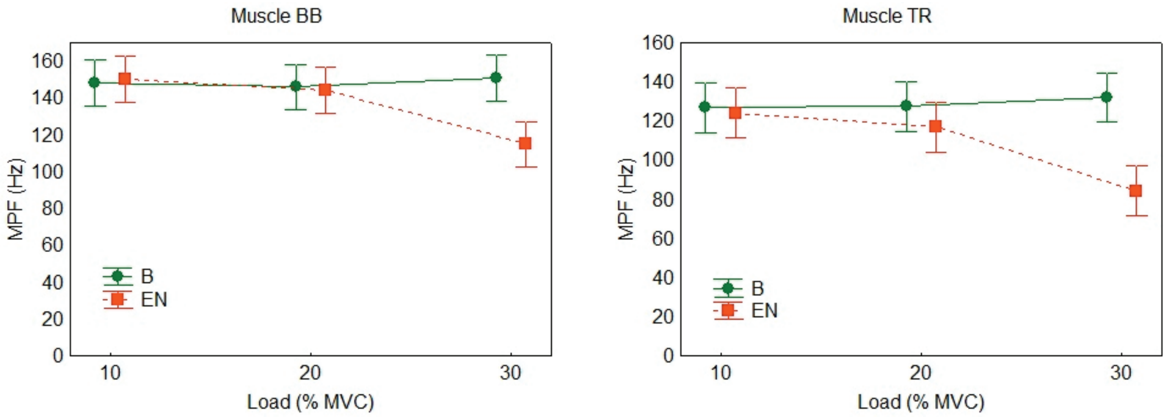

Fig. 4. The mean values and 95% confidence intervals for MPF (mean power frequency obtained with the usage of Fourier transform) parameter from the beginning (B) and the end (EN) fragments of BB (biceps brachii) and TR (trapezius) muscles' activation at three levels of load (10, 20 and 30% MVC)

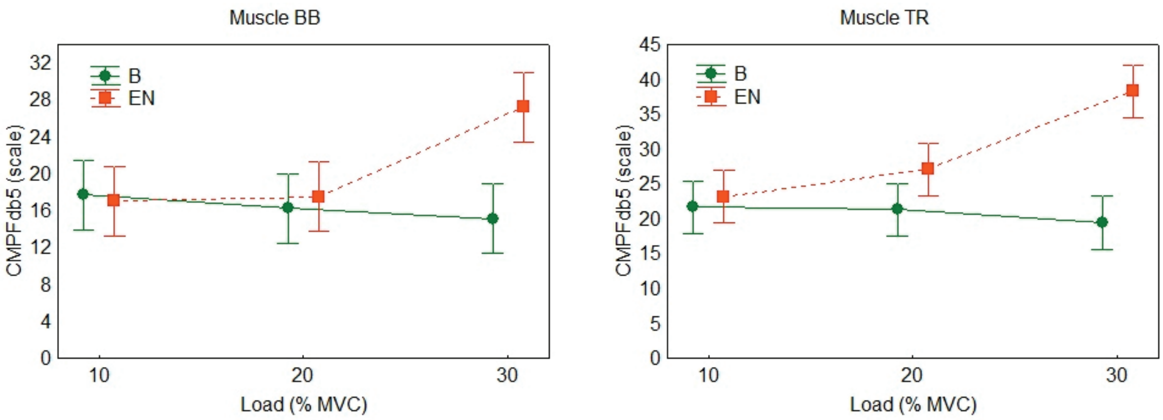

Fig. 5. The mean values and 95% confidence intervals for CMPFdb5 (mean power frequency obtained with the usage of wavelet transform) parameter from the beginning (B) and the end (EN) fragments of BB (biceps brachii) and TR (trapezius) muscles' activation at three levels of load (10, 20 and 30% MVC)

To determine the effect of muscle fatigue on the values of the EMG signal parameters, a statistical analysis using *t*-test was performed. The dependent variables were EMG signal parameters (RMS, MPF and CMPFdb5), while the independent variable were fragments (B and EN). Statistically significant differences ($p \leq 0.05$) in the values of specified parameter between the B and EN fragments indicated a sensitivity of this parameter to muscle fatigue. The differences between B and EN fragments were analysed for all three levels of load (10%, 20% and 30% MVC) together as well as for each of the levels of load separately. Statistica 9.0 was used.

3. Results

The marginal means and confidence intervals for RMS parameter from the beginning (B) and the end (EN) fragments of BB and TR muscles' activation at three levels of load (10, 20 and 30% MVC) are presented in Fig. 3. The marginal means and confidence intervals for MPF and CMPFdb5 parameters are presented in Fig. 4 and 5, respectively.

Table 1 presents the effect of the muscle force (three levels of load: 10%, 20% and 30% MVC) on the values of analysed parameters from the EMG signal registered in fragment B from BB and TR muscles, obtained by ANOVA application.

Table 1. The effect of the muscle force (three levels of load: 10%, 20% and 30% MVC) on the values of the RMS (root mean square), MPF (mean power frequency obtained with the usage of Fourier transform) and CMPFdb5 (mean power frequency obtained with the usage of wavelet transform) parameters from the EMG signal registered in beginning fragment (B) from BB (biceps brachii) and TR (trapezius) muscles, obtained by ANOVA application

Parameter	BB muscle		TR muscle	
	F	*p*	F	*p*
RMS	**19.68**	***0.0001***	**11.02**	***0.0001***
MPF	0.16	*0.8498*	0.26	*0.7742*
CMPFdb5	0.77	*0.4681*	0.66	*0.5240*

On the basis of Table 1 it can be stated that there are statistically significant differences in the values of the RMS parameter between the levels of load in both analysed muscles. In the case of MPF and CMPFdb5 parameters there were no statistically significant differences between the levels of load in any of the mus-

Table 2. The results of the post-hoc analysis for different levels of load (10%, 20% and 30% MVC) carried out using Fisher's test for the values of the RMS (root mean square) parameter from the EMG signal registered in beginning fragment (B) from BB (biceps brachii) and TR (trapezius) muscles

Muscle	10% MVC*20% MVC	10% MVC*30% MVC	20% MVC*30% MVC
BB	*0.0630*	***0.0001***	***0.0001***
TR	*0.0713*	***0.0001***	***0.0075***

Table 3. The effect of the fatigue (fragments of the beginning and the end parts of the EMG signal) on the values of the RMS (root mean square), MPF (mean power frequency obtained with the usage of Fourier transform) and CMPFdb5 (mean power frequency obtained with the usage of wavelet transform) parameters from BB (biceps brachii) muscle, obtained by *t*-test application

Parameter	Three load levels		10% MVC		20% MVC		30% MVC	
	t	*p*	t	*p*	t	*p*	t	*p*
RMS	**–4.29**	***0.0001***	–1.84	*0.0770*	**–3.85**	***0.0006***	**–5.89**	***0.0001***
MPF	**2.17**	***0.0327***	–0.19	*0.8471*	0.27	*0.7901*	**3.35**	***0.0023***
CMPFdb5	**–2.53**	***0.0133***	0.32	*0.7481*	–0.59	*0.5567*	**–3.33**	***0.0024***

Table 4. The effect of the fatigue (fragments of the beginning and the end parts of the EMG signal) on the values of the RMS (root mean square), MPF (mean power frequency obtained with the usage of Fourier transform) and CMPFdb5 (mean powewr frequency obtained with the usage of wavelet transform) parameters from TR (trapezius) muscle, obtained by *t*-test application

Parameter	Three load levels		10% MVC		20% MVC		30% MVC	
	t	*p*	t	*p*	t	*p*	t	*p*
RMS	**–4.98**	***0.0001***	**–2.89**	***0.0074***	**–5.65**	***0.0001***	**–5.69**	***0.0001***
MPF	**3.54**	***0.0006***	0.36	*0.7183*	1.35	*0.1870*	**4.24**	***0.0002***
CMPFdb5	**–4.83**	***0.0001***	–0.73	*0.4699*	**–2.53**	***0.0173***	**–5.38**	***0.0001***

cles examined. The results of the post-hoc analysis for RMS parameter for different levels of load, carried out using Fisher's test are presented in Table 2.

Results presented in Table 2 show that for both muscles statistically significant differences were obtained between the highest load level (30% MVC) and the other levels (10% and 20% MVC). Between levels of load 10% MVC and 20% MVC there were no statistically significant differences in any of the muscles examined.

Tables 3 and 4 present the effect of the fatigue (differences between fragments B and EN) on the values of analysed parameters from BB (Table 3) and TR (Table 4) muscle, obtained by *t*-test application for all three levels of load together as well as for each of the levels of load separately.

On the basis of Tables 3 and 4 it can be said that for all three levels of load together (10, 20 and 30% MVC) values of all parameters studied (RMS, MPF and CMPFdb5) differ significantly between fragments B and EN for both muscles. However, in the case of the analysis for each level of load separately, sensitivity to muscle fatigue is not so clear for the analysed parameters.

In the case of BB muscle for the lowest level of load (10% MVC) there were no statistically significant differences between fragments B and EN in any of the analysed parameters. For the load 20% MVC only RMS differs significantly between fragments B and EN, while for the load 30% MVC statistically significant differences between fragments for all parameters under study were obtained.

In the TR muscle for the load 10% MVC only RMS differs significantly between fragments B and EN, for the load 20% MVC RMS and CMPFdb5 show statistically significant differences and for the highest load (30% MVC), similarly as in the case of BB muscle, all analysed parameters differ significantly between fragments B and EN.

4. Discussion

The results of the research allowed us to determine the effect of muscle force and fatigue on the values of the EMG signal parameters, calculated on the basis of time, frequency and time-frequency analysis, for low levels of load of BB and TR muscles.

The results obtained indicate that the RMS amplitude is sensitive to changes in the EMG signal caused by fatigue of BB and TR muscles, analysed for all three levels of load (10%, 20% and 30% MVC) together as well as for each of the levels of load separately. However, it can be seen that RMS is also sensitive to changes in muscle force. This means that RMS is a less reliable indicator of muscle fatigue than MPF and CMPFdb5 parameters, which do not show statistically significant differences between the different levels of load. Results demonstrating the high sensitivity of EMG amplitude to changes of load, resulting in a reduction of the reliability of muscle fatigue assessment, are in accordance with the results obtained by other authors [38]–[40].

In the case of MPF and CMPFdb5 parameters, for both muscles studied, the obtained results indicate a lack of sensitivity to changes in muscle force and demonstrate the sensitivity to muscle fatigue. Statistically significant differences between B and EN fragments in the values of MPF and CMPFdb5 parameters for all three levels of load together and for 30% MVC were obtained. At 10% MVC CMPFdb5 parameter, similarly to MPF, shows no statistically significant differences between B and EN fragments in any of the muscles under examination. In the case of BB muscle at load level 20% MVC there were also no statistically significant differences between B and EN fragments in the values of MPF and CMPFdb5 parameters. However, at 20% MVC in TR muscle statistically significant difference between fragments B and EN for parameter CMPFdb5 was obtained.

On the basis of the analysis it can be seen that at the load levels as low as 10% MVC, frequency parameters of the EMG signal do not always allow the effective assessment of muscle fatigue. On the other hand, the analysis provided information that at 20% MVC indicator based on the wavelet transform (CMPFdb5) shows sensitivity to muscle fatigue, while MPF does not demonstrate such a relationship. The dependences obtained also show that the effect of muscle fatigue at the level of load 30% MVC is visible in the case of both parameters (MPF and CMPFdb5) for both muscles examined.

The above results indicate that the mean power frequency determined on the basis of the wavelet transform can show similar (muscle BB) or greater (muscle TR) sensitivity to fatigue than the mean power frequency determined on the basis of Fourier transform. The relationships concerning TR muscle are consistent with those presented by other authors [16], [22], who report that time-frequency fatigue indicators seem to be more reliable than the indicators calculated on the basis of frequency analysis, while results of BB muscle are in accordance with da Silva et al. [41], who indicate that both types of indicators show similar effectiveness in the evaluation of muscle fatigue.

On the basis of the analysis there were selected parameters sensitive to force (RMS) and parameters sensitive to fatigue but simultaneously insensitive to force (MPF, CMPFdb5) at low levels of load. Parameters sensitive to changes in muscle force may be used to assess muscular load during short-term activities, while the parameters sensitive to fatigue and insensitive to changes in force allow evaluation of fatigue during prolonged activities.

The results of the present study indicate that the wavelet transform parameters demonstrate a similar or greater dependence on fatigue than the parameters determined on the basis of Fourier transform. This can suggest that, for low levels of load, the wavelet transform parameters can be more effective in assessing muscle fatigue than the parameters based on the Fourier transform. It is important due to the fact that the wavelet parameters do not require the adoption of simplifying assumptions about the stationarity of the signal tested. It should be noted, however, that the analysis has concerned the EMG signal recorded from two muscles and more effective assessment of fatigue for CMPFdb5 parameter than MPF parameter was observed only in the case of one of the muscles tested (TR). It is therefore important to examine the effectiveness of the tested fatigue indicators for a greater number of muscles activated at low levels of load.

5. Conclusions

In the present study, the results regarding the effect of muscle force and fatigue on the values of the EMG signal parameters, calculated on the basis of time, frequency and time-frequency analysis, for low levels of load of BB and TR muscles have been presented. The obtained results can allow for a more precise analysis of muscle fatigue at low levels of load. Further analysis for a greater number of muscles activated at low levels of load, with the usage of the parameters tested is desirable.

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References

[1] MALIŃSKA M., BUGAJSKA J., *The influence of occupational and non-occupational factors on the prevalence of musculoskeletal complaints in users of portable computers*, Int. J. Occup. Saf. Ergon., 2010, 16(3), 337–343.

[2] KAMIŃSKA J., ROMAN-LIU D., ZAGRAJEK T., BORKOWSKI P., *Differences in lumbar spine load due to posture and upper limb external load*, Int. J. Occup. Saf. Ergon., 2010, 16(4), 421–430.

[3] DE LOOZE M., BOSCH T., VAN DIEËN J., *Manifestations of shoulder fatigue in prolonged activities involving low-force contractions*, Ergonomics, 2009, 52(4), 428–437.

[4] FARINA D., ZENNARO D., POZZO M., MERLETTI R., LÄUBLI T., *Single motor unit and spectral surface EMG analysis during low-force, sustained contractions of the upper trapezius muscle*, Eur. J. Appl. Physiol., 2006, 96(2), 157–164.

[5] VISSER B., VAN DIEËN J., *Pathophysiology of upper extremity muscle disorders*, J. Electromyogr. Kinesiol., 2006, 16(1), 1–16.

[6] ROMAN-LIU D., KONARSKA M., *Characteristics of power spectrum density function of EMG during muscle contraction below 30% MVC*, J. Electromyogr. Kinesiol., 2009, 19(5), 864–874.

[7] SOLNIK S., DEVITA P., GRZEGORCZYK K., KOZIATEK A., BOBER T., *EMG frequency during isometric, submaximal activity: a statistical model for biceps brachii*, Acta Bioeng. Biomech., 2010; 12(3), 21–28.

[8] SOLNIK S., DEVITA P., RIDER P., LONG B., HORTOBÁGYI T., *Teager–Kaiser Operator improves the accuracy of EMG onset detection independent of signal-to-noise ratio*, Acta Bioeng. Biomech., 2008, 10(2), 65–68.

[9] PISCIONE J., GAMET D., *Effect of mechanical compression due to load carrying on shoulder muscle fatigue during sustained isometric arm abduction: an electromyographic study*, Eur. J. Appl. Physiol., 2006, 97(5), 573–581.

[10] BARTUZI P., TOKARSKI T., ROMAN-LIU D., *The effect of the fatty tissue on EMG signal in young women*, Acta Bioeng. Biomech., 2010, 12(2), 87–92.

[11] TROIANO A., NADDEO F., SOSSO E., CAMAROTA G., MERLETTI R., MESIN L., *Assessment of force and fatigue in isometric contractions of the upper trapezius muscle by surface EMG signal and perceived exertion scale*, Gait Posture, 2008, 28(2), 179–186.

[12] IOI H., KAWAKATSU M., NAKATA S., NAKASIMA A., COUNTS A.L., *Mechanomyogram and electromyogram analyses during isometric contraction in human masseter muscle*, Australian Orthodontic Journal, 2008, 24(2), 116–120.

[13] DE LUCA C.J., *The use of surface electromyography in biomechanics*, J. Appl. Biomech., 1997, 13, 135–163.

[14] GATES D.H., DINGWELL J.B., *The effects of neuromuscular fatigue on task performance during repetitive goal-directed movements*, Exp. Brain Res., 2008, 187(4), 573–585.

[15] YAMADA E., KUSAKA T., ARIMA N., ISOBE K., YAMAMOTO T., ITOH S., *Relationship between muscle oxygenation and electromyography activity during sustained isometric contraction*, Clin. Physiol. Funct. Imag., 2008, 28(4), 216–221.

[16] BARANDUN M., VON TSCHARNER V., MEULI-SIMMEN C., BOWEN V., VALDERRABANO V., *Frequency and conduction velocity analysis of the abductor pollicis brevis muscle during early fatigue*, J. Electromyogr. Kinesiol., 2009, 19(1), 65–74.

[17] ROMAN-LIU D., TOKARSKI T., WÓJCIK K., *Quantitative assessment of upper limb muscle fatigue depending on the conditions of repetitive task load*, J. Electromyogr. Kinesiol., 2004, 14(6), 671–682.

[18] SMITH J.L., MARTIN P.G., GANDEVIA S.C., TAYLOR J.L., *Sustained contraction at very low forces produces prominent supraspinal fatigue in human elbow flexor muscles*, J. Appl. Physiol., 2007, 103(2), 560-568.

[19] BOSCH T., DE LOOZE M.P., KINGMA I., VISSER B., VAN DIEËN J.H., *Electromyographical manifestations of muscle fatigue during different levels of simulated light manual assembly work*, J. Electromyogr. Kinesiol., 2009, 19(4), 246–256.

[20] DOHENY E.P., LOWERY M.M., FITZPATRICK D.P., O'MALLEY M.J., *Effect of elbow joint angle on force-EMG relationships in human elbow flexor and extensor muscles*, J. Electromyogr. Kinesiol., 2008, 18(5), 760–770.

[21] CECHETTO A.D., PARKER P.A., SCOTT R.N., *The effects of four time-varying factors on the mean frequency of a myoelectric signal*, J. Electromyogr. Kinesiol., 2001, 11(5), 347–354.

[22] LARIVIÈRE C., GAGNON D., GRAVEL D., ARSENAULT A.B., *The assessment of back muscle capacity using intermittent static contractions*, Part I – *Validity and reliability of electromyographic indices of fatigue*, J. Electromyogr. Kinesiol., 2008, 18(6), 1006–1019.

[23] VON TSCHARNER V., *Intensity analysis in time-frequency space of surface myoelectric signals by wavelets of specified resolution*, J. Electromyogr. Kinesiol., 2000, 10(6), 433–445.

[24] DAUBECHIES I., *Ten Lectures on Wavelets*, SIAM, Philadelphia, 1992.

[25] SO R., CHAN K.M., SIU O., *EMG power frequency spectrum shifts during repeated isokinetic knee and arm movements*, Research Quarterly for Exercise and Sport, 2002, 73(1), 98–106.

[26] FLANDERS M., *Choosing a wavelet for single-trial EMG*, J. Neurosci. Meth., 2002, 116(2), 165–177.

[27] POPE M.H., ALEKSIEV A., PANAGIOTACOPULOS N.D., LEE J.S., WILDER D.G., FRIESEN K., STIELAU W., GOEL V.K., *Evaluation of low back muscle surface EMG signals using wavelets*, Clin. Biomech., 2000, 15(8), 567–573.

[28] COOREVITS P., DANNEELS L., CAMBIER D., RAMON H., DRUYTS H., KARLSSON J.S., MOOR G.D., VANDERSTRAETEN G., *Test-retest reliability of wavelet - and Fourier based EMG (instantaneous) median frequencies in the evaluation of back and hip muscle fatigue during isometric back extensions*, J. Electromyogr. Kinesiol., 2008, 18(5), 798–806.

[29] HOSTENS I., SEGHERS J., SPAEPEN A., RAMON H., *Validation of the wavelet spectral estimation technique in Biceps Brachii and Brachioradialis fatigue assessment during prolonged low-level static and dynamic contractions*, J. Electromyogr. Kinesiol., 2004, 14, 205–215.

[30] FARINA D., MERLETTI R., INDINO B., NAZZARO M., POZZO M., *Surface EMG crosstalk between knee extensor muscles: experimental and model results*, Muscle Nerve, 2002, 26(5), 681–695.

[31] ROY S.H., DE LUCA G., CHENG M.S., JOHANSSON A., GILMORE L.D., DE LUCA C.J., *Electro-mechanical stability of surface EMG sensors*, Med. Biol. Eng. Comput., 2007, 45(5), 447–457.

[32] DE LUCA C.J., *Surface electromyography: detection and recording*, DelSys, Boston, 2002.

[33] HERMENS H.J., FRERIKS B., DISSELHORST-KLUG C., RAU G., *Development of recommendations for SEMG sensors and sensor placement procedures*, J. Electromyogr. Kinesiol., 2000, 10(5), 361–374.

[34] HERMENS H.J., FRERIKS B., MERLETTI R., HAGG G., STEGEMAN D., BLOK J. ET AL, EDITORS., *SENIAM 8: European recommendations for surface electromyography*, ISBN:90-75452-15-2: Roessingh Research and Development bv. 1999.

[35[PEROTTO A.O., *Anatomic guide for the electromyographer – the limbs and trunk*, 4th ed. Springfield, Illinois: Charles C Thomas. 2005.

[36] WELCH P.D., *The use of fast Fourier transform for the estimation of power spectra: a method based on time averaging over short, modified periodograms*, IEEE Trans Audio Electroacoust, 1967, AU-15, 70–73.

[37] HOSTENS I., RAMON H., *Assessment of muscle fatigue in low level monotonous task performance during car driving*, J. Electromyogr. Kinesiol., 2005, 15(3), 266–274.

[38] ASTRÖM C., LINDKVIST M., BURSTRÖM L., SUNDELIN G., KARLSSON J.S., *Changes in EMG activity in the upper trapezius muscle due to local vibration exposure*, J. Electromyogr. Kinesiol., 2009, 19(3), 407–415.

[39] HÄGG G.M., LUTTMANN A., JÄGER M., *Methodologies for evaluating electromyographic field data in ergonomics*, J. Electromyogr. Kinesiol., 2000, 10(5), 301–312.

[40] DIMITROVA N.A., DIMITROV G.V., *Interpretation of EMG changes with fatigue: facts, pitfalls and fallacies*, J. Electromyogr. Kinesiol., 2003, 13(1), 13–36.

[41] DA SILVA R.A., LARIVIÈRE C., ARSENAULT A.B., NADEAU S., PLAMONDON A., *The comparison of wavelet- and Fourier-based electromyographic indices of back muscle fatigue during dynamic contractions: validity and reliability results*, Electromyogr. Clin. Neurophysiol., 2008, 48(3–4), 147–162.