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A Study of the Influence of Muscle Type and Muscle Force Level on Individual Frequency Bands of the EMG Power Spectrum

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The aim of this study was to analyse the electromyographic (EMG) power spectrum indicating differences in the frequency bands of the spectrum resulting from differences in muscle type and force level for the extensor digitorum (ED), palmaris longus (PL) and biceps brachii (BB) muscles. The study was performed on 12 young men as 2 tests different in terms of the type of exerted force (30, 15 and 5% MVC, maximum voluntary contraction). The parameters of the EMG power spectrum were obtained as a result of a division of the EMG power spectrum into ranges determined by border frequencies. The results suggest that (a) frequency bands contained in the 30–80 Hz range and over the frequency of 300 Hz depend on muscle force, and (b) the power spectrum in the frequency range of up to 40 Hz and 60–300 Hz indicates muscle type.

EMG power spectrum upper limb muscle type extensor digitorum palmaris longus biceps brachii

1. INTRODUCTION

Diseases of the musculoskeletal system are among the most frequent causes of work inability and premature retirement and pension [1]. Work resulting in excessive load and fatigue of the musculoskeletal system is one of the reasons for those complaints [2, 3, 4].

Recently, surface electromyography has become a commonly used method to assess muscle load and muscle fatigue [5, 6, 7, 8, 9]. When this method is used, muscle fatigue is assessed on the basis of the parameters of the electromyographic (EMG) signal determined in the time (amplitude of the EMG signal) and frequency (mean power frequency, MPF; median frequency, MF) domains. Those parameters are described as global parameters and their values change over time due to the fatigue processes within the muscle [10, 11]. However, changes in the distribution of frequencies of the EMG power spectrum are also affected by changes in force level [12, 13, 14, 15], recruitment of new, not fatigued, motor units [16, 17, 18, 19, 20], the proportion of muscle fibres [21], muscle type [22] and muscle length [15].

The results of studies on the influence of different factors on the values of the EMG signal amplitude and global parameters of the power spectrum such as MF and MPF are varied. Linnamo, Strojnik, and Komi [23] indicated that the mean value of the EMG signal amplitude increased together with the increase in the force of the vastus lateralis, vastus medialis and rectus femoris muscles. Such a relationship was not found for MF. The MF value

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for all three studied muscles remained constant, irrespective of the value of the force. However, Lowery, Nolan and O'Malley [24] demonstrated an increase in the MF parameter together with a force increase in the brachioradialis muscle.

Boissy, Pigeon, Arsenault, et al. [13] indicated that the value of MF of the biceps brachii (BB) decreased with an increase in muscle force. Similar results were achieved by Dolan, Mannion, and Adams [14], who analysed the EMG signal registered from the erector spinae muscle. They suggest that the value of the MF parameter decreased during contraction together with an increase in the area under the power spectrum curve.

Mannion and Dolan [15], too, reported that the force in the erector spinae muscle affected the value of MF, although this relationship varied in the thoracic and lumbar section of this muscle. In the thoracic segment the value of MF increased together with an increase in force up to 40–50% MVC (maximum voluntary contraction), whereas the value of this parameter decreased together with an increase in subsequent force. Nonetheless, for the lumbar section of the erector spinae muscle the value of MF was stable for force of up to 30–40% MVC, whereas above this level the value of MF decreased together with an increase in force. In addition, the results of these authors' studies suggested that the value of MF decreased together with an increase in muscle length. The results of these studies suggested that the values both of MF and MPF and their changes due to force were connected with the structure of the tested muscle. The proportion of type I and type II muscle fibres as well as the thickness of the subcutaneous layer above the tested muscles were probably significant. The same authors [15] also concluded that the EMG power spectrum might contain information about the features of muscle fibres. These suggestions were confirmed by Gerdle, Karlsson, Crenshaw, et al.'s studies [21], which aimed to evaluate the relationship between the proportion of type I and type II muscle fibres and the parameters of the EMG signal such as MF and amplitude (RMS) in the vastus lateralis muscle. This research demonstrated that there were positive correlations between the value of MF and the proportion of type I muscle fibres as well as positive correlations between the value of RMS and the proportion of type II muscle fibres. Also Larsson, Kadi, Lindvall, et al. [22], as a result of an analysis performed on the gastrocnemius lateralis muscle, concluded that MF was positively correlated with the proportion of type I muscle fibres. However, having analysed the work of the first dorsal interosseous muscle, Seki and Narusawa [25] reported that the global parameters of the EMG power spectrum, such as MPF, reflected the size of motor units. The results of these studies indicated that the content of muscle fibres of a determined type as well as the proportion regarding activation of type I and type II fibres influenced the values of the EMG parameters. The quotient of the proportion of type I (slow) to type II (fast) fibres affected the amplitude of surface EMG [21] as well as the values of global parameters of the EMG power spectrum such as MPF and MF [16, 17, 18]. Gerdle, Eriksson and Brundin [26] even suggested that the EMG power spectrum might be a tool for evaluating the features of muscles regarding, e.g., the content of muscle fibres of a specific type.

The studies just presented confirm that the values of global parameters of the EMG power spectrum depend not only on muscle force but also on the type of the tested muscle, including the proportion of specific muscle fibres. This may have a significant influence on the assessment of muscle fatigue performed using an analysis of the EMG signal. These studies also suggest that the MF and MPF parameters reflect the influence of muscle force and muscle type on the EMG power spectrum. Nonetheless, this influence has not been fully analysed yet. The varied values of MF and MPF resulting from differences in the tested muscles and levels of muscle force are probably caused by differences in the shape of the EMG power spectrum. This means it is necessary to develop parameters which make it possible, in greater detail, to determine the influence of factors such as the type of the tested muscle and the level of muscle force on the spectral features of the surface EMG signal.

The aim of this study was to analyse the EMG power spectrum indicating differences in the frequency bands of the spectrum resulting from differences in muscle type and force level for the muscles of the right upper limb: the extensor digitorum (ED), the palmaris longus (PL) and the biceps brachii (BB).

2. METHODS

2.1. Subjects

A group of 12 men participated in the study. They were students at the University of Physical Education in Warsaw, Poland. They did not take part in competitive sports and did not suffer from musculoskeletal disorders. The means (*SD*) of their age, body weight and height were as follows: 22.3 years (1.4); 80.4 kg (7.1); 183.6 cm (5.1).

2.2. Protocol

The study was performed as two tests different in terms of the type of exerted force, which also means the types of muscles activated during measurements. Test A involved the ED and PL muscles of the right upper limb; test B activated the BB muscle of the same limb. During the study the length of the muscles was constant, so measurements were made in isometric conditions.

Both tests consisted of four measurements. Their sequence was very similar. First the EMG signal from the muscles activated during maximum force was measured. Then, the subject maintained a constant value of force at the level of 30, 15 and 5% of the maximum force. This took place at determined time intervals. The tests involved maintaining constant muscle force at a determined level with reference to the maximum force. Each test (i.e., tests 30, 15 and 5) lasted 5 min, and there were 20-min time intervals between beginnings of subsequent tests.

Test A was performed in a standing position with lowered upper limbs (Figure 1). The subject exerted force with his hand on a hand dynamometer which measured grip strength. A frame (Figure 2) was used to perform test B. The subjects stood with their upper limbs placed on the frame and the active limb bent at the elbow at 90°.

During tests the subjects were reminded to maintain the same body position. It was important to maintain muscle contraction in isometric conditions (constant length of tested muscles), which means load distribution in the muscles during the measurements was the same.

Figure 1. Body position while pressing with the upper limb in test A.

Figure 2. Body position while contracting the upper limb in test B.

2.3. Equipment

2.3.1. EMG measurement

The EMG signal was registered with Blue Sensor surface electrodes (Ambu, Denmark). They were placed along muscle fibres at a distance of 2 cm from one another. Before the test the skin was prepared according to a standard procedure applied in such tests (if necessary, it was shaved and cleaned with alcohol) in order to achieve resistance below 2 kΩ between the skin and the electrode following placement of electrodes.

An ME4000P (Mega Electronics, Finland) device was used for measurements and analysis as, when connected to a computer, it makes it possible to observe and register raw signals. The input impedance of the analyser was 10 GΩ, the signal-to-noise ratio was 75 dB. Signal sampling frequency was 2 kHz. The software generated a sheet with measurement results in the ASCII code.

2.3.2. Force measurement

A hand dynamometer which, together with an appropriate transducer, changes the applied force into an electric signal and then displays the course of the force on a chart, was used to measure force. CPS version 2.0 (Characteristic of Force Course) software was used to visualise and to measure force, too. The subject was able to follow on the monitor the real-time value of the plotted force and the level of required force. Consequently, he could maintain muscle force at a constant level.

2.3.3. Analysed parameters

The raw EMG signal in its digital form registered during the first 15 s of the measurement was analysed. The analysed parameters were calculated on the basis of the distribution of data into 0.5-s windows. For each window a mathematical analysis in the time (EMG signal amplitude) and frequency domains using Fast Fourier Transform (FFT) was performed (Figure 3). The values of parameters from 10 subsequent windows (windows No. 20–30) were calculated. That means the analysis included the mean values of parameters determined from file fragments between the 10th and the 15th second of the measurement. The EMG amplitude (RMSS), obtained in each measurement test (30, 15 and 5% MVC) was related to the EMG amplitude obtained during the measurement at maximum force.

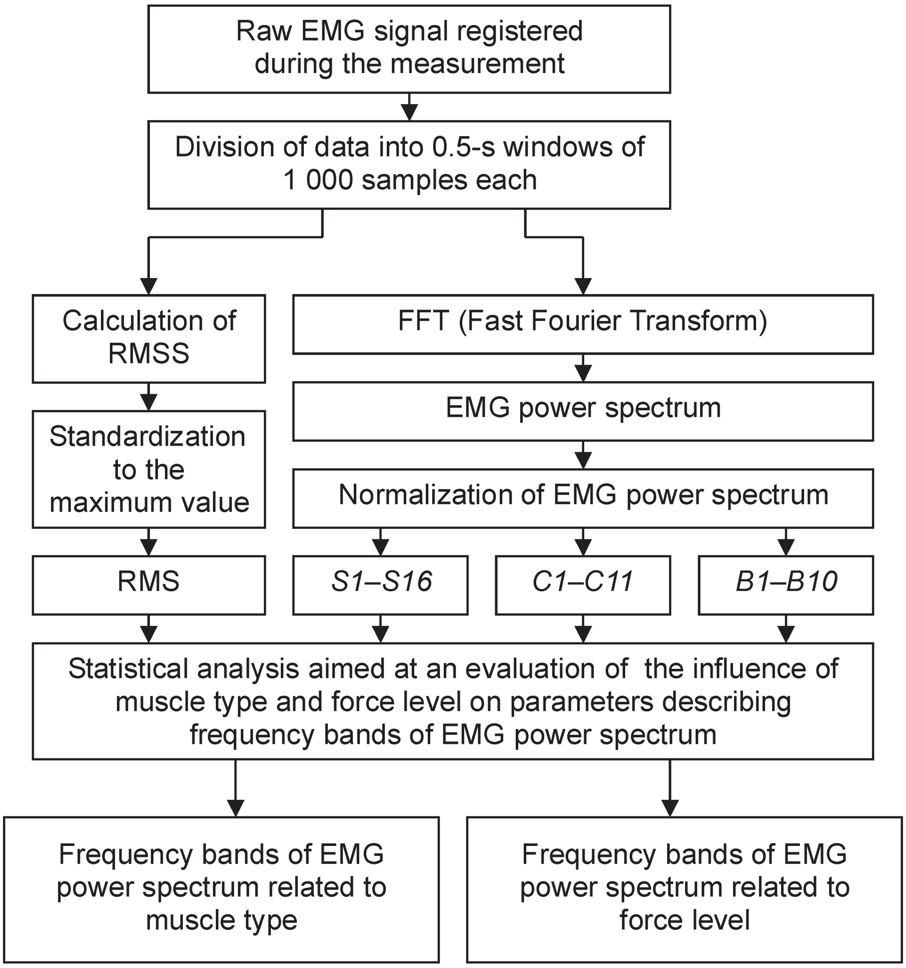

Figure 3. Subsequent steps of the analysis. *Notes.* EMG—electromyography, RMSS—EMG amplitude obtained in each measurement test (30, 15 and 5% MVC), RMS—EMG amplitude obtained in each measurement test (30, 15 and 5% MVC) related to EMG amplitude obtained during measurement at maximum force, *S1–S16, C1–C11, B1–B11*—parameters.

Because a force developed by a muscle affects the EMG power spectrum, the first step of the analysis, before determination of parameters describing individual frequency bands, was normalization of the power spectrum. Normalization consisted of dividing each spectrum sample by the area under the power spectrum curve. The next step was to determine parameters of the spectrum. The parameters were obtained as a result of dividing the EMG power spectrum into ranges determined by border frequencies using two different methods. In the first one border frequencies (limits) were accepted as constant numbers of individual samples (each sample corresponded to a specific frequency). In the second one border frequencies were determined automatically with software on the basis of on accepted assumptions.

When border frequencies were accepted as constant numbers of individual samples in the spectrum normalized to the area under the power spectrum curve (Figure 4), the following values were attributed: *R1* = 20 Hz, *R2* = 40 Hz, ... , *R15* = 300 Hz (the maximum frequency in the spectrum was 500 Hz). As a result of dividing the power spectrum into border frequencies 16 frequency bands were obtained, where the spectrum power was calculated (the *S1–S16* parameters) as the sum of all samples from a given band.

In the analysis that took into account variable limits, border frequencies were determined automatically when specific conditions were met (Figure 5). As a result of the adaptation of the spectrum its values were in the <0, 1> band. It was accepted that the border frequency *B1* was the frequency of the sample for which the

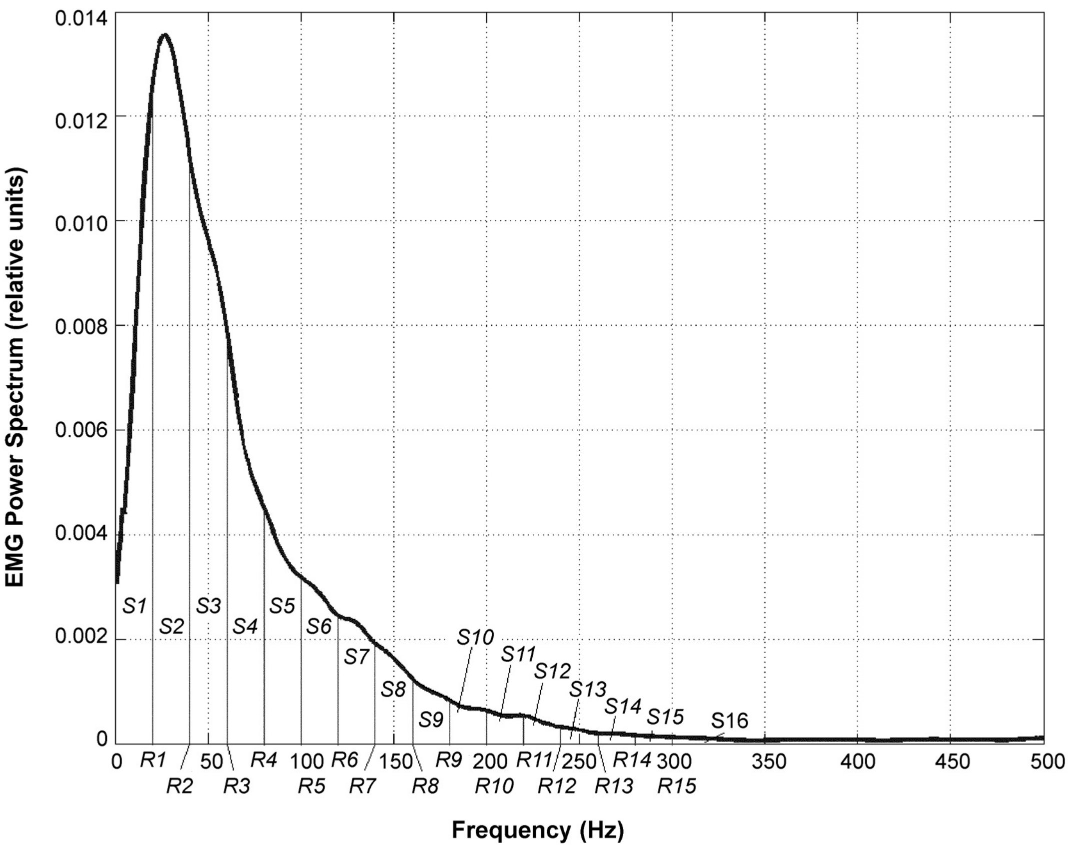

Figure 4. Division of the power spectrum into frequency compartments taking into account constant limits of frequency bands. *Notes*. EMG—electromyography, *S1–S16*—parameters, *R1–R15*—constant numbers.

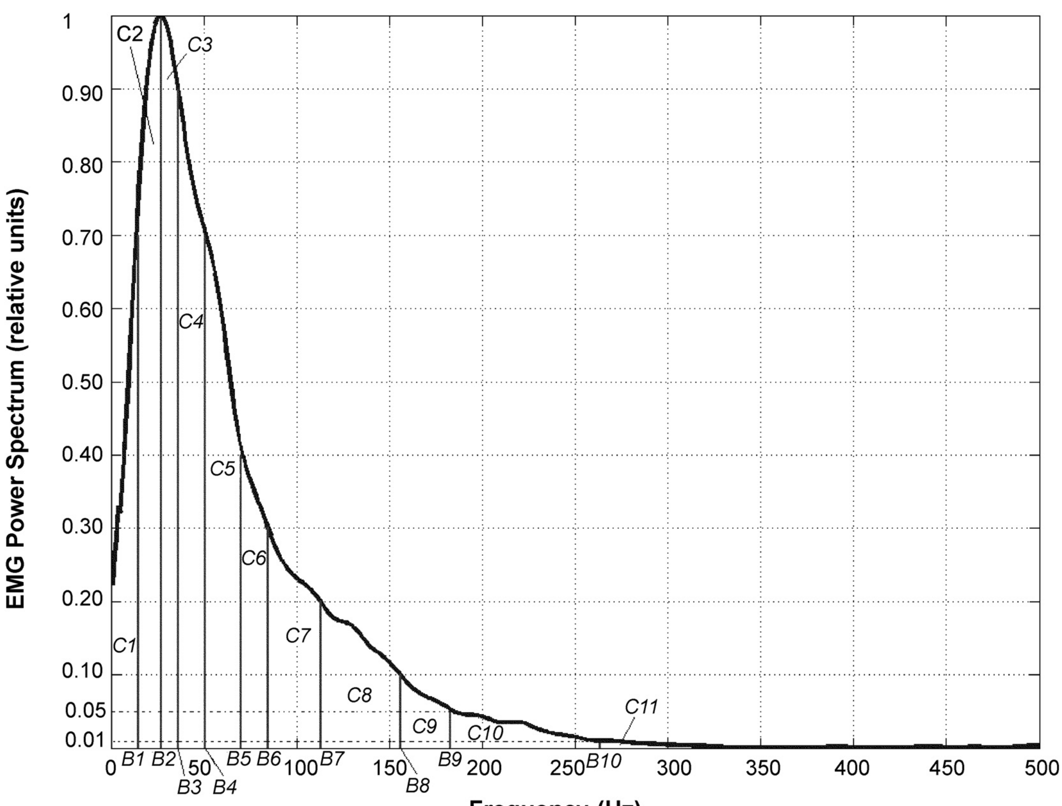

Figure 5. Division of the power spectrum into frequency compartments taking into account variable limits of frequency bands. *Notes*. EMG—electromyography, *C1–C11, B1–B10*—parameters.

power spectrum, at the increasing slope, reached 0.7. Table 1 shows the values of the other *B* parameters. As a result of calculations for such borders 11 parameters (*C1–C11*) describing separate frequency bands of the power spectrum were obtained.

TABLE 1. Method of Attributing the Border Frequencies (*B1–B10*) to Numerical Values on the *y* Axis of the Normalized Electromyographic (EMG) Power Spectrum in Individual Segments of the EMG Power Spectrum

Segment of EMG Power Spectrum	Value of Normalized EMG Power Spectrum	Border Frequency
/	0.70	*B1*
^	1.00	*B2*
\	0.90	*B3*
	0.70	*B4*
	0.40	*B5*
	0.30	*B6*
	0.20	*B7*
	0.10	*B8*
	0.05	*B9*
	0.01	*B10*

Notes. /—increasing slope, ^—maximum value, \—falling slope of the normalized EMG power spectrum.

Differences in *S1–S16*, *C1–C11* and *B1–B10* resulting from the type of the tested muscle and from the differences in the level of muscle force were analysed. Statistica version 6.0 was used for statistical analysis.

3. RESULTS

The aim of the study was to isolate frequency bands reflecting differences in muscle force and the type of the tested muscle from the EMG power spectrum. The EMG signal registered from the three muscles of the right upper limb (ED, PL and BB) was analysed.

Frequency bands of the power spectrum were isolated and described with the *S1–S16* and *C1–C11* parameters; border frequencies were labelled *B1–B10*. Those parameters were analysed. Their mean values and standard deviations were determined (Figures 6–8). Moreover, a statistical analysis of parameter differences was performed using the Kruskal–Wallis test (Tables 2–3). The analysis of *S1–S16*, *C1–C11* and *B1–B10* was performed in two directions:

- differences resulting from the type of muscle (ED, PL, BB) for three force levels (5, 15 and 30% MVC); and
- differences resulting from the level of force (5, 15 and 30% MVC) for each of the tested muscles (ED, PL, BB).

Figure 6 shows the mean values and standard deviations of *S1–S6* determined from the PL muscle at three force levels (5, 15 and 30% MVC). It indicates that in the case of PL the level of muscle force has a great impact on the value of the *S16* parameter, which results in a decrease of this parameter together with an increase in the force developed by the muscle. The differences are also visible in the low frequency bands in the EMG power spectrum (*S1–S4*).

Figure 7 shows the mean values and standard deviations of *C1–C11* determined on the basis of ED, PL and BB at the force level of 15% MVC. An analysis of the *C1–C11* frequency bands with relation to muscle type indicates that the values of *C1*, *C3*, *C5*, *C7* and *C10* differ between the BB muscle and the other two muscles. Most of the differences visible in Figure 7 are also true for the other force levels (5 and 30% MVC).

Figure 8 presents the mean values and standard deviations of *B1–B10* determined on the basis of ED, PL and BB at the force level of 30% MVC. There are visible differences between the BB muscle and the other muscles included in the analysis: the higher the frequency expressed by a parameter, the greater the differences are.

An analysis with the nonparametric Kruskal–Wallis test was performed in order to assess whether differences in the values of parameters were statistically significant. The analysis included all tested muscles (i.e., ED, PL and BB) and three force levels (5, 15 and 30% MVC). Table 2 shows the results of the statistical analysis of all parameters analysed with relation to differences resulting from muscle type.

The results presented in Table 2 indicate there were no statistically significant differences between the parameters obtained for the forearm muscles ED and PL (except for *C11* at

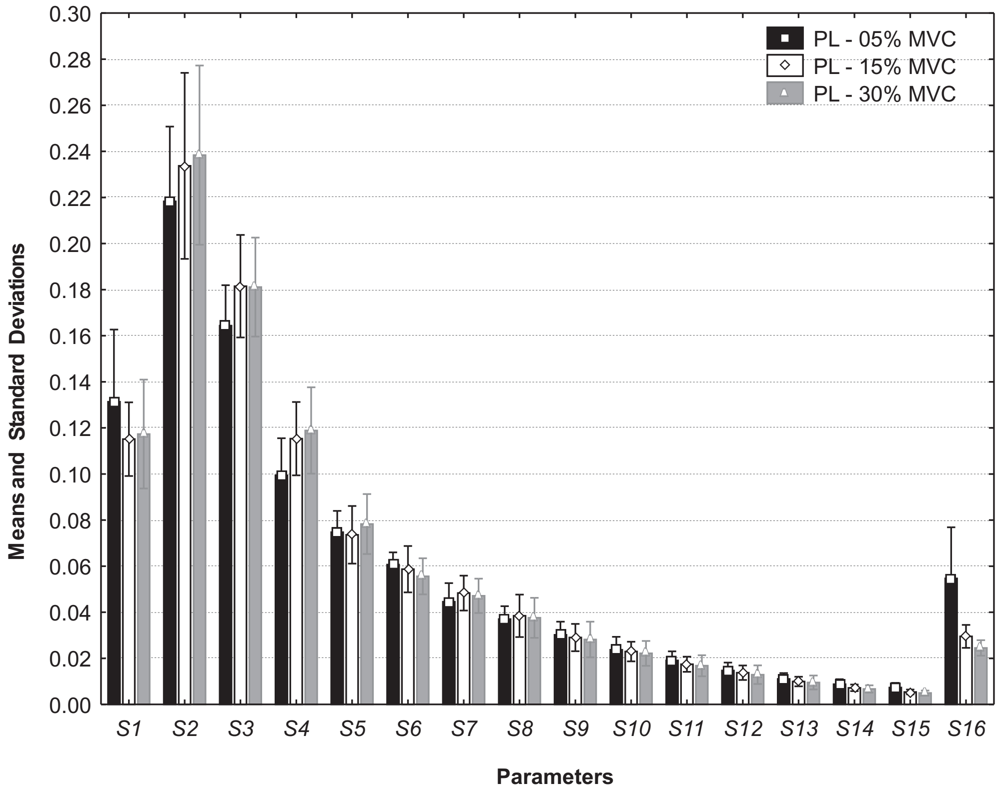

Figure 6. Mean values and standard deviations of the *S1–S16* parameters obtained as a result of tests for the palmaris longus (PL) muscle at three force levels (5, 15 and 30% MVC). *Notes.* MVC—maximum voluntary contraction.

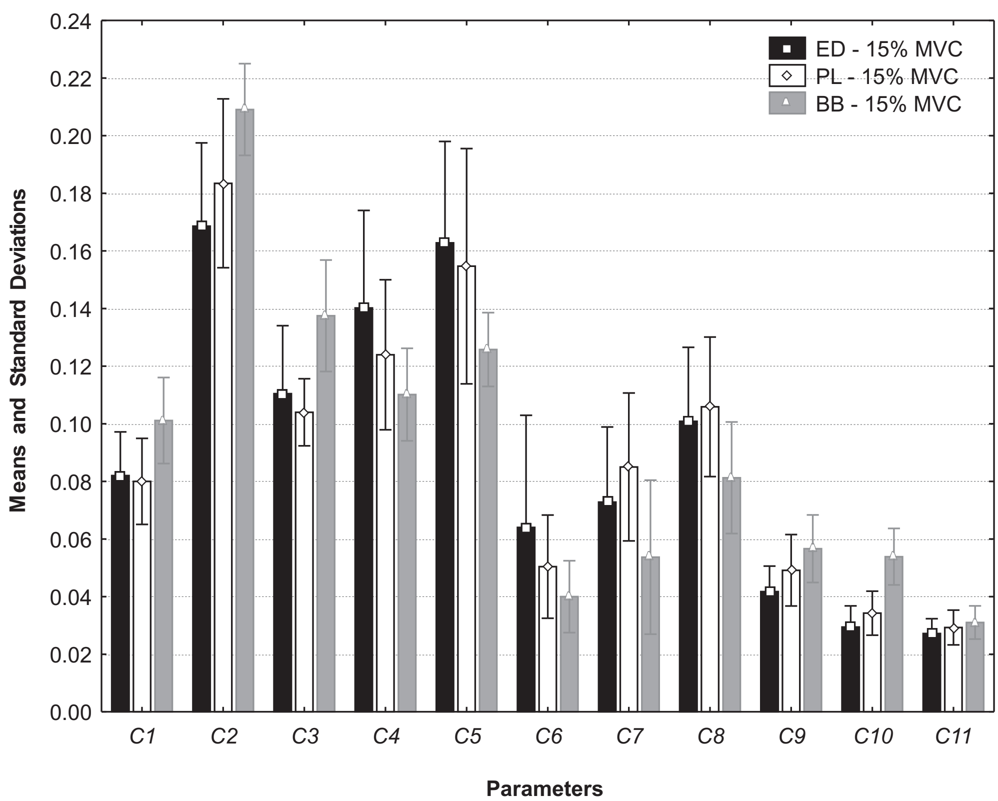

Figure 7. Mean values and standard deviations of the *C1–C11* parameters obtained as a result of tests for the extensor digitorum (ED), palmaris longus (PL) and biceps brachii (BB) muscles at the force level of 15% MVC. *Notes.* MVC—maximum voluntary contraction.

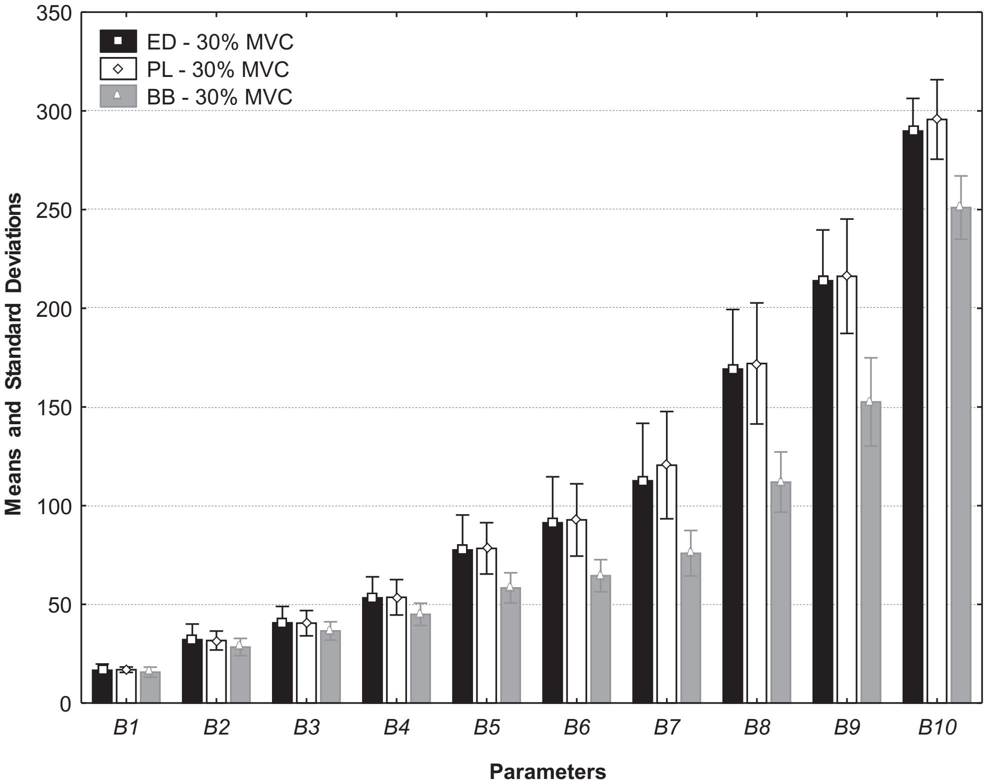

Figure 8. Mean values and standard deviations of the *B1–B10* parameters obtained as a result of tests for the extensor digitorum (ED), palmaris longus (PL) and biceps brachii (BB) muscles at the force level of 30% MVC). *Notes.* MVC—maximum voluntary contraction.

TABLE 2. Statistically Significant Differences According to the Kruskal–Wallis Test Resulting From Muscle Type for Three Force Levels: 5, 15 and 30% MVC

Parameter	Force Level (%MVC)	ED × PL	ED × BB	PL × BB
S	5	—	*S1, S2, S4–S16*	*S1, S2, S4–S16*
	15	—	*S1, S2, S4–S15*	*S1, S2, S4–S16*
	30	—	*S1, S2, S4–S15*	*S1, S2, S4–S16*
C	5	*C11*	*C2, C3, C7, C9, C10*	*C1–C3, C6, C7, C11*
	15	—	*C1–C3, C5, C9, C10*	*C1, C3, C5, C7, C10*
	30	—	*C1, C3, C5, C6, C10, C11*	*C1–C3, C5–C7, C10*
B	5	—	*B1–B10*	*B4–B10*
	15	—	*B3–B10*	*B4–B10*
	30	—	*B5–B10*	*B5–B10*

Notes. ED—extensor digitorum, PL—palmaris longus, BB—biceps brachii.

5% MVC). However, there were statistically significant differences between the parameters of the ED and BB as well as between the parameters of the PL and BB. In most cases, for parameters *S*, *C* and *B*, statistically significant differences were similar for all three force levels. This is especially evident for *S1*, *S2*, *S4–S15*, *B5–B10* and *C3*.

Table 3 shows the results of the analysis of the values of the obtained parameters with reference to the differences resulting from the level of force developed by muscles. There were no statistically significant differences resulting from force level for any *B* parameters (*B1–B10*). Moreover, there were no statistically significant differences between force levels of 15 and 30% MVC for any of the analysed parameters.

TABLE 3. Statistically Significant Differences According to the Kruskal–Wallis Test Resulting From Force Level (5, 15 and 30% MVC) for Three Muscles

Parameter	Muscle	5 × 15	5 × 30	15 × 30
S	ED	*S16*	*S13–S16*	—
	PL	*S15, S16*	*S4, S15, S16*	—
	BB	—	*S15, S16*	—
C	ED	*C11*	*C11*	—
	PL	*C11*	*C5, C11*	—
	BB	—	*C3, C11*	—
B	ED	—	—	—
	PL	—	—	—
	BB	—	—	—

Notes. ED—extensor digitorum, PL—palmaris longus, BB—biceps brachii.

However, statistically significant differences between the values of parameters obtained for the force level of 5% MVC and the values of parameters obtained for 30% MVC were observed in terms of parameters *S15*, *S16* and *C11* for all three tested muscles. In addition, there were differences between force levels of 5 and 30% MVC in the values of *S13* and *S14* for the ED, *S4* and *C5* for the PL and *C3* for the BB. There was a difference between force levels of 5 and 15% MVC in the values of *S16* and *C11* for the forearm muscle ED and in the values of *S15*, *S16* and *C11* for the forearm muscle PL.

4. DISCUSSION

In this study parameters *S1–S16*, *C1–C11* and *B1–B10* were used in a detailed analysis of the EMG power spectrum. It was assumed that those parameters would make it possible to assess in a detailed way the impact of muscle type and muscle force level on individual frequency bands of the EMG power spectrum. The mean values and standard deviations of those parameters were determined. In order to indicate which of the suggested parameters reflected force level and which reflected muscle type statistical analysis was performed to evaluate the differences in the values of parameters resulting not only from muscle type but also from force level.

This study included factors connected with the level of force and the type of the tested muscle; however, it should be noted that differences in the values of the parameters of the EMG power spectrum, when differences in muscle type were analysed, also resulted from differences in the way force was applied in tests A and B. The EMG signal from the ED and PL muscles was recorded during the same test (test A), whereas the BB was activated during another test (test B). These tests were analogical in terms of the sequence of performed measurements, the duration of measurements and of the intervals between them, and force strength; nonetheless, the upper limbs were placed differently.

4.1. Influence of Force Level on Parameters of Power Spectrum

There were statistically significant differences in the values of *S16* in the frequency compartment of 300–500 Hz between the values of this parameter obtained for muscle load at the force level of 5 and 30% MVC, and between 5 and 15% MVC for the ED and PL. A similar relationship for the *S16* parameter was observed for the BB when force at 5 and 30% MVC was compared. In all tested muscles the value of this parameter decreased together with an increase in muscle force. A similar tendency could be seen for the *C11* parameter which also defines the band of high frequencies (~270–500 Hz) in the EMG power spectrum. These relationships are consistent with Bilodeau, Cincera, Gervais, et al.'s [27] conclusions, who reported that for the triceps brachii muscle there was a decrease in the power spectrum at high frequencies together with an increase in force. This suggests that the band of the EMG power spectrum of over 300 Hz is sensitive to the level of muscle force. The analysis also indicated there were no significant differences in the parameters between the force level of 15 and 30% MVC, whereas there were statistically significant differences between the level of 5% MVC and the remaining force levels. According to a hypothesis about the recruitment of muscle fibres at the force level of 5% MVC only type I fibres are probably recruited, and together with the increase in force type II fibres are recruited. Consequently, the proportions of muscle fibres involved in force generation are different for the levels of 5 and 15% MVC, and they are similar at the levels of 15 and 30% MVC. This may suggest that the values of *S15*, *S16* and *C11* (270–500 Hz) might be affected by the proportion of the recruited type I and type II fibres.

Moreover, the effect of the muscle force level on *S4* (band 60–80 Hz) and *C5* (band ~50–70 Hz) in the case of the PL and *C3* (band ~30–40 Hz) in the BB is also visible. In the case of *S4* and *C5* these relationships coincide with the results of Cioni, Giannini, Paradiso, et al. [28]. These authors report that an increase in the band for the frequency 45–162.5 Hz together with an increase in muscle force was observed in the tibialis anterior muscle. This may indicate that muscle force affects bands in the low-frequency compartment; however, this effect differs depending on muscle type, namely the percentage content of type I and II muscle fibres, and the thickness of the subcutaneous layer. In the PL the parameters that increase their values with an increase in the force level are the parameters corresponding to the frequency bands of 50–80 Hz, whereas for the BB these are the frequency bands of 30–40 Hz. Changes in these frequency bands due to the changes in the force level might be connected with recruitment of type I and II muscle fibres as well as with the thickness of the subcutaneous layer. Moreover, as a result of an analysis of the mean values of *S2* (the 20–40-Hz band) an increase in the EMG power spectrum was observed in this range together with an increase in muscle force in the ED and PL, which confirms Dolan et al.'s [14] conclusions that there was an increase in the EMG power spectrum in the erector spinae muscle in the frequency range of 5–30 Hz due to an increase in muscle force. This suggests that in the forearm muscles ED and PL changes in the force level and the related changes in the proportion of recruited muscle fibres may also be visible in the 20–40-Hz frequency band.

Elfving, Liljequist, Mattsson, et al. [29] suggested that an increase in force caused a shift in the EMG power spectrum towards low frequencies. However, an analysis of the values of border frequencies obtained as a result of these studies (*B1–B10*) leads to a conclusion that they do not indicate any statistically significant differences regarding the muscle force level in any of the tested muscles. This indicates that although there is an increase in the power spectrum, it is difficult to talk about its shift due to an increase in muscle force.

4.2. Influence of Muscle Type on Parameters of Power Spectrum

The analysis demonstrated there were no statistically significant differences in the values of the analysed parameters when the ED muscle was compared to the PL muscle. It may be assumed that this was due to the fact that both muscles represent the same muscle group (i.e., the forearm muscles). However, the differences between the ED and BB were similar to those between the PL and BB. In both cases frequency bands *S1*, *S2* and *S4–S15* at all three force levels showed statistically significant differences. That is why it should be assumed that the power spectrum in the frequency ranges of up to 40 Hz and 60–300 Hz indicates muscle type.

An analysis of the differences in the values of the parameters resulting from muscle type should take into account the percentage content of type I and II fibres as well as the impact of the layer between the tested muscle and the electrodes [30]. The level of the subcutaneous layer may be to some extent responsible for existing differences between the BB and the ED and PL. Because both the ED and PL are forearm muscles, it can be assumed that they are separated from the epidermis with a subcutaneous layer of similar thickness. Nonetheless, the distribution of the subcutaneous layer above the BB, which is an arm muscle, may be different in relation to the distribution of the subcutaneous layer above the ED and PL muscles.

Differences in the values of *S1–S16* when comparing the ED and BB muscles were similar to those in the values of the same parameters when comparing the PL and the BB. More diversified results were obtained when a statistical analysis on *C1–C11* was performed. A statistically significant difference between the ED and PL muscles was noted only for *C11* at 5% MVC. The remaining results indicated differences between the arm muscle BB and two forearm muscles ED and PL, which suggests that those differences may be connected with muscle type. The *C3* parameter (the band between the maximum value and 0.9 of the falling slope of the normalized power spectrum, which corresponds to 30–40 Hz) at all force levels indicated differences between the arm muscle BB and the two forearm muscles ED and PL. This suggests that the band in the frequency compartment of 30–40 Hz depends on muscle type.

Differences resulting from muscle type regarding the values of some parameters in *C1–C11* are different for different force levels. The content of the subcutaneous layer may have an impact on the values of these parameters for which differences are seen only at higher force levels (*C1*, *C5*, *C6*, *C11*). This may be due to the fact that at lower force levels differences in the values of parameters may be imperceptible due to an existing suppression of the EMG signal in the subcutaneous layer, whereas at higher force levels, where the EMG signal is stronger, these differences might become visible. Such a state may significantly disturb the results of studies performed for lower muscle force levels, which indicates that it is necessary to perform subsequent studies aimed at an analysis of the impact of the subcutaneous layer on the parameters of the EMG signal.

Border frequencies *B5–B10* may also indicate differences resulting from muscle type, irrespective of force level. Differences in the values of those parameters between the BB and the forearm muscles are visible. For the BB those parameters have lower values than for the ED and PL (e.g., the mean value of the *B5* parameter for the ED and PL is about 75 Hz and for the BB it is 60 Hz; whereas, the mean value of the *B10* parameter for the ED and PL is 300 Hz and for the BB it is 260 Hz). This suggests that the higher the frequency defined by a given parameter, the larger the differences between the BB and the remaining muscles are, which implicates that there is differentiation in the shape of the power spectrum between muscles of different types, and that differences resulting from muscle type are more visible in the values of the parameters representing higher border frequencies.

4.3. Limitations of the Study

The main limitation of this work, which might have affected the results of the analysis, was the fact that none of the subjects had their muscle fibre content and subcutaneous layer thickness determined. The analysis was based on the characteristics of muscle types from the literature which should be treated only as approximate data. The evaluation of direct relationships between the proportion of muscle fibres and the thickness of the subcutaneous layer for all subjects would allow us to draw definite conclusions regarding the influence of muscle fibre proportions on the characteristic of the EMG signal at different force levels.

5. SUMMARY AND CONCLUSION

The aim of the study was to analyse the EMG power spectrum indicating differences in the frequency bands resulting from differences in muscle type and force level for the muscles of the right upper limb (ED, PL and BB).

The relationships obtained as a result of the statistical analysis prove the parameters of the power spectrum indicate changes resulting from force level and muscle type. Thus the EMG power spectrum may be a tool used for evaluating muscles in terms of muscle type or muscle force level. It is also possible to draw the following conclusions:

- the band of the EMG power spectrum above the frequency of 300 Hz is sensitive to the force level, which may be connected with the proportion of recruited muscle fibres;
- frequency bands contained in the range of 30–80 Hz depend on muscle force; however, this relationship is different for different muscles;
- differences between the frequencies separating frequency bands of the BB and the forearm muscles (ED and PL) are visible, with differences resulting from muscle type more obvious in the values of the parameters representing higher border frequencies (over 60 Hz);
- the power spectrum in the frequency range of up to 40 Hz and 60–300 Hz indicates muscle type.

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