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Wavelet analysis of the EMG signal to assess muscle fatigue in the lower extremities during symmetric movement on a rowing ergometer

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Purpose: The aim of this publication was to propose a method to determine changes in fatigue in selected muscle groups of the lower extremity during dynamic and cyclical motion performed on a rowing ergometer. The study aimed to use the discrete wavelet transform (DWT) to analyze electromyographic signals (EMG) recorded during diagnostic assessment of muscle and peripheral nerve electrical activity (electroneurography) using an electromyography device (EMG). *Methods*: The analysis involved implementing calculations such as mean frequency (MNF) and median frequency (MDF) using the reconstructed EMG signal through DWT. The study examined the efficacy of DWT analysis in assessing muscle fatigue after physical exertion. *Results*: The study obtained a negative regression coefficient for DWT analysis in all muscles except for the right gastrocnemius (GAS). The results suggest that DWT analysis can be an effective tool for evaluating muscle fatigue after physical exertion. *Conclusions*: The use of DWT in the analysis of EMG signals during rowing ergometer exercises has shown promising results in assessing muscle fatigue. However, additional investigations are necessary to confirm and expand these findings. This publication addresses the literature gap on the determination of muscle fatigue considering motion analysis on a rowing ergometer using the discrete wavelet transform. Previous studies have extensively compared and analyzed methods such as the Fourier transform (FFT), short-time Fourier transform (STFT), and wavelet transform (WT) for muscle fatigue analysis. However, no previous work has specifically examined the assessment of muscle fatigue by incorporating DWT analysis with motion analysis on a rowing ergometer.

Key words: *DWT, fatigue, EMG, MNF, MDF, rowing ergometer*

1. Introduction

Muscle fatigue is a physiological phenomenon that periodically reduces the potential of muscles to generate force, accompanying intense, repetitive contractions of myocytes. Biochemical changes, insufficient oxygen supply and microdamage to the contractile apparatus, as well as changes in the excitability of the nervous system are important mechanisms underlying this complex and incompletely understood process [1], [38]. Several methods for determining fatigue are described in the literature: determining the onset of muscle fatigue by measuring the time it takes a person to perform a specific task, determining the concentration of lactate in the muscle based on blood samples taken at specific intervals during the performance of a specific exercise, and finally, continuously monitoring local muscle fatigue during the performance of a specific task by measuring the myoelectric activity of individual muscles by surface electromyography (sEMG) [13], [22]. Although fatigue is most often a consequence of physical activity resulting from exercise, most of the studies characterized in the literature have

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been conducted to quantify muscle fatigue resulting from isometric, i.e., constant (static) muscle contractions [10], [14]. However, it is still advisable to conduct further research and mathematical analysis to process the signals received in terms of developing approaches to determine fatigue during movement [41].

Several works describe methods of processing the EMG signal for analysis in static and dynamic motion, and these methods include the wavelet transform (WT) [2], [15], [33], [41], the Fourier transform (FFT) [9], [16], [34] and the short-time Fourier transform (STFT) [24], [33]. It is worth mentioning that the wavelet transform can take two forms: continuous form (CWT) and discrete form (DWT). All of these methods have also been repeatedly compared with each other [3], [5], [6], [9] and analyzed for the effectiveness of application in determining muscle fatigue [7], [33]. The EMG signal is a non-stationary signal [35], which means that it has very complex characteristics in the time and frequency domain. For non-stationary signal analysis, the use of FFTs can be inefficient [43]. The best methods in terms of EMG signal analysis are STFT and WT [8]. In the case of STFT, the choice of window width determines whether a better temporal resolution or frequency resolution is obtained [8], [36]. The use of wavelet analysis is characterized by better accuracy, resolution, and precision than STFT under static and dynamic motion conditions [18], [36]. Several works can be cited describing the use of FFT in the aspect of muscle fatigue [3], [8], [9]. One paper compares the use of FFT and WF in EMG signal analysis and shows that the results obtained are comparable for both methods in the case of static and dynamic exercises with moderate speeds [3]. On the other hand, the work [4] seems to confirm the thesis that the WT technique, which is better at analyzing non-stationary signals, is more suitable for dynamic testing.

In the literature, there are studies using DWT or CWT to analyse the EMG signal in terms of muscle fatigue. In the present study, DWT was used to analyse the EMG signal, which performs better than CWT [3], [26]. The calculation of wavelet coefficients in CWT analysis is difficult and time-consuming due to the constant changes in the signal parameters [6], and there is redundancy of information, which means that the same information about the signal is repeated at different scales. DWT makes it possible to reduce the redundancy phenomenon [43]. Among the works on muscle fatigue and wavelet analysis, there is a division between the use of the CWT [4], [23], [42] and the DWT [7], [21] to analyse EMG signals. Some authors of articles argue the benefits of using DWT as a more effective technique than CWT, while others do not justify their choice.

A compiled study [32] uses the Discrete Wavelet Packet Transform (DWPT), which is an extension of DWT in EMG signal analysis which was used to develop an algorithm to detect muscle fatigue also during rehabilitation exercises. Another study [23] shows that a method to determine, among other things, local muscle fatigue based on slope analysis of a simple regression of the mean frequency of the EMG signal using the CWT during isometric contraction has been clinically validated. A paper [8] aimed to establish CWT analysis as a suitable method for the quantitative evaluation of neck and shoulder muscle fatigue under repetitive conditions. However, in the aspect of assessing the change in muscle fatigue while rowing on water or rowing with a rowing ergometer using different signal processing methods, not many papers were found. One of the few studies [30] characterized improved methods for detecting muscle fatigue in experiments with dynamic rowing test designs on-water. This study is relevant to the present work, since the movement considered is that of a rowing ergometer. In this work, four different algorithms (FFT, STFT, CWT, and instantaneous frequency (IF)) were analysed to study muscle fatigue during water rowing training. The researchers hypothesize that the CWT may be more robust to changes in the time window. One popular application of the wavelet transform, in addition to the aspect of analyzing muscle fatigue processes, is to try to solve the problem of the EMG signal with the classification process [8], [23], [30], [32]. A very common use of WT in this aspect is to determine the wavelet coefficients of an EMG signal using a DWT, and then use them as parameters for a selected (in this case: support vector machine (SVM)) machine learning model [30]. WT is also an important tool in the process of de-noising signal [36], [39]. This process involves performing a decomposition of EMG signals to determine wavelet coefficients, estimating the noise level, selecting an appropriate threshold, and performing a threshold analysis on the wavelet coefficients to derive new coefficients. Finally, the EMG signal is reconstructed using the new modified wavelet coefficients.

However, no description of the computational method for a dynamic movement, such as exercise on a rowing ergometer, has been found in the literature in terms of determining muscle fatigue using DWT. Therefore, the main objective of this publication is to evaluate the change in fatigue of selected muscle groups of the lower limb in a dynamic cyclic movement performed on a rowing ergometer. The goal was decided to be realized by means of determined mean frequency (MNF) and median frequency (MDF) using the decomposition realized by the discrete wavelet transform of the EMG signal on the basis of data within one case. The results presented from tests performed with an athlete in the exercise section of the ergometer were intended to show the fatigue aspect of selected muscles: gastrocnemius muscle (GAS), rectus femoris muscle (RF), and biceps femoris muscle (BF) during symmetrical movement on a rowing ergometer performed with a specific measurement protocol.

Based on the literature review, the following research algorithm was proposed (Fig. 1), which is to be discussed in the following sections.

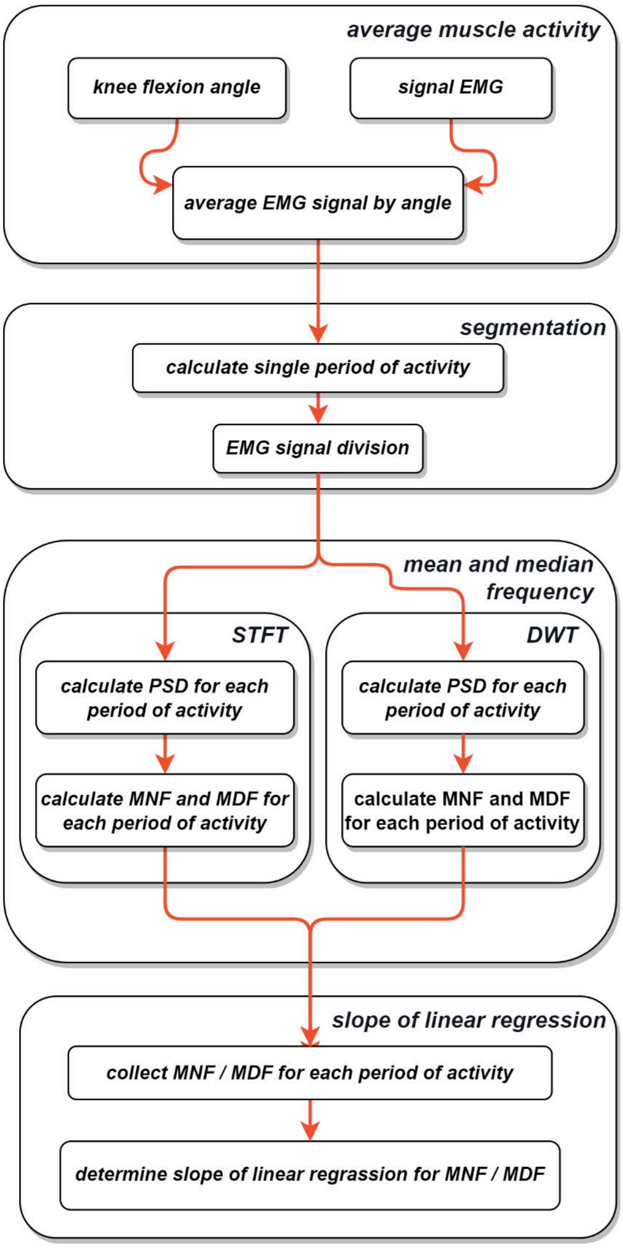

Fig. 1. Algorithm of the proposed method

2. Materials and methods

2.1. Characteristics of the research object

A participant (age: 23, BMI: 26.32, height: 175), who is a member of rowing section the ergometer, was selected to perform the evaluation of limb muscle fatigue in order to develop a methodological approach to study the entire sports section on this basis.

The participant performed the exercise on a CONCEPT II rowing ergometer cyclically (30 times/min) until reaching maximum fatigue according to the Borg scale [39], while being monitored for the study simultaneously. The participant was healthy and had no medical history that could exclude him from the study. The participant did not report any musculoskeletal or neuromusculoskeletal injuries or surgeries (for example, muscle or ligament rupture or bone fracture in the last 12 months). The most recent injury in the past was a shoulder and jaw tendon injury and occurred in 2016 (six years before the current experimental study was conducted). Furthermore, the study participant regularly attends the gym and martial arts and reported that this can result in a rotated pelvis and a strained biceps thigh muscle.

Measurement was carried out with the change of rowing ergometer resistance in cycles of 30 strokes/minute with the rule of setting change on the ergometer: 1 minute – 4 rowing ergometer resistance, 2 minute – 3 rowing ergometer resistance, 3 minute – 2 rowing ergometer resistance, 4 minute – 1 rowing ergometer resistance, movement to the maximum fatigue level (subjective). The objective of adjusting the timing and changing the rowing ergometer resistance was twofold: first, to increase the workload on the legs involved in the movement, which would speed up the onset of muscle fatigue; and second, to improve the accuracy of measuring changes in the limb's position during the movement. This improvement in accuracy was achieved through a simultaneous analysis of movement using markers, a camera, and Myo Video software. The muscle groups: the triceps calf muscle, the quadriceps thigh muscle (including separately: medial vastus, lateral vastus, rectus muscle), the biceps muscle were properly prepared for equipment placement, and then a 32-channel Ultium EMG system (Noraxon, DTS, Desktop Direct Transmission System, Scottsdale, Arizona, USA) with a sampling rate of 4000 Hz was used for the test. Dedicated MyoResearch XP Master Edition software was used for

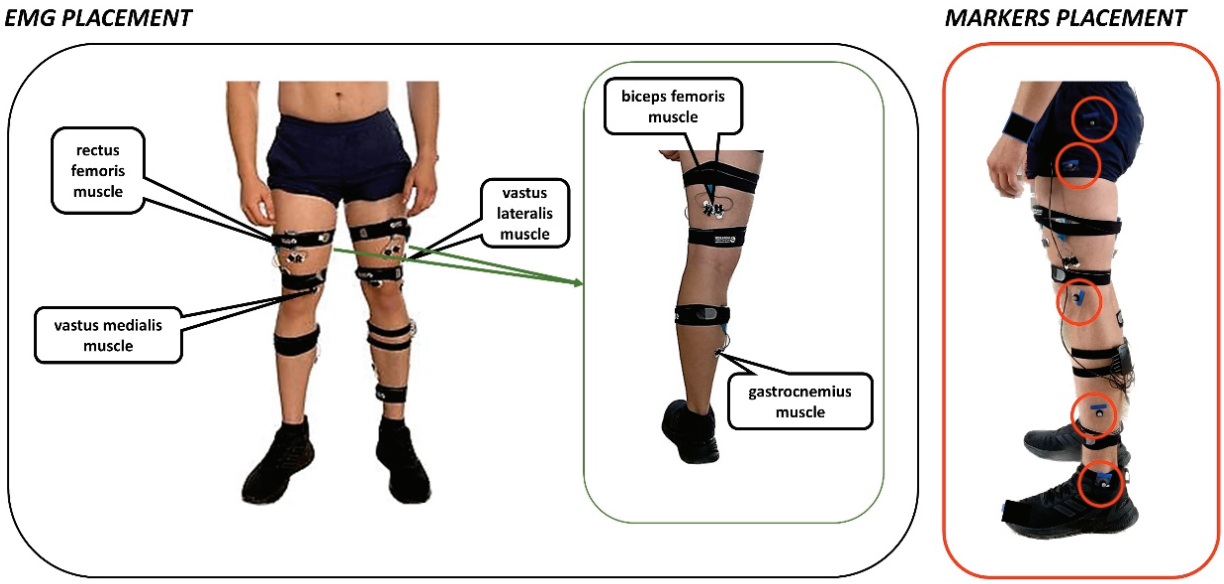

Fig. 2. Placement of EMG electrodes on the muscles: rectus femoris, vastus lateralis, vastus medialis, biceps femoris, and gastrocnemius, and placement of markers

reading and data acquisition [20]. Surface electrodes (Ag/AgCl) were attached with an inter-electrode spacing of 2 cm according to the SENIAM standard [17]. Additionally, changes in limb position were recorded during measurement thanks to Myo Video software, part of the Noraxon system. For this purpose, markers were mounted on the participant. The equipment mounted on the corresponding muscles is presented in Fig. 2.

The measurement procedure was tested several times on the participant. During the tests, there were a number of confounding factors, such as fatigue, mood, sweating (and thus electrode detachment), synchronization of a large number of sensors, measurement duration, determination of marker locations, and others. Therefore, several of the results obtained were considered unrepresentative. This paper presents the results of repetitions of the measurement procedure to verify the proposed calculation methodology. The choice of three repetitions (trials) was based on the need for sufficient data points to ensure the tendency and to assess the consistency of the results obtained.

The participant was familiar with the measurement procedure and the possible risks of the test and confirmed his willingness to participate by giving his written consent. The study is carried out according to the decision of the Ethics Committee for Research with Human Participation of SGGW number 19/22.

2.2. Research method

The diagram developed for the purpose of this article was divided into 4 groups of steps leading to an assessment of fatigue in selected muscles (Fig. 1). The first group called "average muscle activity" contains steps to determine the average muscle activity as a function of the subject's position based on measurements of cyclic movement and EMG activity. The second group called "segmentation" leads to obtaining the division of the EMG signal in cyclic movement into individual movement cycles. In the third group, for each consecutively determined movement cycle, the power spectral density is determined on DWT and STFT, and then the frequency parameters of the EMG signal are calculated, i.e., MNF and MDF. For the series of MDF/MNF values thus created, a linear regression is determined, where the key parameter is the slope of the regression straight line (fourth step), which the result of the present calculations.

2.2.1. Average muscle activity

The detection and classification of activities were performed using a method based on the literature-documented characterization of activation cases, which quantitatively determined the onset and cessation of muscle activation, as well as the duration of muscle activity [37].

The surface EMG signals recorded during periodic movements were processed to detect the onset and cessation of muscle activity, a way to reveal information on muscle coordination during periodic movement [31]. In view of the set protocol, which concerned the execution of symmetric movements, the segmentation method described in the article cited [31] was considered. The process of identifying individual MUAPs

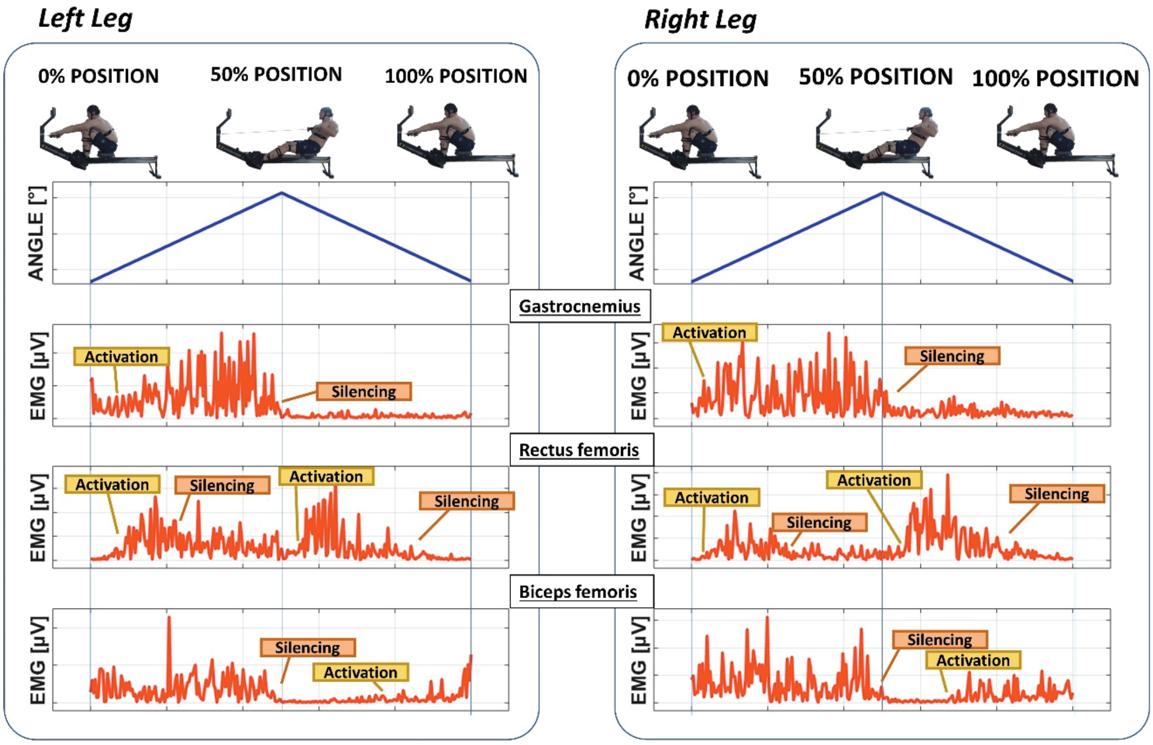

Fig. 3. Moments of activation and deactivation of individual muscle activity depending on the position on the ergometer (drive-recovery)

(motor unit action potentials) in an EMG signal is called EMG signal segmentation [19]. However, in the case of the paper, it is the entire activity in a given movement (compound muscle action potential (CMAP)) that the MUAPs comprise that is relevant. Segmentation was based on isolating each activity relative to each cycle of movement on the rowing ergometer performed to maximum fatigue (cycle = 2.0 s – the pull phase (from the start) and the return phase (to the end of the movement)). In Figure 3, the moments of activation and quieting of the activity of each muscle are marked in relation to the movement (drive-recovery) recorded with the camera and analyzed with Myo Video software.

Table 1. Average, relative duration of activity in cycles lasting around 2.0 seconds

Muscle	Time [%]	
	Left lower limb (L)	Right lower limb (R)
Gastrocnemius muscle (GAS)	45.0	45
Rectus femoris muscle (RF)	80.0	80
Biceps femoris muscle (BF)	35.0	35

On the basis of segmentation, the average duration of muscle activity was determined (Table 1). The time is relative and presented in relation to the duration of the rowing cycle. The muscle groups that were analyzed were GAS, RF and BF. The medial and lateral muscles were omitted due to an excessive measurement error resulting from the movement of the limb on the rowing ergometer (electrodes detach when the limb is flexed).

For further analysis (i.e., DWT and STFT), the sEMG signal was selected during all activities (cycle (100%) that lasts about 2.0 seconds) in each minute of movement (30 cycles/min). The time windows corresponding to these efforts were obtained based on the method described above for EMG activation. This selection was based on the analysis of the cycle time. The participant used an average duration of 2.0 s to perform one movement in the pull and return phases on the rowing ergometer.

Based on the analysis of each activity cycle, the time width of a single segment was determined to be 2 ± 0.082 seconds.

2.2.2. Segmentation of EMG signal

As described in Section 2.2.1, the segmentation of the EMG signal was made possible by monitoring the positions of the lower limbs during the EMG signal measurement. The variation of the function describing changes in the angle of the lower limb over time, from the minimum value, through the maximum value, and

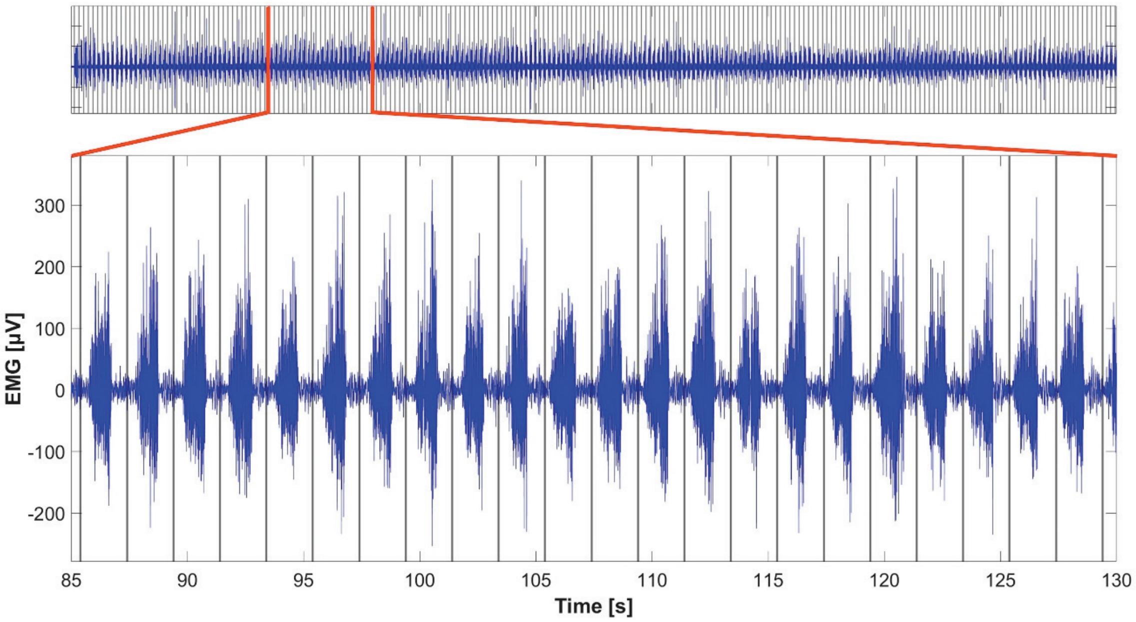

Fig. 4. Segmentation of EMG signal based on muscle activity cycle

back to the minimum value represented one cycle performed by the participant, lasting 2 seconds. Based on this, the EMG signal was divided into 2-second time windows, with limits that coincided with the attainment of the minimal function value. Thanks to the participant's good exercise technique, each time window had a duration of approximately 2 seconds (2 ± 0.082 s). For each 2-second time window, a separate analysis of DWT (Discrete Wavelet Transform) and STFT (Short-Time Fourier Transform) was conducted. The segmentation of a selected portion of the EMG signal is shown in Fig. 4.

2.2.3. Mean and median frequency of EMG signal

MDF and MNF are frequency parameters useful for analyzing EMG signals. The MDF and MNF values are commonly used in EMG analysis for muscle fatigue [4], [21]. Many works focus on the relationship of changes in frequency parameters such as MNF and MDF to muscle fatigue. Many studies show the effectiveness of using MNF and MDF in identifying muscle fatigue based on the analysis of EMG signals under static and dynamic movement [27]. MNF and MDF are described by formulas:

$$\mathrm{MNF} = \frac{\Sigma_{i=1}^{M} f_i P_i}{\Sigma_{i=1}^{M} P_i}, \tag{1}$$

$$\mathrm{MDF} = \frac{1}{2}\sum_{i=1}^{M} P_i, \tag{2}$$

where:

P_i – i-th component of the power spectral density,

f_i – i-th frequency of the power spectral density,

M – the highest harmonic that is taken into account (below the Nyquist frequency).

In the present study, wavelet coefficients determined by DWT decomposition as well as by subjecting the EMG signal to spectral analysis using STFT were used to determine MDF and MNF. The wavelet transform is a spectral estimation technique that allows, in its basic version, to represent a signal as a linear combination of a specific set of functions obtained by transformations such as scaling and translation of a function called the mother wavelet. The process of decomposing the signal leads to a set of wavelet coefficients, which is the set of weights in the linear combination of wavelet functions that constitutes the reconstructed signal [29].

The continuous wavelet transform (CWT) is characterized by continuous wavelets in the time domain. It is described by the formula [21]:

$$W(s,\tau) = \frac{1}{\sqrt{s}}\int x(t)\psi\left(\frac{t-\tau}{s}\right)dt, \tag{3}$$

where:

s – scaling factor (usually defined as $s = 2^{\frac{1}{v}}$ where $v \in \mathbb{Z} \cap v > 1$, [25],

τ – translation factor,

$x(t)$ – signal in time domain t,

ψ – mother wavelet.

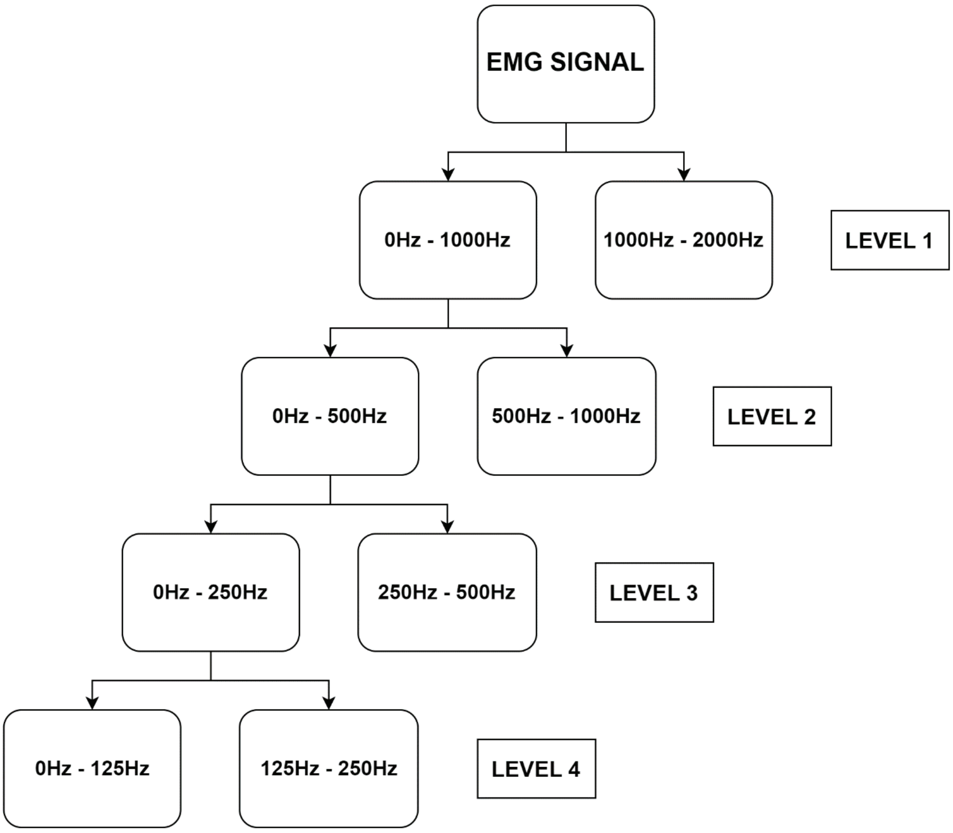

Fig. 5. Four-level decomposition of the EMG signal using the DWT algorithm

For the discrete wavelet transform (DWT), the scaling factor s is always discretized to integer powers of 2, and the translation factor is linearly related to it [21], according to the formula:

$$\{(s_j, \tau_k)\} = \{(2^j, k2^j): j \in \mathbb{Z}^+, \mathrm{k} \in \mathbb{Z}_0^+\}, \tag{4}$$

where:

s_j – scale factor,

τ_k – translation factor,

j – positive integer,

k – non-negative integer.

Wavelet decomposition in DWT can be implemented using a filter bank [6] that allows performing a series of operations on low-pass and high-pass filters and down-sampling [40], resulting in detailed coefficients and approximation coefficients [2], [7], [21], [28]. Due to the presence of down-sampling operations, the wavelet representation is approximately the same size as the original [2]. Based on the level of decomposition of L equal to $\log_2 s_j$ the B frequency bandwidth is determined [8] by the formula:

$$B = \frac{F_S}{2^{L+1}}, \tag{5}$$

where F_S is the sampling frequency.

The authors of the study prove that the most dynamic changes in the EMG power spectrum are symbolized by the Daubechies4 wavelet [7], so in this study it was decided to use the db4 wavelet family. The result of the decomposition consists of detail coefficients and approximation coefficients [28]. The four-level decomposition with the DWT algorithm used in this publication is shown in Fig. 5.

The resulting frequency bands for the decomposition used are summarized in Table 2.

Table 2. Frequency bands for four-level decomposition

Level	1	2	3	4
Frequency band [Hz]	1000–2000	500–1000	250–500	125–250

Matlab software (R2022b) was used to perform DWT analysis. The decomposed signal can be reconstructed through synthesis filters. The reconstructed signal (S) can be expressed as the following vector:

$$S = (A4; D4; D3; D2; D1), \tag{6}$$

where A4 represents the approximation coefficients at the fourth reconstruction level, and D1–D4 represent the detail coefficients at reconstruction levels 1 to 4, respectively (Fig. 6).

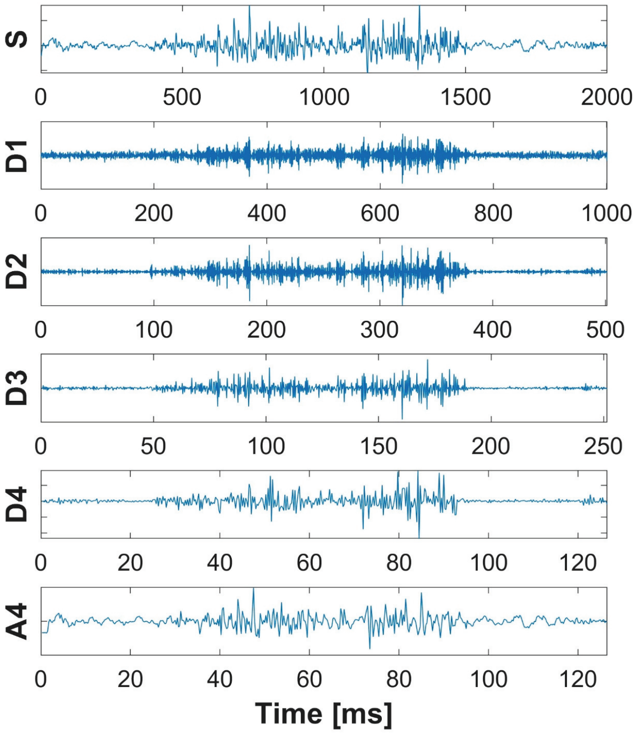

Fig. 6. Approximate and detailed coefficients of an EMG segment

In the next step, the MDF and MNF values were determined for EMG signals from three trials involving three selected muscles of the participant. The estimation was carried out using two different estimators: DWT and STFT analysis. In the case of estimation using DWT, a determined wavelet coefficients were used (each level of decomposition was considered), which allowed for accurate analysis of the signal in the frequency domain. However, for the STFT analysis, a Hanning window of 1024 samples and a window offset of 512 samples were used. All analyses were carried out in the Matlab environment.

2.2.4. Slope of linear regression

The final step of the proposed algorithm was to determine the linear regression equation for the variables MDF and MNF, which are indicators of muscle fatigue, according to the following formula:

$$y = Ax + B\,, \tag{7}$$

where:

A – regression coefficient,
B – shift factor,
y – dependent variable,
x – independent variable.

The determination of MDF and MNF values in the previous step of the algorithm allowed us to determine the regression coefficient A for the R – GAS, R – RF, R – BF, L – GAS, L – RF, L – BF muscles in all three trials.

3. Results

The slopes determined of the linear regression for each muscle in each trial by type of estimator are shown in Figs. 7 and 8.

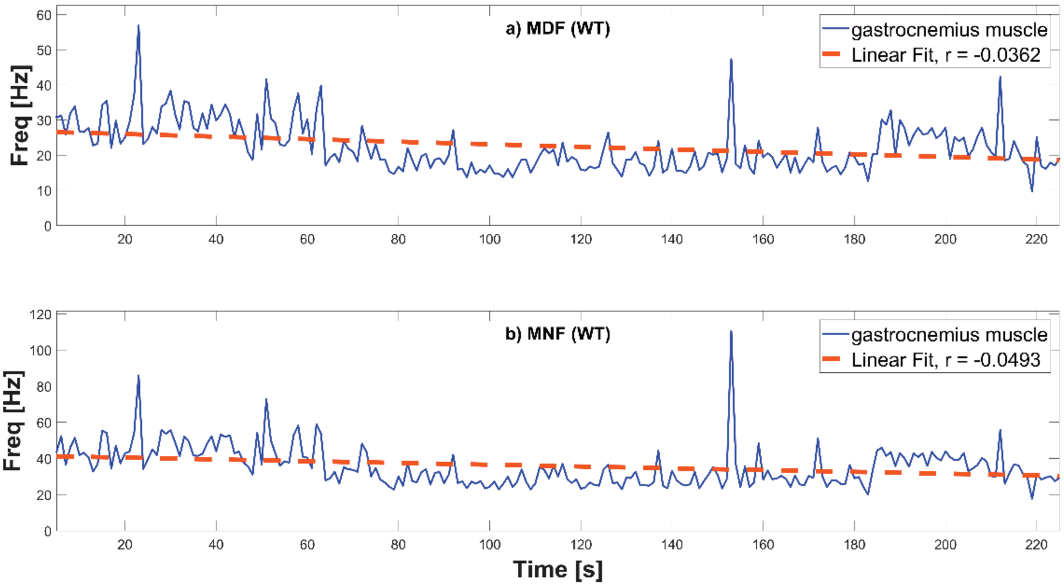

Fig. 7. MDF (a) and MNF (b) with their respective linear regression slopes for GAS. Spectral method estimation: DWT

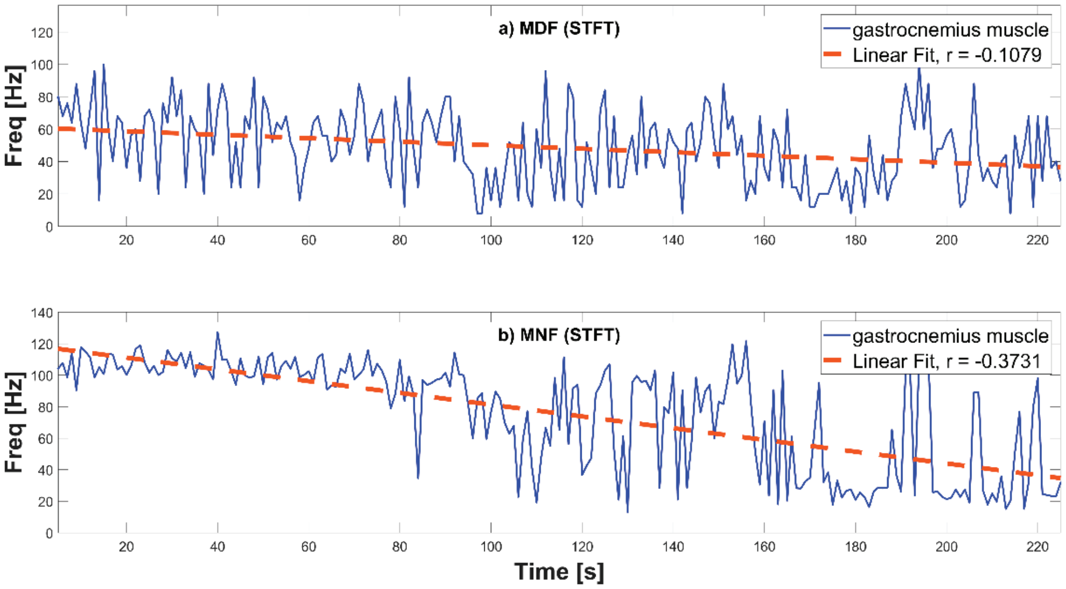

Fig. 8. MDF (a) and MNF (b) with their respective linear regression slopes GAS.
Spectral method estimation: STFT

Table 3. Comparison of linear regression coefficients for MNF and MDF functions
for GAS, RF, and BF muscles (DWT and STFT analysis)

Muscle	Estimator	Trial 1		Trial 2		Trial 3	
		MNF	MDF	MNF	MDF	MNF	MDF
R – GAS	DWT	–0.0493	–0.0362	0.1015	0.1119	0.0333	0.0413
L – GAS		–0.0601	–0.0394	–0.0684	–0.0521	–0.033	–0.0317
R – RF		–0.0394	–0.0192	–0.1132	–0.0356	–0.1044	–0.0298
L – RF		–0.0044	–0.019	–0.0248	–0.0164	–0.153	–0.0832
R – BF		–0.1288	–0.0705	0.0243	0.014	–0.0145	–0.0091
L – BF		–0.0914	–0.0442	–0.0729	–0.0396	0.0244	0.0152
R – GAS	STFT	–0.3795	–0.0882	0.1447	–0.107	0.0885	0.002
L – GAS		–0.0057	0.0507	–0.2119	–0.0852	0.0108	–0.0306
R – RF		0.0198	–0.0242	–0.0137	–0.0228	–0.018	–0.0169
L – RF		0.0104	–0.0353	0.0126	–0.068	–0.0111	–0.0068
R – BF		–0.1107	–0.0428	–0.0253	–0.03	–0.1409	–0.0223
L – BF		–0.0236	–0.0755	–0.1074	–0.092	0.0152	–0.0005

In Table 3, a summary of the linear regression coefficients of the MNF and MDF functions for all muscles and samples and estimators is presented.

A summary of all determined linear regression coefficients for MNF and MDF, along with characteristics of the distribution of this coefficient within the method used for each muscle is shown in Fig. 9.

A study using DWT analysis showed that the average value of the regression coefficient for most muscles (L – GAS, R – RF, L – RF, R – BF, L – BF) is negative, which means that these muscles showed more fatigue after the set training. This applies to the regression coefficients obtained from the MNF and MDF functions. Only the R – GAS muscle was an exception, as its average regression coefficient was positive. STFT analysis, conducted in addition, showed that the values of the linear regression coefficients for MDF were negative for all muscles studied. On the contrary, the values of linear regression coefficients for MNF were negative only for the L – GAS, R – RF, R – BF and L – BF muscles. The proposed training aimed to fatigue all muscles during movement, so the results of the first analysis (DWT) seem to give more reliable results. In conclusion, DWT analysis can be an effective tool to assess muscle fatigue after exercise.

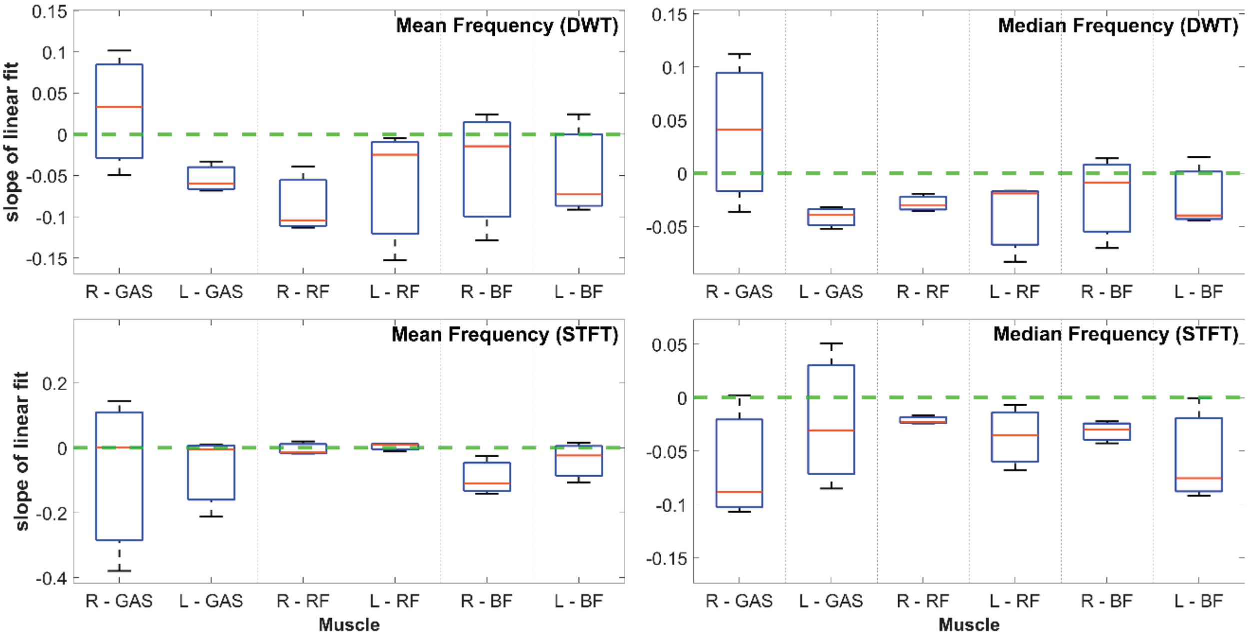

Fig. 9. Comparison of linear regression coefficients for MNF and MDF, along with their distribution characteristics within the applied method, for individual muscles

4. Discussion

To assess lower extremity muscle fatigue, the subject performed cyclic movement (30 times/min) on a CONCEPT II rowing ergometer until reaching maximum fatigue according to the Borg scale. MNF and MDF are the most useful and popular parameters in the frequency domain and are often used to assess muscle fatigue in surface EMG signals [27], and the slope of MDF (negative linear regression coefficient) can be used as an indicator of EMG fatigue [12].

The purpose of the present study was to evaluate the change in fatigue in selected muscle groups of the lower extremity in dynamic cyclic movement based on the linear regression performed. The results show the aspect of muscle fatigue for: the GAS muscle, the RF muscle and the BF muscle. The method presented hereby is not secured by complete control of variables that could affect the results obtained, but one can see a prevailing downward trend in the linear regression results. The pooled results for one participant (from three measurements) also confirm the dependence of fatigue in terms of simple regression (Fig. 9). The upward trend of MNF and MDF parameters occurring for some muscles may have many causes, for example, related to the measurement itself or the athlete's individual predisposition (in the aspect of two positive values for the left calf).

Few articles describe the use of the wavelet transform to assess muscle fatigue, although its effectiveness in this type of analysis has been emphasized [3], [4]. However, the FFT, STFT, CWT and DWT methods have also been repeatedly compared with each other [3], [5], [6], [9] and analysed for the effectiveness of application in determining muscle fatigue [7], [33]. It was also established that CWT analysis is as a suitable method for the quantitative evaluation of neck and shoulder muscle under repetitive conditions [8]. The authors of one of the studies conducted [30] research on a cohort of rowers and did not observe any significant correlation between frequency domain parameters and muscle fatigue. In their investigation, they utilized CWT analysis. Unlike the conditions detailed in the article, the investigations undertaken within this manuscript were conducted under controlled conditions, which could bear significance in the context of the results obtained. Many authors suggest to continue the work on fatigue method analyses taking into consider the type of training, selected muscles and limitations during static or dynamic conditions. However, no work was found that described fatigue assessment in terms of quantitative results and a description of the research methodology for DWT. More importantly, no description of the computational methodology for a dynamic movement such as exercise on a rowing ergometer in terms of determining muscle fatigue using DWT was also found.

For the present study, there may be several limitations to consider. The first is the choice of wavelet or signal decomposition level when analyzed using DWT. Another limitation may be the choice of Hamming window width in the case of STFT analysis. Choosing an inappropriate window width can lead to loss of information or falsify frequency analysis results. The sampling frequency of the EMG signal can also be a limitation. An inappropriate sampling frequency can lead to distorted analysis results, especially for high-frequency signals. All the aforementioned limitations can have an impact on different MDF and MNF values depending on the applied analysis method: DWT or STFT. Furthermore, how the EMG sensor is attached to the participant's body can affect the test results. Proper skin preparation, participant preparation for the test, and any movement of the sensor on the skin associated with dynamic movements can introduce distortions into the readings of EMG signals. Another important factor that can affect the results of the EMG analysis is psychological elements, such as focus, stress, or individual differences in the participant’s preparation for the test. Additionally, the timing of the test, including the number of repetitions, can affect the results of the analysis.

The summary results described in the Results section suggest that the proposed methodology to determine muscle fatigue is valid and reliable, despite the potential limitations that were considered during the study.

In future measurements, the methodology will be analyzed in depth and at this stage of the work there is a signal analysis based on the above methodology for a larger group of individuals. The present work is part of the research being carried out, and the question of a comprehensive description of the test with a description of the materials and research methods has been omitted from the work, as this will be developed in future works. In addition, the measurement performed was used in the aspect of activity and correlation of two signals [11], which is a part of the authors’ work.

5. Conclusions

The proposed method that uses linear regression analysis of MNF and MDF may be effective in evaluating muscle fatigue during dynamic rowing exercises.

Taking into account the proposed method, the tests conducted and the results obtained, the following conclusions were formulated:

- the results demonstrate in muscle fatigue for GAS, RF and BF muscles,
- the application of DWT shows promise for muscle fatigue assessment, highlighting its potential utility in this context,
- limitations such as variable control and wavelet parameter selection should be considered in future research to ensure a more robust and accurate assessment of muscle fatigue,
- this study contributes to the field by providing information on muscle fatigue assessment techniques and emphasizes the need for further validation and exploration of the proposed method,
- the findings support the effectiveness of the proposed methodology and pave the way for future research in the area of muscle fatigue evaluation during dynamic exercises.

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