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Analysis of muscle activity during rowing stroke phases

URSZULA CZAJKOWSKA, EWELINA ŚWIĄTEK-NAJWER*, LUDOMIR JANKOWSKI

Faculty of Mechanical Engineering, Wrocław University of Science and Technology, Wrocław, Poland.

Purpose: Rowing engages large muscle groups and electromyography (EMG) analysis is used to assess athletes' condition and refine sports technique. The aim of the experiment was to evaluate the muscle activation level during different phases of the rowing cycle on an ergometer. *Methods*: In a study involving one professional and five amateurs, the mean EMG amplitudes from the quadriceps, gastrocnemius, biceps and triceps brachii were analyzed during different phases of rowing. A comparison was made between the degree of muscle engagement during the exercise between the professional and inexperienced individuals as well as among the different individuals during recordings obtained at different rowing speeds. The correlation coefficient between the values recorded using a strain gauge and the EMG amplitude recorded from the surface of the biceps and triceps brachii muscles was evaluated. *Results*: The muscle activation pattern during rowing has a predictable character. A difference in the muscle activation pattern during rowing between the professionals and amateurs was observed. The EMG signal is correlated with the force recorded by the resistive strain gauge only in the experienced rower at stroke rates 20 and 25 [1/min]. *Conclusions*: Electromyographic analysis can be useful for assessing the correctness of rowing techniques. The activation pattern of muscles during rowing has a predictable nature. The force generated by the participants increases with an increase in rowing frequency.

Key words: *rowing, electromyography (EMG), muscle activation*

1. Introduction

Rowing is a discipline that engages large muscle groups and uses large amounts of energy [28], [31]. A cycle of one rowing move consists of two main phases characterized by the work of specific muscles [15], [16], [31]: the proper phase, which consists of three sub-phases (the catch, the drive and the finish), and the recovery phase, during which the rower rides up on the seat and assumes the starting position for the next move [6], [25], [28], [30].

Electromyography is one of the tools used to analyze muscle activity in rowers [11], [15], [24]. The analysis of the electromyographic signal (EMG) is a tool for objective assessment of the athlete's condition as well as supporting the development of sports technique, teaching proper movement patterns and checking the effectiveness of sports training [11]. EMG is a useful tool for evaluating strategies of muscle activation. Jabłońska et al. [18] successfully assessed muscle activation in patients with chronic low back pain of the lumbar spine and showed that it significantly deviated from the norms for individual muscles. Electromyography makes it possible to reduce the risk of injuries and increase the efficiency of the exerciser, e.g., by assessing the symmetry of the exercises performed [20], [30]. After an injury, electromyography can help re-educate desired movement patterns and activate specific muscle groups [8], [15], [21], [22]. Gorwa et al. [12] used EMG and a motion capture system to assess the difficulty of five classical ballet positions, suggesting that the teaching sequence in beginning dancers. Another application of electromyographic examination in sports may be "EMG Biofeedback" [17], [22], [23], consisting of real-time observation of changes in electrical activity of muscles during a physical activity [9]. Biofeedback improves the effectiveness of learning how to properly perform exercises, and also motivates the exerciser to use more strength by providing informa-

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* Corresponding author: Ewelina Świątek-Najwer, Wrocław University of Science and Technology, Faculty of Mechanical Engineering, Łukasiewicza 5, 50-371 Wrocław, Poland. Phone: +48 71 320 21 93, fax: +48 (71) 321-12-35, e-mail: ewelina.swiatek-najwer@pwr.edu.pl

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tion about the degree of muscle involvement in a given movement [22], [23].

Correctness of exercise technique is traditionally monitored visually or through individual self-assessment. The drawback of these methods is subjectivity, difficulty in monitoring multiple joints simultaneously and dependence on the evaluator's skills and experience [25]. Optical motion tracking methods are commonly used in biomechanics for analyzing the kinematics of specific movement tasks [29], including systems such as Peak 5, Ariel, OptiTrack, Optotrak and the widely regarded high-accuracy gold standard, Vicon [32]. However, the drawback of these systems is their high cost, which affects their accessibility. The advantages of markerless motion analysis systems also include reducing the risk of human errors and the influence of soft tissue artifacts as well as the ability to conduct measurements in the field [26], [30]. Analyzing video recordings to track the trajectories of individual body parts allows for detecting errors occurring during rowing and easily raising awareness among athletes [13].

The measurement of the force exerted by the rowers is a popular test [13], [33]. In a study conducted by Colloude et al. [13], experienced rowers achieved a maximum pulling force during a full rowing cycle at a level of 1134 ± 108 N, a result consistent with other sources [33].

The aim of the experiment was to evaluate the muscle activation level during different phases of the rowing cycle on an ergometer. As a part of the overall objective, the following specific research questions were posed: 1. Does the muscle activation pattern during rowing have a predictable character? 2. Does the muscle activation pattern differ between experienced rowers and amateurs? 3. Is the recorded electromyographic signal correlated with the force measured by the resistive strain gauge? 4. Does the rowing stroke rate affect the parameters of the EMG signal and the recorded force level?

2. Materials and methods

2.1. Experimental protocol

The study involved 6 adult, healthy, right-handed individuals – 3 women and 3 men – among whom one participant, referred to as the professional (1P), was an experienced rower (masters category), while the remaining individuals had no prior rowing experience. Basic participants information is presented in Table 1.

Table 1. Data on the participants

Participant	Sex	Height [m]	Weight [kg]	BMI
1A	M	86	1.87	24.59
2A	M	92	1.87	26.31
3A	K	75	1.67	26.89
4A	K	63	1.62	24.01
5A	K	45	1.58	18.03
P1	M	93	1.76	30.02

Table 2. Force values, mean values, and standard deviations for individualsat different rowing paces

Participant	Stroke rates [1/min]	Maximum force [N]	Mean value [N]	SD [N]
1P	15	76.7	13.1	22.7
1P	20	82.7	14.3	24.34
1P	25	76.8	16.3	25.7
1A	15	23.1	2.8	5.1
1A	20	20.7	3.7	5.7
1A	25	46.7	5.5	8.3
2A	15	20.65	2.3	5.7
2A	20	28.1	2.5	8.51
2A	25	49.3	8.2	14.1
3A	15	41.1	8.91	11.1
3A	20	39.7	7	12.3
3A	25	48	8.26	13.5
5A	15	43.7	7.7	10.1
5A	20	39.76	5.9	11.37
5A	25	44	8.31	13.39

Table 3. Correlation coefficient value between signals recorded by a straingauge and emg signals

Participant	Stroke rates [1/min]	Biceps brachii	Triceps brachii
1P	15	0.52	0.04
1P	20	0.78	0.84
1P	25	0.79	0.74
1A	15	0.17	0.17
1A	20	0.51	0.51
1A	25	0.06	0.06
2A	15	0.04	0.05
2A	20	0.6	0.6
2A	25	0.05	0.05
3A	15	0.05	0.05
3A	20	0.01	0.01
3A	25	0.05	0.05
5A	15	0.13	0.13
5A	20	0.44	0.44
5A	25	0.06	0.05

The participants performed training on a ergometer while simultaneously recording the bioelectrical activity of four selected muscles and capturing video footage of the exercises. The study was conducted in a closed room with a constant temperature of 22–24 °C. Electrodes were placed on the participant's skin to record the EMG signal from the biceps brachii muscle, lateral head of the triceps brachii muscle, rectus femoris muscle, and medial head of the gastrocnemius muscle. The location of the electrodes was determined under ultrasound guidance using EchoBlaster 128 from Telemed, Lithuania [19], [23]. All tested muscles were located on the right side of the body. To ensure proper electrode placement, reduce interferences, the participants' skin was cleaned with alcohol. Gel surface electrodes (Ag/AgCl) with a round surface and a diameter of 3.8 cm were applied to the skin surface according to anatomical knowledge and guidelines from the literature [40]. A grounding electrode was placed on the olecranon process of the right upper limb. The All New MR XP computer program was used for recording and analyzing the muscle's electrical activity, which also included video recording capabilities.

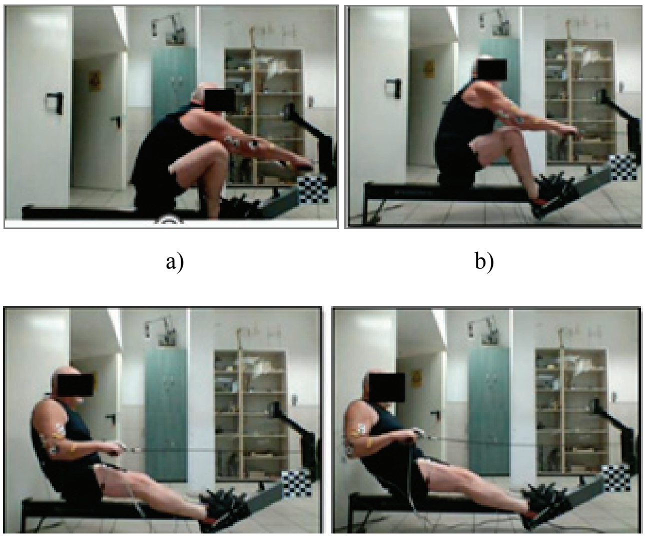
The camera was positioned 1.5 meters away from the ergometer and the sampling frequency during the EMG signal recording was 1004 Hz. The participants underwent training on a Concept 2 ergometer. Initially, each person performed a five-minute warm-up to familiarize themselves with the device and prepare their bodies for exertion. Then, the electrical activity of the aforementioned muscles was recorded during two-minute sets – the first set at stroke rates of 15, the second set at 20 and the third set at 25 cycles per minute. The stroke rates was indicated by an audio signal generated by the All New MR XP program. The participants had a 3-minute rest period between sets.

During rowing on the ergometer, the tensile force was recorded using the Alitec Stretton measurement system with synchronous sampling. The resistive strain gauge was positioned to measure the tension force applied to the ergometer handle during the trials, and the sampling frequency was 50 Hz. Prior to the study, the strain gauge was calibrated by applying and removing weights of 1, 2, 3, 4, and 4.5 kg. The readings of the strain gauge were recorded at the specified loads, which allowed for the conversion of the measured values during rowing into units of force during the analysis of the results

2.2. Signal analysis

The New MR XP program was used for the analysis of the EMG signals. First, the signal was filtered, applying a 20–400 Hz bandpass FIR filter (using a Lanczos window with 79 points). Then, a 48–52 Hz band-stop FIR filter (using the same window) was applied to eliminate power line frequencies. The signal was rectified and smoothed using a 50 ms window. Power spectrum plots were generated for each set. The next step involved dividing the EMG recordings into individual phases of rowing. For determining the phases, videos recorded during the exercise were utilized, and the following assumptions were made:

- the catch phase begins when the direction of the handle changes;
- the drive phase starts when the elbows are above the knees;
- the finish phase begins when the arms are parallel to the torso;
- the recovery phase begins when the handle changes direction (Fig. 1).



a) b)

c) d)

Fig. 1. Beginning of each phase: a) catch phase, b) drive phase, c) finish phase, d) return phase

The average amplitude value of the signal from the analyzed muscles was analyzed (divided into individual phases of the rowing cycle) and the percentage contribution of the EMG signal from each muscle during each phase was calculated. A comparison was made of the muscle involvement during the exercise between the professional and inexperienced individuals as well as among individuals at different rowing speeds. In order to compare the amplitude of the EMG signal among individuals, normalization was performed. One technique used for this purpose is the MVC method, which involves the individual performing a maximum isometric contraction while simultaneously recording the electromyographic activity – the average value of this activity serves as the reference level. Subsequently, the measured values obtained from each individual can be presented as a percentage of MVC [5], [7]. During the study, normalization was performed using actual measurements – the highest observed value of the EMG signal for each muscle was set as 100% signal. Then, each recorded value was divided by the "MVC value", resulting in a percentage value. Additionally, an analysis of the force values recorded by the strain gauge was conducted. For each trial, the maximum force level was recorded and the mean and standard deviation were calculated. The Pearson correlation coefficient was also calculated between the EMG signal from the upper limb muscles and the signal recorded by the strain gauge. To achieve this, considering the difference in sampling frequency, both recordings (EMG and strain gauge) were synchronized.

2.3. Statistics

Additionally, besides MVC normalization, the collected data were also normalized by converting each rowing cycle into a percentage scale, allowing for comparisons between repetitions of different durations. The normality of the data was tested using the Shapiro–Wilk test. Data with a confirmed normal distribution were used for further analysis. Using the Student's *t*-test, the normalized mean values of recorded EMG signal amplitudes for each rowing phase were compared between the professional and amateur participants. The test results showed that the values recorded in individual phases differed between the professional and amateur participants in 71 out of 73 conducted tests, and the *p*-value was $p < 0.001$ for the majority of the tests. In four confirming comparisons, the coefficient did not exceed $p < 0.003$. The Student's *t*-test did not confirm the assumed hypothesis for the P1 vs. A2 pair in the drive phase for the biceps brachii muscle (20 cycles/min), as well as for the P1 vs. A4 pair in the finish phase (25 cycles/min) for the rectus femoris muscle.

3. Results

3.1. Analysis of signal components

For enhanced readability of the results, the experienced person was labeled as P1, while amateurs were denoted as A1, A2, A3, A4 and A5. The recordings obtained during the examination of the professional served as a reference for the remaining results. To validate the data's reliability, a comparative analysis was conducted using literature data [35]. Figure 2 consists graphs depicting the average values of the recorded signals from the tested muscles in P1 during successive measurements (each graph represents one cycle). The percentage of signal contribution from each muscle during the four consecutive rower phases was calculated for the three analyzed speeds (Fig. 2). Video analysis revealed that beginners had a significantly shorter catch phase, at times difficult to grasp. It was clearly visible only in the professional and subject A5, which was excluded from further analysis due to the interference imposed on the recorded signal.

In professional athletes, during the catch phase, activity is evident in all muscles tested, with the largest signal component recorded from the gastrocnemius calf muscle. During the drive phase, regardless of speed, there is an increased involvement of the upper limb muscles, accompanied by a decrease in the percentage of signal coming from the gastrocnemius muscle area. The peak percentage of signal coming from the biceps brachii muscle occurs during the terminal phase, accounting for about 70% of the total signal. During the finishing phase, the professional engages the biceps brachii mus-

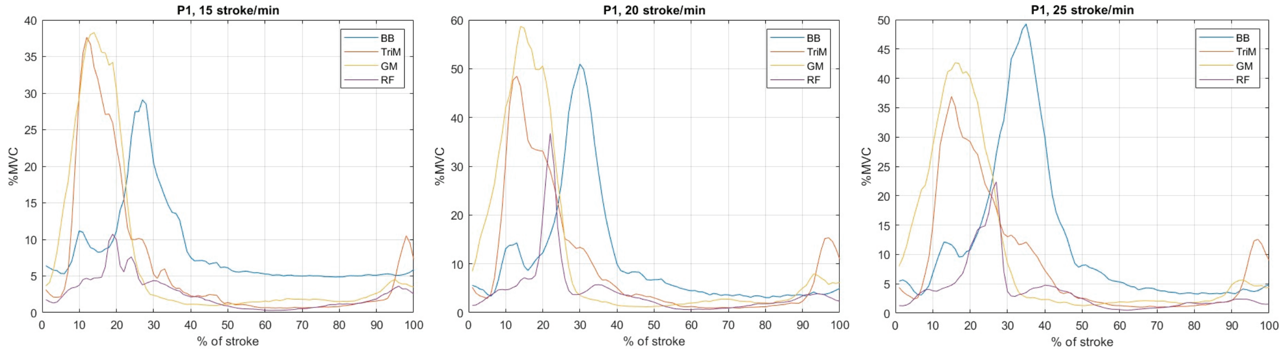


Fig. 2. EMG signal waveform during rowing performed by P1

cle, the rectus thigh muscle and the gastrocnemius muscle to a comparable degree. The involvement of the rectus thigh muscle, responsible for knee extension and hip flexion, does not change significantly between the catch and drive phases, but a noticeable increase is observed during the return phase. Among most amateurs, the activity of the rectus thigh muscle is not so pronounced, with the dominance of the gastrocnemius and biceps brachii muscles. The main muscles involved in the rowing cycle in professionals are the gastrocnemius muscle (flexor of the ankle and knee joint) and the biceps brachii muscle (flexor of the elbow and shoulder joint). The course of the EMG signal and the level of muscle involvement during rowing are shown in the graph for each of the analyzed speeds (Fig. 3).

The graphs generated for the amateur exhibit similar values for each speed, but they differ from those obtained for the professional. In most individuals, there is a predominance of muscle activity in the lower limb, while the biceps arm muscle dominates the finishing phase only in one person (A2), accounting for just 50% of the total signal.

Analyzing the percentages of individual muscle involvement in successive phases of rowing for person A1, one can observe the predominance of signals originating from the lower limb. The exception is the return phase, where an increase in the activity of the biceps arm muscle can be seen. In contrast to P1, this muscle reaches its minimum activity during the finishing phase. The triceps brachii muscle maintains a constant, low level of activity across different rowing speeds.

Analyzing the signals recorded for person A2, one can observe a dominance of signals recorded from the surface of the lower limb muscles and minimal involvement of the triceps brachii muscle. For speeds of 20 and 25 cycles/min, an increase in the involvement of the biceps brachii muscle during the finishing phase can be observed compared to other phases. However, it is not as pronounced as in the case of the professional.

Muscle involvement during rowing in a A3 person is characterized by a predominance of signals coming from the lower limb and, compared to P1 work, one can see an inverted proportion of the signal coming

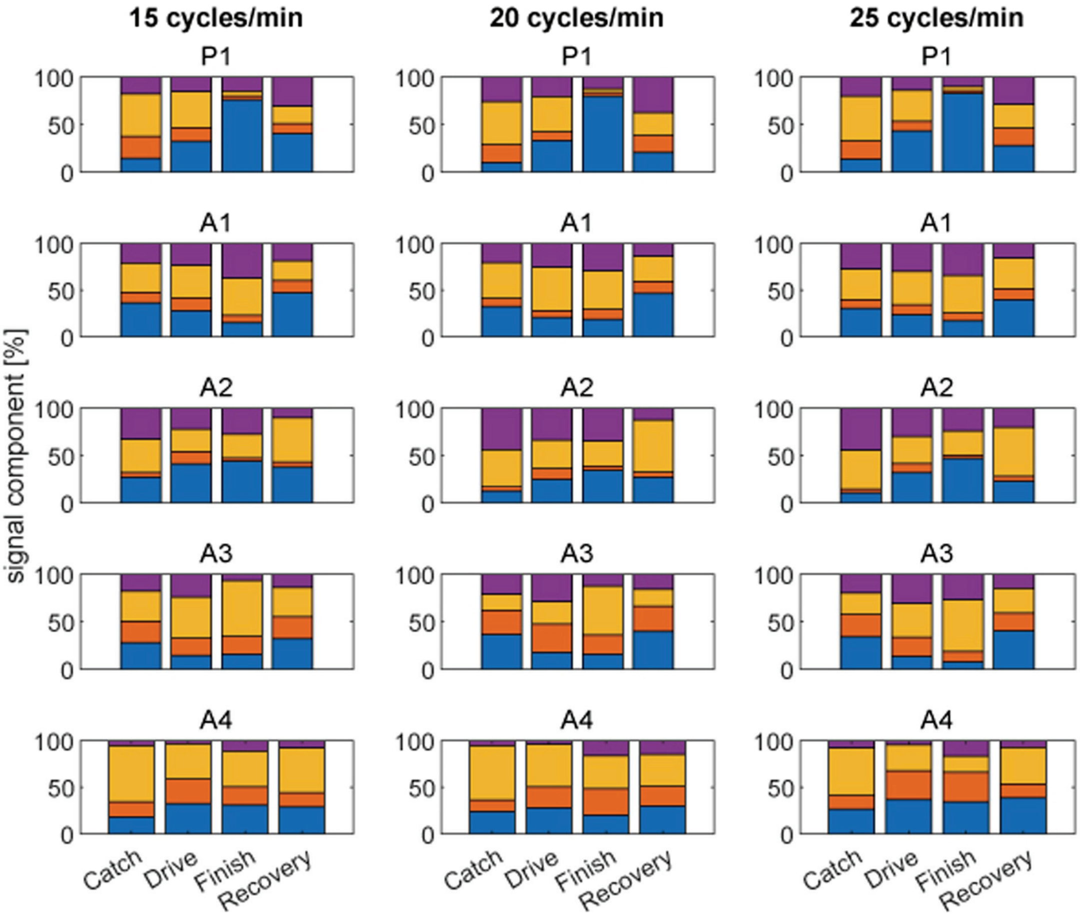


Fig. 3. Average EMG signal components recorded from the muscle surface during different rowing phases: blue – biceps brachii, red – triceps brachii, yellow – gastrocnemius, violet – rectus femoris

from the biceps brachii muscle and gastrocnemius calf muscle and a higher level of involvement of the triceps brachii muscle. For all speeds of the exercise performed, the graphs show similar trends.

Beginner rower A5 performing the movement task at 15 and 20 cycles/min, during all phases, presented a similar percentage of muscle involvement with a noticeable dominance of the work of gastrocnemius calf muscle. When working at a stroke rates of 25 cycles/min, one can the see an increased involvement of the muscles of the upper limb (without a clear predominance of the biceps brachii muscle) with a parallel decrease in the involvement of the gastrocnemius muscle.

3.2. EMG signal amplitude analysis

In Figure 4, graphs showing the average value of EMG signal amplitude expressed in % MVC for all muscles and rowing speed are presented.

It can be observed that for person P1, the signal originating from the biceps brachii muscle and the quadriceps femoris muscle exhibits a similar characteristic for each rowing speed. The signal recorded from the other two muscles also undergoes similar changes for the speeds of 15 and 20 cycles/min (taking the difference in amplitude into account). However, for the highest speed, the graph has a different pattern. In contrast to the first two trials, for the speed of 25 cycles/min, the EMG signal reaches a higher value for the biceps brachii muscle and a lower value for the gastrocnemius muscle. It can be observed that the amplitude reaches the smallest values for a speed of 15 cycles/min and the highest values for a speed of 20 cycles/min.

In the graphs showing amplitude changes for individual muscles in person A1, it can be observed that for all muscles involved, the signal waveform has similar characteristics, with the signal amplitude reaching higher values for a rowing rate of 25 cycles/min.

The graphs exhibit comparable characteristics for speeds of 20 and 25 cycles/min. However, at a speed of 15 cycles/min, in contrast to the faster speeds, during the first three phases, the signal recorded from the

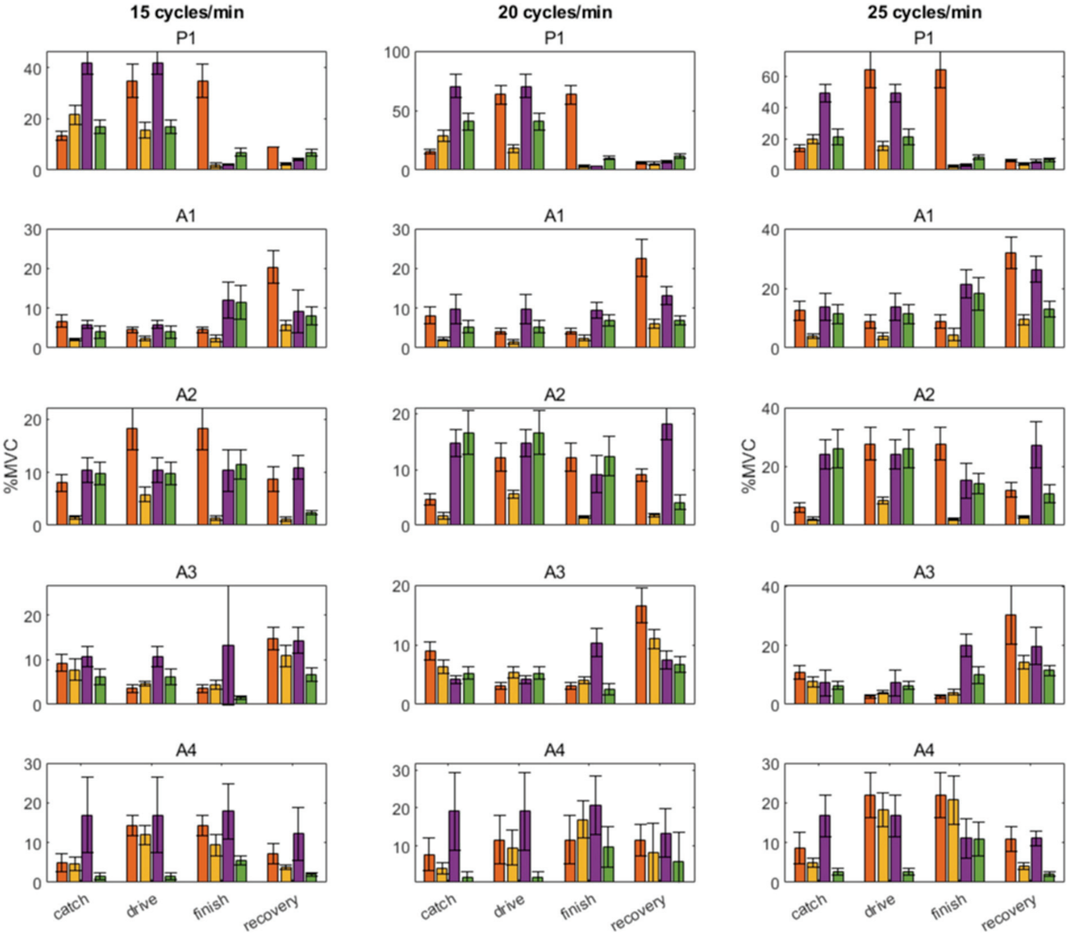


Fig. 4. EMG signal components recorded from muscle surfaces during rowing:
blue – biceps brachii, red – triceps brachii, yellow – gastrocnemius, violet – rectus femoris

surface of the rectus femoris muscle dominates over the signal from the gastrocnemius muscle.

EMG signals recorded during the rowing of subject A3 reach their highest level for a speed of 25 cycles/min. The characteristics generated for the biceps brachii muscle and the triceps calf muscle have a similar course at all speeds, reaching a maximum in the return phase. The work of the gastrocnemius calf muscle does not show the same character for all the tests carried out – for the speed of 15 cycles/min, the characteristics of the amplitude changes in the different phases (the highest values for the recovery phase) differ from those noted at higher speeds (the highest values for the finish phase).

On the charts of signals recorded during the performance of person A4, it can be observed that the amplitudes of signals from the biceps brachii and triceps brachii muscles reach the highest value at a stroke rates 25 cycles/min, while at speeds of 15 and 20 cycles/min, they do not differ significantly. The pattern of muscle activation is similar for the catch and finish phases, but for the other phases, the execution of the motor task varies. The EMG signal of the lower limb muscles does not show clear differences between consecutive speeds – the gastrocnemius muscle operates in a comparable manner at a stroke rates of 15 and 20 cycles/min, while at a stroke rates of 25 cycles/min, a decrease in the signal amplitude can be observed, accompanied by an increase in EMG amplitude originating from the upper limb muscles.

3.3. EMG correlation coefficients – tension force

The correlation coefficient was examined between the values recorded using a strain gauge and the amplitude of EMG recorded from the surface of the biceps and triceps brachii muscles. The results were compiled in Table 1. For individual coefficients listed, the level of significance was $p < 0.001$, confirming the high statistical value of the results. Only in the case of a professional, the correlation coefficients of the tested variables were significant, but not in all trials. The value of the correlation coefficient (R) for a speed of 15 cycles/min was 0.52 for the correlation with the signal from the biceps muscle and 0.04 for the triceps muscle. However, at stroke rates of 20 and 25 cycles/min, it was 0.78 and 0.79 for the biceps muscle, respectively, and 0.84 and 0.74 for the triceps muscle. Only in one of the amateur participants did the correlation coefficient exceed 0.5, while for the majority, it was not greater than 0.1. In Table 2 the maximum and average force values recorded by the strain gauge, as well as the standard deviation. The maximum force generated by the professional was 76.7 N, 82.7 N, and 76.8 N for the respective rowing speeds. The amateurs achieved values that were two to four times smaller. The average value obtained by the professional ranged from 13.1 N to 16.3 N, depending on the rowing pace, while for the amateurs, it did not exceed 10 N. It is worth noting that the standard deviation also reached higher values for the experienced individual compared to the rest of the participants. For participant P1, at the highest speed, the standard deviation was 25.7 N. The amateur participants achieved standard deviations that were two to three times smaller.

4. Discussion

The aim of the conducted study was to assess the level of muscle activation during individual phases of rowing on an ergometer. Video recordings made it possible divide the recorded EMG signal into separate phases, enabling their analysis. Based on the footage, it was also possible to observe technical errors during the exercise. Scientific papers describe the pattern of muscle activation during rowing [13], [32], [34]. In the conducted experiment, the electromyographic signal of the muscles was recorded from the rectus femoris, gastrocnemius as well as the biceps and triceps brachii muscles. The percentage contribution of signals from each channel was calculated to determine the extent of involvement of the examined muscles during the performance of a specific movement. Electromyography is a commonly used tool for analyzing muscle activity in sports and rehabilitation [21], [34]. In our study, while analyzing the amplitude values of the EMG signal in relation to the rowing phase, a recurring pattern of muscle activation was observed throughout the entire exercise series. In the case of the experienced individual, a jump in the amplitude of the signal originating from the surface of the rectus femoris muscle was recorded between the catch phase and the drive phase, which is consistent with the literature reports [13], [32], [34]. Additionally, the percentage contribution of this muscle's activation is the highest during the recovery phase, aligning with its primary function as a knee extensor. These relationships are evident across all analyzed rowing speeds. However, for the amateurs, it is challenging to identify a single pattern. Some individuals exhibit an amplitude jump during the finish phase, while others show it in different phases. Moreover, the percentage contribution of the rectus femoris muscle in their movement is constant throughout the cycle for some individuals, while for others, it varies, reaching its highest value in different phases. The pattern of activation in the biceps brachii muscle for the experienced participant aligns with the results obtained by other authors [32], [34], However, not all amateurs performed the exercise according to this pattern. The amplitude jump in the amplitude of the signal originating from this muscle can be observed in different individuals during the drive phase or the recovery phase. The amplitude of the signal recorded from the lateral head of the triceps brachii muscle is highest during the catch and drive phases for some participants, while for others, it is highest during the finish phase. In the case of an experienced rower, a high signal value can be observed during the catch and drive phases, which is consistent with similar findings by other authors [34].

Video analysis revealed that the examined rowers consistently performed each cycle in the same manner. Most of the EMG signal recordings exhibited a consistent pattern of muscle activation. When comparing recordings made at different rowing speeds, differences in the execution of the exercise were observed among some participants at a stroke rates of 15 cycles/min compared to the higher speeds. This finding is consistent with existing literature. According to Mladenovic et al. [26], the prescribed speed is an important factor in learning rowing technique, with a higher tempo being more desirable.

Fukuda et al. [15] found that the value determined using the RMS algorithm accurately reflects the level of physiological muscle activity during a motor task. They also observed that the relationship between EMG signal amplitude and generated force is linear for small muscles, while for larger muscles, the relationship has a different nature.

In our study, the generated force values ranged from 20 N (for inexperienced rowers) to 82.7 N for the professional rower. It can be observed that proficiency in technique correlates with the level of generated force. We also conducted an analysis of mean force and standard deviation, and these values were significantly higher for the experienced rower as well. Perhaps the professional rower's ability to achieve higher standard deviation values is due to a better exercise technique and more economical movement execution. It is worth noting that our obtained force values were lower than those reported in the literature [13], [33]. However, in the cited experiments, the participants were often instructed to row with the maximum force possible. In our study, the rowers were only given the rowing frequency as a requirement, and as the frequency increased, the majority of individuals exhibited higher mean force, maximum force and standard deviation values.

In the conducted experiment, the handle force on the ergometer was measured and correlated with the EMG signal recorded from the surface of the biceps brachii muscle and the triceps brachii muscle. Only the professional rower exhibited a high correlation coefficient between the generated force and the EMG signal. This could be attributed to the difference in exercise technique between the amateur participants and the experienced rower. It is noticeable that amateurs relied more on lower limb muscles during the exercise. Another factor that may contribute to this difference is gender [22].

A rowing machine can be used not only in competitive sports but also as a tool for athletes, coaches, physiotherapists and sports biomechanics. It offers a wide range of possibilities for studying parameters and conducting various analyses. It allows for measuring the endurance of individuals during exercise and can contribute to the progress of rehabilitation, such as measuring joint angles achieved during rowing. In our own study, we analyzed EMG signals recorded during rowing. The differences observed in the EMG recordings between professionals and amateurs indicate that the signal is dependent on the technique of performing the exercise and can serve as a reference during training. When combined with electromyography, a rowing machine can be beneficial for athletes and coaches in obtaining information about the executed movement pattern, leading to improved effectiveness and the prevention of potential overloads.

5. Conclusions

Based on the literature analysis and the collected data, the following conclusions can be drawn. The activation pattern of muscles during rowing has a predictable nature, as participants consistently repeat a specific movement pattern at each prescribed speed or in the range of 15–20 / 20–25 cycles per minute. There are differences in the muscle activation pattern during rowing between professionals and amateurs. The EMG signal is correlated with the force measured by the resistance strain gauge only in experienced rowers at a stroke rates of 20 and 25 cycles per minute. Proper exercise technique appears to be a significant factor influencing the analyzed correlation coefficient. The force generated by the participants increases with the frequency of rowing. Electromyographic analysis can be useful for assessing the correctness of rowing techniques.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Credit authorship contribution statement

Urszula Czajkowska: B, C, D, E; Ewelina Świątek-Najwer: A, B, E, F; Ludomir Jankowski: A, B.

A. The preparation of the research program B. The execution of research C. The statistical analysis D. The interpretation of data E. Preparation of the manuscript, F. Obtaining financing

Corresponding author

Ewelina Świątek-Najwer, Wrocław University of Science and Technology, Faculty of Mechanical Engineering, Łukasiewicza 5, 50-371 Wrocław, Poland. Phone +48 71 320 21 93, fax: +48 (71) 321-12-35, e-mail: ewelina.swiatek-najwer@pwr.edu.pl

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