Differences in Muscle Activation Between Submaximal and Maximal 6-Minute Rowing Tests

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Abstract

Gerževič, M, Strojnik, V, and Jarm, T. Differences in muscle activation between submaximal and maximal 6-minute rowing tests. *J Strength Cond Res* 25(9): 2470–2481, 2011—This study aimed to establish the differences in muscle activation between a 6-minute simulated race (all-out test) and a submaximal (blood lactate [LA] concentration 4 mmol·L^{-1}) 6-minute effort (submax test) on a rowing ergometer. Eleven healthy, well-trained subjects performed the submax test followed after 1-hour rest by the all-out test. Surface electromyographic (sEMG) signal of muscles *gastrocnemius medialis* (GC), *rectus femoris* (RF), *vastus lateralis* (VL), *biceps femoris*, *gluteus maximus* (GM), *erector spinae* (ES), lower *latissimus dorsi* (LD_lo), upper *latissimus dorsi* (LD_up), *brachioradialis* (BR) and *biceps brachii* (BB), and other biomechanical, biochemical, and respiratory parameters were monitored during rowing. During the all-out test, the subjects covered a longer distance with larger average power output, higher stroke frequency, LA concentration, and oxygen consumption compared to the submax test ($p < 0.05$). During the submax test, the average rectified values (ARVs) of sEMG signal increased significantly only in the RF and LD_lo muscles. During the all-out test, the ARVs of the RF, VL, and GM muscles increased ($p < 0.05$), whereas the MDFs of the RF, ES, and LD_lo muscles decreased ($p < 0.05$). Compared to the submax test, the ARVs of the GC, RF, VL, LD_lo, LD_up, and BB muscles were significantly higher during the all-out test. However, only for the RF muscle, the all-out test resulted in a significantly lower MDF value compared to the submax test. The most involved muscles that would need special attention in training seem to be the leg and shoulder girdle extensors and arm flexors but not the trunk and hip extensors.

Key Words fatigue, electromyography, average rectified value, power spectrum, median frequency

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25(9)/2470–2481

Journal of Strength and Conditioning Research

Introduction

Finding the key muscles that fatigue the first or the most during exercise is an important element of sport training planning. This is all the more important in individual sports, such as cycling, swimming, running, and rowing, where a good knowledge of the key fatiguing muscles is imperative for optimal conditioning and technical preparation.

Muscle fatigue can be monitored using surface electromyography (sEMG) during isometric (9,14,29) and dynamic muscle contraction (1,13,36,41). During submaximal isometric muscle contraction, increased sEMG amplitude is a consequence of the recruitment of new motor units (31) and their higher synchronization (32) helping the muscle to maintain an adequate level of submaximal intensity of action. When a muscle activates all available motor units and these eventually can no longer develop the expected force because of fatigue, the upward trend in the sEMG amplitude either stagnates or reverses (29).

On the other hand, fatigue causes the power spectrum of the sEMG signal to move toward lower frequencies soon after the beginning of muscular activity and much earlier before force or torque decrement (9,14,29). The steep initial decrease, known also as the "fatigue phase," is later stabilized at a certain level, known as the "endurance level" (15). The power spectral shift to lower frequencies (mean [MPF] or median [MDF] power frequency) during fatigue and its causes and mechanisms are well documented (6,7,12) and largely attributed to a diminished muscle fiber conduction velocity, although a discharge rate decline and motor unit synchronization may also play a role (10,43).

The sEMG spectral and amplitude changes, as described above, have also been shown in repetitive isokinetic knee extensions (5,20,21,41) and shoulder flexions (13), during stationary cycling at different intensities and duration (4,33) and maximal exhausting uphill running on a treadmill (1). High reliability (intraclass correlation coefficient [ICC] coefficients 0.80–0.88) and reproducibility (ICC coefficients 0.83–0.98) of the sEMG measures were observed (20,21). Moreover, So et al. (36) reported that during a 6-minute maximal rowing session on an ergometer (simulated race), more experienced and better trained rowers, compared to

younger and less experienced ones, develop a different fatiguing strategy, based on alternation of the MPF between some key muscles (i.e., erector spinae [ES] and rectus femoris [RF]). The authors defined this alternation of the MPF of 2 or more muscles as "biodynamic compensation," which allows time for the restitution process to occur while other muscles take up more of the work to continue the activity. Similar coordination (activation) strategies were also demonstrated in cycling (8), where the increase in activity of gluteus maximus (GM) and biceps femoris (BF) muscles compensate for potential fatigue and loss of force of the knee extensors (i.e., vastus lateralis [VL] and vastus medialis) by a higher moment of the hip extensors.

However, Štirn et al. (39) found no biodynamic compensation during a maximal 100-m front crawl swimming exercise as the MPF of the analyzed triceps brachii, latissimus dorsi, and pectoralis major muscles was only decreasing linearly throughout the exercise. A decrease in the soleus and gastrocnemius muscles was also established by Ament et al. (1) during a maximal intensity running exercise on a treadmill (33% inclination, speed of 5 $km \cdot h^{-1}$), whereas in another study, these authors (2) did not detect any decrease in the MDF of the same muscles during a medium-intensity running exercise (20% inclination, speed of 5 $km \cdot h^{-1}$). These and some others studies (4,33) show that the change in the MPF during a dynamic muscle contraction depends on exercise intensity and duration.

The aim of this study was to determine the muscles, which mostly respond to the all-out rowing test and could therefore be considered as the most relevant muscles for rowing. This was done by comparing the sEMG signals between a maximal (all-out test) and submaximal (submax test) intensity ergometer rowing tests and analyzing changes of the sEMG signals during each test.

Methods

Experimental Approach to the Problem

To find out the most exposed muscles during rowing, 10 rowing specific muscles (*gastrocnemius medialis* [GC], RF, VL, BF, GM, ES, lower *latissimus dorsi* [LD_lo], upper *latissimus dorsi* [LD_up], *brachioradialis* [BR], and *biceps brachii* [BB]) were investigated in 11 well-trained rowers. By comparing their sEMG signals between the submax (steady state) and all-out test, we expected that the muscles mostly involved in rowing would show the greatest difference in sEMG parameters. With another approach, to examine changes in sEMG parameters during each single test, we followed the same logic: the most involved muscles should have a greater response observed with sEMG amplitude and spectral changes.

To provide a steady-state condition at as high as possible intensity of rowing, the submax test intensity was defined by the power output (or speed of rowing) at the blood lactate (LA) concentration of 4 $mmol \cdot L^{-1}$ obtained from the multiphase incremental LA test. The sEMG signals of individual muscles were analyzed separately for each stroke in time and frequency domains (38,39). Using a normalized average rectified value (nARV) and median power frequency (nMDF) of the sEMG signal, the activation and fatigue patterns of individual muscles were monitored. To quantify the differences in the ARV and MDF between muscles and between the tests, these 2 parameters were observed and averaged at 3 key time points: (a) at the start (average of 10 strokes starting 10 seconds after the start–"Time point 10 seconds"), (b) at the end of the "steady-state" period (average of 10 strokes around (5 strokes before and after) 300th second after the start–"Time point 300 seconds"), and (c) at the end of the finishing action (average of the last 10 strokes–"Time point 360 seconds"). These specific key time points were chosen to sample the 3 clearly distinct phases in the simulated rowing race. Namely, a typical rowing race strategy consists of a fast start phase (0-60 seconds), a relatively constant pace of rowing (1-5th minute - e.g. 'steady state' period) and a rigorous finishing action (last minute) (37).

Based on previous studies (36), it was expected that the biodynamic compensation would occur between the leg and back muscles. It was hypothesized that (a) during the all-out test the activity (assessed by the ARV of the sEMG signal–ARV) and fatigue (assessed by the MDF of the sEMG signal–MDF) of the RF, VL, ES, and LD muscles would increase (↑ARV–activity increase and ↓MDF–fatigue increase) and (b) during the submax test the activity of these muscles would remain at the same level or would increase throughout the exercise but no fatigue would be detected (no ↓MDF). It was also hypothesized that (c) the RF, VL, ES, and LD muscles would be more active (↑ARV) during the all-out test and also more fatigued (↓MDF) at the end of the all-out test compared to the submax test. By comparing the differences, the role of individual muscle could be assessed under competitive rowing conditions.

Subjects

Eleven healthy, well-trained male rowers with regular rowing training over at least 4 years volunteered to participate in the study. They were members of 3 Slovenian rowing teams, from the senior and junior categories. Of the 11, 6 rowers had at least once participated in a world championship in a junior or senior category. One of them had competed in the lightweight category–up to 72.5 kg. The subjects' basic statistical data are shown in Table 1. Each subject was informed of potential risks and discomforts associated with the investigation, and all subjects gave their written, informed consent to participate. The study was conducted according to the Helsinki–Tokyo Declaration and had been approved by the National Medical Ethics Committee.

Procedures

Before the measurements were taken, the subjects were asked to participate in the test relatively rested, to avoid highly intensive training directly before the test or a day before, and to be appropriately nourished and hydrated. The subjects underwent

Table 1. Basic statistical data of the subjects ($N = 11$).*

	Mean ± *SD*	Min	Max
Age (y)	20.18 ± 3.09	16.00	27.00
Height (cm)	188.73 ± 5.78	179.00	197.00
Weight (kg)	87.99 ± 8.10	75.00	99.70
Years of training	8.00 ± 3.92	4.00	17.00

*The table shows mean values with SDs (Mean ± SD), and minimum (Min) and maximum (Max) values.

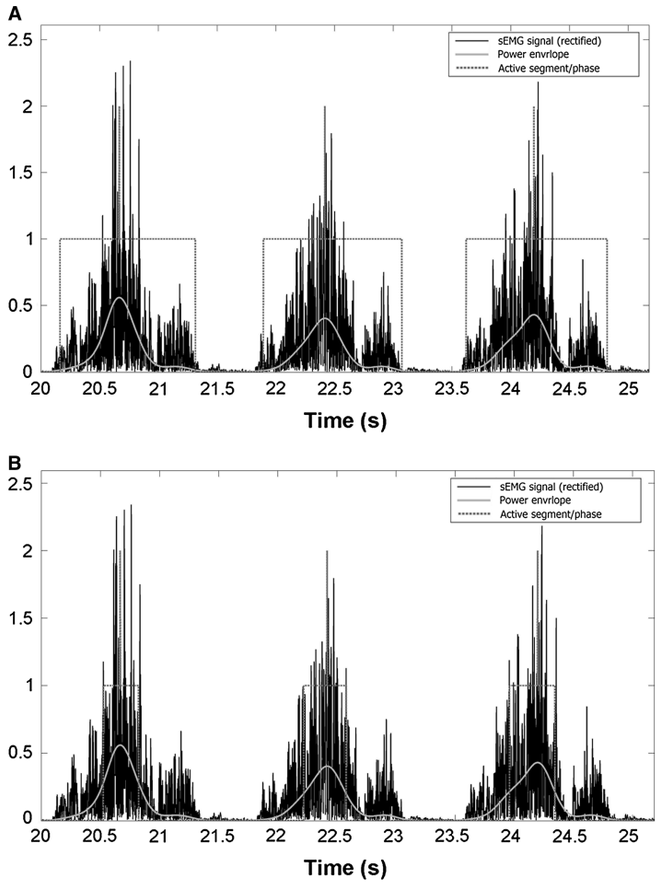

Figure 1. A) Rectified surface electromyographic (sEMG) signal (black line), power envelope of the sEMG signal (gray line), and active phases (dark gray dash line) of the vastus lateralis muscle for 3 consecutive rowing strokes. The active phases for calculating average rectified values (ARVs) are set on 1% of the power envelope's maximums. B) Rectified surface electromyographic (sEMG) signal (black line), power envelope of the sEMG signal (gray line), and active phases (dark gray dash line) of the vastus lateralis muscle for 3 consecutive rowing strokes. The active phases for calculating median power frequencies (MDFs) are set on 50% of the power envelope's maximums.

an experimental protocol, which was conducted over 2 days between which at least 48 hours elapsed. On *the first measurement day* (introductory measurements), the subjects participated in a multiphase incremental LA test on a Concept IIc rowing ergometer (Concept Inc., Morrisville, VT, USA), which consisted of 5 4-minute intervals with increasing speed of 0.11 $m \cdot s^{-1}$ (average pace time for 500 m 3 seconds lower) every step. With the LA test submaximal intensity of rowing was determined for the first of the 2 tests scheduled for *the second measurement day* (principal measurements). The first, submax test consisted of 6 minutes of rowing on an ergometer with the power output of rowing at the LA concentration of 4 $mmol \cdot L^{-1}$ (taken from the incremental LA test). This intensity was chosen because it is the most frequent training, test and predictive intensity in rowing (for review see [28,35]). The second, all-out test was a simulation of the race effort and consisted of 6 minutes of rowing on an ergometer with maximum intensity, the aim of which was to achieve the best result possible at the time. The rowing speed, tempo, and strategy were not predetermined. Both tests were performed after a 10-minute standardized warm-up, and a 60-minute rest was available between the tests. The submax test accounted for 82.60 ± 4.91% of the all-out test's power output.

Taking and Processing of Blood Samples. In the multiphase incremental LA test, a blood sample was taken before the start (at rest) and at the end of each test phase. In the other 2 tests (submax and all-out), a sample of blood was taken before and immediately after the test and in the third, fifth, and eighth minutes after the test. A 10-μl sample of capillary blood was taken from a hyperemic earlobe and was immediately diluted and stored in cuvettes until analysis. Blood LA concentration was determined using an Eppendorf photometer (Hamburg, Germany), and the measurement accuracy was ±0.10 $mmol \cdot L^{-1}$. Blood LA concentration parameters were defined as the LA_{rest} (LA

concentration before each rowing test), LA_{max} (the highest LA concentration after the rowing test in the third, fifth, or eighth minute), and dLA (change in LA concentration, defined as the difference between LA_{max} and LA_{rest}).

Standardized Warm-Up. Before each test, the subjects warmed up with a 10-minute rowing exercise on an ergometer at a constant speed which was 0.11 $m \cdot s^{-1}$ lower (the average pace time for 500 m was 3 seconds higher) than the speed measured at the lactate threshold (LT). The speed at the LT was defined as the braking point where the curve of the lactate concentration vs. rowing speed relationship (LA[v]) from the multiphase incremental LA test started to increase exponentially. The LT speed was therefore lower than the submax test speed.

Surface Electromyographic Signal Sampling and Processing. The EMG electrodes were positioned according to the SENIAM recommendation (18). Pairs of silver–silver chloride (Ag–AgCl) EMG electrodes (Hellige, Freiburg, Germany) with a 9-mm diameter were fastened to the right side of the body, over the GC, RF, VL, BF, GM, ES, LD_lo, LD_up, BR, and BB muscles. The distance between the electrodes in a pair was 2 cm, and the resistance was kept <5 kΩ. The sEMG signal was sampled using the Biovision EMG system (Wehrheim, Germany) and Dasy Lab 7.0 software (2002, National Instruments, Austin, TX, USA) with the sampling frequency of 2 kHz. The signals were processed using MATLAB 7.0.0. (R14) software (2004, The MathWorks, Inc., Natick, MA, USA). The raw EMG signal was first filtered using a fifth-order band-pass Butterworth filter with the lower and upper cut-off frequencies set to of 5 and 500 Hz, respectively. It was then processed in the time and frequency domain.

Within the 6-minute rowing tests, sEMG signals were analyzed only during the drive phase of each rowing stroke.

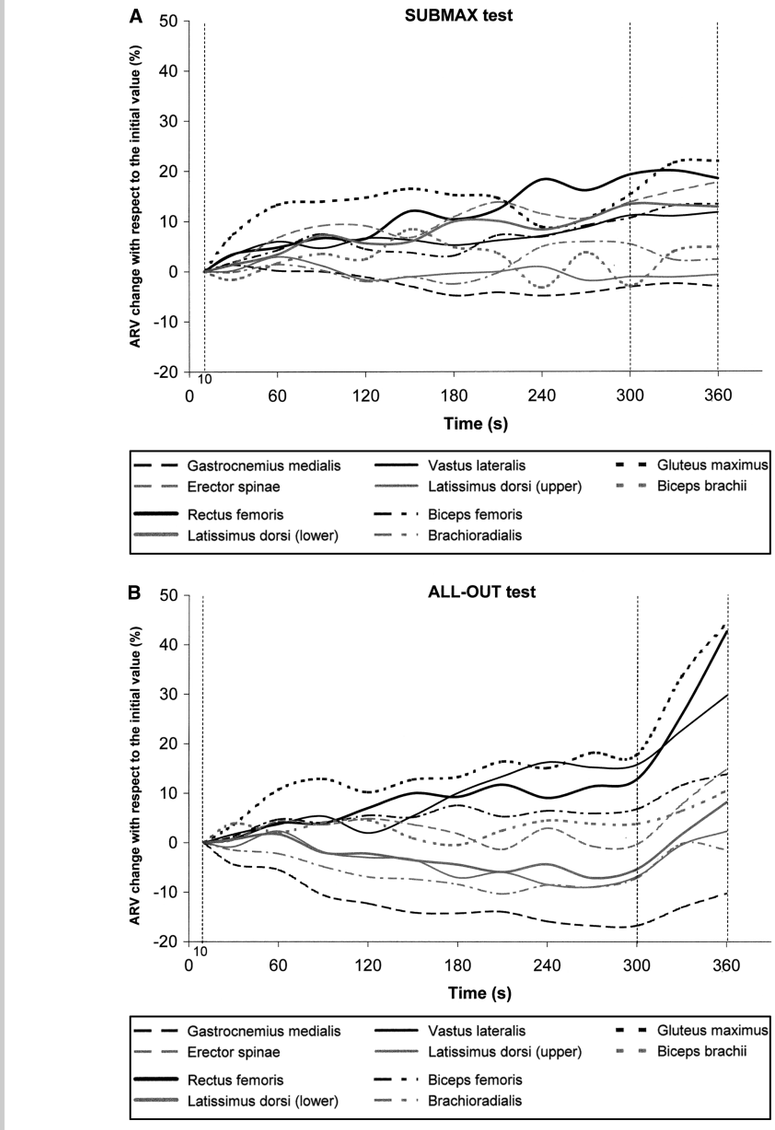

Figure 2. A) The course of mean values of normalized amplitudes (normalized average rectified values [nARV]) of the surface electromyographic (sEMG) signal with respect to the initial value during the submax test ($N = 11$). The data were obtained using equation 2. B) The course of mean values of nARV of the sEMG signal with respect to the initial value during the all-out test ($N = 11$). The data were obtained using equation 2.

During this phase, only the active segments of the sEMG signal (Figure 1) of each muscle were taken into consideration for further analysis. For this reason, the power envelope of the sEMG signal was first calculated using a sliding data window of length n (chosen to correspond to 250 milliseconds), which was advanced along the entire length of the signal. The generalized signal power was estimated at each sample point as an average of squared signal values contained within the data window centered at this sample point according to equation 1 (38,39). This power envelope was used to extract the active phases for each stroke and each muscle individually.

$$P\left(k+\frac{n}{2}\right)=\sum_{k}^{k+n-1}x^2(i). \quad (1)$$

Different approaches were used to extract signal segments for analysis of the signals in time and frequency domains. In the time domain, the average amplitude of the sEMG signal (ARV) was calculated separately for each stroke from the signal values contained within the active phase. The active phase for ARV estimation was defined as the time interval containing the local maximum of the power envelope corresponding to this particular stroke, in which the power of the signal was >1% of the maximum power for this stroke (Figure 1A). In the frequency domain, the standard periodogram method based on the short time Fourier transform (STFT) was used to estimate the power spectrum of sEMG for each stroke, and the median frequency of the power spectrum (MDF) was then calculated. The STFT is best used as spectral estimation method for stationary conditions (achieved, e.g., over short periods of sustained static muscle contractions). However, it has been shown that it can also be used successfully to assess spectral changes in dynamic conditions (25). To avoid the most nonstationary parts of the sEMG signal corresponding to low activity at the end and at the beginning of the active phase of each stroke, the authors decided to use a narrower part of each active phase than in the case of ARV estimation. Our own testing has shown that the differences between MDF values obtained using either 10, 30, or 50% of the local maximum power as the cut-off values for extraction of the active phases for MDF estimation were not significant. The correlations between MDF values obtained using these 3 different cut-off values were high ($R^2 > 0.80$) for all muscles and all tested subjects. The active phase for MDF estimation was therefore defined as the time interval containing the local maximum of the power envelope corresponding to this particular stroke, in which the power of the signal was >50% of the maximum power for this stroke (Figure 1B). By using this relatively high cut-off value (as opposed to the 1% cut-off level used for ARV estimation), only the most intensive part of the sEMG signal from each stroke was used in the spectral analysis.

For every 30 seconds of each 6-minute rowing test (see Figure 2), the average ARV and MDF values of 10 consecutive strokes were calculated. Thus the following 3 parameters were determined for the ARV and the MDF: ARV_10 and MDF_10 as the average of 10 strokes after the 10th second of rowing (to avoid unstable conditions at the

Table 2. Basic statistical data of some biomechanical, biochemical, and respiratory parameters during the 6-minute submaximal test (submax test) and simulated race (all-out test).*†

	Mean ± *SD*			Submax test		All-out test	
Variable	Submax test	All-out test	Sig.	Min	Max	Min	Max
Dist (m)	1,696.0 ± 99.1	1,833.6 ± 74.8	*0.001*	1,494.1	1,810.0	1,700.5	1,940.7
P_{mean} (W)	306.7 ± 39.0	371.67 ± 44.7	*0.000*	245.5	360.9	295.1	438.6
Fr_{mean} ($r \cdot min^{-1}$)	24.91 ± 1.91	29.27 ± 1.97	*0.000*	21.00	27.00	26.00	33.00
LA_{rest} ($mmol \cdot L^{-1}$)	1.25 ± 0.35	1.83 ± 0.45	*0.005*	0.90	2.10	1.20	2.80
LA_{max} ($mmol \cdot L^{-1}$)	4.64 ± 0.77	12.47 ± 1.94	*0.000*	3.10	5.70	9.50	16.00
dLA ($mmol \cdot L^{-1}$)	3.39 ± 0.83	10.65 ± 2.03	*0.000*	1.80	4.80	6.80	14.00
$relV\dot{O}_2max$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	58.89 ± 7.47	62.88 ± 8.67	*0.047*‡	52.42	77.82	50.32	84.33
$absV\dot{O}_2max$ ($L \cdot min^{-1}$)	5.15 ± 0.55	5.49 ± 0.51	*0.023*	4.40	6.08	4.83	6.32
$totV\dot{O}_2$ (L)	25.70 ± 2.58	27.30 ± 2.00	*0.017*	22.05	29.52	24.33	30.98
k_{ECON} ($ml \cdot m^{-1}$)	15.17 ± 1.53	14.90 ± 1.10	*0.459*	13.08	18.18	12.70	16.13

*Dist = total rowing distance, P_{mean} = average power output, Fr = average stroke frequency, LA_{rest} = blood lactate concentration before the test, LA_{max} = the highest blood lactate concentration after the test, dLA = change in blood lactate concentration (difference between LA_{max} and LA_{rest}), $relV\dot{O}_2max$ = maximum relative volume of oxygen consumption per minute, $absV\dot{O}_2max$ = maximum absolute volume of oxygen consumption per minute, $totV\dot{O}_2$ = total volume of oxygen consumption, k_{ECON} = gross economy of rowing, Sig. = statistical significance,

†The table shows mean values with *SD*s (mean ± *SD*) and minimum (Min) and maximum (Max) values for 11 subjects ($N = 11$). Statistically significant differences (p) are shown in bold italics.

‡A nonparametric test was used for calculating the differences because the variable ($relV\dot{O}_2max$) was not normally distributed.

start), ARV_300 and MDF_300 as the average of 5 strokes before and 5 strokes after the 300th second of rowing, and ARV_360 and MDF_360 as the average of the last 10 strokes, with the last 3 strokes being excluded from the analysis. The ARV and MDF values at each time point were also normalized (nARV, nMDF) with respect to the initial ARV and MDF values at the 10th second as shown in equations 2 and 3, where T is an index of the selected time point:

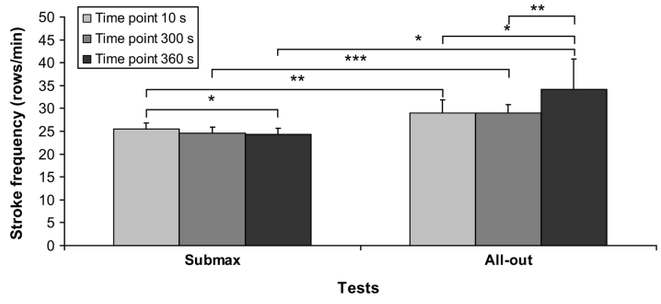

Figure 3. Mean values and *SD*s of stroke frequency during the submax and all-out test at individual time points (10, 300, 360 seconds). Statistically significant differences are shown as follows: *$p < 0.050$; **$p \leq 0.010$, ***$p \leq 0.001$.

$$n\mathrm{ARVT}(\%) = \left(\frac{\mathrm{ARV}_T - \mathrm{ARV}_{10}}{\mathrm{ARV}_{10}} \cdot 100\%\right), \quad (2)$$

$$n\mathrm{MDFT}(\%) = \left(\frac{\mathrm{MDF}_T - \mathrm{MDF}_{10}}{\mathrm{MDF}_{10}} \cdot 100\%\right). \quad (3)$$

Measurement of Oxygen Consumption. Oxygen consumption during the tests was measured using a Cosmed transportable measurement system (model K4b^2, Rome, Italy). Besides the maximum relative ($\mathrm{rel}\dot{V}O_2\mathrm{max}$) and absolute ($\mathrm{abs}\dot{V}O_2\mathrm{max}$) volume of oxygen consumption per minute and the total volume of oxygen consumption ($\mathrm{tot}\dot{V}O_2$), obtained during each 6-minute rowing test, the coefficient of gross economy of rowing ($k_{\mathrm{ECON}} = \mathrm{tot}\dot{V}O_2 \cdot d^{-1}$; where d is the rowing distance) was also calculated.

Measurement of Mechanical Parameters of Rowing. Using the software that was enclosed with the Concept IIc ergometer, the total rowing distance (Dist) and the average rowing power (P_{mean}) were measured, along with the average stroke frequency ($\mathrm{Fr}_{\mathrm{mean}}$) and the stroke frequency at time point 10, 300, and 360 seconds (Fr_{10}, Fr_{300}, Fr_{360}, respectively) in both tests. At each time point, the stroke frequency was averaged the same way as the ARVs and MDFs were (see Experimental Approach to the Problem).

Statistical Analyses

The data were processed by the SPSS 13.0 for Windows statistical package (SPSS Inc., Chicago, IL, USA). Standard statistical methods were used for the calculation of means, *SD*s, and to test normality of the distribution of variables. *The general linear model analysis of variance with repeated measures* (RM ANOVA) was used to test the changes in variables over time (time points 10, 300, and 360 seconds) within the same rowing test. If statistically significant differences were found, additional post hoc analysis was performed for RM ANOVA using the Bonferroni test. A *paired samples t-test* was used for testing the differences between variables of the submax and all-out rowing tests. If variable distribution deviated from normal distribution, a Wilcoxon signed rank sum test for 2 paired samples was used for testing the differences. The $p \leq 0.05$ criterion (2-tailed test) was used for establishing statistical significance.

Results

Biomechanical, Biochemical, and Respiratory Parameters Before, During, and After a 6-minute Rowing Exercise

Table 2 shows the basic statistical parameters of biomechanical, biochemical, and respiratory variables before,

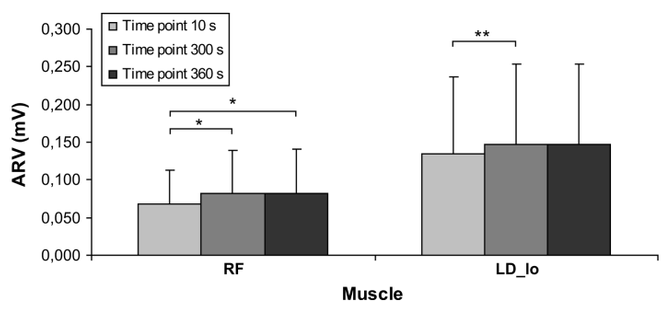

Figure 4. Mean values and *SD*s of average rectified value (ARV) during the submax test at individual time points (10, 300, and 360 seconds) for the rectus femoris (RF) and lower latissimus dorsi (LD_lo) muscles. Statistically significant differences are shown as follows: *$p < 0.050$; **$p \leq 0.010$. There were no significant differences in the ARV in other muscles, which are therefore not shown.

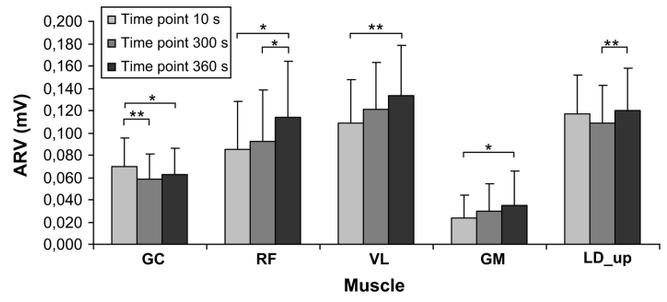

Figure 5. Mean values and *SD*s of average rectified value (ARV) during the all-out test at individual time points (10, 300, and 360 seconds) for the gastrocnemius medialis (GC), rectus femoris (RF), vastus lateralis (VL), and gluteus maximus (GM) muscles and the upper part of the latissimus dorsi (LD_up) muscle. Statistically significant differences are shown as follows: *$p < 0.050$; **$p \leq 0.010$. There were no significant differences in the ARV in other muscles, which are therefore not shown.

during, and after both rowing tests and the statistical significance of the differences between the tests. All variables, but not the maximum relative oxygen consumption (rel$\dot{V}O_2$max) during the submax test ($p = 0.011$), and the stroke frequency at the time point 360 seconds (Fr_{360}) during the all-out test ($p = 0.003$) were normally distributed. Significant differences between the tests ($p < 0.05$) occurred in all variables, except for gross economy of rowing (k_{ECON}).

During the all-out test, the subjects covered a longer distance ($p = 0.001$), developed higher average power output ($p < 0.001$), and achieved higher average stroke frequency ($p < 0.001$) compared to the submax test. Lactate concentration at rest (LA_{rest}) before the all-out test was significantly higher than before the submax test ($p = 0.005$). The maximum lactate concentration (LA_{max}) and the change in the lactate concentration (dLA) after the all-out test were significantly higher compared to LA_{max} and dLA after the submax test ($p < 0.001$ for both parameters). The relative and absolute $\dot{V}O_2$max and the total oxygen consumption (tot$\dot{V}O_2$) were also significantly higher during the all-out test ($p = 0.047$, $p = 0.023$, and $p = 0.017$, respectively), whereas the k_{ECON} did not differ significantly ($p = 0.459$) between the tests.

The stroke frequencies were significantly higher at each time point (Fr_{10}, Fr_{300}, and Fr_{360}) during the all-out test ($p = 0.003$, $p < 0.001$, and $p = 0.018$, respectively). However, there was a significant decrease in the stroke frequency between Fr_{10} and Fr_{360} ($p = 0.033$) during the submax test and a significant increase between Fr_{10} and Fr_{360} ($p = 0.025$) and Fr_{300} and Fr_{360} ($p = 0.005$*) during the all-out test (Figure 3).

Activation and Fatiguing Patterns During the Submax and All-Out Tests

Figure 1 shows the course of changes of normalized amplitudes (nARV) of the sEMG signal of the analyzed muscles with respect to their initial value for the submax and all-out tests. During the submax test, the nARV values of the GC, LD_up, BR, and BB muscles remained relatively steady, whereas nARVs of the RF, VL, BF, GM, ES, and LD_lo were increasing during the entire observation period. However, during the all-out test, there was no change in the normalized sEMG signal amplitude of the ES, BF, and BB muscles, a decrease in nARV of the GC, LD_lo, LD_up, and BR muscles and an increase in nARV of the RF, VL, and GM muscles. Additional increase in the nARV was also observed in all muscles during the finishing action in the last minute of the all-out test.

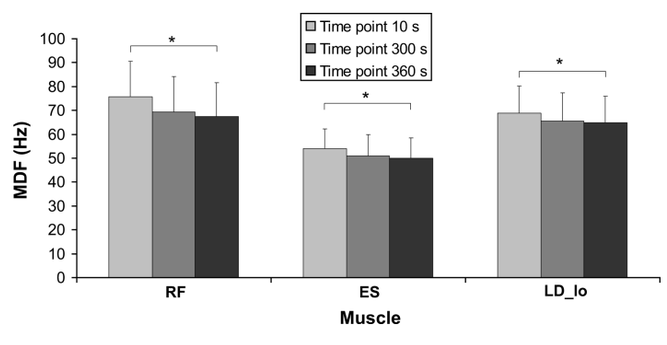

Figure 6. Mean values and *SD*s of the median power frequencies (MDFs) during the all-out test at individual time points (10, 300, and 360 seconds) for the rectus femoris (RF), erector spinae (ES), and the lower part of the latissimus dorsi (LD_lo) muscles. Statistically significant differences are shown as follows: *$p < 0.050$. There were no significant differences in the MDF in other muscles, which are therefore not shown.

Submax Test. Only in the RF muscle was the ARV at the time point 360 seconds (ARV_360) of the submax test significantly higher than the ARV at the time point 10 seconds (ARV_10; $p = 0.041$), whereas in the RF and LD_lo, the ARVs were significantly higher at the time point 300 seconds (ARV_300; $p = 0.023$ and $p = 0.004$, respectively) compared to ARV_10 (Figure 4). There were no

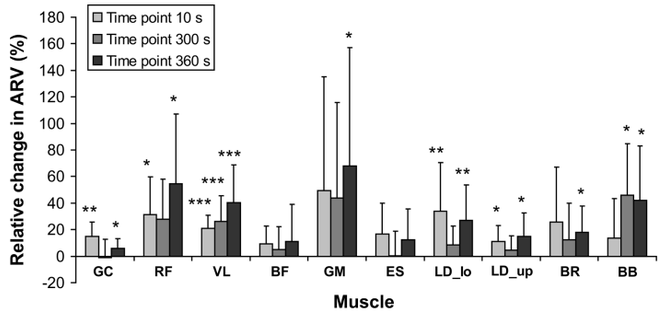

Figure 7. Relative changes in the average amplitude of the sEMG signal (average rectified value [ARV]) between the tests at time points of 10, 300, and 360 seconds (defined as the $ARV_{all\text{-}out}/ARV_{submax}$ ratio) for the following muscles: GC = m. gastrocnemius medialis, RF = m. rectus femoris, VL = m. vastus lateralis, BF = m. biceps femoris, GM = m. gluteus maximus, ES = m. erector spinae, LD_lo = lower part of the m. latissimus dorsi, LD_up = upper part of the m. latissimus dorsi, BR = m. brachioradialis, BB = m. biceps brachii. Mean values and *SD*s are shown. Statistically significant differences between the tests are shown as $^{*}p < 0.050$; $^{**}p \leq 0.010$; $^{***}p \leq 0.001$.

statistically significant differences between ARV_300 and ARV_360 in any of the muscles.

During the submax test, the average MDF did not differ significantly ($p > 0.050$) between individual time points (10, 300, and 360 seconds) in any of the analyzed muscles.

All-Out Test. During the all-out test (Figure 5), the ARV_360 values were significantly higher than the ARV_10 values in the RF ($p = 0.038$), VL ($p = 0.009$), and GM ($p = 0.044$) muscles, and the ARV_300 values in the RF ($p = 0.045$) and LD_up ($p = 0.007$) muscles. Only in the GC muscle were the ARV_300 ($p = 0.002$) and ARV_360 ($p = 0.048$) significantly lower than the ARV_10. There were no statistically significant differences ($p > 0.050$) in other muscles.

On the other hand, the average MDF (Figure 6) at the time point 360 seconds (MDF_360) was significantly lower compared to the time point 10 seconds (MDF_10) of the RF ($p = 0.022$), ES ($p = 0.037$), and LD_lo ($p = 0.027$) muscles. No statistically significant differences ($p > 0.050$) were established between other time points of these and other muscles.

Surface Electromyographic Signal Differences Between the Tests. The greatest statistically significant differences in the ARV between the tests were observed in the VL muscle, because the ARV was constantly higher during the all-out test than during the submax test, and the difference increased with the duration of rowing (Figure 7). A different structure of the differences between the tests was seen in the GC, RF, LD_lo, and LD_up muscles, where the amplitude of the sEMG signal during the all-out test was significantly higher ($p < 0.05$) at the time point 10 and 360 seconds but not at the time point 300 seconds. In the BB muscle, the ARV_10 did not significantly differ between the tests, whereas at the time point 300 and 360 seconds, it did ($p = 0.021$ and $p = 0.015$, respectively). In the GM and BR muscles, only the ARV_360 was significantly higher during the all-out test compared to the submax test ($p = 0.040$ and $p = 0.016$, respectively). In other 2 muscles (BF and ES), no statistically significant differences were found between the tests.

The MDF significantly differed between the tests only in the RF muscle at time points of 300 seconds ($-7.15 \pm 4.60\%$, $p = 0.004$) and 360 seconds ($-10.96 \pm 6.22\%$, $p = 0.001$) but not at the time point 10 seconds (Figure 8). There were no statistically significant differences in the MDF in other muscles.

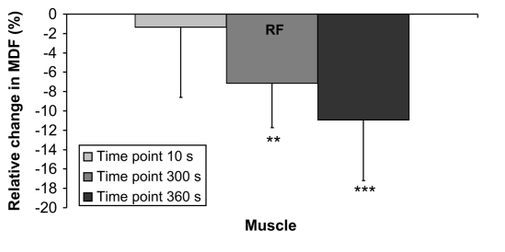

Figure 8. Relative changes in the average median power frequency (MDF) between the tests at time points of 10, 300, and 360 seconds (defined as the $MDF_{all\text{-}out}/MDF_{submax}$ ratio) for the rectus femoris (RF) muscle. Mean values and *SD*s are shown. Statistically significant differences between the tests are shown as $^{**}p \leq 0.010$; $^{***}p \leq 0.001$.

Discussion

As had been expected, during the all-out test the subjects covered a longer distance and achieved higher average power output, higher average stroke frequency, higher LA concentrations, higher maximum relative and absolute, and total oxygen consumption compared to the submax test; however, no substantial differences were observed in gross economy of rowing. The changes in the EMG parameters during the submax test were minimal. The amplitude of the sEMG signal systematically increased only in the RF and LD_lo muscles, whereas no decrease in the MDF was observed in any of the muscles. Slightly larger changes in the sEMG signal occurred during the all-out test, as the ARV of the VL, RF, and GM muscles increased, while at the same time the MDF of the RF, ES, and LD_lo muscles decreased. Compared to the submax

test, during the all-out test, the highest increase in the ARV was observed in the VL muscle and also in the ARV of the RF, LD_lo, LD_up, BB, and GC muscles, whereas the MDF decreased only in the RF muscle.

Compared to other studies, the highest LA concentration during the all-out test in this study (12.47 ± 1.94 mmol·L^{-1}) was slightly lower than the one measured by So et al. (36) (13–14 mmol·L^{-1}) during a maximum 6-minute effort and was within the range of the values reported by Fiskersrand and Seiler (11) for competitive and supramaximal intensity (8–14 mmol·L^{-1}) and by Shephard (35) in his 1998 review article (11–19 mmol·L^{-1}). The maximum relative (62.88 ± 8.67 ml·kg^{-1}·min^{-1}) and absolute (5.49 ± 0.51 L·min^{-1}) oxygen consumption values were also slightly lower when compared with other all-out tests on rowing ergometers (Hagerman [16]: 6.1 ± 0.6 L·min^{-1}; Hagerman et al. [17]: 5.95 L·min^{-1} or 67.6 ml·kg^{-1}·min^{-1}; Lakomy and Lakomy [19]: 4.71 ± 0.39 L·min^{-1}; Mäestu et al. [27]: 67.4 ± 7.4 ml·kg^{-1}·min^{-1}). However, the average power output during the all-out test in this study (371.67 ± 44.69 W) was similar compared to that reported by Mäestu et al. (27) for the national-class rowers (329.44 ± 41.37 W), whereas the average time over 500 m (1:38.6 ± 4.1 seconds) was lower compared to a similar study conducted by So et al. (36) (1:42.1 ± 0.5 seconds) on 2 lightweight rowers. These comparisons lead to the conclusion that the subjects performed the test according to the best of their ability and that the results are relevant for highly trained rowers.

Rowing with the submaximal intensity was indicated by the low blood LA concentration at the end of rowing (4.64 ± 0.77 mmol·L^{-1}). The submax test loading was prescribed with a predefined intensity (4 mmol·L^{-1}), and it was performed by almost complete absence of substantial changes in the sEMG signal parameters. Of all analyzed muscles, the ARV increased significantly only in the RF and LD_lo muscles (20 and 13%, respectively), whereas the MDF values did not change significantly throughout the test. In the study involving professional cyclists who cycled with an intensity of 80% of $\dot{V}O_2$max (comparable to the submaximal intensity in this study) the RMS of the VL muscle increased by about 10, 15, 30, and 40% after 10, 20, 30, and 40 minutes, respectively (33), whereas no statistically significant changes were observed in the power spectrum of the sEMG signal, even though the oxygen consumption was increasing all the time (24,33). It can therefore be concluded that the fatigue of the RF and LD_lo muscles was similar to that reported by Petrofsky (33) for the VL muscle during submaximal intensity cycling (80% of $\dot{V}O_2$max). The increase in the amplitude of the sEMG signal during rowing indicates that new motor units were recruited (31) and that the form of the action potential changed (7) because of fatigue. A higher exposure of the RF muscle in means of higher activation, represented by significant increase in ARV during rowing, appears to be the consequence of the muscle's participation in both knee extension and hip flexion. Therefore, the submax test represented an almost perfect steady state at high-intensity rowing that can serve as a base for comparison with the all-out test.

It was expected that the muscles that showed the signs of fatigue at the submaximal intensity would fatigue even more during the all-out test. As the amplitude of the sEMG signal of the RF muscle increased already during the submax test, it increased significantly also during the all-out test. However, during the all-out test, the amplitude increased not only in the RF but also in the VL and GM muscles. These muscles engage in leg extension. Despite the above, the changes in the ARV in the first 300 seconds were not particularly large, because in some muscles they increased additionally and substantially over the last minute, which indicates the existence of some reserve before the last 60 seconds of the all-out test. The increase in the ARV of the RF, VL and GM muscles until the 5th minute (13-18%) was similar to the increase in the amplitude observed by Mäestu et al. (28) for the VL muscle during 2000-m simulated race on the rowing ergometer (about 20%) and Petrofsky (33), also for the VL during cycling at 100% of VO_2max until failure (about 15%). As well as for the first 5 minutes, the increase in the ARV of the abovementioned muscles in the last minute of the present study was similar to that reported by Mäestu et al. (28) and *Vesterinen et al.* (40) (about 25%) during the last 50 m of each of the four 850-m series of cross-country skiing on roller skies at racing velocity (a combined (summed) amplitude of triceps brachii and VL muscles). However, the overall increase in the amplitude during the all-out test in this study (by 30-44%) was perceptibly (10-14%) greater (depending on the muscle) than the overall change in the amplitude reported by Petrofsky (33), but still similar to those (about 47%) determined by Mäestu et al. (28) for well trained rowers. On the other hand, changes in the power spectrum were not that high (no more than 11%). In a similar study in rowers, So et al. (36) established that the MPF of RF and ES can decrease by >25% during maximum rowing before reaching the lowest value (i.e., endurance level). However, Petrofsky (33) reported a 20% decline in the MPF of VL during cycling at 100% of $\dot{V}O_2$max. The above indicates that the increase in the ARV in the last minute of rowing was mainly because of the finishing action (and not fatigue), when the stroke frequency increased significantly as well. It seems obvious that the subjects rowed with some reserve until the last minute during the all-out test.

A change in the sEMG signal can also stem from the structure of the muscle fibers. In muscles with a higher proportion of slow-twitch and fatigue-resistant fibers, as typically observed in rowers (37), less fatigue and thus smaller changes in the EMG parameters at submaximal intensities can be expected compared to those with a higher proportion of fast-twitch fibers (22,23). Additionally, a temperature compensation for the decline in the MPF (and MDF) can be expected (26). However, given the preliminary 10-minute

standardized warm-up, this effect does not appear very significant because it has been established that the MPF changes by 2.82 ± 0.27 Hz°C^{-1} during high-intensity dynamic exercise (26) and MDF by 3.48% ° C^{-1} at 80% of the maximum voluntary contraction (30), whereas with higher intensity of loading from rest to 100% of $\dot{V}O_2$max the temperature can rise by only about 3.5° C (33).

The last minute of rowing during the all-out test differs considerably from the earlier pattern of muscle activity (Figure 2). It seems less likely that the change could be related only to fatigue. Most probably, the bulk of the increase in the ARV stems from the tactics related to finishing, which is common at the end of a rowing race. Even though the ARV increased in the last minute in most of the muscles, only the changes in the RF and LD_up muscles were statistically significant. One of the reasons lies in the fact that the subjects performed the finish in different ways or with a different intensity, while on the other hand the reason could be in greater fatigue or technical exposure of the 2 muscles. The increase in the amplitude of the sEMG signal because of fatigue is probable only with the RF muscle but not the LD_up muscle, because the ARV of the latter did not change substantially with respect to the initial value until the 300th second, and no significant change occurred in the MDF. Therefore, the increase in the amplitude of LD_up muscle in the last minute of rowing was mainly attributed to tactical reasons.

The GC occupies a special place among the analyzed muscles, because during rowing, its EMG amplitude decreased below the initial value. It is assumed that the plantar flexion was used more prominently in the initial phase of rowing than in the continuation. The GC muscle is a 2-joint muscle enabling a transfer of energy between the segments (42). Moreover, it is a muscle, which is characterized by a high share of fast-twitch fibers (3) and fatigues quickly. However, fatigue is probably not the reason for the lower amplitude of the sEMG signal, because it would also cause a decrease in the MDF, which did not happen. It is therefore more likely that in the later rowing phases a programed decrease in plantar flexion occurred.

The majority of differences in muscle activation between the submax and all-out tests at the start were related to the leg (GC, RF, and VL) and shoulder girdle (LD_lo, LD_up) extensors. It is interesting to note that the hip and trunk extensors and the arm flexors did not engage. In the middle, steady-state phase of rowing, the activation of most of the analyzed muscles did not differ considerably between the 2 tests. Higher activation was only observed in the VL and BB muscles (Figure 7). It therefore appears that these 2 muscles were the most responsible for the maintenance of the pace in that rowing phase, particularly the VL muscle, because the changes in its activation were the most systematic of all the muscles. In the final phase of rowing, the major differences could be seen in muscle activation (and less in fatigue), mainly on account of the finish. Here, the same muscles as at the beginning of rowing were engaged and, additionally, the arm muscles (BR and BB) were also activated. It thus seems that the temporary increase in the tempo (at start and finish) required a complex response of the majority of muscles participating in the execution of a stroke, whereas the maintenance of the pace was because of engagement of only VL and BB muscles.

The increase in the ARV of the GM muscle was the largest in all investigated rowing phases, yet the changes were not statistically significant, with the exception of those at the finish. This shows that rowers might apply different strategies in using this muscle. Particularly interesting was the absence of an increase in the activity of the BF and especially ES muscle, which was, along with RF the most stressed muscle in the study of So et al. (36). This might be related to the specific rowing technique used by the subjects in this study. Slovenian rowers are taller (in this study: 188.73 ± 5.78 cm), and because of this, they do not have to lean too much forward with the trunk at the catch. Thus, they are probably used to rowing with an extended and fixed trunk. However, the Chinese rowers are on average smaller (175.1 ± 3.2 cm [36]) and supposedly, they have to lean forward more. In this way, they have to activate and stress the trunk extensors more. It may thus be concluded that in this study, trunk stabilization was more important than its extension. On the other hand, this may also be associated with pain in the lower back, which is common among rowers (34).

It can be concluded that the majority of changes in the sEMG signals of the analyzed muscles during rowing at a competitive level were related to the increase in the amplitude of the sEMG signal, whereas the changes in the frequency content of the signal were relatively small. The above shows that, at a competitive level, the fatigue processes could be compensated for by additional recruitment of motor units, which is probably owing to rowers' higher proportion of slow-twitch muscle fibers. During the all-out test, the most activated were the leg extensor muscles in general, yet, surprisingly, no substantial increase in ARV was observed in the trunk extensors. At the same time, neuro-muscular fatigue occurred in the RF, ES, and LD_up muscles, whereas no substantial fatigue was seen during the submax test.

Practical Applications

A comparison of the submax and all-out tests showed that at the start, the leg and shoulder girdle extensors were the most important muscles. In the middle part of the simulated race, the knee extensor and elbow flexor muscles were mainly responsible for maintaining a constant rowing pace. However, during the last minute, when the subjects performed the final strain (finishing action), the leg and shoulder girdle extensor muscles were involved again, additionally accompanied by the elbow flexors. Interestingly, trunk extensor muscles do not seem to be critical, which might be related to the specific rowing technique used by the subjects.

Acknowledgments

This study was funded by grants from the Slovenian Research Agency (grant no. L5-6570 and grant no. L5-7112), the Foundation for Financing Sports Organizations in Slovenia

and the Government of the Republic of Slovenia, Ministry of Higher Education, Science and Technology. Special thanks go to the Rowing Federation of Slovenia, to the selector Miloš Janša, and all other coaches who supported this study. The researchers would also like to thank Dr. Radoje Milić and his assistants from the Laboratory for Sports Physiology, Faculty of Sport, University of Ljubljana, and Miloš Kalc for their help with the measurements.

References

1. Ament, W, Bonga, GJ, Hof, AL, and Verkerke, GJ. Electromyogram median power frequency in an exhausting exercise. *J Electromyogr Kinesiol* 3: 214–220, 1993.
2. Ament, W, Bonga, GJ, Hof, AL, and Verkerke, GJ. Electromyogram median power frequency in dynamic exercise at medium exercise intensities. *Eur J Appl Physiol Occup Physiol* 74: 180–186, 1996.
3. Burke, RE, Levine, DN, Tsairis, P, and Zajac, FE III. Physiological types and histochemical profiles in motor units of the cat gastrocnemius. *J Physiol* 234: 723–748, 1973.
4. Camic, CL, Housh, TJ, Johnson, GO, Hendrix, CR, Zuniga, JM, Mielke, M, and Schmidt, RJ. An EMG frequency-based test for estimating the neuromuscular fatigue threshold during cycle ergometry. *Eur J Appl Physiol* 108: 337–345, 2010.
5. Crenshaw, AG, Gerdle, B, Heiden, M, Karlsson, S, and Fridén, J. Intramuscular pressure and electromyographic responses of the vastus lateralis muscle during repeated maximal isokinetic knee extensions. *Acta Physiol Scand* 170: 119–126, 2000.
6. DeLuca, CJ. The use of surface electromyography in biomechanics. *J Appl Biomech* 13: 135–163, 1997.
7. Dimitrova, NA and Dimitrov, GV. Interpretation of EMG changes with fatigue: Facts, pitfalls, and fallacies. *J Electromyogr Kinesiol* 13: 13–36, 2003.
8. Dorel, S, Drouet, JM, Couturier, A, Champoux, Y, and Hug, F. Changes of pedaling technique and muscle coordination during an exhaustive exercise. *Med Sci Sports Exerc* 41: 1277–1286, 2009.
9. Falla, D, Rainoldi, A, Merletti, R, and Jull, G. Myoelectric manifestation of sternocleidomastoid and anterior scalene muscle fatigue in chronic neck pain patients. *Clin Neurophysiol* 114: 488–495, 2003.
10. Farina, D, Fattorini, L, Felici, F, and Filligoi, G. Nonlinear surface EMG analysis to detect changes of motor unit conduction velocity and synchronization. *J Appl Physiol* 93: 1753–1763, 2002.
11. Fiskersrand, Å and Seiler, KS. Training and performance characteristics among Norwegian International Rowers 1970–2001. *Scand J Med Sci Sports* 14: 303–310, 2003.
12. Fitts, RH. Cellular mechanisms of muscle fatigue. *Physiol Rev* 74: 49–94, 1994.
13. Gerdle, B, Elert, J, and Henriksson-Larsén, K. Muscular fatigue during repeated isokinetic shoulder forward flexion in young females. *Eur J Appl Physiol* 58: 666–673, 1989.
14. Gerdle, B, Eriksson, NE, and Hagberg, C. Changes in the surface electromyogram during increasing isometric shoulder forward flexion. *Eur J Appl Physiol* 57: 404–408, 1988.
15. Gerdle, B and Fugl-Meyer, A. Is the mean power frequency shift of the EMG a selective indicator of fatigue of the fast twitch motor units? *Acta Physiol Scand* 145: 129–138, 1992.
16. Hagerman, FC. Applied physiology of rowing. *Sports Med* 1: 303–326, 1984.
17. Hagerman, FC, Connors, MC, Gault, JA, Hagerman, GR, and Polinski, WJ. Energy expenditure during simulated rowing. *J Appl Physiol* 45: 87–93, 1978.
18. Hermens, HJ, Freriks, B, Merletti, R, Hägg, GG, Stegeman, D, Blok, J, Rau, G, and Disselhorst-Klug, C. *European Recommendations for Surface Electromyography.* Enschede, Netherlands: Roessingh Research and Development, 1999.
19. Lakomy, HKA and Lakomy, J. Estimation of maximum oxygen uptake from submaximal exercise on Concept II rowing ergometer. *J Sports Sci* 11: 227–232, 1993.
20. Larsson, B, Karlsson, S, Eriksson, M, and Gerdle B. Test–retest reliability of EMG and peak torque during repetitive maximum concentric knee extensions. *J Electromyogr Kinesiol* 13: 281–287, 2003.
21. Larsson, B, Månsson, B, Karlberg, C, Syvertsson, P, Elert, J, and Gerdle, B. Reproducibility of surface EMG variables and peak torque during three sets of ten dynamic contractions. *J Electromyogr Kinesiol* 9: 351–357, 1999.
22. Linssen, WH, Stegeman, DF, Joosten, EM, Binkhorst, RA, Merks, MJ, ter Laak, HJ, and Notermans, SL. Fatigue in type I fiber predominance: A muscle force and surface EMG study on the relative role of type I and type II muscle fibers. *Muscle Nerve* 14: 829–837, 1991.
23. Linssen, WH, Stegeman, DF, Joosten, EM, Merks, HJ, ter Laak, HJ, Binkhorst, RA, and Notermans, SL. Force and fatigue in human type I muscle fibres. A surface EMG study in patients with congenital myopathy and type I fibre predominance. *Brain* 114: 2123–2132, 1991.
24. Lucía, A, Hoyos, J, and Chicharro, JL. The slow component of $\dot{V}O_2$ in professional cyclists. *Br J Sports Med* 34: 367–374, 2000.
25. MacIsaac, D, Parker, PA, and Scott RN. The short-time Fourier transform and muscle fatigue assessment in dynamic contraction. *J Electromyogr Kinesiol* 11: 439–449, 2001.
26. Madigan, ML and Pidcoe, PE. A muscle temperature compensation technique for EMG fatigue measures. *Med Sci Sports Exerc* 34: 780–784, 2002.
27. Mäestu, J, Cicchella, A, Purge, P, Ruosi, S, Jürimäe, J, and Jürimäe, T. Electromyographic and neuromuscular fatigue thresholds as concepts of fatigue. *J Strength Cond Res* 20: 824–828, 2006.
28. Mäestu, J, Jürimäe, J, and Jürimäe, T. Monitoring of performance and training in rowing. *Sports Med* 35: 597–617, 2005.
29. Merletti, R and Roy, S. Myoelectrical and mechanical manifestations of muscle fatigue in voluntary contractions. *J Orthop Sports Phys Ther* 24: 342–353, 1996.
30. Merletti, R, Sabbahi, MA, and De Luca, CJ. Median frequency of the myoelectric signal. Effects of muscle ischemia and cooling. *Eur J Appl Physiol* 52: 258–265, 1984.
31. Moritani, T, Nagata, A, and Muro, M. Electromyographic manifestation of muscular fatigue. *Med Sci Sports Exerc* 14: 198–202, 1982.
32. Person, RS and Kudina, LP. Cross-correlation of electromyograms showing interference patterns. *Electroencephalogr Clin Neurophysiol* 25: 58–68, 1968.
33. Petrofsky, JS. Frequency and amplitude analysis of the EMG during exercise on the bicycle ergometer. *Eur J Appl Physiol Occup Physiol* 41: 1–15, 1979.
34. Rumball, JS, Lebrun, CM, Di Ciacca, SR, and Orlando, K. Rowing Injuries.*Sports Med* 35: 537–555, 2005.
35. Shephard, RJ. Science and medicine of rowing: A review. *J Sports Sci* 16: 603–620, 1998.
36. So, RCH, Tse, MA, and Wong, SCW. Application of surface electromyography in assessing muscle recruitment patterns in a six-minute continuous rowing effort. *J Strength Cond Res* 21: 724–730, 2007.
37. Steinacker, JM. Physiological aspects of training in rowing. *Int J Sports Med* 14: S3–S10, 1993.
38. Štirn, I. Ugotavljanje utrujenosti mišic med plavanjem na 100 metrov. [Establishing muscle fatigue during 100-meter swimming]. Master's thesis, University of Ljubljana, Faculty of Sport, Ljubljana, 2006.
39. Štirn, I, Vižintin, T, Kapus, V, Jarm, T, and Strojnik, V. Change of mean frequency of EMG-signal during 100 meter maximal freestyle swimming. In: *IFMBE Proceedings 16: 11th Mediterranean Conference on Medical and Biomedical Engineering and Computing–Medicon 2007.* Jarm, T, Kramar, P, and Zupanič, A, eds. Ljubljana, Faculty of Electrical Engineering, 2007. pp. 1002–1005.

40. Vesterinen, V, Mikkola, J, Nummela, A, Hynynen, E and Häkkinen, K. Fatigue in a simulated cross-country skiing sprint competition. *J Sports Sci 27:* 1069–1077, 2009.

41. Wretling, M-L, Henriksson-Larsén, K, and Gerdle, B. Inter-relationship between muscle morphology, mechanical output and electromyographic activity during fatiguing dynamic knee-extensions in untrained females. *Eur J Appl Physiol* 76: 483–490, 1997.

42. Zajac, FE. Understanding muscle coordination of the human leg with dynamical simulations. *J Biomech* 35: 1011–1018, 2002.

43. Zwarts, MJ, Van Weerden, TW, and Haenen, HT. Relationship between average muscle fibre conduction velocity and EMG power spectra during isometric contraction, recovery and applied ischemia. *Eur J Appl Physiol Occup Physiol* 56: 212–216, 1987.