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CHANGES OF PHYSIOLOGICAL TREMOR FOLLOWING MAXIMUM INTENSITY EXERCISE IN MALE AND FEMALE YOUNG SWIMMERS

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ABSTRACT
Purpose. The aim of this study was to determine the changes in postural physiological tremor following maximum intensity effort performed on arm ergometer by young male and female swimmers. **Methods.** Ten female and nine male young swimmers served as subjects in the study. Forearm tremor was measured accelerometrically in the sitting position before the 30-second Wingate Anaerobic Test on arm ergometer and then 5, 15 and 30 minutes post-test. **Results.** Low-frequency tremor log-amplitude ($L_{1–5}$) increased (repeated factor: $p < 0.05$) from –7.92 ± 0.45 to –7.44 ± 0.45 and from –6.81 ± 0.52 to –6.35 ± 0.58 in women and men, respectively (gender: $p < 0.05$) 5 minute post-test. Tremor log-amplitude ($L_{15–20}$) increased (repeated factor: $p < 0.001$) from –9.26 ± 0.70 to –8.59 ± 0.61 and from –8.79 ± 0.65 to –8.39 ± 0.79 in women and men, respectively 5 minute post-test. No effect of gender was found for high frequency range.The increased tremor amplitude was observed even 30 minute post-exercise. Mean frequency of tremor spectra gradually decreased post-exercises ($p < 0.001$). **Conclusions.** Exercise-induced changes in tremor were similar in males and females. A fatigue produced a decrement in the mean frequency of tremor what suggested decreased muscle stiffness post-exercise. Such changes intremorafter exercisemay be used as the indicatorof fatigue in the nervous system.

Key words: fatigue, frequency analysis, swimming, Wingate test

Introduction

Exercise-induced muscular fatigue can be examined, among other methods, with changes in EMG signal [1] or tremor amplitude [2]. Physiological tremor is an involuntary and continuous oscillation of the whole body or its part observed in healthy subjects. Physiological tremor is produced by interaction of mechanical and neural factors. The details of the tremor origin are still a subject of discussions [3–5]. Factors contributing to tremor generation are e.g. discrete structure of muscles and their control system [6], stretch reflex activity [7] central drive [8], synchronization of motor units firing [9], mechanical resonance [4].

Tremor amplitude increases with exercise-induced fatigue. Values of changes in tremor amplitude and frequency depend on the type of effort and its duration [10]. State of elevated tremor is maintained from half hour to over four hours post-exercise [11]. In extreme cases, the elevated tremor, as an effect of fatigue, might be observed even on the following day. Furness et al. [12] demonstrated that fatigue-induced changes in tremor amplitude result from temporary disturbance of the mechanism of control of the nervous system.

Muscular fatigue is defined as limited ability to generate force or power caused by physical effort [8]. Fatigue might also have the origins of both central and peripheral character. One of the symptoms of increasing central fatigue is a decline in the frequency of motor unit excitation [13]. Cresswell and Löscher [14] demonstrated, that in the EMG signal spectrum, components of fatigue with frequencies of several Hertz are increases and are the cause of reduced mean spectrum frequency. Other researchers [15] explained changes in low-frequency range of EMG signal spectrum (10 to 20 Hz) with synchronization of excitation of motor units and attribute them [16] to the effect of stretch reflex. The stretch reflex plays an essential role in accumulation and using elastic energy contained in muscles and tendons in a stretch-shortening cycle. The fatigue-induced changes in the characteristics of this reflex have a substantial effect on reduction of the ability to generate peak power in strength and speed sports. As demonstrated by Avela et al. [17], properties of stretch reflex are quickly changed following the fatigue. The sensitivity of muscle spindles to mechanical stimuli reduces with repeated eccentric contraction. Consequently, the activity in afferent nerve pathways declines and total excitation of motor neurons decreases. Apart from elevated metabolites levels in muscles, the mechanical effect of reduced stiffness of muscle fibres is likely to be another cause of decreased activity in afferent nerve

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pathways. The attempts to solve the problem of diagnosis of fatigue using non-invasive methods are particularly attractive for sports practice. It seems that changes in the parameters of physiological tremor analysis in the domain of frequency might be the basis for immediate and non-invasive evaluation of body response to physical exercise.

The aim of this study was to determine changes in postural physiological tremor following maximum intensity effort performed on arm ergometer by young male and female swimmers.

Material and methods

Participants

Nine male and ten female young swimmers served as participants in the study. Their mean (± *SD*) age, body mass, body height and training experience are presented in Table 1.

The study was approved by the Ethics Committee at the Institute of Sport in Warsaw, Poland. All participants were informed about the study aim and methodology as well as about the possibility of immediate resignation at any time of the experiment. Subjects gave their written consent to the above conditions.

Tremor measurements

Forearm tremor was measured accelerometrically in the sitting position before the 30-second Wingate Anaerobic Test on arm ergometer and then 5, 15 and 30 minutes post-test. Participants were seated on a comfortable chair, back and elbow supported, forearm in horizontal position. A three axis accelerometer was placed on one-kilogram load held as motionless as possible with the subject's dominant hand. The 32-second course of acceleration was recorded (200 Hz sampling frequency) for each subject. In order to avoid a mirror effect each signal was low-pass filtered at the frequency of 100 Hz using a second order analogue filter. Power spectrum density function was estimated only for vertical component using the fast Fourier transform procedure (MatLab 2007). In order to average the values of power spectral density, we used Welch procedure which determines the function proportional to spectral density $G(\mathrm{f})$ (1) of the random signal and reduces random error of the spectral density estimator. The computation procedure requires division of the sets of samples $N_{total} = 6144$ into $N_d = 9$ overlapping segments, each of them with the length of $N = 1024$.

$$G(\mathrm{f_i}) = \frac{1}{\mathrm{N_d}} \sum_{k=1}^{\mathrm{N_d}} \mathrm{G_k}(\mathrm{f_i}), \quad (1)$$

where i = 1,…,N/2; k = 1,…,N_d.

Detailed analysis of the changes observed in amplitudes of power components of tremor is based on a logarithmic index of tremor amplitude $L_{f1\text{-}f2}$ defined as a mean log value of power spectral density function within the frequencies range <f_1, f_2).

$$\mathrm{L_{f_1-f_2}} = \frac{1}{\mathrm{f_2\text{-}f_1}} \int_{\mathrm{f_1}}^{\mathrm{f_2}} \ln G(\mathrm{f})\mathrm{df}, \quad (2)$$

In order to estimate possible frequency shifts of the tremor maxima the average frequencies (ν_{f1-f2}) were computed for chosen frequency ranges:

$$\nu_{\mathrm{f_1\text{-}f_2}} = \frac{\int_{\mathrm{f_1}}^{\mathrm{f_2}} \mathrm{fPSD(f)df}}{\int_{\mathrm{f_1}}^{\mathrm{f_2}} \mathrm{PSD(f)df}}. \quad (3)$$

Analysis of variance ANOVA for repeated measures (fixed effect: gender) was employed to detect differences between subsequent measurements. When a significant F-ratio occurred for the main effects, post-hoc (LSD) Fisher test was used to locate the source of difference. The relationship between mean power and level of physiological tremor were evaluated by means of Pearson's correlation coefficients. Level of significance in all tests was set to $\alpha = 0.05$.

Wingate anaerobic test

The Wingate Anaerobic Test [18] for arm was performed on a cycle ergometer (Monark 874 E, Sweden) connected to a PC, using the MCE 4.0 software package ("JBA" Zb. Staniak, Poland). Participants were asked to pedal as fast as possible for 30 s against a braking force that was determined as 0.055 body weight (BW). Peak power (P_{peak}) was estimated as the average power over a 5 s period with the highest performance. Mean power (P_{mean}) was calculated as the average power during the 30 s period. Both P_{peak} and P_{mean} were expressed as Watts (W) and relative to body mass in Watts per kilograms ($W \cdot kg^{-1}$).

Table 1. Characteristics of subjects tested in the study

	Age (years)	Body mass (kg)	Body height (cm)	Training experience (years)
Male (*n* = 9)	14.8 ± 0.5	67.3 ± 6.4	180.6 ± 7.2	6.4 ± 1.8
Female (*n* = 10)	15.0 ± 0.9	58.9 ± 6.3	171.6 ± 6.5	6.2 ± 1.6

Results

The athletes generated the following mean upper limb power in the Wingate test: male subjects: 5.91 ± 0.48 W · kg^{-1} and female subjects: 4.45 ± 0.48 W · kg^{-1}.

Figure 1 presents an eight-second raw acceleration signal for representative subject.

Figure 2 shows the Power Density Function corresponding to the 32-second acceleration course of which part is presented in Figure 1. Two maxima at about 3 Hz and 10 Hz are specific to forearm tremor.

Comparison of the tremor spectra obtained for individual subjects revealed that power of tremor signal showed a substantial inter-individual variability in the whole frequency domain. The results of previous studies [8] suggested the skewness of tremor power distribution in the population. The skewness obtained for female and male subjects are presented as frequency functions in Figure 3. The reduction in rightward skewness of distribution was obtained using logarithmic transformation of power spectral density (PSD) for the function. Figure 4 presents skewness of PSD profiles for men and women after transformation. Further analysis of tremor power was carried out based on logarithmized profiles.

Figures 5 and 6 illustrate the mean (averaged for 10 female and 9 male, respectively) PSD function graph of the tremor PSD obtained before Wingate test. Because of the above discussed skewed distribution of PSD values among subjects along the frequency domain, the resultant averaged curves were obtained by averaging log-powers:

$$PSD_a(f) = \exp\left(\frac{1}{n}\sum_{i=1}^{n} \ln PSD_i(f)\right), \tag{4}$$

$$PSD^{\pm}(f) = \exp(\ln PSD_a(f) \pm SD(\ln PSD(f))), \tag{5}$$

where: n = number of subjects; i = 1, 2,…n; SD(lnPSD(f)) – standard deviation of lnPSD for frequency f.

The profiles of the function are characterized by distinct similarity of shape: they point to the consistency of frequencies where maxima and similar proportions can be observed for individual components. Due to the profile of spectral function of physiological tremor power, the results from the frequency ranges of 1–5 Hz and 8–14 Hz were separated for further analysis.

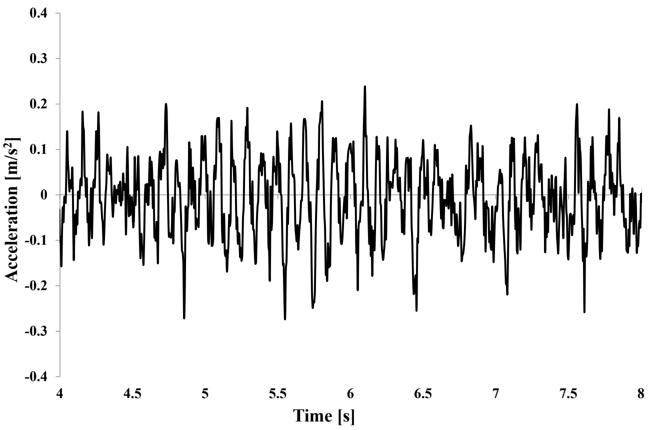


Figure 1. A raw acceleration signal of forearm tremor recorded for a representative subject before the Wingate test

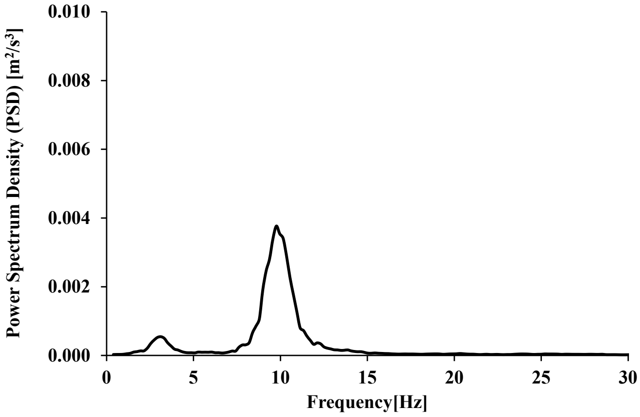


Figure 2. Power Spectrum Density Function of the tremor acceleration for representative subject (the same whose raw acceleration course was presented in Figure 1)

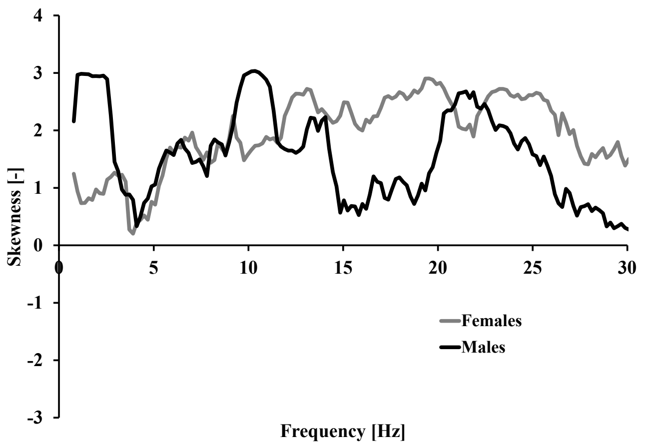


Figure 3. Skewness of PSD distribution along frequency domain; measurement 0 (before an effort)

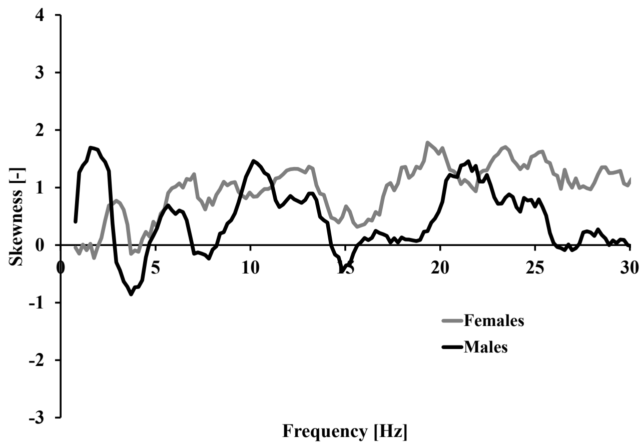


Figure 4. Skewness of PSD distribution along frequency domain after logarithmic transformation; measurement 0 (before an effort)

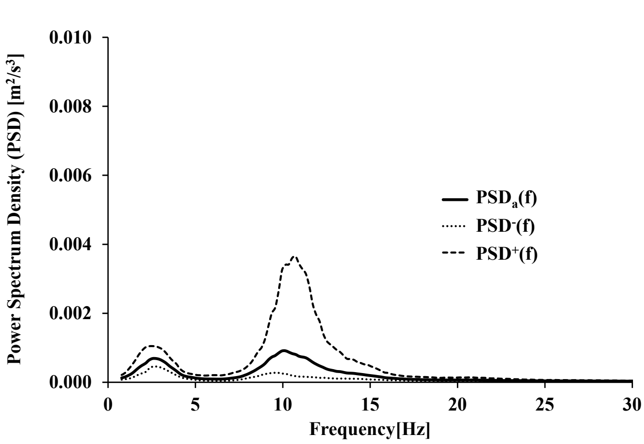


Figure 5. Mean profile of the tremor spectrum (PSD$_a$(f) – averaged for 10 female subjects) and PSD$^-$(f) and PSD$^+$(f) computed according to formulas 4 and 5; before an effort

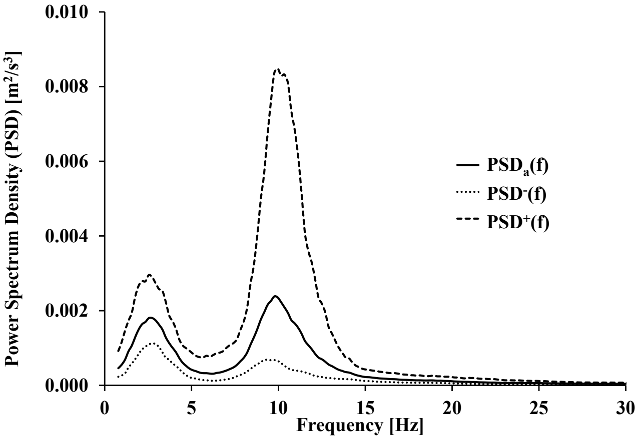


Figure 6. Mean profile of the tremor spectrum (PSD$_a$(f) – averaged for 9 male subjects) and PSD$^-$(f) and PSD$^+$(f) computed according to formula 4 and 5, before an effort

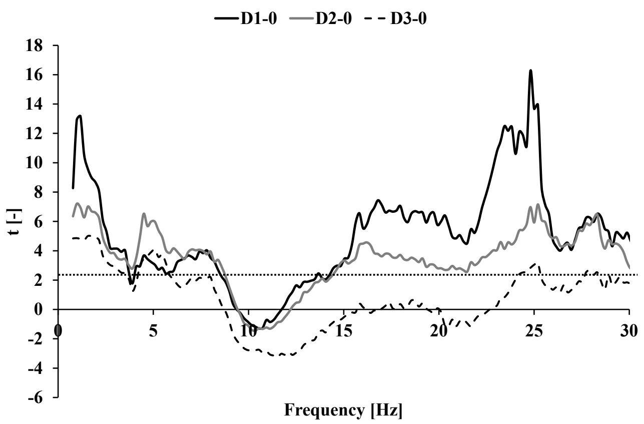


Figure 7. Function t(f) illustrating the significance of increases in tremor power measured 5 min post-test (1), 15 min post-test (2) and 30 min post-test (3) in relation to the initial measurement (0) for female subjects (D1-0, D2-0, D3-0, respectively)

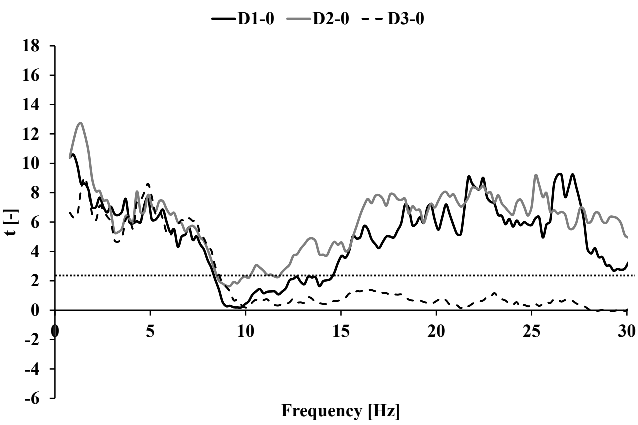


Figure 8. Function t(f) illustrating the significance of increases in tremor power measured 5 min post-test (1), 15 min post-test (2) and 30 min post-test (3) in relation to the initial measurement (0) for male subjects (D1-0, D2-0, D3-0, respectively)

Changes in tremor in relation to other results were evaluated in the frequency domain by means of t(f) function calculated for the entire group as values of the Student's *t* statistics in the frequency domain for the increases of the spectrum logarithms. The following formula was used:

$$t(f) = \frac{\ln PSD_i(f) - \ln PSD_0(f)}{s_\Delta}\sqrt{n}, \qquad (6)$$

where: $PSD_i(f)$ – power density component for frequency f in measurement i = 1, 2, 3; $s_\Delta(f)$ – standard deviation of the lnPSD differences for frequency f; *n* – number of subjects.

The greater the value of function t(f), the more significant PSD differences for the given frequency are. The critical value t (8 degrees of freedom) is 2.31 for men and (9 degrees of freedom) 2.26 for women. Figures 7 and 8 illustrate the graph of the t(f) function for women and man, respectively.

Due to the profile of the t(f) function of post-exercise measurements with respect to measurements at rest, further analysis, apart from the results obtained for the frequency range of 1–5 Hz and 8–14 Hz, was also based on these values in the frequency range of 15–20 Hz.

Table 2 presents means (± *SD*) of indices L_{1-5}, L_{8-14} and L_{15-20} obtained for consecutive measurements by male and female swimmers. Index L_{1-5} describes power of low-frequency components of tremor signal, index L_{8-14} concerns power of components located near the second maximum of the spectrum, whereas index L_{15-20} concerns the power of these components which changed after the exercise to the most significant degree (Figure 7, 8).

Analysis of the index L_{1-5} ($F_{3,51} = 22.25$; $p < 0.001$) demonstrated, that it changes significantly during subsequent measurements both in female and male subjects. No significant changes in the index L_{8-14} ($F_{3,51} = 2.48$; $p > 0.05$) were found during subsequent measurements of this index in both groups. Furthermore, it was demonstrated that the index L_{15-20} changes significantly during sub-

Table 2. Means (± *SD*) for the index $L_{1–5}$, $L_{8–14}$ and $L_{15–20}$ obtained in consecutive measurements

	Female			Male		
	$L_{1–5}$	$L_{8–14}$	$L_{15–20}$	$L_{1–5}$	$L_{8–14}$	$L_{15–20}$
PRE-TEST	–7.92 ± 0.45	–7.62 ± 1.00	–9.26 ± 0.70	–6.81 ± 0.52	–6.83 ± 1.04	–8.79 ± 0.65
5' POST-TEST	–7.44 ± 0.45^{a}	–7.26 ± 0.70	–8.59 ± 0.61^{a}	–6.35 ± 0.58^{a}	–6.78 ± 1.23	–8.39 ± 0.79
15' POST-TEST	–7.30 ± 0.57^{a}	–7.33 ± 0.75	–8.64 ± 0.69^{a}	–6.27 ± 0.59^{a}	–6.85 ± 1.05	–8.46 ± 0.72
30' POST-TEST	–7.55 ± 0.39^{a,c}	–7.70 ± 0.75	–9.19 ± 0.61^{b,c}	–6.31 ± 0.53^{a}	–7.04 ± 0.99	–9.02 ± 0.83^{b,c}

^{a} significant with respect to pre-exercise measurement, $p < 0.05$;
^{b} significant with respect to the measurement 5 min post-test, $p < 0.05$;
^{c} significant with respect to the measurement 15 min post-test, $p < 0.05$

Table 3. Means (± *SD*) frequencies $\nu_{1–5}$ and $\nu_{8–14}$ obtained in consecutive measurements

	Female (n = 10)		Male (n = 9)		All (n = 19)	
	$\nu_{1–5}$ (Hz)	$\nu_{8–14}$ (Hz)	$\nu_{1–5}$ (Hz)	$\nu_{8–14}$ (Hz)	$\nu_{1–5}$ (Hz)	$\nu_{8–14}$ (Hz)
PRE-TEST	2.79 ± 0.16	10.66 ± 0.49	2.80 ± 0.15	10.34 ± 0.43	2.80 ± 0.15	10.51 ± 0.48
5' POST-TEST	2.73 ± 0.12	10.73 ± 0.60	2.69 ± 0.13	10.29 ± 0.64	2.71 ± 0.12**	10.52 ± 0.64
15' POST-TEST	2.71 ± 0.11	10.71 ± 0.55	2.67 ± 0.15	10.21 ± 0.52	2.69 ± 0.13***	10.47 ± 0.58
30' POST-TEST	2.70 ± 0.15	10.49 ± 0.54	2.72 ± 0.13	10.18 ± 0.62	2.71 ± 0.14***	10.35 ± 0.58

** $p < 0.01$, *** $p < 0.001$ significant with respect to pre-exercise measurement

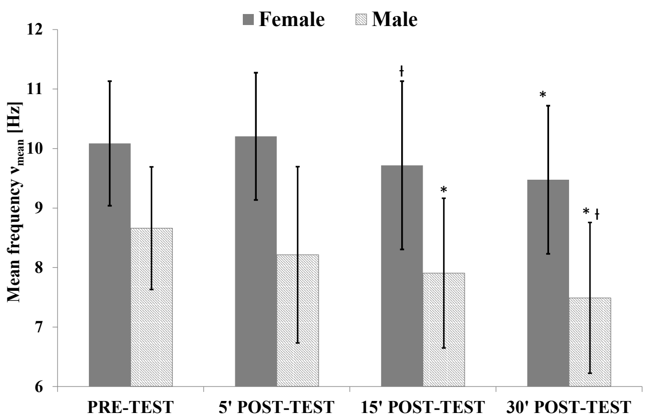
sequent measurements in both groups studied ($F_{3,51}$ = 16.08; $p < 0.001$).

A statistically significant difference was also observed for the index $L_{1–5}$ between genders ($F_{1,17}$ = 26.80; $p < 0.001$). No effect of gender was found for high frequencies.

No correlation was found between the value of mean power developed between upper limbs in the Wingate test and increments of indices.

Table 3 presents mean frequency (ν) with standard deviations for 1–5 Hz and 8–14 Hz. It was demonstrated, that mean frequencies for 1-5 Hz range gradually decreased post-exercise ($F_{3,51}$ = 7.72; $p < 0.001$) in both groups. No effect of gender was observed ($F_{1,17}$ = 0.047; $p > 0.05$).

Figure 9 presents mean frequency with standard deviations for individual measurements. It was demonstrated, that measurements in both groups differ from each other significantly ($F_{3,51}$ = 11.29, $p < 0.001$). The differences were also observed between the groups ($F_{1,17}$ = 11.64, $p < 0.01$).



* significant with respect to pre-exercise measurement, $p < 0.05$
ƚ significant with respect to the measurement 5 min post-test, $p < 0.05$

Figure 9. Mean frequencies (± *SDs*) obtained in subsequent measurements

Discussion

The aim of this study was to determine changes in postural physiological tremor following maximum intensity effort performed on arm ergometer by young male and female swimmers.

In our study, the subjects performed exercise in the form of a 30-second Wingate test with upper limbs and generated mean power of 5.91 ± 0.48 W · kg^{-1} (male subjects) and 4.45 ± 0.48 W · kg^{-1} (female subjects). In a study by Ogonowska et al. [19] male and female swimmers generated mean power in upper limbs of 5.97 ± 0.8 and 4.22 ± 0.3 W · kg^{-1} for the external load of 0.055 kg BW and 0.045 kg BW, respectively. The mean power generated by male and female athletes in our study is consistent with literature data.

A study carried out in the group of 159 young athletes [20] showed that the components of tremor power spectrum for individual frequencies have log-normal distributions in the population. Therefore, the logarithmic measures were used in this study for description of tremor amplitude and power. Skewness of distribution in the population as a property of the component of tremor power in the frequency domain was also supported in this study (Figure 3 and 4).

Two maxima noticeable in the spectrum profiles averaged for men and women for the frequencies of ca. 3 and 10 Hz (Figure 5, 6) have been already described and interpreted in the studies by numerous authors [2, 21] and are consistent with the expectations.

The study also demonstrated a significant effect of physical exercise at peak intensity on the increase in the amplitude of physiological tremor in upper limbs [2, 22]. Particularly substantial fatigue-induced increments in the components of tremor signal were observed for relatively low (1–5 Hz) and high (15–20 Hz) frequencies. A maximum for the spectrum (for frequencies from 2 to 5 Hz) occurs presumably as a result of the simultaneous effect of mechanical properties of limbs and stretch effect [3]. However, recent findings reported by Herbert [23] and Lakie et al. [24] questioned the role of the stretch reflex. The authors suggested a dominant role of a mechanical resonance driven by muscle force irregularities. It can be expected that the same (or similar) level of fatigue causes similar increments in logarithmic index of tremor amplitude in different subjects. This means that following the fatigue, amplitude (expressed in absolute terms) increases proportionally compared to the initial (rest) level. In this study, a significant increase in power of low-frequency components was observed for measurements 1 (5' post-test), 2 (15' post-test), 3 (30' post-test) with respect to the measurement at rest (0) both in women and men. The highest significant difference was recorded 15 minutes post-exercise. Such changes in tremor after exercise may be result of temporary disorders of control mechanisms in the nervous system. As suggested by Lakie et al. [25], a delayed increase in tremor post-exercise amplitude might be caused by the potassium shift to plasma changing its concentration in the interstitial fluid in the muscle. However, this effect has not been tested in the present study. A recovery from increased tremor was observed in swimmers half an hour after ergometer test. The most significant changes of tremor amplitude after this relatively short and intense effort were observed mostly for components of frequencies higher than 15 Hz. Previous results [2] suggested that fatigue affected also components of less frequencies (greater than 10 Hz). However, this discrepancy could be the result of a different loading condition applied (spring). Significant shift of the tremor spectrum maximum (1–5 Hz range) to lower frequencies is most probably caused by decrease of resonant frequency of the hand-forearm system [24] This effect can result from decreased muscle stiffness under fatigue. Changes of muscle stiffness evoked by prolonged stretch-shortening cycles were demonstrated and discussed by Kuitunen et al. [26]. Our results support those findings.

Conclusions

1. A significant effect of maximum physical exercise on the increase of the physiological tremor amplitude was found in both women and men. Compared to the result obtained at rest, the power of low-frequency components increased significantly (decline in movement precision), reaching the highest values 15 minutes post-exercise.

2. A significant shift of the tremor spectrum maximum (1–5 Hz range) to lower frequencies can be attributed to decreased muscle stiffness evoked by prolonged stretch-shortening cycles.

3. Measurements of physiological tremor might become the basis for quantitative evaluation of body response to physical exercise since changes in parameters of physiological tremor in time and frequency domains are subjected to the laws of quantitative character.

Acknowledgements
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