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CHANGES IN PHYSIOLOGICAL TREMOR RESULTING FROM SLEEP DEPRIVATION UNDER CONDITIONS OF INCREASING FATIGUE DURING PROLONGED MILITARY TRAINING

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ABSTRACT: The aim of the study was to define the changes of the characteristics of physiological postural tremor under conditions of increasing fatigue and lack of sleep during prolonged military training (survival).The subjects of the study were 15 students of the Polish Air Force Academy in Dęblin. The average age was 19.9±1.3 years. During the 36-hour-long continuous military training (survival) the subjects were deprived of sleep. Four tremor measurements were carried out for each of the subjects: Day 1 – morning, after rest (measurement 0); Day 2 – morning, after overnight physical exercise (measurement 1); afternoon, after continuous sleep deprivation (measurement 2); Day 3 – morning, after a full night sleep (measurement 3). The accelerometric method using an acceleration measuring kit was applied to analyse tremor. A significant difference between mean values of the index evaluating tremor power in low frequencies L_{2-4} in measurement 0 and measurement 3 was observed ($p<0.01$). No significant differences were found in mean values of index L_{10-20}. Mean frequencies F_{2-4} differed significantly from each other ($F_{2,42}=4.53$; $p<0.01$). Their values were 2.94±0.11, 2.99±0.9, 2.93±0.07 and 2.91±0.07 for successive measurements. A gradual, significant decrease of F_{8-14} was observed ($F_{2,42}=5.143$; $p<0.01$). Prolonged sleep deprivation combined with performing tasks demanding constant physical effort causes long-lasting (over 24 hours) changes of the amplitude of low-frequency tremor changes. This phenomenon may significantly influence psychomotor performance, deteriorating the ability to perform tasks requiring movement precision.

KEY WORDS: muscular tremor, soldiers, military training, survival

INTRODUCTION

Physiological tremor is generally defined as involuntary muscle movement occurring in specific body areas of a healthy person resulting from an interaction of mechanical and nervous factors. These include tissue viscoelasticity, strength fluctuations resulting from the summation of contraction strength of individual motor units, stretch reflex, synchronization of motor unit recruitment and the rhythmic activity of the central nervous system. The interaction between the stretch reflex activity and the viscoelastic properties of the muscles, ligaments and tendons as well as limb moment of inertia determines the net frequency and amplitude of low-frequency tremors [1, 2]. This frequency is 3-5 Hz for the forearm and may vary depending on the external load. However, recent findings reported by Herbert [3] and Lakie et al. [4] questioned the role of the stretch reflex. The authors suggest a dominant role of mechanical resonance driven by muscle force irregularities. In the tremor spectrum there exists a so-called 'physiological component' equal to the frequency of about 10 Hz. It is assumed that the stretch reflex may be the reason for the synchronization [5]. McAuley et al. [6] believe that the oscillations in the feedback loops result from the delay of the nerve signal conduction. Other researchers seek the source of the physiological component in the rhythmical activity of the motor cortex [7, 8]. Tremor components within the 8-12 Hz range do not alter their frequency when the external load changes. Takanokura and Sakamoto [2] demonstrated using a theoretical model that limb oscillations in this frequency range might be produced by the supraspinal system.

An increase in the tremor amplitude influenced by emotions and fear is a universally known phenomenon [9, 10]. Growdon et al. [11] proved that in stressful situations the tremor amplitude rises while at the same time its frequency decreases. From a mechanical point of view, the decrease in frequency of the power maximum can be attributed to decreased muscle stiffness, which can also increase the acceleration amplitude of low-frequency tremor (typical for a resonance system). However, the main reason for increased tremor amplitude is certainly linked to increased irregularities in muscle forces (motor units synchronization) [6]. The tremor amplitude rises also because of the fatigue resulting from physical effort [12]. The values of the amplitude changes and tremor frequency depend on the type of physical effort and on its duration [13, 5]. The state of increased tremor lasts for a period ranging from 30 minutes to over 4 hours after exercise [14]. In extreme cases increased tremor resulting from fatigue may be observed even the next day [12]. Furness et al. [14] proved that the changes in the tremor amplitude triggered by fatigue result from temporary disturbances of the control mechanisms in the nervous system. Increased tremor amplitude may also result from prolonged sleep deprivation [13]. The simultaneous influence of fatigue and sleep deprivation may strengthen this effect. Until now, during military training the muscle tremor fluctuation level has not been determined.

Much research, however, has been conducted determining the changes of the coordination of motor abilities. Special military training of soldiers such as survival training has received particular attention. It is part of SERE (Survival, Evasion, Resistance, and Escape) training. The analysis of the described real-life actions of soldiers in isolation revealed that these changes may last from several hours to several days [15]. The influence of prolonged military training on psychomotor performance, balance, motor accommodation and the ability to differentiate forearm muscle strength was studied [16, 17, 18, 19, 20, 21, 22]. It may be presumed that fatigue resulting from sleep deprivation will cause an increase in muscle tone and, consequently, increased physiological tremor amplitude [23, 24] and possibly shift in frequencies of power spectral density (PSD) maxima. The results of the study could deliver important information on effects influencing performance of soldiers as well as other professionals such as surgeons, athletes, airline personnel, etc., especially as an attempt to increase movement precision might enhance tremor amplitude [25], causing an opposite result.

The aim of the study was to define the changes of the characteristics of physiological postural tremor under conditions of increasing fatigue and lack of sleep during prolonged military training (survival).

MATERIALS AND METHODS

The subjects of the study were 15 students of the Polish Air Force Academy in Dęblin. Ethical approval for this study was provided by the local ethical committee. All participants were informed about the study aim and methodology, as well as the possibility of withdrawing from the study at any time. Participants agreed to the above conditions in writing. The study was performed according to the Declaration of Helsinki.

The anthropometric measures characterizing the tested subjects are presented in Table 1.

TABLE 1. ANTHROPOMETRIC CHARACTERISTICS OF SUBJECTS (N=15)

Variable	Mean ± SD	Range
Age [years]	19.9 ± 1.3	18.8 – 24.2
Weight [kg]	72.0 ± 8.0	52 – 87
Height [cm]	178.1 ± 7.3	163 – 187

During the 36-hour-long continuous military training (survival), the subjects were deprived of sleep. The training consisted of basic military skills, action after a tactical alert, stealth regrouping, coup d'oeil, surveillance, patrol action, action in a contaminated area, transporting casualties, building shelters and assault course exercises. The overall distance covered was 30 km. During the training each subject had a backpack with basic equipment and a rifle. The complete equipment weighed 10-12 kg.

Four tremor measurements were carried out for each of the subjects (non-dominant extremity):

Day 1 – morning, after rest (measurement 0);

Day 2 – morning, after overnight physical exercise (measurement 1); afternoon, after continuous sleep deprivation (measurement 2);

Day 3 – morning, after full night sleep (measurement 3).

The accelerometric method using an acceleration measuring kit (ZPP-3D/BC; JBA Zb. Staniak) was applied to register tremor courses. The accelerometer was attached to a one kilogram weight resting upon the palm of the subject, whose task was to try to hold it motionless in a supinated position. During the test, the subject was sitting with his trunk and elbow supported. The subject's back (scapulas and pelvis) and elbow were touching a vertical wall. The measurement was 32 seconds long. The sampling was conducted at 200 Hz frequency, which allowed for specification of the function of the power spectral density of the signal within the 0-100 Hz range. 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. The acceleration signal, after analogue-to-digital conversion, was submitted to frequency analysis, whose aim was to obtain corresponding functions of PSD. This function defines the distribution of signal variance in the frequency domain. Frequency resolution (Δf) was about 0.195 Hz, since we averaged 6 signal segments each 5.12 seconds long ($\Delta f=200/1024$). The MATLAB program (R2007a) applying the fast Fourier transform (FFT) algorithm was used to estimate the PSD. Courses of the PSD were subjected to logarithmic transformation due to the distinctly positively skewed distribution of the components of the power spectrum in the examined group. Two indices defining the amplitude of the tremor signal components were isolated for analysis: L_{2-4} and L_{10-20}. The first denoted the mean logarithm of the low-frequency components' power of the analysed signal (2 – 4 Hz). The latter referred to high-frequency components (10 – 20 Hz). Each index was calculated from the following formula:

$$L_{f_1-f_2} = \frac{1}{f_2 - f_1} \int_{f_1}^{f_1} \ln(PSD(f)df \cdot \quad (1)$$

In order to investigate frequency shifts, mean frequencies (F_{f1-f2}) in maxima surroundings were computed in the ranges 2-4 Hz and 8-14 Hz:

$$F_{f_1\text{-}f_2} = \frac{\int_{f_1}^{f_2} fPSD(f)df}{\int_{f_1}^{f_2} PSD(f)df} \quad (2)$$

Statistical methods

The analysis in the frequency domain was performed with Microsoft Excel. The Student's t function computed along the frequency domain was used to compare the mean power courses. The comparison of mean values of the indices during consecutive measurements was made using multivariate analysis of variance (MANOVA) for repeated measures. Tukey's test was used for post-hoc comparisons. Statistical significance $\alpha = 0.05$ was assumed.

RESULTS

Figure 1 presents a four-second raw acceleration signal for a representative subject.

Figure 2 shows the power density function corresponding to the 32-second acceleration course part of which is presented in Figure 1. Two maxima at about 3 Hz and 10 Hz are typical for forearm tremor.

Figure 3 presents the mean (averaged for 15 subjects) PSD function graph of the tremor signal PSD obtained in the morning of the day preceding the overnight activity (measurement 0). Because of the skewed distribution of PSD values among subjects along the frequency domain, the resultant curves were obtained by averaging log-powers:

$$\mathrm{PSD}_{a}(f) = \exp\left(\frac{1}{n}\sum_{i=1}^{n}\ln\mathrm{PSD}_{i}(f)\right), \quad (3)$$

$$\mathrm{PSD}^{\pm}(f) = \exp(\ln\mathrm{PSD}_{a}(f) \pm \mathrm{SD}(\ln\mathrm{PSD}(f))), \quad (4)$$

where:

$n=15$,

$i=1,2,\ldots n$,

SD(lnPSD(f)) – standard deviation of lnPSD for frequency f.

Tremor changes in relation to rest results were evaluated in the frequency domain by means of the t(f) function calculated for the entire subject group as the values of the Student's t statistic in the frequency domain for the increases of the spectrum logarithms.

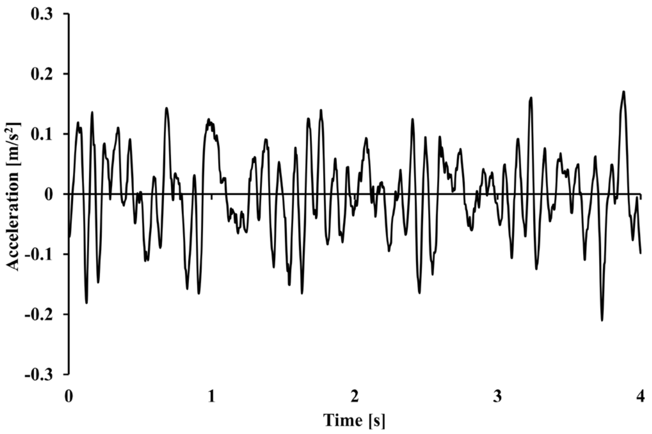

FIG. 1. A RAW ACCELERATION SIGNAL OF FOREARM TREMOR REGISTERED FOR A REPRESENTATIVE SUBJECT BEFORE SLEEP DEPRIVATION

The following formula was used:

$$t(f) = \frac{\ln\mathrm{PSD}_{i}(f) - \ln\mathrm{PSD}_{0}(f)}{s_{\ddot{A}}}\sqrt{n},$$

where:

$\mathrm{PSD}_i(f)$ is the power density component for frequency f in measurement $i=1, 2, 3$,

$s_{\Delta}(f)$ is the standard deviation of the lnPSD differences for frequency f,

n is the number of subjects.

The greater is the value of function t(f), the more significant are the PSD differences for the given frequency. The critical value t for 14 degrees of freedom is 2.14. Figure 4 presents the graph of the t(f) function for the tremor signal after overnight physical exercise. The t(f) functions for results obtained in the afternoon after continuous sleep deprivation and in the morning after 24-hour rest are presented in figures 5 and 6, respectively.

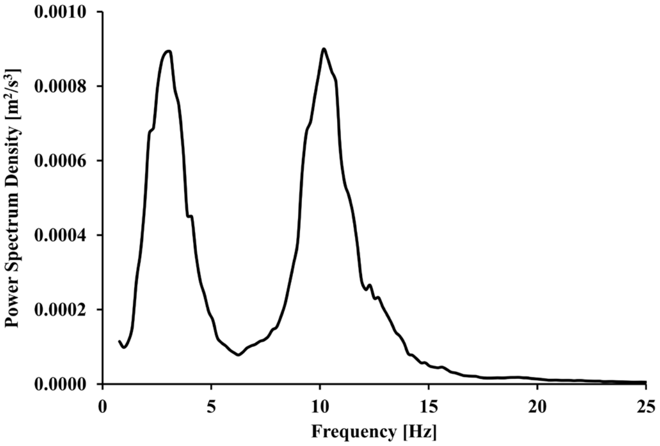

FIG. 2. POWER SPECTRUM DENSITY FUNCTION OF THE TREMOR ACCELERATION FOR A REPRESENTATIVE SUBJECT (THE SAME WHOSE RAW ACCELERATION COURSE IS PRESENTED IN FIG. 1)

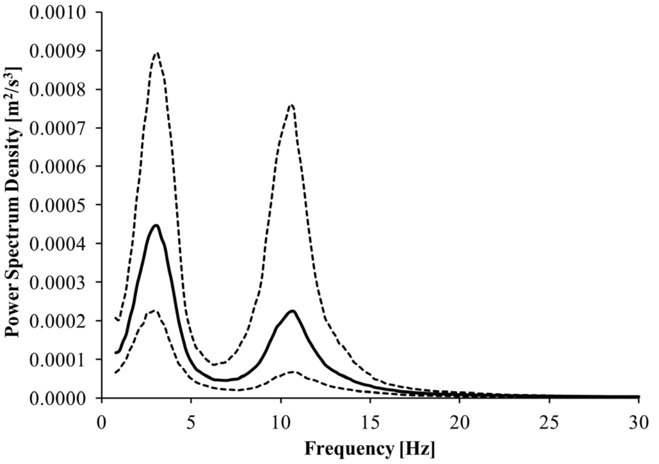

FIG. 3. MEAN COURSE OF THE TREMOR SPECTRUM (PSDA(F) – AVERAGED FOR 15 SUBJECTS (SOLID LINE) AND PSD^{-}(F) AND PSD^{+}(F) COMPUTED ACCORDING TO FORMULA 4 (DOTTED LINES); DAY 1, MORNING, AFTER REST (MEASUREMENT 0)

The analysis of L_{2-4} and L_{10-20} revealed that they changed significantly during measurements ($F_{6,9}=3.41$; $p<0.05$). Figure 7 presents mean values of index L_{2-4} in consecutive measurements.

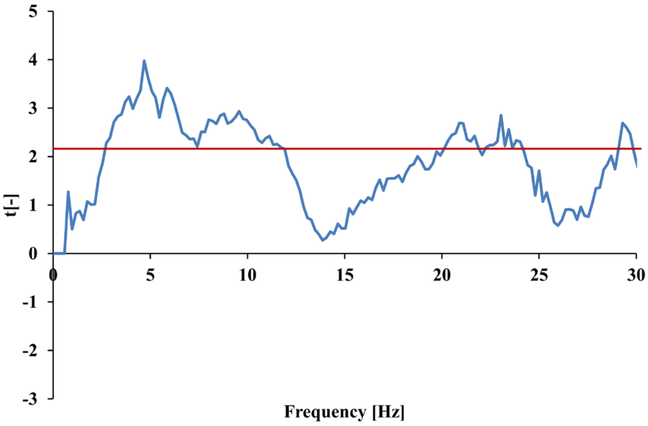

FIG. 4. FUNCTION t(f) ILLUSTRATING THE SIGNIFICANCE OF TREMOR POWER IN THE MORNING AFTER OVERNIGHT PHYSICAL EXERCISE (MEASUREMENT 1) IN RELATION TO THE INITIAL MEASUREMENT

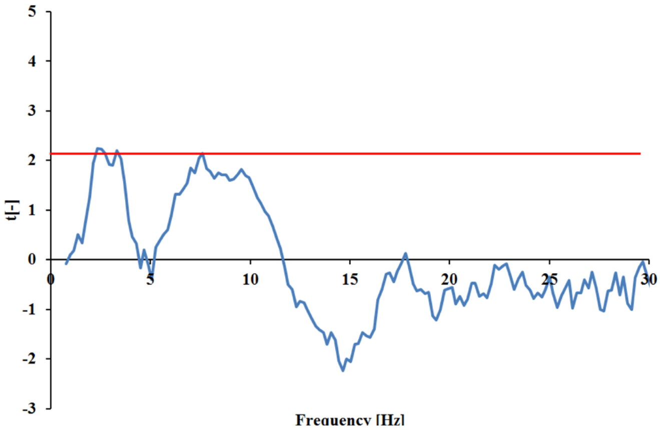

FIG. 5. FUNCTION t(f) ILLUSTRATING THE SIGNIFICANCE OF TREMOR POWER IN THE AFTERNOON AFTER CONTINUOUS SLEEP DEPRIVATION (MEASUREMENT 2) IN RELATION TO THE INITIAL MEASUREMENT

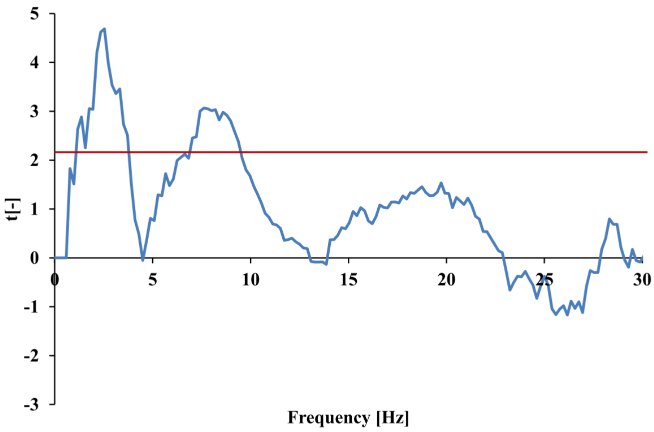

FIG. 6. FUNCTION t(f) ILLUSTRATING THE SIGNIFICANCE OF TREMOR POWER THE NEXT MORNING AFTER A FULL NIGHT SLEEP (MEASUREMENT 3) IN RELATION TO THE INITIAL MEASUREMENT

Post-hoc comparisons revealed (Figure 7) that the difference concerning mean values of the index evaluating tremor power in low frequencies L_{2-4} at measurement 0 and measurement 3 differed significantly ($p<0.01$). No significant differences were found in mean values of index L_{10-20}, which was -10.27±0.74, -9.96±0.64, -10.34±0.50 and -10.10±0.65 in consecutive measurements. In relation to the result obtained in a state of rest, the power of the low-frequency components (movement precision) increased, reaching the highest values in the morning after a full night sleep (Measurement 3).

Mean frequencies F_{2-4} differed significantly from each other ($F_{2,42}=4.53$; $p<0.01$). Their values were 2.94±0.11, 2.99±0.9, 2.93±0.07 and 2.91±0.07 for successive measurements. The post-hoc test revealed a significant difference between measurements 1 and 3. A gradual, significant decrease of F_{8-14} was observed ($F_{2,42}=5.143$; $p<0.01$). Their values are presented in Figure 8.

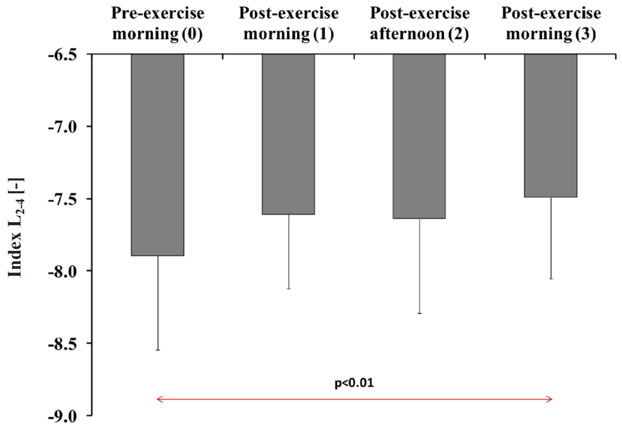

FIG. 7. MEANS (±SD) OF THE L2-4 INDEX (DEFINING THE POWER OF THE LOW-FREQUENCY COMPONENTS OF THE TREMOR SIGNAL) OBTAINED IN CONSECUTIVE MEASUREMENTS

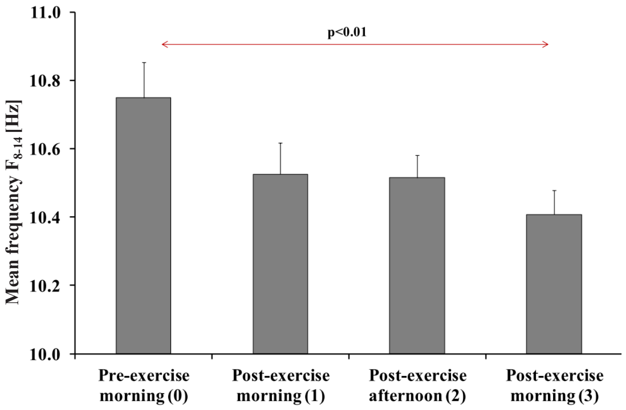

FIG. 8. MEANS (±SD) OF MEAN FREQUENCIES IN THE RANGE BETWEEN 8 AND 14 HZ OBTAINED IN SUCCESSIVE MEASUREMENTS

DISCUSSION

It has been known for a long time that fatigue is one of the factors causing an increase in the tremor amplitude [7, 26, 12]. The changes in tremor amplitude are ascribed to the central nervous system affecting the muscle groups directly involved in effort [7]. There is also circumstantial evidence that the changes in tremor after greater effort (i.e. involving more work) may also be related to changes in potassium levels in the intercellular channels in muscles [27]. It was confirmed that the tremor increases when the potassium concentration in the intercellular channels in muscles falls, leading to the release of potassium into the bloodstream. Post-workout tremor changes may also be attributed to the concentration of lactate, cortisol and testosterone in blood [28].

Although the changes of tremor amplitude after relatively short, intense effort are related mostly to tremor components of frequency higher than 10 Hz [13], the tremor changes observed during intense training of the officer trainees manifested increased amplitude for low-frequency components (2-4 Hz). Such changes are evidence of a decrease in movement precision. The highest values of tremor amplitude occurred in the morning of the second day, after a full night sleep. The results of the experiment are consistent with the opinion of Orzeł-Gryglewska [24] about the effects of sleep deprivation. It was also observed that prolonged effort of relatively low intensity does not cause tremor changes similar to those observed after short, highly intensive effort [13]. The tremor frequency range and the long-lasting changes observed display significant differences. After high-intensity effort the increase in tremor is found mostly in high-frequency components, and these changes subside relatively soon – within a few hours. Prolonged effort, combined with sleep deprivation, causes a much longer-lasting increase in tremor. Such changes are undoubtedly connected with a long-lasting decrease in movement precision. As Morrison and Keogh [25] pointed out, an attempt to increase movement precision might result in increased tremor.

Performing various precise activities during military action is gaining significance. Soldiers operate devices which demand high dexterity and involve multitasking above all. Strength and stamina have ceased to be the main motor abilities characterizing the soldier's physical capacity. In recent years special attention has been paid in Poland to research in coordination changes of motor abilities during survival training [16, 18, 21, 22]. The influence of long-lasting military training on psychophysical fitness has also been researched repeatedly. The changes of balance levels, the ability to differentiate the forearm muscle strength, visual-motor coordination and the ability to multitask were determined [16, 18, 21]. It was observed that performing psychomotor tests (reaction time with multiple choice, reaction rate, effect of multitasking) lasting 90-100 seconds at various stages of the survival training did not affect the results obtained. Presumably, despite fatigue caused by prolonged moderate physical effort, the trainees, as a result of agitation connected with the execution of the tasks, were able to muster themselves to perform the tasks at their optimum level. Interesting observations were made during dynamic balance tests using a rotating chair, conducted on air force soldiers [16]. It was revealed that the dynamic balance level of long-service military pilots is not affected by long-lasting survival training. The results were opposite for trainee officers tested at the beginning of their service. It may be presumed that many years of training on specialized equipment resulted in increased balance disorder resistance.

Another significant skill essential for operating precision instruments is the ability to differentiate forearm muscle strength. This weakened for both the military pilots and trainee officers after about 36 hours of training. Such change was not noted during the tests conducted on special forces soldiers [21]. In order to explain such diversity, Physical Education programmes in air forces and special forces would have to be analysed.

Shooting tasks constitute another important component of military training. These require, along with shooting skills, concentration and controlling muscle tremor, especially under conditions of inertial load applied to the extremity. In our experiment, a one-kilogram weight was used as a stable base for the accelerometer. The weight simulated a real external load. It caused a shift of the low-frequency oscillations to lower frequencies compared to unloaded conditions [29]. In our study, loading conditions remained the same at every measurement. Biathletes experience a deterioration of shot accuracy resulting from significant physical effort [30]. It may be assumed that a similar situation will take place during military shooting tasks. It seems that analysing muscle tremor and determining whether there exists a correlation between muscle tremor and shooting agility would provide useful information. Decrease of mean frequency in the 2-4 Hz range after sleep deprivation can probably be explained by decreased muscle stiffness that results in increased tremor displacement. A gradual decrease of the mean frequency in the 8-14 Hz range in successive measurements has no direct effect on shooting accuracy, but it evidences changes in muscle-nervous functioning. It may indicate a decrease in conduction velocity in the stretch-reflex loop [5] or decreased frequency of the central drive [7].

CONCLUSIONS

Prolonged sleep deprivation combined with performing tasks demanding constant physical effort causes long-lasting (over 24 hours) changes of the amplitude of low-frequency tremor changes. This phenomenon may significantly influence psychomotor performance, deteriorating the ability to perform tasks requiring movement precision.

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