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Method of time-frequency analysis of compound electromyogram in estimation of neurogenic control efficiency in human skeletal muscles

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Abstract

OBJECTIVE: The main objective of the work was to estimate the role of neurogenic component in the formation of compound electromyogram in patients with brain and spinal cord diseases.
METHODS: The method of time-frequency analysis of electromyogram was developed and tested in humans to increase efficiency of compound electromyogram estimation.
RESULTS: The regularities of frequency parameters of normal and pathologic electromyogram signals are established. The numerical criterion for estimation of human neuromuscular system functional state is offered. The processing of electromyogram curves is quickened using the proposed technique.
CONCLUSIONS: The method allows quantitative estimation of functional state of skeletal muscles central control in patients with injuries and diseases of brain and spinal cord.

Introduction

Compound electromyogram (EMG) is a recognized method of investigating the central and peripheral control of skeletal muscle, based on registration and qualitative-quantitative analysis of compound bioelectrical activity of motor units set with epicutaneous electrodes (Blanchi & Vila 1985; De Luca *et al* 2010). Parameters of registered electromyographic signal are considered objective diagnostic criteria of muscle groups' functional state with or without central control. Traditional methods of EMG analysis are based on the calculation of statistical parameters (mean arithmetic amplitude and frequency of potentials) and visual estimation of EMG general form (Blanchi & Vila 1985). There is also a turn-amplitude analysis method (Willison 1964) and the method of spectral analysis (Kumar & Prasad 2010; Polturi *et al* 2013; Kauppi *et al* 2015). EMG visual estimation method and defining of EMG under several types, as suggested by Y. Yusevich (Yusevich 1967, 1970), is of substantial diagnostic value, but requires the analysis of EMG level of saturation with bioelectric potentials, which could be done only with quantitative estimation of signal. Willison turn-amplitude analysis (Willison 1964) is mostly a graphical visual method as well, and only allows defining the character of injury in case of its sufficient expressiveness. In general, a visual interpretation of signal by an expert is often defined by experience and skills of the last (Hassan *et al* 2011, 2013; Polturi *et al* 2013; Laguna & Sörnmo 2014).

Quantitative analysis of biomedical signals is a source of reliable information on the signal characteristics and is used to make the expert's own interpretation more integral. Still, the above mentioned methods of quantitative estimation (statistical and spectral analysis methods) have substantial disadvantages, as they consider EMG signals as linear static signals, which is an obstacle for depicting their time-frequency structure and dynamics of parameters' changing during the whole contraction period. For example, lack of information on the localization of signal frequency components in time is a disadvantage of spectral analysis method (Cattani *et al* 2015), which along with poor elaboration of theoretical and methodological diagnostic materials on this method resulted in its low popularity.

A system is named "stationary" in the theory of digital signal processing if its statistical characteristics remain the same in all time sections (Cattani *et al* 2015). Besides, the frequency content of stationary signals does not change in time. Most biomedical signals do not satisfy such conditions and are considered non-stationary (Hassan *et al* 2011; Cattani *et al* 2015), which means their characteristics change substantially in time. Signal characteristics and transformations calculated for the whole interval of registration significantly smooth these changes.

For better information content and empowerment of modern medicine it is advisable to develop methods and technical tools for processing and analysis of biomedical signals, which adequately reflect the processes in physiological systems. This approach to research is particularly important to assess the functional state of the central control of the skeletal muscles. Thus, this paper suggests using time-frequency transformation method for EMG signal analysis, which is naturally non-stationary. Preliminary research showed good results of this method use in treatment and rehabilitation effectiveness estimation.

This article features survey results of a compound EMG, registered in healthy subjects and patients with disorders of the central control of skeletal muscle function. The time-frequency transformation method was used to process EMG signals.

Material and methods

33 healthy subjects (21 males and 12 females; mean age – 21 years) and 34 patients with disordered motor functions of leg muscles due to joints and spinal cord pathology (6 males and 28 females; average age – 50 years) were observed. The group of healthy persons included weightlifters and non-athletes.

Electrophysiological studies were carried out at the Republic Scientific and Practical Centre of Traumatology and Orthopedics (Minsk, Belarus) with newly designed two-channel software-hardware unit for registration and processing of compound EMG-signals of human neuromuscular system.

10 mm skin electrodes ("3M Red Dot") were used to register EMG signals, fixed around the muscle motor point areas. Distance between electrodes did not exceed 20 mm. Bioelectrical activity of bilateral leg muscles (*m. tibialis anterior, m. gastrocnemius medialis, m. rectus femoris, m. vastus lateralis*) was registered at their maximum voluntary concentric tension: upper lead – EMG of left leg muscles; lower lead – EMG of right leg muscles. The testing motion was performed after a preliminary instruction according to developed cycle model (on the basis of animation graphics): 1) muscle contraction (1.5 sec); 2) keeping muscle in a state of maximum contraction (4 sec); 3) muscle relaxation (1.5 sec). The offered graphical model allows synchronizing subjects' actions and unifying the study conditions, which results in comparability of compound EMG results analysis.

The developed software allows EMG processing by time-frequency representation method in real-time mode. This method is realized on the basis of short-time Fourier transformation. Signal is divided into time segments ("windows") which are short enough to consider them stationary. These time segments are known as quasi-stationary, and the whole approach – as short interval analysis (Coorevits *et al* 2008; Cattani *et al* 2015). The initial signal on a chosen segment is multiplied by window function and undergoes short-time Fourier method according to the formula:

$$STFT_x^{(\omega)}(\tau_k, f) = \int_t [x(t) \cdot \omega^*(t - \tau_k)] \cdot e^{-j2\pi f t} dt$$

where *x(t)* – is the initial signal, *w(t)* – window function, t_k – time offset value, *k* – index number of window offset, *f* – frequency, *t* – time, and *w*(t)* – is a complex conjugate window function (Cattani *et al* 2015).

After performing this operation the spectrogram segment for analyzed window is retrieved by squaring of the current part (amplitude) of the Fourier window transformation:

$$Spectrogram\ X(t) = |STFT(\tau_k, f)|^2$$

Then a window offset by the value t_k is performed and the procedure is repeated: the window transformation of current time segment is carried out and the appropriate spectrogram segment is built. The offset value is specified in the way to provide overlapping of segments during processing (the "sliding window" method) and continuous time-frequency distribution (Laguna & Sörnmo 2014; Cattani *et al* 2015). All signal sub-intervals are analyzed in a similar way and a resultant spectrogram is built. It is a two-dimensional matrix which lines correspond time counts *t* from 0 sec till the end of EMG signal registration and columns – frequencies *f* from 0 to 1000 Hz with cells showing calculated EMG amplitude *A[f,t]*.

The following parameters were empirically chosen as key ones for time-frequency processing: Henning window, transformation size in 32768 counts, sampling frequency – 44 kHz, window overlap – 50%. These characteristics provide qualitative time-frequency EMG representation and high frequency (1.34 Hz) and time (0.37 sec) resolution.

During the whole period of testing, the characteristics of EMG-signal amplification and software settings remained the same.

The parameters of compound EMG time-frequency representation for a quantitative analysis are calculated in health and disease: the low-frequency limit, the median frequency, the high-frequency limit and the effective spectrum width. The average signal amplitude is additionally calculated using the formula:

$$A_m = \frac{1}{N}\sum_{i=1}^{N} |A[i]|$$

where *A[i]* – is the amplitude of the *i*-count of registered signal and *N* – is the number of signal counts.

The above time-frequency processing characteristics allow full-scale estimation of EMG frequency repletion. Thus, low-frequency and high-frequency limits specify the effective spectrum width, i.e. the range of frequencies having no less than 90% of signal power. The frequency is called median when it divides the area under the spectrum power density curve into two equals (Coorevits *et al* 2008; Polturi *et al* 2013; Cattani *et al* 2015). Unlike the arithmetic mean, the median is a part of robust statistics, and it is not influenced by large declinations and allows better description of central trend of value range. No researches of EMG median frequency have been carried out before.

Frequency characteristics are defined automatically upon the results of EMG spectrogram on the basis of special software (developed in MATLAB environment). The value of EMG signal energy is calculated in each cell of the spectrogram:

$$E\,[i,j] = A\,[i,j]^2$$

where *A[i,j]* – is the EMG amplitude in *i* line and *j* column.

Then a column with number *j* is defined, which stands for spectral energy density at *j* time moment and (in order to find the median frequency fm_j) a median is searched in the selected column based on the following: the difference between total energy of signal from 0 Hz till required frequency and total energy from required frequency till *F* is minimal in modulus:

$$\left|\sum_{p=1}^{f_{m_j}} E\,[p,j] - \sum_{q=f_{m_j}}^{F} E\,[q,j]\right| \to 0$$

Then the signal energy concentrated in the effective spectrum width $E_{eff}[j]$ and valuing above 90% (an exact value from 91% to 99% is specified here) of the total sum of all column elements is calculated:

$$E_{eff}[j] = 0{,}95\sum_{k=1}^{F} E\,[k,j]$$

Then the lower frequency limit f_{lj} is defined from this condition: the difference between the sum of column elements with indexes from f_{lj} till f_{mj} and the value of $1/2E_{eff}[j]$ is minimal in modulus:

$$\left|\sum_{k=f_{l_j}}^{f_{m_j}} E\,[k,j] - \frac{1}{2}\,E_{eff}[j]\right| \to 0$$

The higher frequency limit is defined from this condition: the difference between the sum of column elements with indexes from f_{mj} till f_{uj}, and the value of $1/2E_{eff}[j]$ is minimal in modulus:

$$\left|\sum_{k=f_{m_j}}^{f_{u_j}} E\,[k,j] - \frac{1}{2}\,E_{eff}\,[j]\right| \to 0$$

The EMG effective frequency band Δf_j is calculated by the formula:

$$\Delta f_j = f_{u_j} - f_{l_j}$$

The values of f_{lj}, f_{mj}, f_{uj}, Δf_j, as well as the mean amplitude value in the column A_{mj} are calculated for all spectrogram columns $j = 0\ldots T-1$. This provides one-dimension arrays of dependencies between lower frequency limit, median frequency, higher frequency limit, effective spectrum width and average EMG amplitude on time – $f_l[t]$, $f_m[t]$, $f_u[t]$, $\Delta_f[t]$, $A_m[t]$, respectively, and also mean arithmetical values of f_{lm}, f_{mm}, f_{um}, and Δf_m.

Results and discussion

In order to perform correct analysis of data recorded in the group of patients with disordered motor function of leg muscles appropriate EMG signals were split into three groups according to the character of changes in amplitude-frequency characteristics of bioelectrical activity: interference EMG, reduced EMG and atypical EMG. The interference EMG, by its generation type, fits normal health and reflects the total activity of large number of motor units (Blanchi & Vila 1985). The lower limit of the amplitude range for interference EMG signals was chosen on the basis of statistical data retrieved from non-athletes' EMG processing and corresponds with amplitude values of the normal EMG compound parameters (Hassan *et al* 2011, 2013). A substantially reduced (compared with the normal) type of bioelectrical activity was demonstrated by patients with an expressed degree of pathologic alterations. Such type of activity is advisable to name "reduced" (Polturi *et al* 2013).

EMG signals consisting of separate action potentials of motor units and characterized by amplitude lower than 30 μV, as well as total bioelectrical silence were grouped in "atypical EMG". The decrease of compound EMG amplitude lower than 20 μV increases the likelihood of irreversible changes in structure and function of elongated muscle. Besides, an EMG of such low amplitude, together with action potentials of motor units, integrates a significant proportion of tissue noise, which does not allow performing of correct quantitative analysis of frequency characteristics (Polturi *et al* 2013). Due to this, frequency parameters were not calculated for this group.

The time-frequency analysis method in qualitative (visual) estimation of human neuromuscular system functional state was presented in several spectrograms. EMG signals and appropriate spectrograms of *m. gastrocnemius medialis* in health and disease are shown in Figure 1. Time in seconds is shown on the x-axis, logarithmic frequency scale (Hz) on the y-axis, color corresponds to signal level at the given frequency (when signal increases the color changes from dark-blue (−85 dB) to red (−60 dB); in greyscale print – from dark-grey to black, respectively).

A comparative analysis of normal and pathologic EMG signals and spectrograms of *m. gastrocnemius*

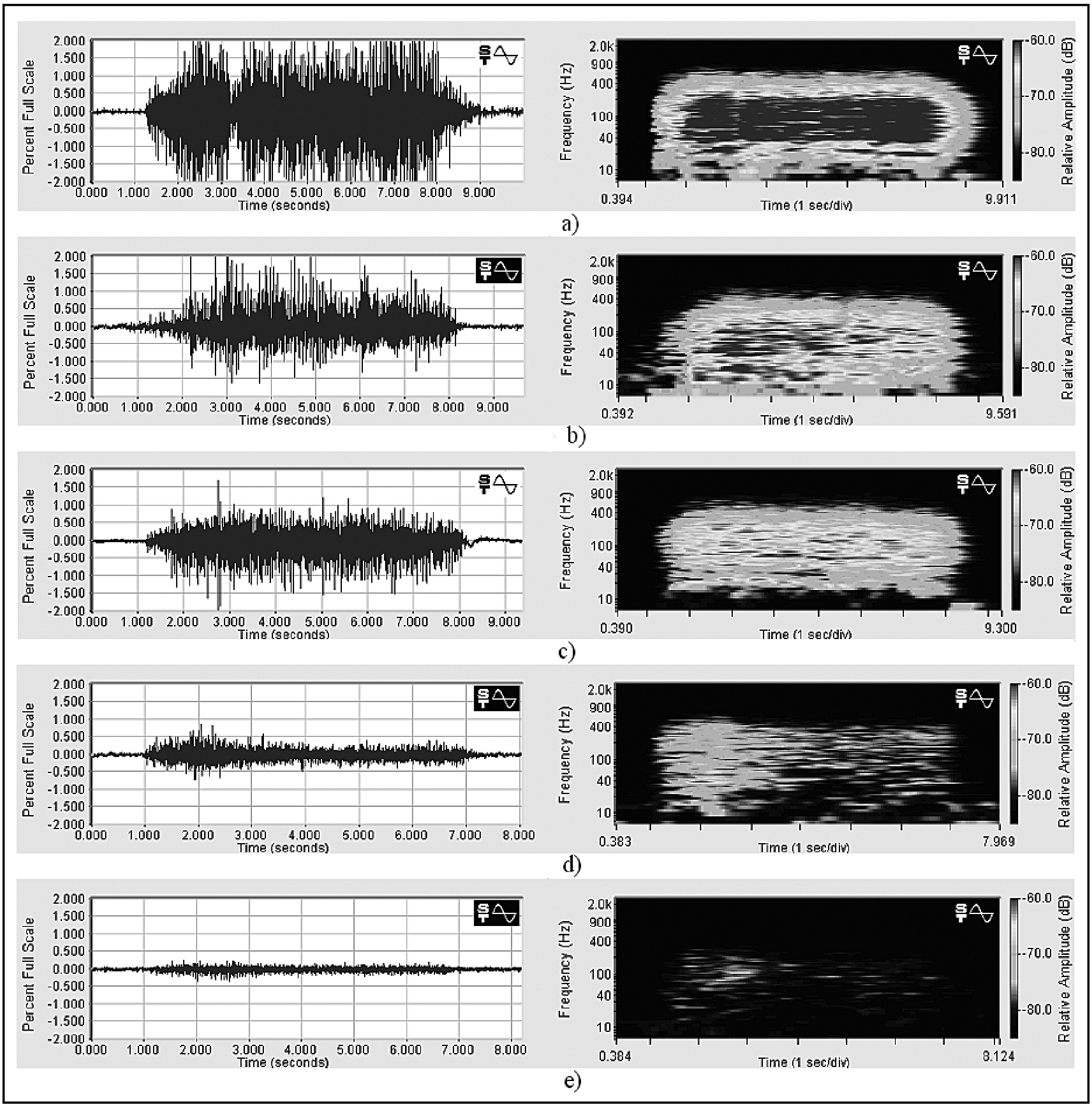

Fig. 1. Compound EMGs (left) and appropriate spectrograms (right) of *m. gastrocnemius medialis* in health (athletes - a), non-athletes - b) and disease (interference - c, reduced - d, atypical - e).

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medialis in black-and-white illustrations (Figure 1) revealed the following:

Red and yellow colors in the spectrogram match high amplitude of EMG signals in health and interference EMG in disease. This relationship is shown in Figure 1a, b, c in black and white. Low amplitude reduced EMG signals are shown as light-green and blue colors in the spectrogram, thus visually differing from the normal one. This relationship is shown in Figure 1d in black and white, also. Atypical EMG is depicted as rare narrow stripes of dark blue (Figure 1e) (the article has greyscale variant).

Unlike EMG, spectrogram contains information on EMG signal time-frequency structure, thus allowing visual estimation of signal frequency repletion and dynamics of its spectral components in time. Reduced EMG in disease is characterized on spectrogram mostly by a widened frequency range (Figure 1d) compared to EMG signal in health (Figure 1c). Atypical EMG is depicted as substantially narrowed (compared to normal one) frequency range (Figure 1e).

Spectrogram allows estimating muscle potential for concentric tension, namely: normal concentric tension is depicted by prolonged amplitude retention at the same level (Figure 1a) while pathologic processes affecting neuromuscular system make muscle tone weak, which results in amplitude peaks (Figure 1d, e) and valleys during muscle contraction shown as areas of various color shades.

Based on the above, a conclusion about informational significance and expediency of spectrograms use in qualitative estimation of human neuromuscular system functional state should be made.

Graphs of dependencies of $A_m[t]$, $f_m[t]$ and $\Delta f[t]$ for EMG signals of *m. gastrocnemius medialis* in health and disease depicted in Figure 1b, d are shown in Figure 2. Graphs in Figure 2 show increased amplitude, decreased median frequency and narrowing of effective EMG signal spectrum width in health compared to disease. There is amplitude growth at the beginning of muscle contraction and then muscle tone does not maintained and amplitude decreases (in disease), while normal pattern demonstrates high amplitude level until the beginning of muscle relaxation.

Results of quantitative estimation of *m. gastrocnemius medialis* EMG signals in health and disease (mean values standard deviations of A_m, f_{lm}, f_{mm}, f_{um}, and Δf_m parameters as $M \pm m$) are shown in Table 1.

Quantitative analysis of *m. gastrocnemius medialis* compound EMG revealed following regularities (Table 1):

Mean amplitude of normal EMG signals is maximal (359.72±159.10 µV) in athletes and is about 196.16±84.00 µV in non-athletes. It substantially

Tab. 1. Mean values of EMG signals of *m. gastrocnemius medialis* in health and disease

	healthy subjects		joint pathology		spinal cord pathology	
	athletes	non-athletes	interference EMG	reduced EMG	interference EMG	reduced EMG
A_m, µV	359.72±159.10	196.16±84.00	155.92±27.14	68.36±27.16	153.00±20.08	59.28±20.56
f_{lm}, Hz	31.03±3.84	29.98±4.77	36.62±14.02	34.59±6.10	33.79±9.27	35.94±13.30
f_{mm}, Hz	107.44±28.71	122.00±30.06	138.25±32.38	156.86±37.33	135.48±43.33	155.61±35.96
f_{um}, Hz	412.12±69.82	445.90±66.22	434.71±80.21	478.93±93.01	457.52±64.87	485.46±70.16
Δf_m, Hz	381.09±71.38	415.92±65.35	398.09±69.05	444.34±88.46	423.73±60.26	449.51±65.44
n	20	46	10	20	8	14

n – number of studied muscles

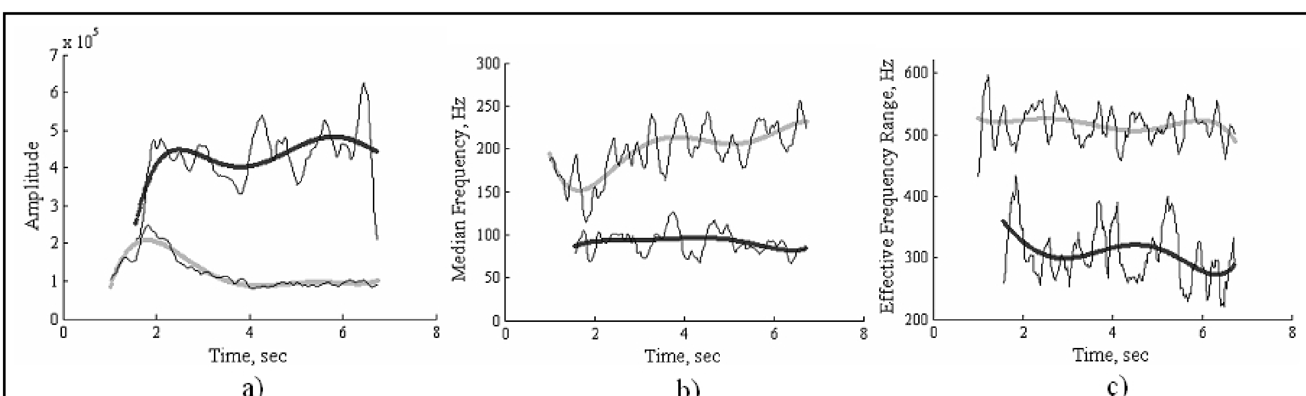

Fig. 2. Changes in mean amplitude (a), median frequency (b) and effective spectrum width (c) depending on time for EMG signal of *m. gastrocnemius medialis* in health (black interpolation line) and disease (grey interpolation line).

exceeds mean amplitude values of reduced EMG signals in disease (68.36±27.16 μV and 59.28±20.56 μV in joint and spinal cord pathologies, respectively);

Values of lower frequency limit do not differ substantially in health and disease;

Median frequency is minimal in healthy patients (107.44±28.71 Hz and 122.00±30.06 Hz in athletes and non-athletes, respectively), is higher in those with joint (138.25±32.38 Hz and 156.86±37.33 Hz in interference and reduced EMG, respectively) and spinal cord pathologies (135.48±43.33 Hz and 155.61±35.96 Hz in interference and reduced EMG, respectively);

Upper frequency limit in healthy subjects is 412.12±69.82 Hz and 445.90±66.22 Hz in athletes and non-athletes, respectively. It is normal in interference EMG in joint pathology (434.71±80.21 Hz) and reaches 478.93±93.01 Hz in reduced EMG (in those with spinal cord pathologies the same parameters have increasing trend and are 457.52±64.87 Hz and 485.46±70.16 Hz respectively);

Effective spectrum width is 381.09±71.38 Hz and 415.92±65.35 Hz in athletes and non-athletes in health, respectively. It is 398.09±69.05 Hz and 444.34±88.46 Hz in those with joint pathologies in interference and reduced EMG, respectively (in those with spinal cord pathologies the same parameters have increasing trend and are 423.73±60.26 Hz and 449.51±65.44 Hz, respectively). At the same time, increase in effective spectrum width in disease is mainly caused by the rise of upper frequency limit, while lower frequency limit remains unchanged. This is due to coordinated effort of all muscle motor units in its normal state compared to desynchronization processes in disease.

The regularities specified above are demonstrated by other muscle clusters as well (*m. tibialis anterior, m. rectus femoris, m. vastus lateralis*) and median frequency is the only exception with its values being rather ambiguous.

It is proposed to use the index of EMG signal mean amplitude ratio to the effective spectrum width ($A_m/\Delta f$, μV/Hz) as a quantitative criterion for human neuromuscular system functional state estimation taking into account the specified pattern of mean amplitude increase and effective spectrum width decrease in health and disease. This amplitude-frequency criterion must be substantially higher in healthy subjects compared to diseased ones. This hypothesis is proved by calculated mean values of amplitude-frequency criterion in health and disease (Table 2).

The proposed amplitude-frequency criterion is characterized by high reliability and informational content in estimation of human neuromuscular system functional state on the base of compound electromyography.

CONCLUSIONS

Clinical studies of compound electromyogram registered in two groups (healthy subjects and patients with disorders of the central control of skeletal muscle function) were carried out. The analysis of compound EMG results in health and disease using time-frequency transformation method showed its efficiency for informative qualitative and quantitative estimation of human neuromuscular system functional state. Qualitative analysis of non-stationary by nature EMG signal structure (including time localization of its spectral components) and parameter dynamics during muscle contraction is carried out on the base of spectrogram, which represents graphical visualization of amplitude, frequency and time components of biomedical signal in real-time mode. It is also possible to assess the muscle's ability to concentric tension using the spectrogram. For quantitative estimation of compound EMG the calculation of signal mean amplitude and parameters of time-frequency representation (lower frequency limit, median frequency, upper frequency limit and effective spectrum width) was carried out (Coorevits *et al* 2008; Polturi *et al* 2013; Cattani *et al* 2015). Comparative analysis of calculated parameters, both in health and disease, showed a range of regularities: the values of upper frequency limit and effective spectrum width are higher in pathology than those in normal EMGs, which can be explained by disruption in muscle motor units coordinated work of the central nervous system, processes of their desynchronization and adaptive functional reorganization of their activity in disease. Based on the established regularities an amplitude-frequency criterion for human neuromuscular system functional state estimation is offered: the index of EMG signal mean amplitude ratio to the effective spectrum width. This criterion allows paying respect to main parameters of non-stationary biomedical signal (amplitude and frequency), thus enabling swift and effective express-diagnostics of neuromuscular system functional state using automated complexes for time-frequency processing of EMG signals.

The offered methods of qualitative and quantitative assessment of compound EMG signals can be used

Tab. 2. Mean values of suggested amplitude-frequency criterion of human neuromuscular system functional state in health and disease calculated for EMG signals of *m. gastrocnemius medialis*.

	healthy subjects		joint pathology		spinal cord pathology	
	athletes	non-athletes	interference EMG	reduced EMG	interference EMG	reduced EMG
$A_m/\Delta f$, μV/Hz	1.01±0.54	0.50±0.29	0.41±0.16	0.16±0.06	0.37±0.08	0.14±0.05

for predicting the period of disordered motor functions recovery; as a criterion when selecting means and methods of physical rehabilitation; to control the dynamics of disordered functions and unbiased assessment of treatment efficiency. The processing of electromyogram curves is quickened using the proposed technique. The method allows quantitative estimation of functional state of skeletal muscles central control in patients with injuries and diseases of brain and spinal cord.

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