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## Investigation of distribution laws of the phase difference of the envelopes of electromyograms of antagonist muscles in Parkinson's disease and essential tremor patients

**Olga S. Sushkova, Alexei A. Morozov, Ivan A. Kershner, Nadezhda G. Petrova**

Kotelnikov Institute of Radioengineering and Electronics of RAS, <http://www.cplire.ru/>  
Moscow 125009, Russian Federation

*E-mail: o.sushkova@mail.ru, morozov@cplire.ru, ivan.kershner@gmail.com, petrova@cplire.ru*

**Alexandra V. Gabova**

Institute of Higher Nervous Activity and Neurophysiology of RAS, <http://ihna.ru/>  
Moscow 117485, Russian Federation

*E-mail: agabova@yandex.ru*

**Larisa A. Chigaleychik, Alexei V. Karabanov**

FSBI Research Center of Neurology, <https://www.neurology.ru/>  
Moscow 125367, Russian Federation

*E-mail: chigalei4ick.lar@yandex.ru, doctor.karabanov@mail.ru*

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**Abstract:** An investigation of surface electromyogram (EMG) of antagonist muscles in patients with Parkinson's disease (PD) and essential tremor (ET) was carried out. A comparison was made between two methods for calculating instantaneous phases of envelopes of EMG signals. The first method is based on calculating the ridges of wavelet spectrograms of envelopes of EMG signals. The second method is based on using the Hilbert transform. Statistically significant difference between the mean values of the phase difference of the EMG signal envelopes was found in the antagonist muscles in PD and ET patients.

**Keywords:** phase difference, electromyogram, EMG, wavelet spectrogram, wavelet, Parkinson's disease, essential tremor, ridges of wavelet spectrograms, the Hilbert transform

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### 1. INTRODUCTION

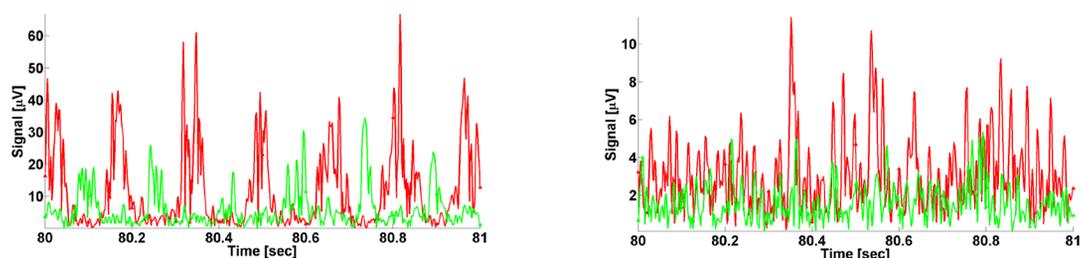
Differential diagnosis of Parkinson's disease (PD) and essential tremor (ET) in the early stages is an urgent problem of modern medicine. The existing methods of clinical diagnostics do not allow in some cases to unambiguously make a diagnosis, that is, to distinguish between parkinsonian and

essential tremor. This is due to the fact that in some patients the form of tremor is implicitly expressed, in addition, during the examination of the patient, the tremor sometimes visually changes, which can lead to an incorrect diagnosis by the doctor.

Electromyogram (EMG) and accelerometer registration methods are usually used to study tremor [1-4]. There are different methods of signal processing, the main methods are spectral analysis [5] and phase synchronization research. Methods based on the use of wavelets are a variety of spectral analysis [7-13]. The advantage of wavelet analysis is the ability to take into account the time-frequency dynamics of signals. So, in the works of Yu.V. Obukhov and co-authors [14,15], the so-called “ridges” of wavelet spectrograms are used. The use of ridges allows to select the leading frequency in the signal, as well as to find signal areas with a high signal-to-noise ratio. In [8-13], an approach is used based on the method of analysis of wave train electrical activity, a distinctive feature of which is that not the original signals are analyzed, but wave trains of the spectral power density on wavelet spectrograms. Unlike standard wavelet analysis, this method allows to reveal the properties of electrophysiological signals (EMG, tremor, and electroencephalograms) over long time intervals and at the same time, in comparison with Fourier analysis, take into account local time-frequency changes in the characteristics of non-stationary signals.

This article will focus on another area of research in the field of biomedical signal processing - the study of phase synchronization. Currently, a large number of methods for analyzing phase synchronization have been developed [16-21]. When examining PD and ET, tremor of the arms and legs are studied. There are several types of tremor, including tremor with so-called alternating and synchronous patterns. An alternating pattern is a pair of signals in which peaks in one signal alternate with peaks in another signal (**Fig. 1, left**). A synchronous pattern is a pair of signals in which the peaks on one signal roughly coincide in time with the peaks on the other signal (**Fig. 1, right**). Unfortunately, it is not always possible to make an accurate diagnosis during the studying the morphology of signals from real patients.

In Russia, the leading scientific direction in the study of phase synchronization is the study of coherence [1,2,22]. This approach compares the electromyographic signals of antagonist muscles. In [22], it is indicated that in postural tremor both PD and ET are characterized by both alternating and synchronous tremor patterns, which makes it very difficult to distinguish tremor in PD from tremor in ET. In this approach, the phase shift is measured at the tremor frequency as estimated from accelerometer data. In [22], no statistically significant differences were found between the groups of patients with PD and ET during postural tremor. In the study of resting tremor, it was shown that the synchronous pattern



**Fig. 1.** Envelopes of EMG signals of the left hand with trembling hyperkinesia. On the left - a sample with an alternating pattern; a patient with PD in the first stage. On the right - a sample with a synchronous pattern; patient with ET. Red line is signal from the extensor muscle; green line is signal from the flexor muscle. 1-second time intervals are considered. The patients were in a sitting position with their arms outstretched.

does not allow distinguishing between ET and PD; moreover, the synchronous pattern is characteristic of PD with an essential tremor phenotype. In addition, in [22] it was shown that the value of coherence in the range of 8-12 Hz is statistically significantly lower in the group of patients with ET as compared to the group of patients with PD. There were no statistically significant differences in the 4-7 Hz range, which was also considered by the authors [22], between the groups of patients with PD and ET.

The disadvantage of coherent analysis is that it is not designed to study non-stationary signals. Coherent analysis does not take into account the time-frequency dynamics of signals, therefore, in a situation where the signal contains areas with different types of tremor (alternating and synchronous), as well as areas of the signal with different signal-to-noise ratios, the coherent analysis will produce an average picture that will vary depending on the ratio of the lengths of sections with different types of tremor. To study the phase synchronization of tremor in PD and ET, it is necessary to use a more accurate method of analysis. In this paper, phase difference histograms are used to perform this analysis. The phase difference histograms show the statistical distribution of the instantaneous phase difference observed on the two signals of interest. If there is no statistical relationship between the instantaneous phase of the signals, then the histogram of the phase difference will be a rectangular distribution. If there is synchronization between the signals, then one or more peaks will be present on the histogram. In particular, if a peak near zero is observed on the histogram of the phase difference, this indicates the presence of a statistical relationship between the signals; however, the reason for such synchronization can be both a real causal relationship between the signals, and the presence of the same noise component in both signals. Therefore, of special interest are cases when the peak on the histogram is shifted relative to zero. In this case, we can assume that

there really is a statistical relationship between the signals, not due to the noise component. In addition, the presence of a peak shifted relative to zero indicates that one signal is lagging behind the other. Note that synchronization between signals does not necessarily mean there is a causal relationship between signals; a statistical relationship may arise due to the fact that the source of the first signal somehow influences the source of the second signal, or both of these signals are a consequence of the influence of some third source.

The instantaneous phase of a signal can be calculated in different ways. This article compares two methods for calculating the instantaneous phase of EMG signals. The first method is based on the calculation of complex ridges of wavelet spectrograms of signals. The second method is based on the use of band-pass filtering of signals and Hilbert transform [23]. A method for studying biomedical signals using the ridges of wavelet spectrograms was proposed in the works of Yu.V. Obukhov and co-authors [14,15]. The idea of the method is in that it is possible to distinguish the trajectory of the change in the leading signal frequency in time on the wavelet spectrogram. It is assumed that the leading signal frequency characterizes some oscillatory process that makes the greatest contribution to the power spectral density of the signal under study. We use a complex ridge of wavelet spectrograms [14]; the local maxima of the spectral power density are calculated on the wavelet spectrograms of the envelope of EMG signals at each moment of time, the calculated local maxima constitute the ridge of the wavelet spectrogram. The complex values of the ridge of the wavelet spectrogram contain information about the instantaneous amplitude and instantaneous phase of the signal at each moment of time. We extract information about the instantaneous phase of the signal from the complex values of the ridge of the wavelet spectrogram using the four-quadrant arctangent. The four-quadrant arctangent differs from the usual one in that its range of values is in the range

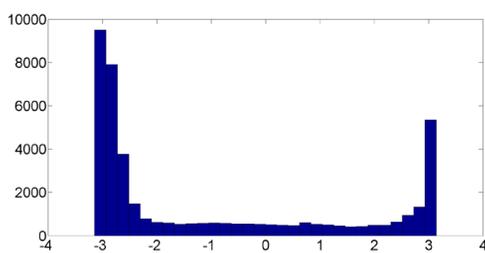
from  $-\pi$  to  $\pi$ , and not from  $-\pi/2$  to  $\pi/2$  as in the usual arctangent.

The method for analyzing EMG signals is discussed in Section 2. Section 3 describes the experimental data used for the study. Section 4 discusses the results of group data analysis. Section 5 contains a discussion of the results obtained.

## 2. METHOD OF ANALYSIS

When studying tremor using EMG, it is customary to analyze not the original signal, but its envelope [5]. We use the Hilbert transform to calculate the signal envelope. After that, we estimate the instantaneous phase of the signal envelope and build histograms of the difference in the instantaneous phase of the EMG signal envelopes of the antagonist muscles. For details on the measurement procedure, see Section 3.

Let us consider the histograms of the phase difference of the envelopes of EMG signals in a patient with PD in the first stage with trembling hyperkinesia on the left hand (Fig. 2). The EMG recording was carried out in a pose with outstretched arms. Fig. 2 shows that the arm with hyperkinesia tremors exhibits phase synchronization, with a phase shift of approximately  $\pi$  radians. This phase shift corresponds to an alternating tremor. A fragment of the original EMG signal is shown in Fig. 1 (left). In Fig. 2, the phase shift relative



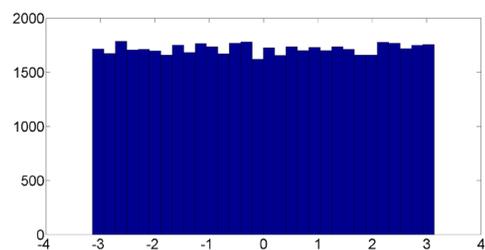
**Fig. 2.** Histogram of the phase difference of the envelopes of EMG signals in a patient with PD at the first stage with trembling hyperkinesia on the left hand. The EMG on the left arm is examined, the pose with outstretched arms. The instantaneous phase is calculated from the complex ridges of the wavelet spectrograms. The abscissa axis is radians; the ordinate axis is the number of hits in the phase intervals.

to zero is visually determined, however, in order to prove that phase synchronization occurs, it is necessary to analyze the histogram using mathematical statistics. Let us apply the Wilcoxon statistical test (one-sample Mann-Whitney test). The test will show whether there is a difference between the median of the general population of the studied sample from zero. If the probability of error is low, less than 5%, it means that phase synchronization is present.

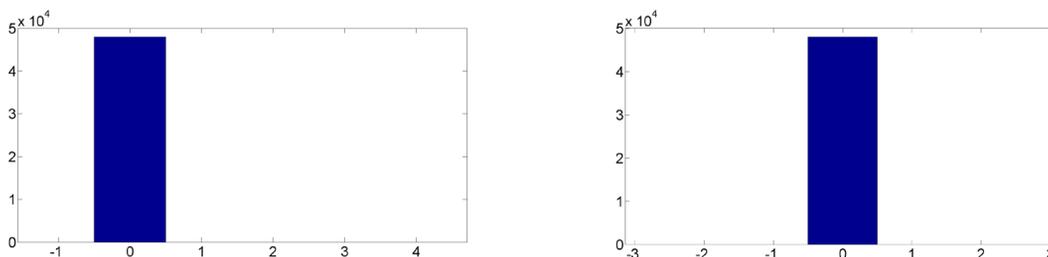
Let's consider a test case No. 1. It is specified that the phase difference at all points of the signal is a random variable. Fig. 3 shows a histogram of the phase difference. The uniform distribution of random numbers is used on the interval from  $-\pi$  to  $\pi$ . The Wilcoxon test did not reveal statistically significant differences in the median of the sample of phase difference from zero ( $p$ -value = 0.48). This means that phase synchronization is not observed.

For the left hand with trembling hyperkinesia in the example in Fig. 2,  $p$ -value < 0.001 (Wilcoxon test), that is, phase synchronization was detected.

Note that the phase is a cyclical quantity, so the peak in Fig. 2 is split; we see on the histogram part of the peak on the left and part on the right. In such a situation, the statistical test may not reveal statistically significant differences in the median of the phase difference from zero. One way to solve this problem is to use two histograms in different ranges, shifted relative to each other. For example,



**Fig. 3.** Histogram of the difference of random phases distributed according to a continuous uniform law. Range is from  $-\pi$  to  $\pi$ . The abscissa axis is radians; the ordinate axis is the number of hits in the phase intervals.

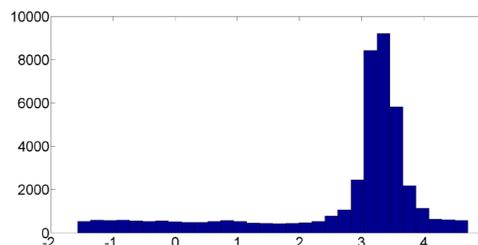


**Fig. 4.** Histograms of the phase difference in the degenerate case, when the phase difference is always zero. On the left - in the phase range from  $-\pi/2$  to  $2\pi-\pi/2$ , on the right - in the phase range from  $-\pi$  to  $\pi$ . The abscissa axis is radians; the ordinate axis is the number of bits in the phase intervals.

the first range is from  $-\pi$  to  $\pi$  and the second is from  $-\pi/2$  to  $2\pi-\pi/2$ .

Let's consider a test example No. 2. It is specified that the phase difference at all points of the signal is equal to zero (**Fig. 4**). Left - in the range from  $-\pi/2$  to  $2\pi-\pi/2$ , on the right - in the range from  $-\pi$  to  $\pi$ . In the range from  $-\pi/2$  to  $2\pi-\pi/2$ , statistically significant differences were found on the histogram ( $p$ -value = 0), while in the range from  $-\pi$  to  $\pi$  there are no such differences ( $p$ -value = 1). This means that if we consider the range from  $-\pi$  to  $\pi$ , the Wilcoxon test will not reveal statistically significant differences in the median phase difference from zero. At the same time, when considering the range from  $-\pi/2$  to  $2\pi-\pi/2$ , the Wilcoxon test will reveal statistically significant differences from  $\pi/2$  (that is, from the middle of the range under consideration).

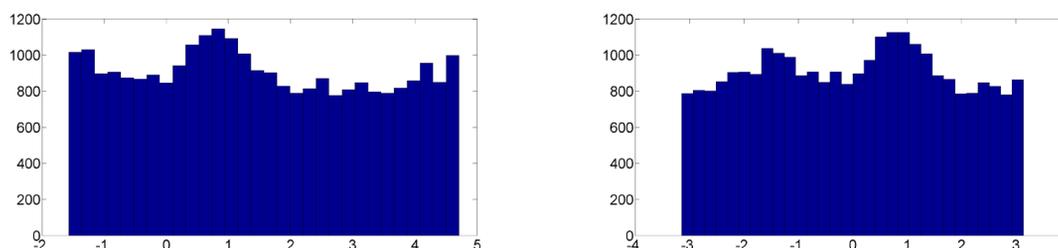
Let's recalculate the histogram of the phase difference for the patient, considered in the example in Fig. 2, in a different range, namely in



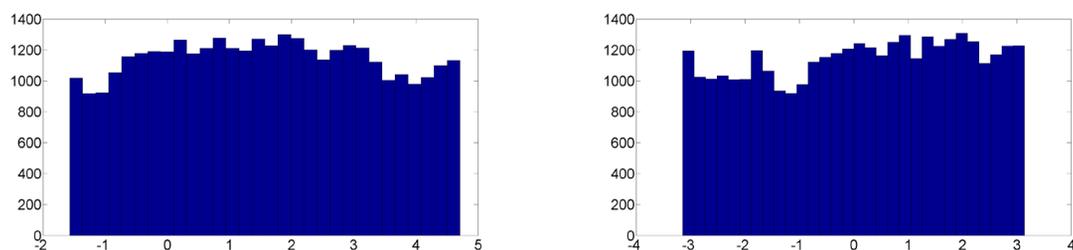
**Fig. 5.** Histogram of the phase difference of the envelopes of EMG signals in a patient with PD at the first stage with trembling hyperkinesia on the left hand. The EMG on the left arm is examined, the pose with outstretched arms. The instantaneous phase is calculated from the complex ridges of the wavelet spectrograms. The abscissa axis is radians; the ordinate axis is the number of bits in the phase intervals.

the range from  $-\pi/2$  to  $2\pi-\pi/2$  (**Fig. 5**). For the left hand with trembling hyperkinesia,  $p$ -value  $< 0.001$  (Wilcoxon test), that is, phase synchronization is observed. Note that the peak in the histogram is not split.

Let's consider a few more examples on real data. **Fig. 6** shows a histogram of the phase difference of a patient with ET, the EMG of the left arm with trembling hyperkinesia, a pose with



**Fig. 6.** Histograms of the phase difference of the envelope EMG signals in a patient with ET. EMG is examined on the left arm with trembling hyperkinesia, a pose with outstretched arms. On the left - the phase is considered in the range from  $-\pi/2$  to  $2\pi-\pi/2$ , on the right - in the range from  $-\pi$  to  $\pi$ . The instantaneous phase is calculated from the complex ridges of the wavelet spectrograms. The abscissa axis is radians; the ordinate axis is the number of bits in the phase intervals.



**Fig. 7.** Histograms of the phase difference of the envelopes of EMG signals in a patient with PD, a hand without trembling hyperkinesis (left hand), a pose with relaxed arms is considered. On the left - the phase is set in the range from  $-\pi/2$  to  $2\pi-\pi/2$ , on the right - in the range from  $-\pi$  to  $\pi$ . The instantaneous phase is calculated from the complex ridges of the wavelet spectrograms. The abscissa axis is radians; the ordinate axis is the number of bits in the phase intervals.

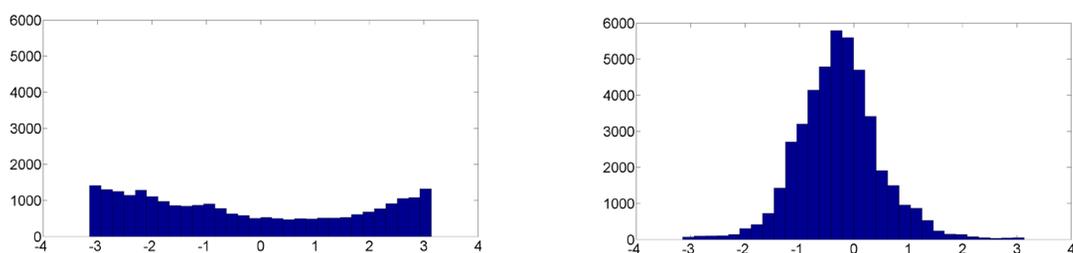
outstretched arms is examined. In the range from  $-\pi/2$  to  $2\pi-\pi/2$  (Fig. 6, left), statistically significant differences were found ( $p$ -value  $< 0.001$ ). At the same time, no statistically significant differences were found in the range from  $-\pi$  to  $\pi$  (Fig. 6, right) ( $p$ -value = 0.9). This example demonstrates the need to consider the phase in two different ranges to identify the phase synchronization of EMG signals.

**Fig. 7** shows a histogram of the phase difference of a patient with PD; the left hand without trembling hyperkinesis is considered. Relaxed arms pose. In the range from  $-\pi/2$  to  $2\pi-\pi/2$  (Fig. 7, left), no statistically significant differences were found ( $p$ -value = 0.71). In the range from  $-\pi$  to  $\pi$  (Fig. 7, right), statistically significant differences were found ( $p$ -value  $< 0.001$ ). Thus, in contrast to the example shown in Fig. 6, statistically significant differences are revealed when considering the phase in the range from  $-\pi$  to  $\pi$ .

In most of the patients with PD at the first stage we studied, a phase shift of approximately

equal to  $\pi$  was observed in the arms with trembling hyperkinesis in the pose with outstretched arms. However, in some PD patients, a different phase shift was observed in the outstretched arms pose, or phase synchronization was not observed at all. In particular, 5 subjects in the PD group showed phase synchronization with a phase shift of approximately zero. In a pose with relaxed arms in PD patients, a similar pattern is observed, in some patients there is a phase shift by  $\pi$  (see **Fig. 8**, left), while in other patients a different phase shift is observed, or phase synchronization is not observed at all. In particular, 2 subjects in the PD group showed phase synchronization with a phase shift of approximately zero.

Let us consider the histograms of the phase difference in a patient with PD at the first stage (see Fig. 8). The hand with trembling hyperkinesis (left hand) is examined. This case is interesting because the patient has a  $\pi$  phase shift not in the pose with outstretched arms,



**Fig. 8.** Histograms of the phase difference of the envelopes of EMG signals in a patient with PD at the first stage with trembling hyperkinesis on the left hand. EMG on the left hand is examined. On the left - a pose with relaxed arms. On the right - a pose with outstretched arms. The instantaneous phase is calculated from the complex ridges of the wavelet spectrograms. The abscissa axis is radians; the ordinate axis is the number of bits in the phase intervals.

but in a relaxed state. The phase difference histogram corresponding to the relaxed EMG recording is shown in Fig. 8, left. The histogram shows a phase shift by  $\pi$ , which corresponds to an alternating tremor. The histogram in Fig. 8 (right) corresponds to an EMG recording in an outstretched arms pose. No phase shift is observed, which corresponds to synchronous tremor. Note that synchronous tremor is characteristic of patients with ET, which could lead to erroneous diagnostics when examining EMG in only one pose. For resting tremor (Fig. 8, left)  $p$ -value  $< 0.001$ . For postural tremor (Fig. 8, right)  $p$ -value  $< 0.001$ .

Patients with ET are characterized by the absence of a phase shift on the histogram of the phase difference; in some cases, phase synchronization is not observed at all. Consider the histograms of the phase difference in a patient with ET (Fig. 9). The EMG recording was carried out in a pose with outstretched arms. Trembling hyperkinesia is observed on both hands. Examination of the histograms of the phase difference shows the presence of phase synchronization on both hands, while no phase shift is observed. The absence of a phase shift corresponds to a synchronous tremor. The section of the EMG signal of this patient is shown in Fig. 1 (right). For the left hand with trembling hyperkinesia,  $p$ -value = 0.006. For the right hand with trembling hyperkinesia,  $p$ -value  $< 0.001$ .

We consider it appropriate to examine EMG recorded in two different poses. We proceed from

the hypothesis that if at least one posture shows a phase shift by  $\pi$ , then the diagnosis of PD is confirmed. In order to test this hypothesis, a group analysis of the data was carried out, the results of which are presented in Section 4.

A comparison was made between two methods for calculating the instantaneous phase. The first method is based on the calculation of complex ridges of wavelet spectrograms of EMG signals. To calculate the wavelet spectrograms, the complex Morlet wavelet with the parameters  $Fb = 1$ ,  $Fc = 1$  was used. Local maxima on the wavelet spectrogram make up its ridge. In this work, the local maxima were calculated in the 4.1-7.9 Hz frequency band. The phase of complex numbers that make up the ridge of the wavelet spectrograms is taken as the instantaneous phase of the signal. The second method is based on the use of band pass filtering and Hilbert transform. An 8th order Butterworth bandpass filter was applied with a bandwidth from 4.1 to 7.9 Hz, filtering was carried out in the forward and then in the opposite direction. After that, the Hilbert transform was used to calculate the instantaneous phase. Thus, in signal processing, the Hilbert transform was used two times. The first time is to extract the envelope of the signal, the second time is to calculate the instantaneous phase.

Fig. 10 shows an example of calculating phase difference histograms in two different ways. In the histogram on the left, the instantaneous phase is calculated from the complex ridges of

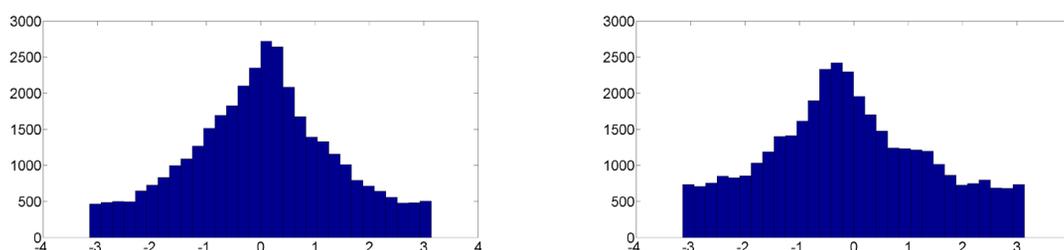
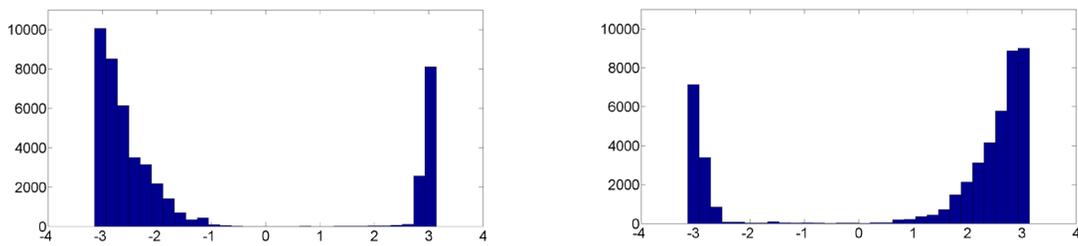


Fig. 9. Histograms of the phase difference of the envelopes of EMG signals in a patient with ET. On the left - for the left hand with trembling hyperkinesia, on the right - for the right hand with trembling hyperkinesia. Outstretched arms pose. The instantaneous phase is calculated from the complex ridges of the wavelet spectrograms. The abscissa axis is radians; the ordinate axis is the number of bits in the phase intervals.



**Fig. 10.** Histograms of the phase difference of the envelopes of EMG signals in a patient with PD at the first stage with trembling hyperkinesia on the left hand. EMG on the left hand is examined; pose with outstretched arms. On the left - the instantaneous phase is calculated from the complex ridges of the wavelet spectrograms. On the right - the instantaneous phase is calculated using the Hilbert transform. The abscissa axis is radians; the ordinate axis is the number of hits in the phase intervals.

the wavelet spectrograms. In the histogram on the right, the instantaneous phase is calculated using the Hilbert transform. The histograms demonstrate that the considered calculation methods give approximately the same results, while the mean values of the phase differences differ. On the left histogram, the mean is  $-1.31$  radians, and on the right histogram, the mean is  $1.22$  radians.

### 3. EXPERIMENTAL DATA

Data from untreated patients with early stage PD were compared with data from patients with ET. Note that the group of PD patients included patients at the first stage of PD according to the classical Hen-Yahr scale with onset (clinical manifestations of tremor) on the left hand (10 people) and on the right hand (12 people), 22 people in total. The clinical diagnosis is a mixed form of PD. The number of ET patients was 13. All PD and ET patients were right-handed. Patient participation in all studies conducted was voluntary. The subjects signed an informed consent in accordance with the standards of the Declaration of Helsinki of the World Medical Association "Recommendations for physicians involved in biomedical research with human participation" [24].

EMG signals were recorded using a 41-channel multifunctional complex for neurophysiological studies Neuron-Spectrum-5 (Neurosoft). EMG electrodes were located both on the outer sides of the arms, on the extensor muscles (Musculus extensor carpi radialis longus), and on the

inner sides of the arms, on the flexor muscles (Musculus flexor carpi radialis). During the EMG recording, the subjects were in two special poses: (1) sitting in a chair, arms extended in front of them (pose with outstretched arms), and (2) sitting in a chair, hands are on the armrests, hands are lowered (pose with relaxed arms). Each EMG recording was carried out for 2 minutes. To isolate the signal envelope, bandpass filtering and Hilbert transform were applied. Namely, an 8th order Butterworth filter with a bandwidth from 60 to 240 Hz was used, filtering was carried out in the forward direction and then in the opposite direction.

### 4. GROUP DATA ANALYSIS

The majority of the subjects showed phase synchronization in both poses. However, in the group of patients with ET, in one of 13 people (7.6%), phase synchronization was observed only in the pose with outstretched arms, while phase synchronization was not observed in the pose with relaxed arms. In the group of patients with PD, in one of 22 people (4.5%), phase synchronization was also observed only in the pose with outstretched arms.

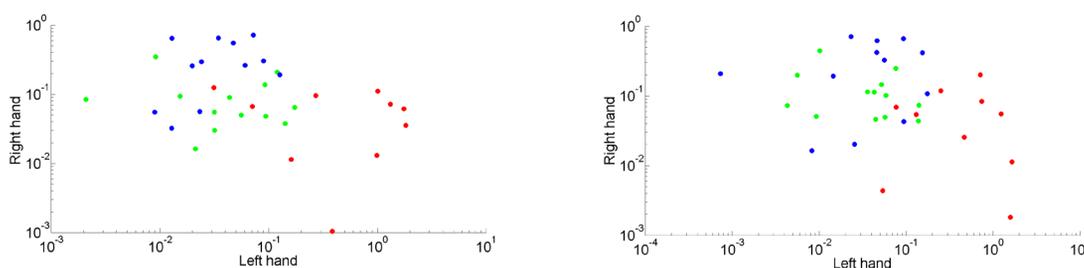
To estimate the phase shift between EMG channels on histograms of the phase difference, various methods can be used, such as calculating the median, mean, truncated mean. In this study, for group data analysis, we compared the mean values of the phase differences in PD patients and in ET patients. To construct scatter diagrams and perform

statistical analysis, we used the absolute values of the phase differences. A two-sample Mann-Whitney statistical test was applied, in addition, ROC curves were constructed and areas under the ROC curves (AUC) were calculated.

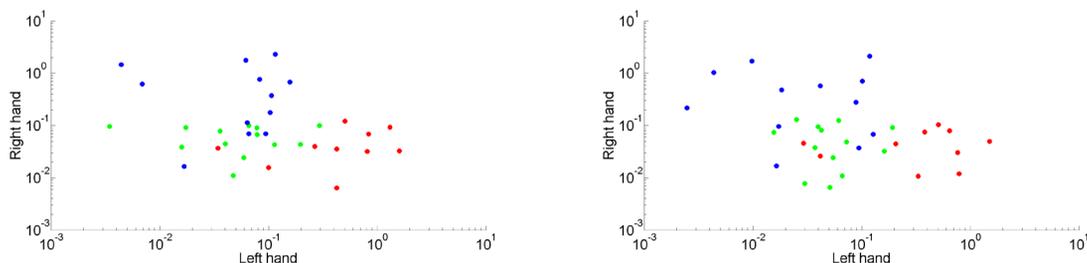
Consider a pose with outstretched arms. Let us compare the mean values of the phase differences of the envelopes of EMG signals in the hands with trembling hyperkinesia in the group of PD patients and in the group of ET patients (**Fig. 11**). Fig. 11 on the left shows the scatter diagram of the mean values of the phase difference, the instantaneous phase is calculated from the complex ridges of the wavelet spectrograms, on the right is a similar scatter diagram when calculating the instantaneous phase using the Hilbert transform. When calculating the phase from the complex ridges of wavelet spectrograms, when comparing the phase differences on the left hands with trembling hyperkinesia in PD patients and in ET patients, statistically significant differences were found,  $p$ -value = 0.0021. The study of the ROC curves showed that the area under the ROC curve AUC = 0.8923. When comparing the phase differences on the right hands with trembling hyperkinesia in PD patients and in patients with ET,  $p$ -value = 0.0114. The area under the ROC-curve AUC = 0.7981. When calculating the phase using the Hilbert transform when comparing the phase differences on the left hands with trembling hyperkinesia in PD

patients and in patients with ET,  $p$ -value = 0.00005. The area under the ROC-curve AUC = 0.9308. When comparing the phase differences on the right hands with trembling hyperkinesia in PD patients and in ET patients, no statistically significant differences were found ( $p$ -value = 0.1827). Thus, when considering the posture with outstretched arms on the subjects' right arms, the best results were obtained using the method based on calculating the phase from the ridges of wavelet spectrograms. At the same time, when comparing the phase differences on the left hands, the best results were shown by the method based on calculating the phase using the Hilbert transform. It is obvious that the results of comparing the methods for calculating the instantaneous phase turned out to be ambiguous.

Consider a pose with relaxed arms. Let us compare the mean values of the phase difference in the hands with trembling hyperkinesia in the group of PD patients and in the group of ET patients (**Fig. 12**). Fig. 12 on the left shows a scatter diagram of the mean values of the phase difference calculated from the complex ridges of the wavelet spectrograms, on the right - a similar scatter diagram when calculating the instantaneous phase using the Hilbert transform. When calculating the phase from the complex ridges of wavelet spectrograms when comparing the phase differences on the left hands with trembling hyperkinesia in patients with PD and



**Fig. 11.** Scatter diagram of the mean values of the phase difference in hands with trembling hyperkinesia in a group of PD patients and in a group of ET patients. The abscissa axis corresponds to the phase difference on the left hand. The ordinate axis corresponds to the phase difference on the right hand. The axes are shown in a logarithmic scale. The pose with outstretched arms is considered. Green dots - patients with ET, red dots - PD patients with trembling hyperkinesia on the left hand, blue dots - PD patients with trembling hyperkinesia on the right hand. Left - the instantaneous phase is calculated from the complex ridges of the wavelet spectrograms. Right - the instantaneous phase is calculated using the Hilbert transform.



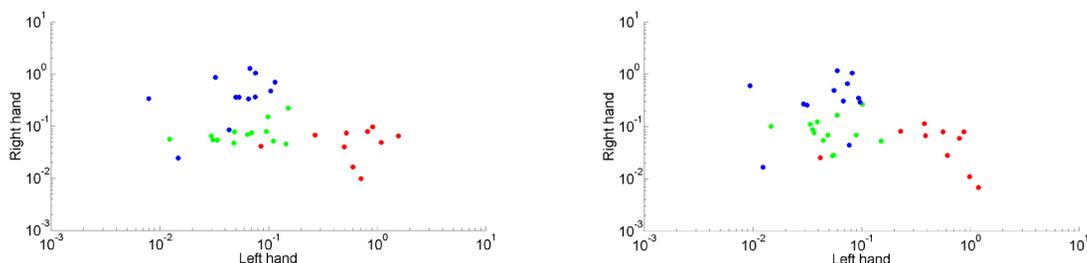
**Fig. 12.** Scatter diagram of the mean values of the phase difference in the hands with trembling hyperkinesia in the group of patients with PD and in the group of patients with ET. The position with relaxed arms is considered. The designations and axes are the same as in the previous figure.

in patients with ET,  $p$ -value = 0.0017. The area under the ROC-curve  $AUC = 0.8923$ . When comparing the phase differences on the right hands with trembling hyperkinesia in PD patients and in patients with ET,  $p$ -value = 0.0036. Area under the ROC-curve  $AUC = 0.8462$ . When calculating the phase using the Hilbert transform when comparing the phase differences on the left hands with trembling hyperkinesia in PD patients and in patients with ET,  $p$ -value = 0.0048. The area under the ROC-curve  $AUC = 0.8577$ . When comparing the phase differences on the right hands with trembling hyperkinesia in PD patients and in ET patients,  $p$ -value = 0.0051. The area under the ROC-curve  $AUC = 0.8333$ . Thus, when considering the pose with relaxed arms for both arms of the subjects, the best results were obtained using the method for calculating the instantaneous phase based on the use of the ridges of the wavelet spectrograms.

It follows from the data that statistically significant differences in the mean values of the phase difference were detected both in the pose with outstretched arms and in the pose

with relaxed arms. As described above, this is due to the fact that the tremor in different patients manifests itself in different positions. In view of this, we decided to combine the mean values of the phase difference for these two poses (hereinafter,  $S$  is the mean value of the phase shift for the pose with outstretched arms,  $R$  is the mean value of the phase shift for the pose with relaxed arms) by calculating the mean value  $(S+R)/2$ .

Consider the combined metric  $M = (S+R)/2$ . Let us compare the values of the  $M$  metric in the group of PD patients and in the group of ET patients (**Fig. 13**). Fig. 13 on the left shows a scatter diagram of the mean values of the phase difference calculated from the complex ridges of the wavelet spectrograms, on the right - a similar scatter diagram when calculating the instantaneous phase using the Hilbert transform. When calculating the phase from the complex ridges of the wavelet spectrograms when comparing the phase differences on the left hands with trembling hyperkinesia in PD patients and in patients with ET,  $p$ -value = 0.00002. The



**Fig. 13.** Scatter diagram of the mean values of the phase difference in the hands with trembling hyperkinesia in the group of patients with PD and in the group of patients with ET. The combined metric  $M$  is considered. The designations and axes are the same as in Fig. 11.

area under the ROC curve  $AUC = 0.9615$ . When comparing the phase differences in the right hands with trembling hyperkinesia in PD patients and in patients with ET,  $p$ -value = 0.00006. The area under the ROC curve  $AUC = 0.9038$ . When calculating the phase using the Hilbert transform when comparing the phase differences on the left hands with trembling hyperkinesia in PD patients and in patients with ET,  $p$ -value = 0.00004. Area under the ROC-curve  $AUC = 0.9385$ . When comparing the phase differences on the right arms with trembling hyperkinesia in PD patients and in patients with ET,  $p$ -value = 0.0043. The area under the ROC curve  $AUC = 0.8397$ . Thus, when considering the combined M metric, both  $p$ -value and AUC were better for both methods of calculating phase, compared to considering outstretched arms and relaxed arms separately. In addition, when considering the combined metric, the best results were obtained using the method based on calculating the phase from the ridges of wavelet spectrograms (for both arms of the subjects). The obtained AUC values are close to 1, which shows that the proposed metric can be used not only for group analysis, but also for differential diagnosis of patients with PD and ET.

5. DISCUSSION

Comparison of the two methods for calculating the instantaneous phase showed that neither of these methods has a clear advantage over the other. When calculating the phase using the Hilbert transform, the recognition results turned out to be better only in one case: when comparing the phase differences on the left arms with

trembling hyperkinesia in patients with PD and ET when considering the pose with outstretched arms. In all other cases, the best results were obtained by calculating the instantaneous phase using complex ridges of wavelet spectrograms. The results obtained are explained by the fact that at a sufficiently high signal-to-noise ratio, various methods for calculating the instantaneous phase give approximately the same results. At the same time, different methods for calculating the instantaneous phase are based on different assumptions about the properties of the signal under study, in particular, the use of complex ridges of wavelet spectrograms assumes that in the frequency range under study there is only one leading frequency at any time. Unfortunately, the study of real EMG data shows that this assumption is not always fulfilled; in some patients, not one, but two peaks are observed on the EMG signal envelope spectrum in the 4.1-7.9 Hz range (Fig. 14, left), in some cases on In the spectrum of the envelope of the EMG signal, there is not a single pronounced peak at all. Obviously, in this situation, the ridge of the wavelet spectrogram can give incorrect values of the instantaneous phase of the signal, because the initial assumption about the uniqueness of the leading frequency is not fulfilled. The method for calculating the instantaneous phase, based on the Hilbert transform, in this situation can give an advantage, because the Hilbert transform allows mathematically to accurately determine the instantaneous phase of any signal even in the absence of a clearly expressed leading frequency [23]. Note that the widespread belief that the Hilbert transform can only be used to

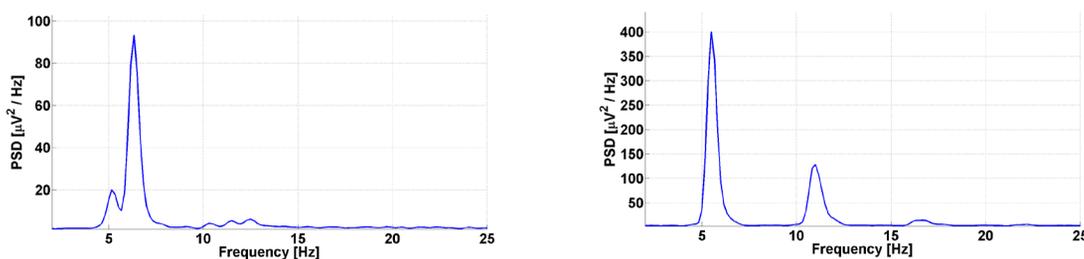


Fig. 14. Examples of the spectra of the EMG signal envelopes of the extensor muscles in patients with PD. The left hand with trembling hyperkinesia was examined. On the left is an example of a split-peak EMG spectrum. On the right is an example of a spectrum with three additional harmonics. The abscissa is the frequency; the ordinate is the power spectral density.

analyze narrowband signals is wrong; Hilbert transform (or the so-called analytical signal complement) is defined for any kind of signals, including broadband ones. At the same time, in a situation where there is one pronounced peak in the signal spectrum, the method for calculating the instantaneous phase using complex ridges of wavelet spectrograms may be preferable, because it, in fact, performs nonlinear transformation of the signal, isolating the component with the highest power spectral density and discarding the rest of the signal components.

In the present study, the presence of statistically significant differences in the mean values of the phase difference of the EMG signal envelopes in the 4.1-7.9 Hz range of antagonist muscles in the group comparison of PD patients and ET patients with both resting tremor and postural tremor was shown. Note that the authors of [22] did not find differences between PD and ET in postural tremor. In resting tremor, differences were found only in the range of 8-12 Hz, no differences were found in the range of 4-7 Hz [22]. There are several possible reasons for this discrepancy. In article [22], the rectification method was used to isolate the envelope of EMG signals. The term rectification in neurophysiology is the calculation of the absolute value of the signal. Rectification is not a mathematically rigorous way to calculate the signal envelope. As a result of applying this operation, a certain mixture of the signal envelope and the original signal itself is obtained, which complicates the correct physiological interpretation of the data analysis results. In addition, the authors of [22] used coherent analysis. In our research, phase difference histograms were used to estimate the phase shift. We also note that the duration of patient records in [22] was significantly shorter than in our study. The length of the patient records in [22] was about 30 seconds, in our work the length of the records was about 90 seconds. In [22], it is noted that EMG spectra in PD are characterized by a greater number of harmonic frequency peaks than in ET, namely, it is shown that PD is characterized by the presence of four

or more harmonics in the EMG spectrum of the elbow flexor. Our research showed that in PD patients, in addition to the main peak, one additional harmonic is usually observed on the spectra of the envelopes of EMG signals, rarely two or three (**Fig. 14, right**). With ET, additional harmonics in the spectra of EMG signals are observed much less frequently.

## 6. CONCLUSION

The study of surface EMG signals of antagonist muscles in patients with PD and ET was carried out. Comparison of two methods for calculating the instantaneous phase of the envelopes of EMG signals is carried out - using the complex ridges of wavelet spectrograms and using the Hilbert transform. It is shown that both methods give approximately the same results, but the mean values of the phase differences differ. Statistically significant differences were found in the mean values of the phase difference of EMG signals envelopes of antagonist muscles in the group comparison of PD patients and ET patients both in the pose with outstretched arms and in the pose with relaxed arms. The most significant differences were obtained when analyzing a special metric that combines the results of the analysis of these two poses. When analyzing the ROC curves, AUC values close to 1 were obtained, which suggests that the studied metric can be used for differential diagnosis of PD and ET.

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