Determining the Type of Muscle Motor Activity by Applying the Wavelet Theory and Theory of Random Walks to Characterize the Neuronal Noise

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Abstract. We have studied the discharge dynamics of fusimotor neurons by applying the Wavelet transform technique (WT) and Detrended Fluctuation Analysis (DFA). Here we adopt that the neuronal discharge dynamics is manifested by random thime series of interspike intervals (ISI). We found two different power-low type behaviors along interspike time intervals time scale, which are separated by the pertinent crossover region. Our results reveal that different types of muscle motor activity can be characterized by different critical exponents. Thease exponents are the characteristics of neuronal noise.

INTRODUCTION

Noisy data, which emerge from systems with spatial and temporal randomness, such as various biological and physiological phenomena, have been successfully investigated using methods established within modern statistical physics [1]. This is how the scale-invariant properties of a number of biological systems have been established, while the use of modern methods derived from statistical physics has led to elucidation of principles of organization in seemingly irregular biological data sequences [2].

In this spirit, we have performed an extensive statistical analysis of the fusimotor neuron activities. We have used the wavelet transform (WT) analysis [3] and the modification of random walk analysis, called the detrended fluctuation analysis (DFA) [4], for the time series of fusimotor neuronal discharges. Fusimotor neurons belong to a complex neural system of skeletal muscles [5, 6]. They take part in the shaping and transmitting of proprioceptive information (about the temporary position and movement of relevant extremity). Like other neurons, fusimotor neurons generate action potentials, brief and uniform pulses of electrical activity (henceforth we will refer to them, in standard parlance, as spikes; see Fig. 1a), communicating thereby with muscle spindles, sensory objects within muscles. There is a dominant belief that the time series comprised of the consecutive appearance of spikes (see Fig. 1a), or, equivalently, subsequent interspike intervals - ISI (see Fig. 1b), should be the key object in unveiling the true role of fusimotor activity. For this reason, in this paper we investigate, using the above mentioned statistical methods, the time series of fusimotor discharge behavior. We have analyzed

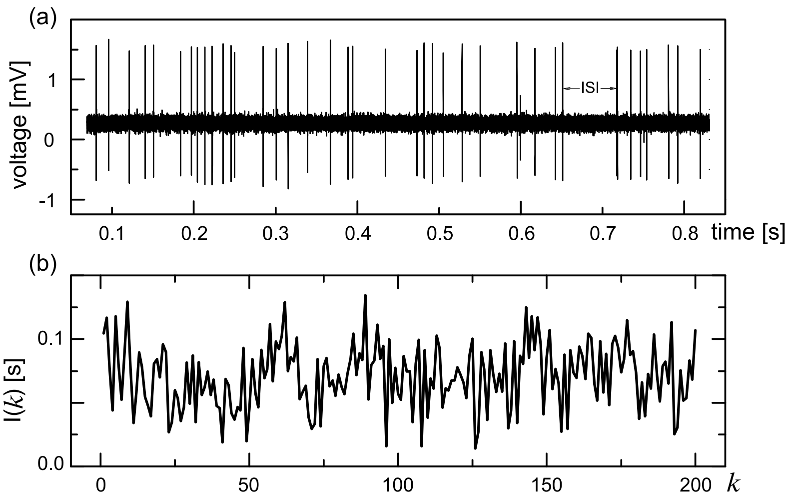

FIGURE 1. (a) The recorded electrical activity of the cat fusimotor neuron. This activity results in appearance of random series of spikes (action potentials), separated by the random time intervals, which are called the interspike intervals (ISI). (b) A sequence of 200 ISIs (durations) $I(k)$ depicted versus the ISIs consecutive enumeration number k (to obtain the definitive results we used representative sequence of the order 10^4).

spontaneous [7, 8] and stimulated (by mechanical and electrical activation of relevant muscle) [9] activity, recorded from fusimotor neurons of decerebrated cats (*felis domesticus*). Having in mind the specific role of fusimotor neurons within the neuromuscular system, we are particularly interested whether our methods can discern these different types of muscle motor activity.

WAVELET TRANSFORM METHOD AND RESULTS

WT is useful in analyzing nonstationary or inhomogeneous signals, giving both the frequency and coordinate (time, or space) characteristics of the signal under study [4], see Fig. 2. We have applied the DOG (Derivatives of Gaussian) wavelets [10] to investigate various sets of ISI data.

To reach quantitative conclusions (which can be compared with the DFA results), we have to calculate corresponding scalegrams (wavelet power spectra) $E_W(a)$. The scalegram $E_W(a)$ can be related to the corresponding Fourier power spectrum $E_F(w)$, so that if the two spectra, $E_W(a)$ and $E_F(w)$, exhibit power law behaviors, then they should be described by the same exponent β [4].

Presented scalegrams in Fig. 3 have been calculated with the second order DOG wavelet. One can see two regions of different power-law behavior (straight lines in log-log scale), separated by the crossover point. In the region below the crossover point, critical exponent is $\beta = 0$ for the scalegram obtained for spontaneous fusimotor activity, while for stimulated activity we can see changes in the character of ISI series at small scales and critical exponent reaches value $\beta = 0.5$. Namely, wavelet power spectra show appearance of long-range correlations within ISI series when external stimuli are applied

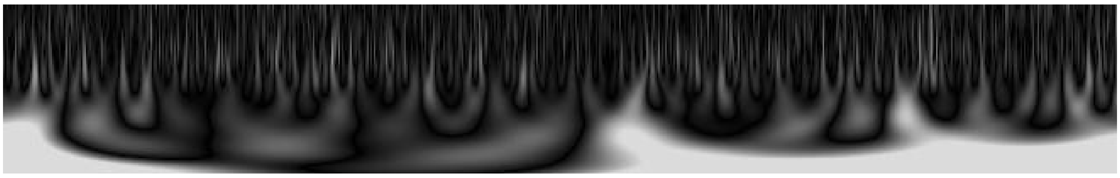

FIGURE 2. Pattern of wavelet transform coefficients for fusimotor ISI series. Transform is performed using derivatives of Gaussian (DOG) of second order.

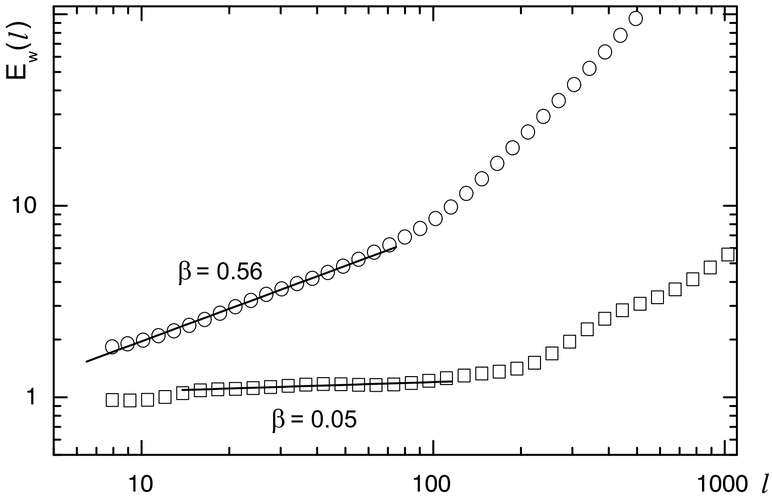

FIGURE 3. Typical example of the scalegrams, $E_W(l)$, of the second order of applied wavelet function, in the case of the spontaneously active fusimotor neuron (small squares), and of the externally stimulated fusimotor cell (small circles). Straight lines represent correlations of the power-law type, while the slope of these lines corresponds to power spectrum critical exponent β. The appearance of long-range temporal correlations of the power-law type (in the presence of external stimulation) is demonstrated by the differences of slopes in the areas below crossover regions. In the case of the spontaneous activity wavelet power spectrum behaves in accord with the power-law with the exponent $\beta \approx 0$, which implies the white noise in the fusimotor temporal dynamics. In the case of the stimulated β activity acquires value close to 0.5.

to appropriate muscle, compared to the case of a non-stimulated fusimotor activity, when no correlations appear (that is, when $\beta = 0$, which is characteristics of white noise). For large scale (in the region above the crossover point) critical exponent β is larger, and it acquires values characteristic for $1/f$ noise, for both cases studied. Moreover, obtained values of β, bigger than one, indicate possible non-stationarity of ISI series in areas of large segment sizes [2].

DFA METHOD AND RESULTS

DFA method relies on the random walk theory for calculation of the so-called detrended fluctuation function $F(l)$ [3]. DFA is a technique that has been widely used for detection of long-range correlations, when the fluctuation function behaves as $F(l) \sim l^{\alpha}$. In

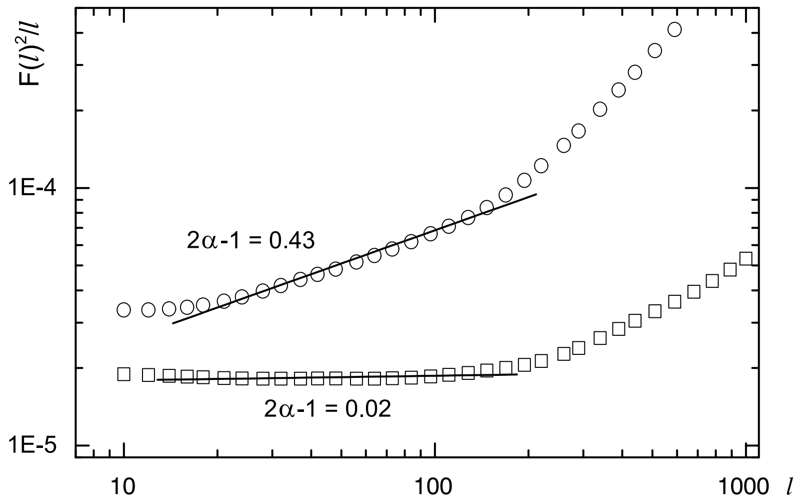

FIGURE 4. Typical example of DFA functions, $F(l)$, in the case of the spontaneously active fusimotor neuron (small squares), and of the externaly stimulated fusimotor cell (small circles). Straigth lines represent correlations of the power-law type, while the slope of these lines corresponds to DFA critical exponent α. DFA functions are presented in the form $F(l)^2/l$ versus l, in order to compare the results with wavelet transform analysis. Slopes of DFA functions in the area below crossover region behave in an identical way as those obtained by the WT analysis. In the case of the spontaneous activity DFA exponent is $\alpha \approx 0$, while in the case of the stimulated activity α is bigger than 0.5.

the case of short-range data correlations (or no correlations at all) it turns out that the analyzed time series displays properties of a standard random walk (white noise), and $F(l)$ behaves as $l^{1/2}$ [2]. On the other hand, for data with power-law long-range correlations one may expect that $\alpha > 0.5$. In addition, the exponent α, associated with the detrended fluctuation function $F(l)$, can be related to the power spectrum exponent through the scaling relation $\alpha = (\beta + 1)/2$ [11].

In Fig.4 we present the results obtained by the use of DFA technique on time series of fusimotor discharges. It is important to notice here that the white-noise-like behavior of the spontaneously active cells is equivalent to the result previously found by the WT analysis. The application of DFA technique on externally stimulated fusimotor data reveals that the response of fusimotor neurons to external electrical and mechanical stimulation is marked by the onset of temporal correlations as it is shown above.

DISCUSSION AND CONCLUSIONS

In this paper we have studied the discharge dynamics of fusimotor neurons by applying the wavelet transform (WT) method and the detrended fluctuation analysis (DFA). We demonstrated that the application of WT and DFA methods reveals power-law type behavior across a reasonable large segment of scale. The obtained results also suggest that complex neuronal dynamics (at least in the case under study) may change in the presence of external stimulation and thus differentiate between the two types of muscle motor activity. These results confirm previously obtained findings, in the case of sensory neurons from spinal cord (the so-called DHN cells, see [12]). Both approaches (WT and DFA) confirmed the existence of the white noise in the fusimotor activity in the cases of spontaneous activity, and the existence of correlated noise in the cases of stimulated activity of relevant muscles, in the small scale regions.

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