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BIOPHYSICS AND MEDICAL PHYSICS

Shannon Entropy in the Research on Stationary Regimes and the Evolution of Complexity

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Abstract—The questions of the identification of complex biological systems (complexity) as special self-organizing systems or systems of the third type first defined by W. Weaver in 1948 continue to be of interest. No reports on the evaluation of entropy for systems of the third type were found among the publications currently available to the authors. The present study addresses the parameters of muscle biopotentials recorded using surface interference electromyography and presents the results of calculation of the Shannon entropy, autocorrelation functions, and statistical distribution functions for electromyograms of subjects in different physiological states (rest and tension of muscles). The results do not allow for statistically reliable discrimination between the functional states of muscles. However, the data obtained by calculating electromyogram quasiatttractor parameters and matrices of paired comparisons of electromyogram samples (calculation of the number k of "coinciding" pairs among the electromyogram samples) provide an integral characteristic that allows the identification of substantial differences between the state of rest and the different states of functional activity. Modifications and implementation of new methods in combination with the novel methods of the theory of chaos and self-organization are obviously essential. The stochastic approach paradigm is not applicable to systems of the third type due to continuous and chaotic changes of the parameters of the state vector $x(t)$ of an organism or the contrasting constancy of these parameters (in the case of entropy).

Keywords: entropy, quasiattractor, third-type system, thermodynamics of non-equilibrium systems.

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INTRODUCTION

The creators of the thermodynamics of non-equilibrium systems, including I.R. Prigogine, who was the founder of this field of research, undertook active attempts to describe real biological systems (complexity) within the conceptual framework of entropy E, the rate of entropy increase $P = dE/dt$, the stability of stationary states, and evolution. The theorem (principle) of the minimum production of entropy ($dP/dt \le 0$) for the rate P ($= dE/dt$) of the change of entropy E has been proven true for many systems (processes). However, this inequality is not necessarily true for nonlinear processes and special third-type systems (TTSs) currently referred to as complexity; the general Prigogine–Glansdorff criterion for the evolution of thermodynamic systems (in the form of $d_xP/dt \le 0$) may not be fulfilled either. The problem of the assessment of evolution (the rate and direction of evolution) for nonlinear biological systems currently defined as TTSs [1–6] arises in this case.

F. Schlegl [5] noted the close connection between the second variation of entropy E and the information that is obtained upon the transfer from a state with the probability P_i to a state with the probability P_i^1 ($K(P_i, P_i^1) = \Sigma P_i \ln((P_i/P_i^1))$; therefore, we suggest the use of the function K as the Lyapunov function. Schlegl's criterion of stability has the form $dK/dt \le 0$ in this case. The Lyapunov stability criterion remains the basic criterion in the theory of stability of complex non-equilibrium systems, especially in the case of systems with dynamics that are amenable to analytical description. Such models for TTSs are virtually nonexistent and since TTSs cannot be assigned to linear or non-linear (in the conventional sense) systems that are amenable to analytical description, the problem of the assessment of the stability and evolution of TTSs within the new interpretation arises [7–11].

The questions of the definition of generalized forces and flows that are successfully used in the thermodynamics of living systems, including the analysis of processes that occur at the molecular level, remain under discussion in the case of TTSs. Experimental assessment of these forces and flows in complex TTSs is very difficult; therefore, the direct thermodynamic calculations for TTSs (complexity) are rather complicated. Therefore, the only approach for finding an

analytical solution for a problem at this level is the direct calculation of entropies and analysis thereof for the assessment of stationary states. The problem of the detection of the deviation of TTSs from these stationary states arises at the same time. As we showed previously [8–13], the concept of stationarity (within the framework of stochastics) is not applicable to TTSs (all statistical functions $f(x)$ of any coordinate x_i of the entire state vector of the system $x = x(t) = (x_1, x_2, ... x_m)^T$ derived from consecutive samples change chaotically in homeostasis) [8–14]; therefore, this problem becomes even more complex. This phenomenon, which is termed the Eskov–Zinchenko effect in psychophysiology, provides a quantitative description of N.A. Bernshtein's hypothesis ("repetition without repetition") in biomechanics [15].

We use a range of new methods based on the calculations of matrices of pairwise comparison of the samples x_i and quasiattractors (QA) to perform quantitative comparison of the theory of I.R. Prigogine (the thermodynamics of non-equilibrium systems) and the actual processes of $x(t)$ dynamics in TTSs. A special problem concerning the very idea of a stationary mode in TTSs arises in this case [2–8]. We compared the values of TTS entropy for different modes of TTS functioning within the newly developed approaches [9–14, 16, 17]. No changes of the entropy E in the stationary TTS modes were expected, in contrast to evolution, for which such changes were expected. How should stationarity and evolution be interpreted in the case of complex regulatory biological systems, such as the human functional systems (HFSs) of the body as defined by P.K. Anokhin? Is it possible to perform quantitative registration of changes in the mental state (cognitive processes) in psychology? Which state should be considered as the unmodified state of an HFS or the human psyche? What criteria are needed for this? Psychophysiology enables the elucidation of the mental state based on parameters of the HFSs; therefore, the problem formulated above can be common for both physiology and psychology and involve the assessment of stationary modes or the evolution of HFS parameters in a person exposed to different stimuli. If the precise quantitative values of the parameter x_i are available, both the changes in an HFS and changes in mental state can be registered [1–3, 8, 16]. Overall, it is now possible to transform psychophysiology into a precise science that employs mathematical modeling, even though the general indetermination of changes in mental state can be proven by the methods of stochastics [9–14, 16–18].

1. GENERAL LAWS OF NON-EQUILIBRIUM SYSTEM THERMODYNAMICS FOR LIVING SYSTEMS

The absence of stationary states in the traditional (deterministic–stochastic) sense is a principal characteristic of TTSs [8–13, 16]. Our numerous earlier reports [11, 13, 14, 16, 17] pointed to the constant and continuous nature of $dx/dt \neq 0$ in TTSs within the framework of functional (deterministic) analysis. This is the second postulate (principle) of the organization of any HFS (and the mental status of a person) that immediately excludes TTSs from the domain of determinism [9–11]. At the same time, the statistical distribution functions $f(x)$ are changing continuously if any parameter x_i of the state vector $x(t)$ is registered sequentially for a complex biological system that remains in the same homeostatic state. Any sample j and any statistical function $f_j(x_i)$ will be unique and random from sample to sample, that is, for any component x_i during each time interval δt_j. This is the mathematical basis of the Eskov–Zinchenko effect in the biomechanics and psychophysiology of movement. The question of the dynamics of entropy E for TTSs in a certain stationary mode (homeostasis) remains open. In other words, we raise the fundamental question of the applicability of entropy and nonequilibrium system thermodynamics developed by Prigogine in research on HFSs and the psychophysiological status of a person.

The fundamental theorem of the production of entropies E in an open system with time-independent boundary conditions (Prigogine's theorem) for infinitesimal variations states that the production P of entropy E for any open system that is approaching an equilibrium state (when $E \to \max$) must satisfy conditions of the minimum of its rate of change:

$$P = dE_i/dt = \min. \quad (1)$$

Moreover, when the system is in equilibrium (the conditions of the maximal value of the entropy E and the minimal change in the entropy production rate and variations P are fulfilled), the condition in the form of the second condition for the increment of P must be satisfied:

$$dP = 0. \quad (2)$$

If linearity of all the processes addressed below is assumed (this is almost always true for the small time intervals δt), we can verify the requirement (2) for processes that involve a change of tremor and tapping parameters, cardiac intervals, muscle contraction (interference electromyography (EMG) at various levels of contraction strain), and changes in EEG parameters in healthy and sick (epileptic) people under the conditions of external stimulation. In all these cases we can test the dynamics of the rate of change of Shannon entropy, which many renowned physicists have assumed to be equivalent to the Boltzmann entropy or thermodynamic entropy S up to constants (direct proof for all processes was not provided; however, at least there are no decisive reasons to deny this assumption) [11, 13]. Overall, the assumption of equality (within the limits of constant factors) of all three kinds of entropy (Boltzmann, Shannon, and

thermodynamic entropy S) remains a generally accepted statement rather than a proven theorem. However, this assumption still remains true for all processes that are known and observed; therefore, the statement is considered true.

If these conditions (in form (1) and (2)) are not satisfied, one can assume a loss of linearity of the TTSs under investigation, the violation of the independence of boundary conditions of time (this is more realistic for TTSs, given their quasilinear properties on small t intervals), or the general lack of applicability of Prigogine's non-equilibrium thermodynamics for TTSs. The latter assumption currently appears to be the most reasonable, as well as the assertion that the chaos and self-organization theory (CST) is beyond the scope of modern deterministic–stochastic science [9–11]. At the same time, we will attempt to verify the evolution conditions formulated by Prigogine, that is, the fulfilment of the condition $dE \le 0$ upon a deviation from the equilibrium state. Many published articles and monographs emphasize that nonequilibrium system thermodynamics cannot be applied to nonlinear biological systems that do not allow easy identification (formalization) of the concept of the "force" (thermodynamic force) X_S and thermodynamic flow (reaction rate) due to considerable heterogeneity and even uncertainty of the very concept of "force." Therefore, a paradoxical situation arises: it is possible to register the entropy $E = E(t)$ during the evolution of biological systems, but the registration of X_S (and flows) turns out complicated. The X_S value can usually be inferred from the results of the control of the dynamics of the parameters of a biological system. This implies that the well-known linear phenomenological expression:

$$J_r = \sum_{S=1}^{k} L_{rs} X_S \qquad (3)$$

will be true for any TTS. These systems are not described by standard deterministic equations for any component $x_i(t)$ of the state vector of a TTS (in the form $x = x(t) = (x_1, x_2, \ldots x_m)^{\mathrm{T}}$, where x_i is any parameter of the biological system). In the case under consideration, we cannot evaluate the equilibrium in the form of $dx/dt = 0$ (stationary state) or $dx/dt > 0$ (positive rate of change). Moreover, the very notion of a stationary mode or motion (evolution) of the TTSs acquires a meaning completely different from that ascribed to these notions in deterministic and stochastic science [6, 9–11]. The deterministic–stochastic approach and Prigogine's non-equilibrium thermodynamics impose definite requirements on the rate of change of the components of the state vector of the system $x = x(t) = (x_1, x_2, \ldots x_m)^{\mathrm{T}}$ in the form of $dx/dt = 0$, the conservation of $f(x)$ for $x(t)$ samples, or adherence to the conditions set by Prigogine's theory, namely, minimal production P of entropy ($dE/dt \to$ min) and maximal value of entropy ($E =$ max at $P \to 0$) in the vicinity of the stationary state. However, all these conditions are not fulfilled for many TTSs, as shown in a wide variety of studies that we performed previously [1–3, 6–13, 16, 19]. Certain (most typical) examples that illustrate this statement for TTSs are presented below.

2. LIMITATIONS OF STOCHASTICS IN THE ANALYSIS OF TREMOROGRAMS

One cannot imply the stationary character of TTSs within the framework of the deterministic–stochastic approach in cases when the statistical distribution functions $f(x)$ change upon the transition from one sample (TTS state) to another (another TTS state). The function $f_j(x_i)$ for any sample j cannot be derived arbitrarily. The situation turned out to be even more complex, since $f(x)$ recorded for many biological systems was not conserved even for the same person in the case of repeated (number of samples $N = 15$) registration of parameters ($N = 15$). Calculation of pairwise comparison matrices for tremorogram or tappinggram (TPG) samples for 15 series of experiments with 15 samples in each series showed that the probability of sample "coincidence" (for instance, for tremor) was very small. Virtually all samples were different, but the number k of coincident pairs for the samples for tremor never exceeded 5–6% (on average); this is a distinctive feature of systems of the third type for tremorograms. These quantitative results form the basis of the Eskov–Zinchenko effect in biomechanics and psychology [3, 4, 11].

A representative example of a pairwise comparison matrix for tremorogram samples recorded for the same subject (number of repetition series $N = 15$) is shown in Table 1. The non-parametric Wilcoxon criterion was used to construct the matrix. The number of coincidences $k = 4$ for supposedly identical tremorogram samples derived from a person in the same physiological state (homeostasis). Only three pairs of all of the possible pairwise combinations used for comparison (105 in total) could be assigned to the same general population, while the remaining 102 pairs were different. Moreover, multiple repetitions of the experiment (15 recordings of series of 15 tremorogram samples) revealed only slight variation of the number of coincidences k, with a 3–7% level coincidences among the 105 pairs possible for tremor. This is the actual cost of the stochastic approach to the investigation of the neuromuscular system. All statistical functions $f(x)$ for tremorograms and electromyograms (EMG) are different and the use of these functions in the assessment of tremor is highly problematic (virtually impossible); this is a manifestation of the Eskov–Zinchenko effect.

Analysis of all 15 series of experiments that involved the construction of pairwise sample comparison matrices (similar to that shown in Table 1) for each series gave the overall result of $k < 8$ for all subjects (including the subject whose results were shown in

Table 1. The matrix of pairwise comparisons of tremorogram samples from the subject GDV (number of repetitions $N = 15$). The Wilcoxon test was used (significance level $p < 0.05$, number of coincidences $k = 4$)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.0	0.0	0.0	0.26	0.0	0.0	0.0	0.0	0.0	0.0	0.02	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.37	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.26	0.37	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.81	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.81	0.0	0.0	0.0	0.0	0.0	0.0
11	0.02	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.37	0.0	0.0
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.37	0.0	0.0	0.0
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 1). The average k value was 4.9, which is similar to the results obtained for other series. In other words, pairwise sample comparison matrices exhibited statistical stability of $\langle k \rangle$, although $f(x)$, spectral densities thereof, and the autocorrelation functions $A(t)$ were unstable. Statistical stability of the number k of coincidence pairs in the sample was observed for the different samples as pairwise comparison matrices for the tremorograms recorded in one subject were compared.

3. CALCULATION OF THE VALUES OF SHANNON's ENTROPY FOR PARAMETERS OF TREMOR UNDER LOAD

The Shannon entropy was calculated for all series of tremorogram samples presented above in order to analyze the level of randomness in the temporal pattern of the tremorogram. The entropy approach in the analysis of tremorogram samples did not reveal any differences in the values of the entropy E, in contrast to statistics that pointed at chaotic changes of the statistical functions $f(x)$, the $A(t)$ for these functions, and the amplitude-frequency characteristics. According to these results, samples of tremor data could be attributed to one general population if the Shannon entropy values for the tremorograms were considered. The matrix of pairwise comparisons of E samples for all 15 series is shown in Table 2. The significance level of the Wilcoxon test is $p > 0.05$ at the threshold significance level $p < 0.05$ and the number of coincidence pairs $k = 102$. In other words, all these samples (15 series of 15 repetitions) show no statistical differences with regard to the Shannon entropy values (Table 2). Similar matrices were obtained in the case of experimental comparison of uniform distributions (chaos is the permutation property). Pairwise comparison matrices for these samples demonstrated 97–99% coincidence as well. Almost complete statistical coincidence of 15 E samples in 15 series of experiments (15 tremorograms in each series) is evident from Table 2.

The possibility of the use of Shannon's entropy values was analyzed in more detail in a study that involved the registration of tremor parameters without loading and with static retention of a load (300 g) fixed to the finger of the subject. This study revealed a definite regularity in the change in the number of coincidences during the construction of pairwise comparison matrices for tremorograms. The regularity was manifested as a definite increase of the number k upon the registration of tremor under load. The quasiattractor areas for the tremorogram samples [10–12] were calculated within the CST and a regular increase of the values of the areas was demonstrated (Table 3). As shown in Table 3, the sample of 15 quasiattractor areas S for an experiment with loading is significantly different ($p = 0.00$) from the sample of areas S recorded in an experiment without loading ($\langle S_1 \rangle = 3.02$ a.u. versus $\langle S_2 \rangle = 6.91$ a.u. for an experiment with loading).

However, calculation of the Shannon entropy for the two tremorogram samples (with and without loading) did not reveal any significant change. According to the values of Shannon entropy (Table 4), mechanical loading had no effect on the state of the human body (tremor parameters) and these results imply that the test subject was in an allegedly stationary state without load and under load, although the latter condition is apparently associated with a deviation from a stationary relaxed state. The values of Shannon

Table 2. The matrix of pairwise comparisons of Shannon entropy E samples for the quasiattractors of the tremorograms from the subject GDV (number of repetitions $N = 15$). The Wilcoxon test was used (significance level $p < 0.05$, number of coincidences $k = 102$)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.0	0.81	0.17	0.76	0.15	0.89	0.94	0.86	0.53	0.31	0.55	0.33	0.53	0.92	0.36
2	0.81	0.0	0.2	0.65	0.16	0.94	0.81	0.86	0.82	0.31	0.75	0.39	0.68	0.75	0.44
3	0.17	0.2	0.0	0.55	0.59	0.18	0.13	0.24	0.55	0.02	0.35	0.96	0.29	0.07	0.59
4	0.76	0.65	0.55	0.0	0.27	0.81	0.74	0.83	0.82	0.29	0.91	0.44	0.75	0.8	0.55
5	0.15	0.16	0.59	0.27	0.0	0.02	0.15	0.17	0.39	0.01	0.16	0.61	0.05	0.09	0.61
6	0.89	0.94	0.18	0.81	0.02	0.0	0.84	0.93	0.54	0.15	0.8	0.31	0.58	0.76	0.45
7	0.94	0.81	0.13	0.74	0.15	0.84	0.0	0.84	0.51	0.39	0.45	0.27	0.66	0.92	0.37
8	0.86	0.86	0.24	0.83	0.17	0.93	0.84	0.0	0.64	0.16	0.83	0.28	0.8	0.78	0.21
9	0.53	0.82	0.55	0.82	0.39	0.54	0.51	0.64	0.0	0.0	0.8	0.72	0.89	0.45	0.55
10	0.31	0.31	0.02	0.29	0.01	0.15	0.39	0.37	0.16	0.0	0.17	0.13	0.13	0.37	0.09
11	0.55	0.75	0.35	0.91	0.16	0.8	0.45	0.83	0.8	0.17	0.0	0.48	1.0	0.68	0.59
12	0.33	0.39	0.96	0.44	0.61	0.31	0.27	0.28	0.72	0.13	0.48	0.0	0.51	0.24	0.93
13	0.53	0.68	0.29	0.75	0.05	0.58	0.66	0.8	0.89	0.13	1.0	0.51	0.0	0.48	0.68
14	0.92	0.75	0.07	0.8	0.09	0.76	0.92	0.78	0.45	0.37	0.68	0.24	0.48	0.0	0.35
15	0.36	0.44	0.59	0.55	0.61	0.45	0.37	0.21	0.55	0.09	0.59	0.93	0.68	0.35	0.0

entropy E calculated for the experiment are shown in Table 4 ($p = 0.53$). Physiological and psychological considerations clearly demonstrate that the test subject senses a load and has significantly more difficulty in keeping their finger at the same point in space, but this is not reflected by values of entropy E (the mind or HFS remains in a stationary mode). However, a CST-based approach reveals considerable changes in quasiattractor parameters (Table 3) that can be regarded as evolution. This is proved by the more than twofold dif-

Table 3. The values of QA areas S for tremorogram samples from the subject GDV (number of repetitions $N = 15$) in a relaxed state and with a load of 300 g (significance level $p = 0.00$, pairwise comparisons for the Wilcoxon test)

No.	Quasiattractor area for tremor without a load, $S_1 \times 10^{-8}$, a.u.	Quasiattractor area for tremor with a load (300 g), $S_2 \times 10^{-8}$, a.u.
1	5.78	38.59
2	2.29	8.7
3	1.42	6.8
4	3.89	4.5
5	1.61	5.34
6	3.03	6.75
7	3.86	9.75
8	1.69	7.23
9	1.77	9.76
10	6.27	4.56
11	1.92	4.06
12	2.02	9.44
13	3.42	4.84
14	3.98	2.86
15	2.27	5.77
S	3.02	6.81

Table 4. The Shannon entropy values for tremorogram samples from the subject GDV (number of repetitions $N = 15$) in a relaxed state and with a load of 300 g (significance level $p = 0.53$, pairwise comparisons for the Wilcoxon test)

No.	Quasiattractor area for tremor without a load, $S_1 \times 10^{-8}$, a.u.	Quasiattractor area for tremor with a load (300 g), $S_2 \times 10^{-8}$, a.u.
1	3.32	3.12
2	3.12	2.92
3	3.32	3.32
4	3.12	3.32
5	3.32	3.12
6	2.92	3.32
7	3.32	3.32
8	3.32	3.12
9	3.32	3.32
10	3.32	3.12
11	3.12	3.32
12	3.12	3.12
13	3.32	3.12
14	3.32	3.12
15	3.12	3.32
E	3.23	3.20

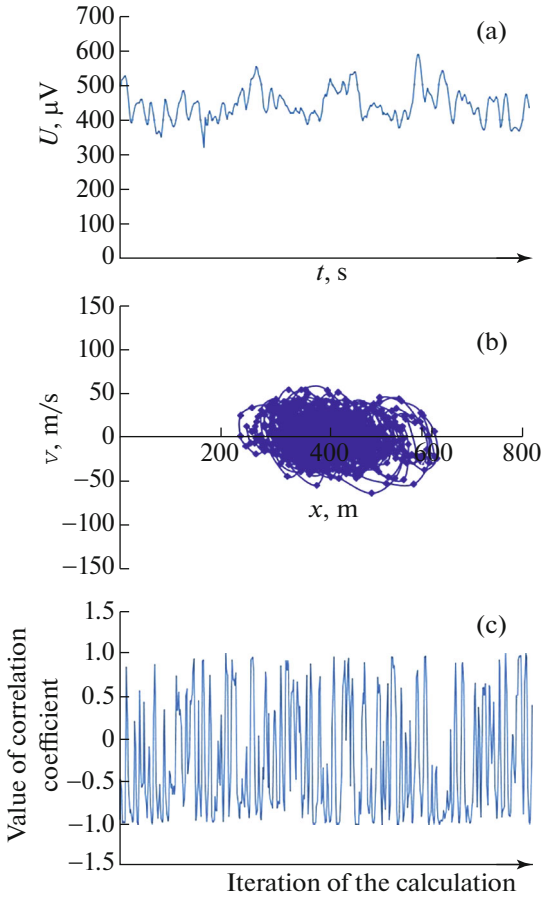

Fig. 1. The result of processing of the data from the experiment with weak muscle tension (F_1 = 5 daN). Results for the subject KAE shown are representative of the whole group: (a) temporal pattern of the signal; (b) phase trajectories of the electromyogram (x—MBP, $v = dx/dt$—the rate of MBP change) characterized by quasi-attractor area S_1 = 29 824 a.u.; (c) autocorrelation function of the signal $A(t)$.

ference between $\langle S_2 \rangle$ and $\langle S_1 \rangle$, $\langle S_2 \rangle$ being higher. Thus, the application of evolution criteria [11, 14] points at substantial changes in the state of the TTS (here, it implies the mental state and changes in the parameters of the HFS).

Thus, no changes in E are observed upon a transition from one stationary state to the other (the latter state is unstable, since it is physically impossible to keep a load in the same position). However, a twofold increase of quasiattractor volume is observed and this change is associated with an evolutionary (substantial) change in TTSs within the CST. It is necessary to emphasize that neither the entropy E nor the quasiattractor areas (in the form of S) changed significantly in the relaxed state, that is, rest could be regarded as rest both within non-equilibrium system thermodynamics and within the CST. Perturbation of the psychophysiological state of the subject (impact of the load) led to deviation from this initial stationary state of the mind (and HFS as well).

4. CALCULATION OF SHANNON's ENTROPY VALUES FOR ELECTROMYOGRAM PARAMETERS CORRESPONDING TO DIFFERENT STATIC LOADS

Visual assessment of electromyographic recordings involved graphic representation of the temporal pattern of the signal (Fig. 1a) and the conversion of this pattern into certain numerical series (samples of muscle biopotentials (MBP)). Analysis of the temporal series of electromyography data shows that the observed MBP signal $x = x(t)$ is a unique function of time for each subject. At the same time, the definite regularity related to the area S of the quasiatttractor in the phase space of x_1 and x_2, where $x_1 = x(t)$ is the MBP value and $x_2 = dx_1/dt$ is the rate of MBP change, is preserved (Fig. 1b).

Each of the vectors of electromyogram (EMG) dynamics in the form of $x = x(t)$ along axes x_1 and x_2 can be situated in a phase plane that describes the chaotic dynamics of the behavior of a two-dimensional vector $x = (x_1, x_2)^T$ shown in Fig. 1b. A definite similarity between the EMG, on one hand, and the tremorogram and the autocorrelation function $A(t)$, on the other hand, is evident from the figure (with regard to the absence of controlled statistical repetitions of tremor, EMG, or $A(t)$).

The distribution functions $f(x)$ for many homeostatic parameters are essentially unstable (that is, change continuously and randomly); therefore, the use of distribution functions $f(x)$ for EMG matrices similar to Table 1 may be inappropriate (since $\langle k \rangle \approx 5$ for EMG, as well as for tremor). A continuous change of these functions is observed as EMG samples are compared and any EMG has a unique distribution law and $f_j(x)$ for each observation interval δt_j. Matrices of pairwise comparisons of EMG samples were constructed for all 15 subjects and two values F_1 and F_2 of dynamometer compression force ($F_2 = 2F_1$); the regularity in the changes of the number k of pairs of "coincidences" in the samples of EMG parameters was elucidated as well. Analysis of a 15 × 15 matrix (105 different pairs of comparisons) yielded $k_1 = 5$ in the first case (for F_1, F_1 = 5 daN) (Table 5). An increase of the strain to F_2 = 10 daN was accompanied by an increase of the number of coincidences to $k_2 = 20$. The matrix for F_1 is shown in Table 5. Similar calculations were performed for 15 EMG samples recorded from every subject. As an example, the number of coinciding pairs for a weak static load was $k_1 = 11$ for another subject and increased to $k_2 = 22$ as the applied strain was doubled. Therefore, the number of coincidence pairs k in the EMG samples can characterize the distinctive MBP features of each study subject. However, the

Table 5. The pairwise comparison matrix for electromyograms from a group of girls (number of repetitions $N = 15$) with weak muscle tension ($F_1 = 5$ daN). Wilcoxon test was used (significance $p < 0.05$, number of coincidences $k = 5$)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0.0	0.0	0.0	0.26	0.0	0.0	0.0	0.0	0.0	0.0	0.02	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.37	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.26	0.37	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.18	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.04	0.0
9	0.0	0.01	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.81	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.81	0.0	0.0	0.0	0.0	0.0	0.0
11	0.02	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.37	0.0	0.0
13	0.0	0.0	0.0	0.18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.37	0.0	0.0	0.0
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.04	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 6. The values of quasiattractor area S for electromyogram samples from a group of 15 girls and from 1 girl for weak ($F_1 = 5$ daN) and strong ($F_2 = 10$ daN) muscle tension

No.	Group of girls		One girl	
	S_1^Γ, 5 daN	S_2^Γ, 10 daN	S_1^1, 5 daN	S_2^1, 10 daN
1	26794	106222	26508	107260
2	29824	203886	24300	114935
3	42051	101192	35802	139755
4	77848	149919	27459	111734
5	15420	102954	32208	119712
6	23095	123024	18792	101084
7	42824	105701	29548	152609
8	39128	298496	24336	191360
9	16435	72625	16968	100000
10	17770	81557	16968	68904
11	41832	189280	21242	116864
12	18028	162909	15200	101403
13	28586	61712	18984	104682
14	26342	93635	20304	113634
15	45124	84224	30965	86064
S	32721	129155	23992	115333

Wilcoxon test for the significance of functions $f(x)$, $p = 0.01$, T-test for the significance of functions $f(x)$, $p = 0.00$.

pairwise comparisons performed for different subjects yielded a pattern similar to that observed for a single subject, as shown in Table 5 [4, 6, 22–24].

Comparison of S values for the QA in a group of 15 girls and 15 samples from a single girl is illustrated in Table 6. The table reveals a clear difference between the two states characterized by weak (F_1) or strong (F_2) muscle strain. The mean values $\langle S \rangle$ of quasi-attractor areas for the same subject differed by approximately five times. At the same time $\langle S_1^\Gamma \rangle = 32\,721$ and $\langle S_2^\Gamma \rangle = 129\,155$ for a group of girls, that is, $\langle S_2^1 \rangle / \langle S_1^1 \rangle \approx 4$. A similar difference was observed in the case of data

recorded for a single subject: $\langle S_1^1 \rangle = 23\,992$ and $\langle S_2^1 \rangle = 115\,333$ (Table 6).

The Shannon entropy was calculated for the same results in order to characterize and compare the levels of chaos in the temporal patterns of electromyograms. The entropy approach did not reveal differences upon the analysis of electromyograms, while the results of an analysis based on this approach showed that the data samples for a group of girls or the same girl belonged to one general population. Moreover, the calculations for pairwise comparison of four pairs of entropy samples did not reveal statistical differences (all samples were attributed to the same general population), even though the groups were compared to the E samples for a single person within the thermodynamic approach [10, 12].

The form of the phase trajectories and quasiattractor areas for F_1 and F_2 (in a single representative experiment) is illustrated in Fig. 1. The phase coordinate x_1 shows the actual value of the biological potentials, whereas $x_2 = dx_1/dt = V$ is the rate of MBP change. A three-fold increase of the area S_2 relatively to S_1 was observed in the illustrated experiment. Calculation of these two values of quasiattractor areas in the form of S_1 and S_2 was performed for many subjects and the pattern always remained the same: if the muscle strain increased by two times, the EMG quasiatttractor area increased by 3 to 5 times relative to the initial value (at $F_1 = 5$ daN and $F_2 = 10$ daN). The value of the Wilcoxon criterion p was characteristically higher than 0.05 for the same subject (15 repetitions), and exceptions were rare.

No other method for quantitative description of the parameters of changes of muscle biopotential (EMG) related to increased muscle strain (at $F_2 = 2F - 1$) within the framework of determinism or stochastics is currently available. One can currently state that EMG quasi-attractors in the FBS are definite models of the electrical activity of muscles. The approaches of stochastics (calculation of the amplitude-frequency characteristics (AFC), (t), $f(x)$, etc.) do not yield models that would essentially distinguish between these two states of a muscle (EMG at F_1 and F_2). The phase plane can apparently be used for efficient assessment of chaos by EMG within the framework of the CST upon repetition of the experiments (recording of repeated samples) and the construction of EMG sample quasiattractors. However, it is not yet advisable to reject stochastics completely. Modifications and the introduction of new methods in combination with the methods of CST are required [1–3, 6–14, 16, 17, 19].

CONCLUSIONS

1. Multiple repetitions of tremorogram recording (15 series of 15 samples each) revealed the statistical stability of both HFS parameters and psychophysiological status of the subject in a state of rest. Changes in the HFS state (and the psychological changes related to the emergence of different sensations) led to a change in the parameters of tremorogram quasiattractors. The quasiattractor area S increased by more than two times. These changes should be considered evolutionary within the framework of CST (the changes are short-term, but they could acquire a permanent character, for instance, upon a transition to a different planet where the free-fall acceleration $g_2 > g_1 = 9.81$ m/s^2 for the Earth).

2. The entropy E for the tremorograms does not change in a stationary state and upon the transition from a stationary mode (rest) to an unstable state. This limits the possibilities of using Prigogine's thermodynamics of non-equilibrium systems for a description of non-equilibrium biological systems (such as the HFS and psychophysiological status of a person addressed in the present study). Calculation of quasi-attractor areas in the form of S is an effective criterion for the identification of such changes.

3. Comparison of traditional statistical methods of electromyogram processing to the TCS methods revealed the low efficiency of the traditional statistical methods. Calculations of entropy, AFC, autocorrelation functions $A(t)$, and statistical distribution functions $f(x)$ for EMGs of subjects in different physiological (muscular tension) states are extremely difficult (within the framework of stochastics). The stochastic paradigm is not applicable for TTSs due to continuous chaotic changes or the lack of changes (in the case of E).

4. New CST-based methods of EMG calculation that use a two-dimensional phase space with EMG coordinates x_1 and x_2 and the method for calculating pairwise comparison matrices for electromyogram samples (calculation of the number k of coinciding pairs in tremorogram and electromyogram samples) can actually characterize the integral values of parameters of tremorograms, electromyograms, and many other parameters of HFS [4–14] for different states of muscles and the HFS as a whole.

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