Constraints-controlled metastable dynamics of exercise-induced psychobiological adaptation

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Summary. *A fundamental question in the theory of psychobiological adaptation and specifically of sports training is the problem of how adaptation to sports performance demands occurs as a consequence of systematic exercise. In this position paper, we review some results of our previous and current research conducted on several different levels of exercise-induced effects. Based on these results, we contend that the control of psychobiological systems during exercise is constraints based. Constraints direct the flow of behavioral changes on a rugged metastable landscape. Such adaptive behavior is soft-assembled, consisting of context-sensitive cooperative configurations of system components that dwell on different time scales.*

Background

One reason why biological systems are titled as "complex" is because they are hard to be understood within the framework of one underlying theory that would, at least in general, explain the basic principles of their functioning. On the other hand, this is the main aim of scientific theories: the explanation of maximal set of phenomena using minimum number of independent principles. The integrative functioning and the multivariability of biological systems is a trivial but disturbing fact for any scientist striving to capture the big picture of biological systems. At the first glance, from these considerations it would seem that complex biological systems could not satisfy the aims of general scientific theories. There may be fragmented, highly specialized explanations for different domains of biological systems, but not unified principles able to deal with biological complexity. This is the current state of affairs in the majority of sciences dealing with the biological order.

Any macroscopic behavior of a complex adaptive system, e.g. a sport performance, is a result of an immense number of highly coordinated spatiotemporal processes. In other words, macroscopic behavior is a collective effect of sets of highly interdependent components within the system, i.e. a result of their synergy in space and time. Not so recently it has been shown (2) that such collective (or cooperative) effects can be successfully studied by searching for, so-called task-specific, and hence, soft-assembled, collective variables, which capture the coherent, coordinated behavior of system component processes. It has been argued that these collective variables, otherwise called "order parameters" since they represent the macroscopic state of biological order, are the most adequate for studying complex systems behavior. Presumably, the reason for this is because these variables capture system behavior in its approximately linear, but also nonlinear regime of operation. These variables are best determined close to the points of qualitative, discontinuous change where a large set of other variables become subservient to them and the behavior of the system becomes low dimensional. As they contain compressed information of all subservient variables, they also become the most informative quantities, i.e. "informators" to the external observers (e.g. researchers) about the macroscopic behavior of complex systems (3).

One viable way of investigating the type of integration of any complex system seems to be by testing the behavior of collective variables under the change of constraints. Complex adaptive systems may exhibit different kinds of collective behavior such as stationary, nonstationary, i.e. metastable, periodical, or chaotic behavior. The mode of behavior depends basically on the configuration of constraints, i.e. control parameters, variables that do not specifically prescribe or impose the behavior of

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[1]Actually some complexity measures are based on the estimating the difficulty of an observer to infer a model of the system of interest or on the convergence of model's predictions with system's behavior (1).

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the system but constrain it indirectly. In short, the control of dynamical systems is constraints based. For a certain configuration of constraints, nonlinear systems suffer a qualitative change of its behavior, a partial or complete rearrangement of its component interactions and hence a discontinuous change of the order parameter. These events are so-called bifurcation phenomena. One reason why this phenomenon arises is because there is more than one possible stable state and this property, i.e. multistability, stems from the nonlinear interactions between system components.

Metastability is an inherent property of multistable complex adaptive systems (4). It is usually invoked as a mechanism responsible for their behavioral flexibility and is manifested in the transient and nonstationary evolution of such systems (5). Metastable behavior typically arises when there are many weakly stable or weakly unstable system states so that it switches spontaneously among various cooperative configurations of its degrees of freedom. These and other connected concepts of nonlinear dynamics seem to be universal in a sense that they can be detected in systems widely separated with respect to their level of organization or material substrate. Nonlinear effects such as bifurcations, metastability, hysteresis have been already observed at various levels of organization of psychobiological systems subject to exercise and some of them will be briefly reviewed here.

In contrast to the conceptual universality, there is a vast diversity in the nature of the collective variables (order parameters) and associated control parameters characterizing the variety of behaviors that emerge. Presumably, this diversity is, in part,

a consequence of the accumulated contingencies and evolutionary stabilized context dependencies of biological systems. It is this unity of universal phenomena and context dependency that is a hallmark of complex adaptive system behavior. Our aim in this position paper is to show how exercise-induced phenomena at different time scales and levels of biological system organization strongly indicate nonlinear integrative mechanisms at work as manifested by the dynamics of a variety of context dependent, task-specific, i.e. soft-assembled, collective variables.

Performance level. Nonlinearities in dose-effect interactions in sports training process

By the 1980s of the last century, two general types of organismic adaptive responses to exercise were experimentally firmly established (6). These adaptive effects dwell on time scales of days, weeks, and months. Both depend mostly on the temporal concentration of the workload. For lower workload density, a positive effect accumulates on approximately daily basis. The second one, so-called long delayed training effect, the positive training effect develops after prolonged suppression of the performance variable, on time scales of few weeks to few months.

First, what becomes immediately visible from Fig. 1 (A and B) is that there is no one-to-one mapping between the workload provided by training stimuli, i.e. dose, and the training effect. By slowly increasing the workload and then decreasing it, a "memory effect" is being produced, i.e. a lasting increase in the performance. It is important to note,
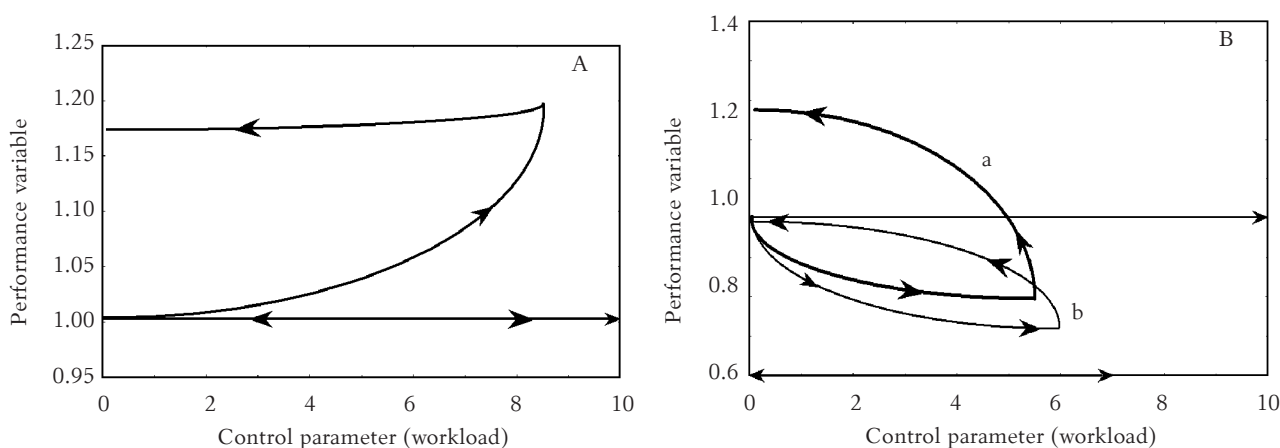

Fig. 1. Two general types of adaptation to training workload represented in the control space

A. Increasing the workload increases the performance. During decreasing the workload, performance does not follow the same path but typically follows a less steep trend. B. Trajectory (a) depicts the so-called long delayed training effect where during the increasing phase of the workload, a suppression of the performance variable is attained (an overreaching phase), and during the decreasing phase of the workload, a positive training effect follows. For a small change of the workload increasing history one gets trajectory (b). The overreaching phase does not convert into positive training effect, but to an overtraining phase depicted by asymptotic convergence of the performance toward the initial state while decreasing the workload. This event marks the overreaching to overtraining bifurcation (adapted from 10).

however, that these residual, i.e. "memory effects," are transient, that is, strictly speaking, they are not stable states (attractors) of system's dynamics toward which the performance would tend in the long term. This means that the changes of the coupling tendencies of component processes within the complex psycho-physiological system are of ephemeral character, i.e. they are soft-assembled, and are prone to reconfigure asymptotically if the kind of workload, i.e. context, that stimulated their emergence ceases to exist. These temporary stable configurations corresponding to temporal characteristics of training stimuli may dwell on different time scales (7, 8). Such behavior points to the inherently metastable, i.e. temporary stable, dynamics of the exercise-induced couplings in complex neurobiological systems. It indicates that coordinative metastability of functional components of system may be a generic mechanism that underpins the flexibility and capacities for adaptation and re-adaptation of athletes toward ever changing environmental demands.

Second, a small change in the workload history may produce an overtraining effect (6) (see Fig. 1 B and the explanation therein). Because bifurcations, i.e. qualitative discontinuous changes, and hysteresis effects are demonstrably present in these performance variables, it seems reasonable to assume that the maxima of physical abilities like power, strength, speed, and so forth may be treated as collective variables (informators) of athletes conceptualized as complex adaptive systems. This seems reasonable since maximal values of these variables are being attained by the, at the moment, best possible coordination of component processes encompassing the whole interval from metabolic to interorganic levels. As informators, they inform external observers about the level of the athlete-task coupling fitness (9).

The overreaching-overtraining bifurcation seems to be a very important indicator of the highly nonlinear integration of the human psychobiological components. The recovery period needed for overcoming the overtraining consequences may be naturally explained as a nonlinear hysteresis effect. Since overtraining may be classified as a fatigue phenomenon, it follows that there may be a scaling relationship between different types of fatigue phenomena spanned on different time scales (7, 8, 11). More generally, such considerations mean that sports training has to be modeled as a multiscaled process (12) dwelling on a metastable rugged energy landscape (7).

Electrophysiological level. Metastability of heart dynamics

Recent research appears to indicate a potential advantage of a fractal framework application for analyzing cardiovascular signal data. These data are largely analyzed using traditional time and frequen-cy domain measures. However, such measures may not be detectable by traditional analysis methods. The complementary role of advanced signal analysis methods and emerging multiscale techniques is, therefore, an important frontier area of investigation (13, 14). Moreover, the attenuation of an oscillatory pattern or its impaired responsiveness to a given stimulus can also reflect an altered target function and thus can furnish interesting prognostic markers. The dynamic assessment of these changes may provide important diagnostic and prognostic information, not only in relation to cardiovascular, but also noncardiovascular changes. As linear methodologies fail to provide significant information in conditions of extremely reduced variability (e.g. strenuous exercise, heart failure) and in presence of rapid and transient changes, the development of new nonlinear approaches seems to provide a better framework for the cardiovascular system investigation (15) as a part of a complex adaptive system.

In particular, techniques based on mono- and multifractal analyses, raised from nonlinear dynamics, have been successfully applied to the investigations of living systems (14). However, it is relevant to understand which methods should be selected and applied. Observational studies have suggested that some indices describing nonlinear dynamics, such as fractal scaling exponents, heart rate turbulence, and deceleration capacity, may provide useful prognostic information in various clinical settings and their reproducibility may be better than that of traditional indices. For example, approximate entropy, a nonlinear index of heart rate dynamics, which describes the complexity of RR interval behavior, has provided information on the vulnerability to atrial fibrillation (16).

In a recent study, standard 12-lead ECG signals were recorded during provocative exercise tests. Athletes accomplished a typical Rouffier test protocol. During the test on bicycle ergometer, they underwent protocol, which consisted of warm-up (100 W) and load (200 W). The volunteer participants were 14 healthy long-distance runners aged 20±2.4 years. Computerized ECG analysis program "Kaunas-load" was used for data recording and analysis. The parameter discriminants calculated from the following ECG time series were duration of RR interval taken from the II standard lead, duration of QRS complex, duration of JT interval, and amplitude of ST segment taken from the V standard lead. Two synchronous time series (x_n:=0, 1, 2,..) and (y_n:=0, 1, 2,..), which represent the ECG parameter measurements, were structured and analyzed using the numerical characteristics of the second-order matrix and the main components of it (17, 18):

$$A_n := \begin{bmatrix} x_n & x_{n-1} - y_{n-1} \\ x_{n+1} - y_{n+1} & y_n \end{bmatrix} \qquad (1)$$

The most informative characteristics raised from matrix definitions and it was discriminants of matrix:

$$Dsk\ A_n = ((x_n - y_n)^2 + 4((x_{n-1} - y_{n-1})*(x_{n+1} - y_{n+1}))) \qquad (2)$$

Complexity measure, reflecting the degree of coupling between heart electrophysiological variables, was expressed as the value of discriminant (Dsk). If the value of discriminants decreases and is close to zero, the interaction between two synchronous numerical time series (ECG signals) increases, but the complexity of the adaptive system decreases.

ECG signals recorded during exercise tests were used to identify and analyze the coupling dynamics of heart electrophysiological parameters in order to reveal dynamical peculiarities of the human body processes and fatigue, depending on different scales of observation. Reduced discriminant of RR interval and QRS complex concatenation during exercise test indicate the increase of coherence between these indices. The onset of workout is conditioned by dynamical changes of regulatory processes, which are likely a combination of central and peripheral factors.

The variability of registered signals accompanied by alterations according to provocative physical load

Fig. 2. Concatenation dynamics between RR interval and QRS complex (A) and between ST segment and JT interval (B) in the participant V.M. during bicycle ergometry

enabled the formation of a new stable state through fluctuations. The analysis of different levels of the system revealed different fluctuation dynamics. An examination of supplying (cardiovascular) system was carried out by the evaluation of the ST segment and JT interval coupling, which allowed detection of endogenous, functional changes within the heart (see Fig. 2 A and B). The instant increase of fluctuations level was noticed at the onset of the exercise test in the interaction of ST segment and JT interval, and the values of discriminants were relatively higher than in systemic level concatenations.

Depending on the scale of observation notably differentiated the level of fluctuations and consequently the values of interactions expressed by discriminants of the matrices. The faster and substantial transitions of the dynamics to the new state were indicated in subsystemic level (coherence of ST segment and JT interval, see Fig. 2B). Fluctuations of coupling dynamics result in the emergence of substantially new stable state and suggest decreased resistance to fatigue. Finally, the analysis of the typical individual behavior of the dynamic physiological system shows that provocative exercise test induces an increase of fluctuations as the fatigability enhances. The coherence between parameters often is being modulated in an individual-dependent manner revealing their local functionality with respect to the global context. The dynamic coupling between heart electrophysiological parameters shows characteristic patterns of a context dependent metastable, soft-assembled functioning, typical for flexible adaptive biological systems.

Kinematic level. Why and how exercise terminates? Metastability and exercise termination

Exercise termination is a macroscopic event. It is manifested as an abrupt shift of the activity, toward lower energy expenditure levels or rest. The activity shift exists on a much shorter time scale than the activity itself, which may dwell on scales of seconds, minutes to hours. In a recent study (11), we sought to pinpoint the possible mechanism of exhaustion-induced exercise termination. On 5 days during 2 weeks, six participants who were familiar with the task performed a quasi-isometric arm-curl exercise holding an Olympic bar with an initial elbow flexion of 90 deg to the point of spontaneous termination of the exercise due to exhaustion. Participants were encouraged to persist to exhaustion even if the initial position was lost, so the task constraints did not include a constant exertion requirement.

As shown in Fig. 3 (for details see 11), it seems very likely that as fatigue develops, the instability encompasses higher control loops presumably responsible for attention, motivation, and so forth.
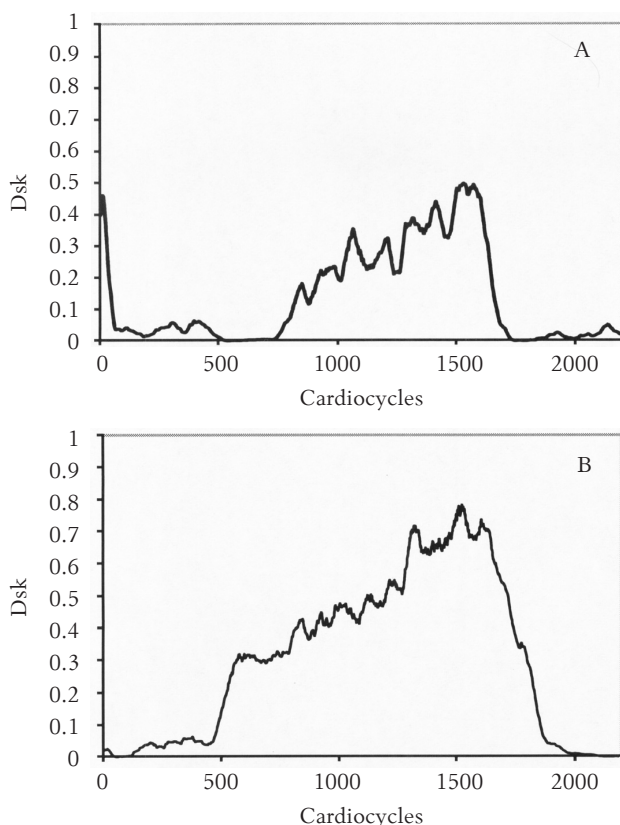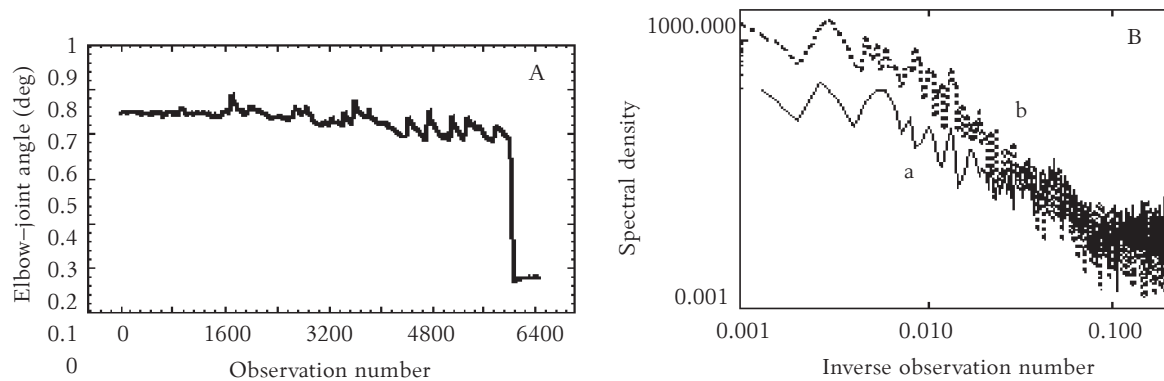
Fig 3. A. Time series of the elbow-angle data of participant 1. B. A typical difference of power spectral density values of the online fluctuations of the elbow angle in the first (a) and the last (b) third of the quasi-static exercise. The elbow angle variability difference becomes larger already on subsecond interval and grows toward larger time scales signifying developing instability of the system under fatigue.

The power spectrum data showed a globally correlated enhancement of variability of the order parameter of the quasi-isometric action kinematics, the elbow-joint angle. Hence, from the dynamical point of view, the exercise-induced fatigue represents an ever-increasing destabilization of the previous configurations of the neuromuscular network and their continual reconfiguration, under immediate organismic, task, and environmental constraints. In a word, fatigue, seen dynamically, may be viewed as a typical constraint-induced self-organization of metastable, soft-assembled configurations of action system components.

On the other hand, since the system before termination dwells close to the instability point, many contingent and also emergent accidental events (a small increment of discomfort or pain, onset of nausea, dizziness, and so forth) may sufficiently perturb the already destabilized action system's organization. This may trigger the exercise termination, i.e. the switch toward the low activity, rest state, being a global minimum of the rugged metastable energy landscape. In this sense, the exercise termination is an emergent phenomenon: a consequence of fatigue-induced instability/dissolution of the couplings within the distributed control loops responsible for the maintenance of the intended activity. This means that the system flows through its dynamical states controlled by immediate constraints, and there is no need for a specialized exercise-termination module or a superordinate "calculations performing algorithm" within the brain that would be responsible for controlling and switching off the activity by exerting commands to the periphery. What suffices is a distributed neuromuscular network of components that self-organize under constraints into a local, ephemeral, or eventually a global energy minimum state. This nonlinear, *constraint-based control* of the exercise flow and termination is also experimentally demonstrable in the hysteresis behavior of the collective variable with respect to some physiological constraints (19).

Psychological level. Emergence and dynamics of task-related thoughts and urges to terminate during exhausting exercise

For a long time it has been known that close to exercise termination, the attention focus becomes more adhered to task-related thoughts (TRT). This fact may be a consequence either of a deliberate strategy used by athletes or simply because TRT are more easily attainable close to the exercise termination. If the last is correct than one might ask, why is this so? We conducted two preliminary experiments with aim to shed a light on these issues from dynamical viewpoint. In the first experiment, participants were asked to impose and maintain intentionally any kind of task-unrelated thought (TUT) and during the treadmill exercise (80–90% of HRmax) to report about possible spontaneous switches to TRT. In the second experiment, another group of participants was asked to report about the spontaneously emerging urges to terminate the quasi-isometric exercise (80% of 1 RM) by uttering "down" and "up" if/when the motive to persist recovered. Both exercises were performed until exhaustion. From the time series obtained in the first experiment (Fig. 4A), we calculated the dwell times, that is times the system spends in one of the states, i.e. TUT or TRT, and probabilities of finding the system in one of those states for 10 nonoverlapping time windows. From the time series obtained in the second experiment (Fig. 4B), we calculated the probabilities of finding the system in "up" or "down" states, also for 10 nonoverlapping windows.

Preliminary results of both experiments show that as exercise unfolds, probabilities of switching to the TRT states and emergence of urges to terminate the exercise (down states) grow (see Fig. 4 A and B).
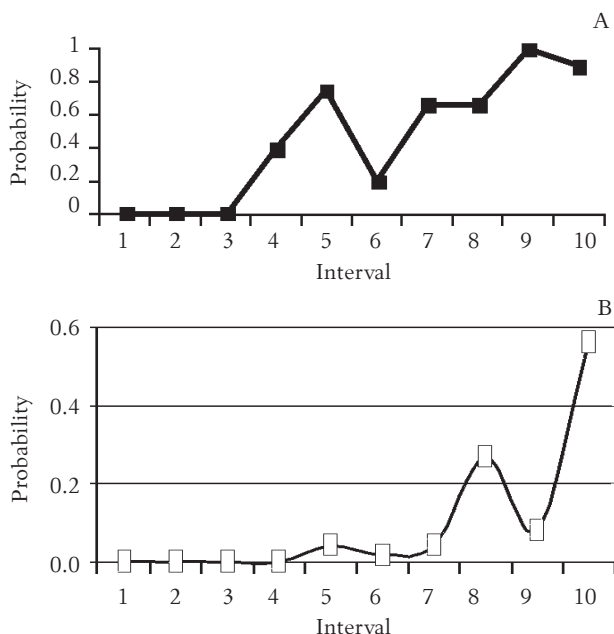
Fig. 4. A. Change of probability of finding the system in the "task–related thought (TRT)" state. B. Probability of finding the system in the "urge to terminate" state. The horizontal axis represents the observed time window.

absolutely unstable spontaneously giving a way to the unique dynamically globally stable state (20). This fits neatly with the data discussed previously about the developing instabilities during the voluntarily maintained exercising activity. The bifurcations in the dynamics of these variables make them viable candidates for representing the task-specific collective behavior in these separate psychobiological levels.

In general, it is highly likely that developing dynamic instabilities within the whole neuro-muscular axis, encompassing the psychological, physiological and motor/action domains are a hallmark of psycho-physiological fatigue and a general principle of exercise termination. The termination is triggered always when the previous cooperative dynamic state becomes absolutely unstable or is perturbed by some contingency, so that it finds the global energetic minimum, a unique state that remains stable.

Conclusions

The dynamics of biological integration is highly likely to be nonlinear, soft-assembled, and metastable. Generally, the exercise-induced effects and control may be explained through the "*self-organization under constraints*" paradigm. This generic mechanism would enable the immense behavioral flexibility of biological systems in their permanent striving to adapt to task and environmental demands. It seems likely that a viable way of studying psychobiological adaptation under exercise is the study of collective variables, which are products of the cooperative, coordinated interactions among component processes. As shown in this paper, potential collective variables may be observed at different levels of the human psychobiological continuum. Especially significant should be the study of the reconfigurations of such coordinated dynamics on different time scales and at the same time, the study of key control parameters, i.e. configurations of constraints, that act upon the stability properties of such coordinated states. Exercise-induced psychobiological adaptation likely evolves as a consequence of such soft-assembled, ephemeral, cooperative states dwelling on different time scales.

In other words, the intentionally imposed states that were intended to be kept over the whole exercise period switched spontaneously, i.e. involuntarily, to their antidotes. Consciously accessible urges[2] to cancel emerged with growing probability in the brain-body system under the increasing bodily changes. These data indicate the possibility that systems participating in the control of exercising activity are themselves subject to dynamic instabilities. That is, brain systems do not only integrate peripheral information but are also strongly constrained by it, and this is evidenced by the change and lost of stability of intentionally imposed motives and the type of the attention focus as the fatigue develops. In both cases, initially imposed states passed from stable into metastable phase and ultimately became

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[2]Note that these urges are simply consciously interpreted collective states of the affective-motivational components of the psycho-physiological system of the athlete.

Sukelta fizinio krūvio ir kontroliuojama apribojimais nestabili psichobiologinės adaptacijos kaita

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Raktažodžiai: adaptacija, pratimas, nuovargis, atlikimas, metastabilumas, bifurkacija, apribojimai, tolygi atranka, saviorganizacija.

Santrauka. Esminis psichobiologinės adaptacijos teorijos, ypač sporto mokslo klausimas – kaip pasireiškia adaptacija priklausomai nuo sportinio krūvio poreikių. Šiuo aspektu mes nagrinėjame kai kurių ankstesnių mūsų ir dabartinių mokslinių tyrinėjimų rezultatus, gautus analizuojant įvairių lygių fizinio krūvio sukeltas pasekmes. Remiantis šiais rezultatais, galima teigti, kad psichobiologinės sistemos kontrolė krūvio metu pagrįsta apribojimais, kurie yra tiesioginis elgsenos pokyčių srautas, pagrįstas metastabilumu. Toks adaptacinis elgesys yra tolygiai pasirenkamas, jis sudarytas iš jautrių kooperacinio pobūdžio sistemos elementų, kurie pasireiškia skirtingose laiko skalėse.

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