Original Article

Interaction mechanisms of muscular and cardiovascular systems of elite cyclists in different physiological states during a muscular activity

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Abstract.

Objective. The objective of the work is to study the activity and relationships of muscular (MS) and cardiovascular (CVS) systems of cyclists in various physiological states during muscular activity. **Material and methods.** The study involved 15 highly skilled athletes. Methods for recording heart rate (HR) and electrical activity of the lower extremity muscles were used. HR was recorded by AsCARD Gray v.07.205 electrocardiograph, whereas a Noraxon MR 3.10, TeleMyo 2400 DTS electromyograph was used for recording electrical activity of muscles. Experimental material was processed by different statistical methods, including sliding smoothing, correlation and regression analysis.

Results. It was found that increase and synchronization of MS and CVS activity during physical exercise performance on a 300 W bicycle ergometer before a forced failure is characterized by a change in the form of their interaction: from linear at rest and under fatigue, to exponential during working in and in steady state. The exponential character of HR dependence on the activity of the lower extremity muscles indicates an increase in integration degree of CVS and MS, enhancement in the reactivity of CVS to MS activity by the end of the working in and steady state periods. The strongest impact on HR changes is exerted by interconnected activity of quadriceps muscle of thigh (QMT), gastrocnemius muscle (GM) and long peroneal muscle (LPM), that of QMT, GM and biceps femoris (BF), that of GM, LPM and BF, and that of QMT, BF and GM at rest, during working in, in steady state and under fatigue, respectively.

Conclusions. The ratio of interacting muscles of the lower extremities has a greater impact on CVS activity than the partial influence of individual muscles, or the sum of their individual effects. Fatigue is characterized by redistribution of the lower extremity muscle activity, inclusion of additional mechanisms for cardiac activity stimulation, reduction of electrical activity and discoordination in the relationships between the leading muscles.

Keywords: interconnections, muscles, cardiovascular system, states, load, cyclists..

Introduction

The mechanisms of conjugated functioning of somatic and vegetative systems in different physiological states during muscular activity have been studied by experts in the field of physiology of motor activity and sports physiology for many decades [Bell, 1976; Koc, 1986; Monogarov, 1986; Abazalov, 2004; Wilmore, & Costill, 2005].

As a result of multi-year research, morphofunctional and metabolic mechanisms of physiological systems adaptation to physical loads have been studied [Koc, 1986; Mishchenko, 1990; Pelliccia, 1996; Wilmore, & Costill, 2005] as well as the mechanisms of their conjugated functioning in different physiological states: before, during and after muscular activity [Mishchenko, 1990; Gerasimov, 2003; Jascaninas, Monogarov, 1987; Monogarov, 1986; Tucker, Bruenger, Doster, Hoffmeyer, 2011; Koc, 1986].

The accumulated experimental material reflects the priority of motor skills in the activation of vegetative systems [Mishchenko, 1990; Coc, 1986; Wilmore, & Costill, 2005], in determining their reserve capacities during muscular activity [Gorodnichenko, Chalova, Petrova, Tritsuk, 2004].

At the same time, the authors have not fully covered the interaction mechanisms of physiological systems in the dynamics of physiological states: at rest, during warm-up, at different periods of physical load - during working in, in a steady state, during fatigue development, in the recovery period after physical loads. Their coverage is associated with the disclosure of intra- and intersystem interactions, mechanisms of vegetomotor integration in the process of long-term adaptation to physical loads [Wilmore, & Costill, 2005; Meyerson, Pshennikova, 1988; Pryimakov, 2012].

Highlighting this problem envisages specification of integration mechanisms of physiological systems before, during and after muscular activity in athletes specialized in various sports events.

Due to immediacy of this problem, its versatility and insufficient treatment, the **objective of this work** is to study the activity and relationships of muscular (MS) and cardiovascular (CVS) systems of highly skilled cyclists in various physiological states during muscular activity.

Material and methods.

Participants. The study involved 15 highly skilled cyclists aged 19-24 years.

Study protocol was approved by Ethic Committee University. The research was fulfilled in compliance with WMA Declaration of Helsinki – Ethical Principles for Medical Research Involving Human Subjects (2013).

Procedure. Instrumental methods for recording heart rate (HR) and electrical activity of the lower extremity muscles were used. HR was recorded by AsCARD Gray v.07.205 electrocardiograph. A Noraxon MR 3.10, TeleMyo 2400 DTS electromyograph was used for recording electrical activity of muscles.

Heart rate and electrical activity of the lower extremity muscles of highly skilled cyclists were synchronously recorded in a state of relative rest during performance of physical load of 50 watts and 300 watts. A five-minute aerobic load of 50 W represented a warm-up, whereas that of 300 W was performed until a forced failure. The following physiological states of the body were manifested during 300 W load performance: working in, steady state, fatigue [Koc, 1986; Mishchenko, 1990; Pryimakov, Monogarov, 2000].

During the entire test, bioelectric activity of gastrocnemius (GM) and long peroneal muscles (LPM), biceps femoris (BF) and the head of the quadriceps muscle (QMT) of thigh, was recorded every 2 min - the amplitude of electromyogram (EMG) in μV . Throughout the work, heart rate was recorded by electrocardiograph.

Statistical analysis. Obtained material was processed by various statistical methods, including sliding smoothing, correlation and regression analysis [Borovikov, Ivchenko, 2006].

Results.

Obtained experimental material indicates that the transition from a state of rest to muscular activity of moderate (load of 50 W) and then high (load of 300 W) power is accompanied by an increase in the bioelectric activity of the muscular and cardiovascular systems [Table. 1].

Table 1

Electrical activity of muscles (in μV) and HR (bt/min) in different states during muscular activity of cyclists

Conditions:		Statist. parameters	HR $\text{bt} \cdot \text{min}^{-1}$	LPM μV	GM μV	BF μV	QMT μV	Averaged EMG μV
Rest		$\bar{X}$	71,2	133,3	317,5	88,9	77,1	154,2
		$\pm m$	2,89	21,4	47,8	18,1	16	16,7
50 W load		$\bar{X}$	96,1	308,4	458,9	281,3	218,6	316,8
		$\pm m$	1,89	28	33	25,5	16	13,8
300 W load	Working in	$\bar{X}$	140	574,5	685,4	422,7	429	542,9
		$\pm m$	4,4	37,2	39,9	46,7	64	19,7
	Steady state	$\bar{X}$	189,4	578,4	573,2	552,6	596,7	575,2
		$\pm m$	1,87	51,1	63,9	48,8	64,1	20,7
	Fatigue	$\bar{X}$	214,4	549,9	578,7	523,1	629,8	570,4
		$\pm m$	2,65	55,4	68,9	73,6	66,2	24,2

Minimal activity of MS and CVS is observed in a state of relative rest. Performing work on a 50 W and 300 W bicycle ergometer is accompanied by an increase in HR and electrical activity of all examined muscles. The most pronounced changes are manifested under loads of high power - 300 W.

The curves shown in Fig. 1 reflect the dynamics of changes in the electrical activity of individual muscles of the lower extremities and heart in different physiological states - at rest and under two physical loads (of moderate and high power).

Fig. 1. Electrical activity of muscles (in μV) and HR (bt·min⁻¹) in different states of highly skilled cyclists

Parallelism dominance in the dynamics of the curves of studied indices (Fig. 1), as well as the degree and sign of reliable correlation coefficients (Table 2), reflect the specificity of interaction mechanisms of the somatic and vegetative systems, as well as intermuscular interactions in different physiological states during muscular activity: at rest, during warm-up, working in, in a steady state and under fatigue.

Table 2

Paired interrelations (r) of individual lower extremity muscles and HR in different physiological states of cyclists' body.

Indices		Body physiological states											
		Rest				Working in				Steady state			
		LPM	GM	QMT	BF	QMT	GM	BF	GM	LPM	GM	QMT	BF
HR	r	0,990	0,936	0,704	0,449	0,883	-0,050	0,526	-0,124	-0,480	-0,934	-0,800	-0,720
	p	<0,01	<0,01	<0,01	<0,05	<0,01	>0,05	<0,05	>0,05	<0,05	<0,01	<0,01	<0,01
BF	r	0,665	0,308	0,837	-	-0,475	-0,880	-	-	-	0,852	0,956	-
	p	<0,05	>0,05	<0,01	-	<0,05	<0,01	-	-	-	<0,01	<0,01	-
QMT	r	0,800	0,445	-	0,037	-	-	-0,967	0,902	-0,505	0,945	-	-
	p	<0,01	>0,05	-	>0,05	-	-	<0,01	<0,01	<0,05	<0,01	-	-
GM	r	0,914	-	-	-	0,659	-	-0,77	-	-0,808	-	-	-
	p	<0,01	-	-	-	<0,01	-	<0,01	-	<0,01	-	-	-

The degree and sign of the pair correlation coefficients reflect the varying degree and closeness of intermuscular relationships (Table 2), as well as those between the somatic and vegetative systems (Figure 2) in the course of testing.

Fig.2. The relationship between EMG amplitude of the lower extremity muscles and HR in various physiological states during muscular activity.

The value and direction of the correlation coefficients presented in Fig. 2 reflect the linear dependencies of HR on the electrical activity of the lower extremity individual muscles: high at rest and during fatigue, and low or moderate—during working in and in a steady state.

A graphic analysis of the dynamics of averaged over all studied muscles electromyogram and HR showed that parallelism in their shifts covers two periods: working in and steady state. Then the parallelism in their shifts impairs and the indices change in different directions (Fig. 3).

Analysis of the curves presented (Fig. 3) indicates that at the end of the working in period (5 min after the beginning of work) and a short stabilization period in a steady state, unidirectional HR and EMG shifts become multidirectional. As a result, the continued HR increase is accompanied by a decrease in the amplitude of the averaged EMG. A positive correlation between them changes to a negative one.

Fig.3. Dynamics of averaged overall studied muscle electromyogram (EMG) and HR during performance on 300 W bicycle ergometer.

Application of sliding smoothing and stepwise regression methods [Borovikov, 2006] allowed to develop mathematical models of HR dependence on the interconnected activity of the studied lower extremity muscles at rest, during working in, in a steady state and under fatigue (Table 3).

Table 3

Mathematical model of HR (bt·min⁻¹) dependence on electrical activity of the lower extremity muscles (μV) in the body different physiological states before and during physical load.

№	Physiological states	Equations	R ²	Model parameters
1.	Rest	$63,25 + 0,08x_1 - 0,034x_4 - 0,0005x_2 \pm 0,11$	0,999	x_1 - LPM, μV; x_2 - GM, μV; x_3 - BF, μV; x_4 - QMT, μV
2.	Working in	$88,8 + 0,042x_3 + 0,27x_4 - 0,18x_2 \pm 0,003$	0,999	
3.	Steady state	$261,2 - 0,08x_1 - 0,0387x_2 - 0,0075x_3$	0,999	
4.	Fatigue	$201,5 + 0,08x_4 - 0,048x_2 - 0,013x_3$	0,999	

Mathematical models presented in the Table indicate that different activity and ratio of the lower extremity muscles during load determine both different and similar character of HR changes at different periods of work. The high level of determination coefficients for each model ($R^2 = 0.999$, $r < 0.001$) reflects a close to functional HR dependence on the interconnected activity of the lower extremity muscles in different states.

The linear, synchronized character of the activity and interaction of the lower extremity muscles and CVS at rest and under fatigue, and exponential—during working in and in a steady state, is approximated with a high confidence degree by the multiple regression equations presented in Table. 3.

For instance, *at rest*, changes of HR from 64 to 76 beats · min⁻¹ are due to the variability of activity and interaction of LPM, GM and QMT. At that, the greatest influence on HR shifts is exerted by LPM and QMT. During the *working in period*, the leading muscle that determines the exponential character of HR changes while performing cyclic work on a bicycle ergometer is QMT. Statistical and graphical analysis, high determination coefficient ($R^2 = 0.998$, $p < 0.001$) point to that (Fig. 4).

Fig. 4. HR changes depending on alterations of EMG of quadriceps muscle of thigh during working in.

The exponential character of graphical model curve indicates that in the initial period of working in at relatively small values of electrical activity, the HR dependence on the activity of QMT is low. The linear segment reflecting high correlation of the two systems is in the range of changes in the amplitude of EMG of QMT from 500 to 630 μV .

According to data presented in Table. 3 (equation 2), GM and BF are also included in the mathematical model, reflecting HR dependence on their electrical activity during working in. Weakly interacting with HR and with each other in a paired analysis (Table 2), they begin to interact closely with each other and with QMT during cooperative activity. As a result, a close to functional HR dependence on their combined and interacting effect is manifested ($R^2 = 0.999$, $p < 0.001$).

In a steady state (Table 3, Equation 2), HR is most dependent on the combined influence of LPM, BF and GM, each of which weakly correlates with HR individually (Table 2). During joint functioning, they determine the exponential character of CVS activity, demonstrating, by the end of a steady state, a greater than at the beginning, HR dependence on their interacting activity.

Strong HR dependencies on interacting muscle activity in a steady state are similar to correlations in the period of working in.

The exponential nature of heart rate changes with an increase in muscle activity indicates enhanced integration degree of studied systems in the second half of the working in period and towards the end of the steady state. Calculations on the basis of regression equations showed that if an increase in the amplitude of QMT electrical activity by 40% at rest determines HR increase by 5.8 ± 0.3 beats / min, then at the end of working in - by 28.1 ± 2.7 beats / min, which reflects an increase in the reactivity of CVS to electrical activity of the QMT, strengthening of their interconnections.

During fatigue development, the character of relationship acquires the opposite direction: with a decrease in the electrical activity of studied muscles before failure to work, in the stage of decompensated fatigue [4], HR continues to increase.

Strong negative correlations between HR and EMG of the lower extremity muscles reflect reduced HR dependence on their activity, since HR increase occurs against the background of a decrease in the amplitude of bio potentials, in the face of their decreased participation in work.

Analysis of muscle electrical activity *during fatigue* reflects a predominant increase of EMG in the compensated phase and significant decrease in the amplitude of all leading muscles before failure — in decompensated phase [Pryimakov, Monogarov, 2000] (Table 4).

Table 4

Electrical activity of the lower extremity muscles in the phase of compensated and decompensated fatigue (μV).

EMG	Steady state		FATIGUE			
			compensated		decompensated	
	$\bar{X}$	$\pm m$	$\bar{X}$	$\pm m$	$\bar{X}$	$\pm m$
EMG	575,2	20,7	764,4	39,2	425,2	47
LPM	578,4	51,1	690,8	104,1	399,5	66,4
BF	573,2	63,9	896,2	57	267,7	45,5
GM	552,6	48,8	763,4	57,6	354,8	80
QMT	596,7	64,1	753,2	37,7	526,3	103,8

Electrical activity of the leading muscles decreases during decompensated fatigue development, and the athlete fails to maintain the work of a given power.

Analysis of intermuscular interactions during performance of 300 W work (in general, excluding work periods) indicates a high degree of synchronization of the activity of studied muscles (time shifted for antagonist muscles), which is expressed mainly in high pair correlations between them (Fig. 5).

Fig. 5. Pair correlation coefficients between individual muscles during performance of 300W work (r , p).

It is noteworthy that in their interconnections a predominantly linear, mutually contributing character of interaction is manifested. In general, among studied muscles, the closest interaction was observed between quadriceps and long peroneal muscles.

Discussion.

In the process of studying the correlations between muscular and cardiovascular systems of cyclists during strenuous muscular activity, experimental material that reflects the primacy of the motor system in determination of vegetative shifts was obtained.

The results are consistent with the ideas of experts in the physiology of muscle activity and sport on the mechanisms of somato-vegetative integration during physical loads [Fudin, Klassina, Pigareva, Vagin, 2015; Fudin, Klassina, Pigareva, 2015; Meyerson, Pshennikova, 1988; Mishchenko, 1990].

At the same time, the application of modern statistical analysis methods allowed to concretize and specify the mechanisms of intermuscular interactions [Pryimakov, Monogarov, 2000; Pryimakov, 2011], as well as those of MS and CVS in body various physiological states: at rest, during warm-up, at different periods of physical load (during working in, in steady state, under fatigue) [Fudin, Klassina, Pigareva, Vagin, 2015; Fudin, Klassina, Pigareva, 2015; Pryimakov, 2012].

It was found for the first time that increased activity and synchronization of muscular and cardiovascular system functioning during physical load of 300 W power before forced failure is characterized by different form of their interaction: from linear at rest and under fatigue, to exponential during working in and in steady state. As a result, both general and specific features of the functioning and interactions of muscular and cardiovascular systems in each physiological state were identified. General features include the most pronounced, close to linear dependence of CVS activity on the complex impact of interacting lower extremity muscles. At that, among the complex of interacting muscles of the lower extremities, the strongest influence on CVS activity is produced by the QMT and GM. Specific features of studied system functioning include: 1) changing role of individual muscles in determination of CVS activity in each physiological state (before and during physical loads); 2) variable nature of their interaction, which determines the linear form of HR dependence on the activity of studied muscles at rest and under fatigue, and exponential one during working in and in a steady state. The exponential nature of HR dependence on muscle electrical activity during working in and in a steady state is indicative of enhanced integration degree of somatic and vegetative systems by the end of each of these periods. This also indicates an enhancement of cardiovascular system reactivity to increased muscular activity [Pryimakov, 2012; Mishchenko, 1990; Mishchenko, Lysenko & Vinogradov, 2007].

It was revealed for the first time that: the strongest determinant of HR changes is the interconnected activity of QMT, GM and LPM, that of QMT, GM and BF, that of GM, LPM and BF, and that of QMT, BF and GM at rest, during working in, in steady state and under fatigue, respectively.

The results indicate that a certain ratio of interacting lower extremity muscles has a greater impact on CVS activity than the partial influence of individual muscles, or the sum of their individual effects. The absence of strong paired relationships of HR with individual muscles in a steady state and presence of strong dependence on their joint and interacting functioning indicate the manifestation of the principle of emergence in the body systemic activity, in accordance with which, the interconnections of the lower extremity muscles acquire the character of mutual assistance.

The change in the character of correlations between CVS and MS during fatigue development may be explained, on the one hand, by a compensatory increase in the activity of minor muscles [Monogarov, 1986; Pryimakov, Monogarov, 2000], and on the other hand, by activation of humoral mechanisms of cardiac activity regulation, the degree of influence of which on the body during strenuous muscular activity increases exponentially [Koc, 1986; Pryimakov, 2012]. The revealed interconnections may be considered as one of the criteria for the reserve capacities of muscular and cardiovascular systems during adaptation to physical loads [Gorodnichenko, 2004; Orlov, Fudin, Fetisov, Strizhakova, Novikova, 2017; Pryimakov, 2011, 2012].

Conclusions.

Performance of high power physical load, while determining different muscle and heart activity at the beginning, in the middle, and at the end of work, determines predominantly linear character of intermuscular relationships. The state of physiological rest and fatigue is characterized by the linear nature of somato-vegetative interaction, whereas that of working in and the steady state by exponential one. The exponential character of somato-vegetative interaction reflects an increase in CVS reactivity to the activity of MS in the dynamics of each of these states. At each period of work (working in, steady state, fatigue), in the functional system of realized movement the optimal relationships of its components are formed, which determine the specificity of the body adaptation mechanisms to altered conditions of functioning.

The strongest determinant of HR changes during cyclic work performance on bicycle ergometer to failure is the interconnected activity of quadriceps muscle of thigh and gastrocnemius muscle. Fatigue is characterized by a compensatory redistribution of the lower extremity muscle activity, the inclusion of additional mechanisms of cardiac activity stimulation.

Conflict of interests. The authors declare that there is no conflict of interests.

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