

Specific characteristics of neurohumoral stimuli in cardiorespiratory responses and energy supply during rowers' performance

PENGCHENG GUO¹, ANDRII DIACHENKO², OLGA RUSANOVA³, GUO RENHAO⁴, MEICHENZI WANG⁵, WEI YILUN⁶

¹ Jiangxi Normal University, CHINA

^{2,3,4,5,6} National University of Physical Education and Sport of Ukraine, UKRAINE

Published online: March 31, 2026

Accepted for publication: March 15, 2026

DOI:10.7752/jpes.2026.03047

Abstract.

This study evaluated the physiological conditions under which load-induced hypoxia, hypercapnia, and lactate acidosis elicit responses in the rowers' cardiorespiratory system (CRS). **Materials and methods:** Forty elite male rowers (age 25.5 ± 2.3 years, weight 95.5 ± 3.7 kg, height 191.7 ± 2.8 cm) participated in the study. The role of neurohumoral stimuli ("drives") was investigated by simulating the transitional processes of hypoxia–hypercapnia–lactate acidosis a cross different phases of a simulated 2000-m race. **Results.** An analysis was conducted on athletes with high (group A) and low (group B) levels of specialized work capacity. The mean $\pm$ SD values for specific work capacity were 438.5 ± 7.6 for group A and 405.3 ± 10.8 for group B (significant difference: $t = 4.248529$, $p = 0.000022$). Aerobic capacity (VO₂ max) was 5.62 ± 0.18 for group A and 5.09 ± 0.19 for group B ($t = 3.919930$, $p = 0.000089$), and anaerobic capacity (La max) was 18.51 ± 0.93 for group A and 16.60 ± 0.81 for group B ($t = 4.014509$, $p = 0.000060$). The “drives” data — the stimulus–response characteristics — comprised the following metrics for Groups A and B: EQPaCO₂ test 10 s: A = 2.02 ± 0.13 ; B = 1.74 ± 0.11 ; $t = 4.014509$, $p = 0.000060$. EQPaCO₂ test 30 s: A = 3.81 ± 0.11 ; B = 3.63 ± 0.10 ; $t = 3.875478$, $p = 0.000106$. VCO₂ test 30 s: A = 3.89 ± 0.25 ; B = 3.73 ± 0.20 ; $t = 2.343236$, $p = 0.019118$. EQCO₂ ST (step test): A = 34.54 ± 1.39 ; B = 35.70 ± 1.24 ; $t = 2.937021$, $p = 0.003314$. VCO₂ ST: A = 5.69 ± 0.14 ; B = 5.19 ± 0.18 ; $t = 3.919930$, $p = 0.000089$. La at VO₂ max: A = 14.50 ± 0.64 ; B = 13.35 ± 0.93 ; $t = 3.079945$, $p = 0.002071$. EqCO₂ CrP: A = 36.53 ± 0.79 ; B = 35.72 ± 1.08 ; $t = 3.510523$, $p = 0.000060$. La test 30 s / La CrP (%): A = 60.05 ± 1.04 ; B = 52.55 ± 2.15 ; $t = 4.014509$, $p = 0.000060$. EqO₂ ST / EqO₂ CrP (%): A = 4.63 ± 1.99 ; B = 5.20 ± 2.65 ; (not significant: $t = 0.677774$, $p = 0.497915$). EqCO₂ ST / EqCO₂ CrP (%): A = 6.48 ± 1.63 ; B = 3.69 ± 2.20 ; $t = 3.215083$, $p = 0.001304$. **Conclusion.** An adequate and complete response to workload-induced hypoxia, hypercapnia, and lactate acidosis was manifested by enhanced rapid kinetics of the CRS (EqPaCO₂ test 10 s and 30 s, VCO₂ test 30 s), prolongation of the steady state (VCO₂ ST, EqVCO₂ ST, La at VO₂ max), and mobilization of functions during fatigue compensation (La test 30 s / La CrP, EqO₂ ST / EqO₂ CrP, EqCO₂ ST / EqCO₂ CrP). Taken together, these responses form the structure of the reactive properties of the rowers' CRS.

Keywords: rowing, hypoxia, hypercapnia, lactate acidosis, power of the work.

Introduction

Currently, the potential reserves of healthy individuals during high-intensity sports training are being actively explored. The way of increasing the level of functional readiness of athletes by increasing the volume and intensity of training is reaching its limits. Therefore, the direction of training based on the development of mechanisms of functional protection of specialized work capacity during high-intensity athletic activity is actively being developed [Daniels, 2001; Mishchenko & Suchanowski, 2010].

Issues of energy supply, strength characteristics of work, neurodynamic functions of the body, and the response of the cardiorespiratory system (CRS) are considered in accordance with the requirements of the sport, specialization, sex, age, and qualification of the athletes [Guo et al., 2023; Herda & Cramer, 2015; Korobeynikov et al., 2018]. The highest response indicators reflect the degree of physiological strain from the load and characterize the level of athletes' functional preparedness.

At the same time, the importance of regulatory and stimulating mechanisms during intense competitive activities has been recognized [Mischenko et al., 2007]. The response of the CRS and energy systems to hypoxia, hypercapnia, and lactate acidosis reflects the body's adaptation to load and influences the ability of athletes to react quickly, adequately, and fully — that is, reactively — to training and competition stresses [Mishchenko & Bulatova, 1993]. The reactive properties of the CRS under load-induced hypoxia, hypercapnia, lactate acidosis,

and transitional physiological states have been studied through the "stimulus-response" relationship [Lysenko, 2015]. In the specialized literature, the quantitative and qualitative characteristics of neurohumoral (neurogenic, hypoxic, and acidemic) stimuli on CRS responses and work energy supply are discussed as criteria for changes in the "stimulus-response" relationship during intense motor activities [Mischenko et al., 2007].

The most significant factor to which sensitivity during intense physical activity may determine individual differences in CRS response is acidosis. The pulmonary ventilation response is particularly sensitive [Ozkaya et al., 2021] because it is largely driven by high sensitivity to the $\text{CO}_2\text{-H}^+$ stimulus [Mischenko & Monogarov, 1995]. Another key factor determining CRS physiological reactivity is neurogenic input from working limbs and the brain, depending on both the overall exertion and the frequency, force of movements, and type of muscle contractions [Diachenko et al., 2021; Miyamoto et al., 1987].

An adequate and full response to load-induced hypoxia, hypercapnia, and lactate acidosis manifests as enhanced rapid kinetics of the CRS, prolongation of the steady-state phase, and mobilization of functions during fatigue compensation. These physiological states are accompanied by neurogenic stimulation of functions. Together, these responses form the structure of the rowers' CRS reactive properties.

Issues of physiological reactivity have been studied at both the scientific and methodological levels, demonstrating hyper-, hypo-, and normo-reactive types of responses to shifts in respiratory homeostasis at rest (simulated hypoxia and progressive hypercapnia) and under standard physical loads [Lysenko, 2015; Mischenko & Monogarov, 1995]. Studies by Y. Liu et al. (1995) and Ozkaya O. et al. (2021) have shown the effect of threshold levels of CO_2 partial pressure on the development of the ventilatory compensation response to metabolic acidosis and the kinetics of metabolic reactions [Liu et al., 1995; Ozkaya et al., 2021]. Typological features of the body's reaction to hypoxia and hypercapnia loads, and associated manifestations of aerobic and anaerobic energy supply power and capacity, have also been demonstrated [Garnacho-Castaño et al., 2019; Mischenko & Monogarov, 1995].

In cyclic sports, specific quantitative and qualitative "stimulus-response" characteristics have been assessed, such as pulmonary ventilation responses to changes in partial pressure of CO_2 ($\text{VE} \cdot \text{PaCO}_2^{-1}$), CO_2 output ($\text{VE} \cdot \text{CO}_2^{-1}$), and O_2 uptake ($\text{VE} \cdot \text{VO}_2^{-1}$) [Mishchenko & Suchanowski, 2010; Salazar-Martínez et al., 2018]. An important part of the evaluation is the difference between the CRS response during steady-state and during fatigue compensation (RER , $\text{VE} \cdot \text{VCO}_2^{-1}$ at steady state / $\text{VE} \cdot \text{VCO}_2^{-1}$ during fatigue compensation, %; $\text{VE} \cdot \text{VO}_2^{-1}$ at steady state / $\text{VE} \cdot \text{VO}_2^{-1}$ during fatigue compensation, %) [Wang et al., 2019].

Particular attention has been given to the stimuli affecting the initial part of the response — rapid kinetics. It has been shown that neurogenic and hypoxic stimuli influence the speed of CRS activation and the power of aerobic and anaerobic energy supply during submaximal and maximal intensity loads [Puype et al., 2013; Whipp et al., 2005; Withers et al., 1993]. Opportunities for neurogenic stimulation of functions under moderate and low-intensity loads have also been demonstrated [Tabata et al., 1997]. These findings are based on assessing the time to half-response ($\text{T}_{50} \text{ VO}_2$, $\text{T}_{50} \text{ VE}$, $\text{T}_{50} \text{ VCO}_2$, $\text{T}_{50} \text{ HR}$) under standard measurement conditions [Guo et al., 2023].

The effect of lactate acidosis on the power of aerobic energy supply has been shown by R. Warren (1987), and P. Guo and A. Diachenko (2021) [Diachenko et al., 2021; Warren, 1987]. Lactate acidosis acts as a VO_2 stimulus depending on individual reactivity and the level of functional preparedness of the athletes. Practical aspects of lactate acidosis as an acidemic stimulus are considered based on assessing blood lactate concentration at the anaerobic threshold (La AT) [Melbo, 1996] and at maximum aerobic power $\text{VO}_2 \text{ max}$ ($\text{La VO}_2 \text{ max}$) [Bompa & Buzzichelli, 2018]. In cyclic sports, the stimulatory role of lactate acidosis is associated with preserving anaerobic reserves during the second half of the race [Wang et al., 2019].

In this regard, there is growing interest in studying the aspects of athletes' functional capabilities that enable them to reach the limits of physiological functions during competitive activities. The ability to reach functional limits can be expressed in specific measurement units that reflect the degree of cardiorespiratory system (CRS) and energy supply system responses to physiological states and transitional processes between them.

Diagnosing the reactive properties of CRS based on the assessment of neurohumoral stimuli makes it possible to identify the reserves of athletes' functional preparedness. The challenge lies in the content of monitoring, the methods of assessment, and the interpretation of indicators.

The complexity of recording and evaluating the influence of neurohumoral stimuli stems from the fact that during competitive activity, physiological states are accompanied by complex transitional processes where the development and compensation of hypoxia are associated with the progression of hypercapnia and the accumulation of anaerobic metabolism products (lactate acidosis). Moreover, the structure of CRS reactive properties changes depending on the duration and intensity of physical activity and the individual reactivity of athletes' CRS.

All of this necessitates the use of specialized forms of monitoring functional support for specific work capacity, interpretation of indicators, and evaluation of the effectiveness of neurohumoral stimulation of CRS and energy supply. This would help determine the quantitative and qualitative characteristics of athletes' functional capacities related to the stimulation of functional support for specific work capacity.

In cyclic sports, the solution to this problem can be based on modeling the initial, middle, and latter parts of a race during periods of active fatigue accumulation. This approach makes it possible to assess specific stimuli related to fast kinetics of reactions, steady-state functioning, and fatigue compensation. The relevance of solving this problem for academic rowing is due to the high level of hypoxia at the start of the distance (O_2 deficit at 90 s – 9.1–13.6 $\text{ml}\cdot\text{kg}^{-1}$), the development of hypercapnia (VCO_2 at 120 s – 58.0–62.3 $\text{ml}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$), and lactate acidosis (La VO_2 max – 14.5–16.4 $\text{mmol}\cdot\text{l}^{-1}$, La max – 18.2–22.0 $\text{mmol}\cdot\text{l}^{-1}$) [Guo et al., 2023; Lacour et al., 2009]. These data indicate a high level of physiological strain during the load.

The body's adaptation to hypoxia, hypercapnia, lactate acidosis, and transitional processes is associated with reaching the limits of aerobic power and anaerobic capacity, as well as optimizing CRS reactive properties during mobilization (fast kinetics) and functional realization (respiratory compensation for metabolic acidosis). However, the existing literature provides only episodic descriptions of "stimulus–response" characteristics for the 2000 m distance, limiting the ability to apply specialized (or auxiliary) training tools for optimizing CRS reactive properties.

This study evaluated the physiological conditions under which load-induced hypoxia, hypercapnia, and lactate acidosis elicit responses in the rowers' cardiorespiratory system.

Materials & methods

Participants. The study included forty elite male rowers from Jiangxi and Shandong provinces, all competing in the open-weight category (25.5 ± 2.3 years, 95.5 ± 3.7 kg, 191.7 ± 2.8 cm). All athletes were finalists of the Chinese National Games.

The participants were divided into two groups based on differences in work performance. Performance indicators were recorded during a 2000-meter simulation on the Concept "Erg Rowing" ergometer. Group "A" included rowers ranked 1–20, and Group "B" included rowers ranked 21–40, according to ergometric work output (watts).

Ethical Approval. All participants were informed about the study requirements beforehand, and written informed consent was obtained from their parents and coaches. All procedures complied with the spirit of the Declaration of Helsinki and were approved by the local ethics committee (NUUFES).

Procedures and Evaluation. Measurements of cardiorespiratory responses, blood lactate concentration, and athletes' work capacity were carried out by experts from the key Lab of Aquatic Training Monitoring and Intervention of General Administration of Sport of China.

Procedures and Evaluation – Physical Characteristics. Gas exchange measurements: oxygen consumption (VO_2), carbon dioxide production (VCO_2), and minute ventilation (VE) were measured breath-by-breath using an Oxycon Mobile (Jaeger) metabolic cart. The device was calibrated with a known gas mixture (16.00% O_2 , 4.00% CO_2).

Biochemical measurements: blood lactate concentration was determined using the "Biosen S. line lab+" laboratory system. Load Simulation: load simulation was performed using the Concept "Erg Rowing" ergometer.

Procedures and Evaluation – Day One: 2000 m Specific Performance Test. Under standardized load conditions, a 6-minute specific performance test was conducted on the Concept "Erg Rowing" ergometer, with measurements of the average ergometric work output (watts) during the 6-minute test.

Procedures and Evaluation – Day Two: Simulation tests of the compositional components of competing activities

The testing program included two modules, where the duration and intensity were designed to simulate the "stimulus–response" conditions of hypoxia, hypercapnia, and lactate acidosis transitional processes during a 2000-meter race. The composition of the tests and the specific characteristics of neurohumoral stimuli are presented in Tables 1 and 2.

Table 1. Characteristics of Neurohumoral Stimuli of the Response

Indicator	Indicator Description
EqPaCO_2 ($\text{VE}\cdot\text{PaCO}_2^{-1}$)	Indicator of the ratio of the ventilatory response to the increase in partial pressure of CO_2 in arterial blood
EqVCO_2 ($\text{VE}\cdot\text{PaCO}_2^{-1}$)	Indicator of the ratio of the ventilatory response to the increase in CO_2 concentration in exhaled air
EqVO_2 ($\text{VE}\cdot\text{VO}_2^{-1}$)	Indicator of the ratio of the ventilatory response to the reaction of O_2 consumption
La max VO_2 max	Blood lactate concentration level at which the athlete reaches VO_2 max
$\text{VE}\cdot\text{VCO}_2^{-1}$ VO_2 max step test / $\text{VE}\cdot\text{VCO}_2^{-1}$ critical power	Increase in the level of strain of functional support for specific work capacity under conditions of fatigue development during the critical power test same as above, with respect to oxygen consumption
$\text{VE}\cdot\text{VO}_2^{-1}$ VO_2 max step test/ $\text{VE}\cdot\text{VO}_2^{-1}$ critical power	
$\text{La test 30s /La critical power}$ (CrP)	Ratio of power and capacity of lactate-based energy supply (anaerobic reserve for the second half of the race)

Table 2. Testing Program for Measuring Neurohumoral Stimuli of the Response

Test Parameters	Indicators of Stimuli Response ("drives")
Компонент анализа – быстрая кинетика	
Test "10s"	VE/PaCO ₂
Test "3-s"	VE/PaCO ₂
	VE/VCO ₂ «30»
	La max test 30 s
Recovery period is 7 minutes. Blood sampling for lactate measurement at 3 and 5 minutes. The higher value is recorded.	
Analysis Component – Steady State (Characteristics of Steady State in the Step Test ST)	
Step test: 1 step 250-watt, 2 (3, 4, 5...) step +30 watt	VE/VCO ₂ VO ₂ max
	VE/VO ₂ VO ₂ max
	La max VO ₂ max
Recovery period is 7 minutes. Blood sampling for lactate measurement at 3 and 5 minutes. The higher value is recorded.	
Analysis Component – Fatigue Compensation	
Test «Critical power» (CrP)	VE·VCO ₂ ⁻¹ VO ₂ max step test / VE·VCO ₂ ⁻¹ CP120s
	VE·VO ₂ ⁻¹ 2 VO ₂ max step test / VE·VO ₂ ⁻¹ CP120s
	La CrP
	La test30s / La CrP

Statistical Analysis. For the evaluation and analysis of the obtained data, the statistical software package SPSS 10.0 was used. Descriptive statistics included the calculation of the arithmetic mean ($\bar{x}$), standard deviation (S), median (Me), maximum (max) and minimum (min) values, as well as the 25th and 75th percentiles. Correlation analysis was employed. As a statistical tool, the Spearman rank correlation coefficient was used. The data were checked for compliance with the normal distribution using the Shapiro–Wilk test. If the data distribution did not meet the normal distribution criterion, non-parametric Wilcoxon tests were used to determine the statistical significance of differences. The probability of error in the statistical analysis was set at $p = 0.05$ (level of significance).

Results

An analysis was conducted on the relationship between the indices of the cardio-respiratory system (CRS) response and the energy supply mechanisms in highly qualified rowers ($n=40$). Specific attention was given to indicators influencing the achievement of reaction limits and shaping the structure of functional support for the specific work capacity of rowers. Physiological mechanisms with the highest degree of impact on the mobilization and realization of the body's functional reserves were considered as physiological stimuli ("drives") for fast kinetics, reaction stability, and fatigue compensation.

Below are the correlation relationships ($p < 0.05$) between CRS indices and work energy supply, which were observed during the simulation of the initial section of the race distance, the period of steady-state performance, and the fatigue compensation phase ($n=40$). These segments of competitive activity were distinguished by differences in levels of hypoxia, hypercapnia, and blood lactate concentration.

The analysis of the indicators in the initial part of the distance revealed a correlation between PaCO₂ and $\dot{V}E$ in the 10-second test (EqPaCO₂, $r = 0.89$) and a tendency toward correlation in the 30-second test (EqPaCO₂, $r = 0.47$); a tendency toward correlation between PaCO₂ and La test 30 s ($r = 0.49$); a correlation between PaCO₂ and VCO₂ in the 30-second test ($r = 0.59$); and a tendency toward correlation between EqPaCO₂ and VO₂ ($r = 0.46$). Significant attention is drawn to the correlations between EqPaCO₂ in the 10-second (30-second) tests and VO₂ max ST and VO₂ max CrP, respectively ($r = 0.71$ ($r = 0.57$), $r = 0.69$ ($r = 0.53$)). The "stimulus-response" characteristics of fast kinetics include indicators such as EqPaCO₂ test 10 s (30 s) and VCO₂ test 30 s. The analysis of steady-state indicators during the step test (period of maintaining 98–100% VO₂ max for 30 seconds) revealed tendencies for correlations between VO₂ and VCO₂ ($r = 0.56$), VO₂ and La VO₂ max ($r = 0.55$), and $\dot{V}E$ and VCO₂ ($r = 0.51$). The linear increase of lactate acidosis (La VO₂ max) and hypercapnia (VCO₂) stimulates the development of VO₂ power and stability. An increase in respiratory exchange ratio ($RER > 1.1$), production of excess CO₂ (CO₂ excess), and pulmonary ventilation ($\dot{V}E$ excess) stimulates the respiratory compensation response for metabolic acidosis, clearly seen through the linear increase of the VE/VCO₂ ratio (EQCO₂). The "stimulus-response" characteristics of the steady state include EQCO₂, VCO₂, and La VO₂ max. The analysis of fatigue compensation indicators (critical power load) showed a correlation between VCO₂ CrP and EqCO₂ CrP ($r = 0.63$), La CrP and VCO₂ CrP ($r = 0.74$), a tendency toward correlation between La CrP and La test 30 s / La CrP ($r = 0.51$), EqCO₂ ST / EqCO₂ CrP ($r = 0.51$), EqO₂ ST / EqO₂ CrP ($r = 0.49$), and a negative correlation between VO₂ CrP and EqO₂ ST / EqO₂ CrP ($r = -0.53$). The stimulus for fatigue compensation is the preservation of the anaerobic reserve (La test 30 s / La CrP) and the enhanced response of pulmonary ventilation to the production of excess (buffered) CO₂. Under conditions of fatigue compensation, physiological stress levels increase. During this time, CRS indices and energy supply reach their maximum levels. The compensatory tension of functions is associated with the activation of buffering systems, particularly the displacement of CO₂ by bicarbonates during lactate formation [6]. Increased pulmonary

ventilation is associated with the production of excess CO₂ (RER ST > RER CrP). The degree of VCO₂ increase depends on anaerobic capacity (La CrP) and anaerobic glycolytic reserve (La test 30 s / La CrP), as well as the buffering power of the organism. Physiological load stress is accompanied by the maintenance and increase of VO₂ power and stability. The presented data characterize general patterns of stimulation of functional capabilities in rowers. Of particular interest is the evaluation of the influence degree of these characteristics on the functional support of specific work capacity. For this purpose, the rowing performance indicators were recorded during a simulated 2000 m distance on a Concept "Erg Rowing" ergometer. According to the ranking position, the rowers were divided into two groups: group "A" (athletes with high work capacity) and group "B" (athletes with low work capacity). Table 3 presents the working performance, aerobic, and anaerobic power indicators of group "A" (n=20) and group "B" (n=20) rowers in the open weight category.

Table 3. Indicators of Functional for specific Work Capacity of Rowers from Group "A" and Group "B" during a 2000 m Distance Simulation

Statistics	Data					
	Group A			Group B		
	W ₂₀₀₀	La	VO ₂ max	W ₂₀₀₀	La	VO ₂ max
X	438.5	18.51	5.62	405.3	16.60	5.09
Me	436.0	18.10	5.60	402.2	16.70	5.00
S	7.6	0.93	0.18	10.8	0.81	0.19
min	430.0	16.90	5.30	387.0	15.00	4.90
max	455.0	20.30	6.00	423.1	17.70	5.50
25%	432.0	17.90	5.50	398.5	16.20	5.00
75%	444.5	19.10	5.70	416.0	17.40	5.20

Differences of indices «A» and «B»: W₂₀₀₀ – t=4.248529, p=0.000022; La – t=4.014509, p=0.000060; VO₂ max – t=3.919930, p=0.000089 The average ergometric power of rowers in group "A" (ranked 1–20) was 438.5±7.6 watts, while in group "B" (ranked 21–40) it was 405±10.8 watts (p<0.05). Rowers in group "A" demonstrated higher aerobic power and anaerobic energy capacity (VO₂ max, La). This allowed for distinguishing the athletes in group "A" as rowers with a high level of functional support for specific work capacity, and the athletes in group "B" as those with a low level. A comparative analysis of the specific "drives" characteristics — EQPaCO₂ test 10 s, EQPaCO₂ test 30 s, VCO₂ test 30 s, EQCO₂ ST, VCO₂ ST, La VO₂ max, EqCO₂ CrP, La test 30 s / La CrP (%), EqO₂ ST/EqO₂ CrP (%), EqCO₂ ST/EqCO₂ CrP (%) — between group "A" and group "B" is presented in Table 4.

Table 4. Data "drives" of fast kinetics, steady state, and fatigue compensation

Statistics	Group	Data «drives»									
		Fast kinetics			Steady state			Fatigue compensation			
		EQPaCO ₂ test 10 s	EQPaCO ₂ test 30 s	VCO ₂ test 30 s	EQCO ₂ ST	VCO ₂ ST	La VO ₂ max	EqCO ₂ CrP	La test 30 s / La CrP (%)	EqO ₂ ST / EqO ₂ CrP	EqCO ₂ ST / EqCO ₂ CrP
X	«A»	2.02	3.81	3.89	34.54	5.69	14.5	36.53	60.05	4.63	6.48
	«B»	1.74	3.63	3.73	35.7	5.19	13.35	35.72	52.55	5.2	3.69
Me	«A»	1.98	3.78	3.9	35	5.7	14.6	36.4	60.1	4.76	6.56
	«B»	1.77	3.63	3.8	35.8	5.2	13.5	35.19	52.67	4.79	2.89
S	«A»	0.13	0.11	0.25	1.39	0.14	0.64	0.79	1.04	1.99	1.63
	«B»	0.11	0.1	0.2	1.24	0.18	0.93	1.08	2.15	2.65	2.2
min	«A»	1.83	3.64	3.4	32	5.4	13.4	35.1	58	1.25	3.85
	«B»	1.58	3.4	3.4	32.78	5	11.3	34.18	48.05	1.23	0
max	«A»	2.24	4.08	4.3	37	5.9	15.6	37.80	61.75	9.1	8.7
	«B»	1.92	3.79	4	37.5	5.5	15.1	37.8	55.77	11.85	8.08
25%	«A»	1.91	3.74	3.7	33.42	5.6	14	36.0	59.2	3.16	5.4
	«B»	1.68	3.57	3.6	35.2	5	12.8	35.0	51.2	3.48	2.17
75%	«A»	2.15	3.84	4	35	5.8	14.9	36.9	60.59	5.6	7.91
	«B»	1.84	3.72	3.9	36.61	5.3	14	36.50	54.2	6.7	4.79
t		4.014509	3.875478	2.343236	2.937021	3.919930	3.079945	3.510523	4.014509	0.677774*	3.215083
p		0.000060	0.000106	0.019118	0.003314	0.000089	0.002071	0.000447	0.000060	0.497915	0.001304

* – differences are not statistically significant

From the table, it is evident that the rowers of group "A" exhibited a higher degree of neurohumoral response stimuli across most indicators. The absence of statistically significant differences in EqO₂ ST / EqO₂ CrP (%) is attributed to the increase (maintenance) of the O₂ consumption response in group "A" or its decrease in group "B" under critical power load conditions.

Under the assumed RER CrP = 1.1 ± 0.5 , the differences in EqCO₂ CrP and EqO₂ CrP range from 1.0% to 1.5%. The differences between EqCO₂ ST and EqCO₂ CrP are between 3.0% and 5.0%, and between EqO₂ ST and EqO₂ CrP range from 1.0% to 3.0%. Such tendencies in differences contribute to the quantitative and qualitative characteristics of effective functional regulation during fatigue development and serve as stimuli for reaching the limits of the energy supply functions of rowers under fatigue conditions.

These typological features are characteristic of a larger number of high level rowers and are prerequisites for athletes' functional readiness for intense competitive activity.

At the same time, the analysis structure did not consider extraordinary functional characteristics that highlight unique aspects of rowers' preparedness. Unique features of physiological stress under load exceed the general model range values ($n > \bar{x} \pm S$, according to the 3-sigma rule [25]). For instance, the individual anaerobic glycolytic energy capacity of athlete L. was La CrP = $22.0 \text{ mmol} \cdot \text{l}^{-1}$, La test 30 s / La CrP = 72.7%, which stimulated a significant increase in excess pulmonary ventilation. In this case, the EqCO₂ ST / EqCO₂ CrP ratio rose to 7.1%, while the EqO₂ ST / EqO₂ CrP ratio remained relatively stable at 5.5%, corresponding to the degree of increase in O₂ consumption.

Thus, the characteristics of group "A" rowers demonstrate their ability to reach the limits of cardio-respiratory system (CRS) functions and energy supply during fatigue development and compensation, mobilizing functional reserves. In contrast, the responses of group "B" rowers indicate the depletion of energy substrate reserves and a decline in buffering power at an early stage of intense physical activity. In this case, physiological load stress is associated with reaching the limits of pulmonary ventilation responses and a clear tendency toward a reduction in VCO₂ CrP, VO₂ CrP, La CrP, and La test 30 s / La CrP. At the same time, the EqCO₂ ST / EqCO₂ CrP and EqO₂ ST / EqO₂ CrP ratios may exceed 7.0–10.0%.

Discussion

At present, there is a clear understanding that the reserves for improving the effectiveness of specific physical fitness through increasing the volume and intensity of training work have been exhausted. The key direction for future development lies in enhancing the specialized orientation of specific physical fitness by forming and implementing the structure of functional support for the specific work capacity of rowers. A number of key studies have been dedicated to solving this problem [Bompa & Buzzichelli, 2018; Daniels, 2001; Mischenko et al., 2007].

At the same time, it has become clear that evaluating the functional reserves of athletes' specific work capacity solely through indicators of aerobic and anaerobic energy power and capacity is clearly insufficient. This method allows for the assessment of athletes' potential, but realizing this potential requires additional evaluation of the mechanisms of regulation and stimulation of functions under simulated competitive conditions. These characteristics form part of the overall assessment of physiological load stress. They shape the structure of functional support for specific work capacity and ensure a high degree of mobilization of the body's functional reserves.

In cyclic endurance sports, this problem is particularly important. During the competitive distance, athletes express the components of functional support for specific work capacity — fast kinetics, steady state, and fatigue compensation. Each of these elements has a unique structure and mechanisms for the regulation and stimulation of functions. Their systemic interaction forms the overall structure of specific physical fitness according to the type of sport, competition format, and specialization [Wang et al., 2019]. In the specialized literature, the quantitative and qualitative characteristics of these components of specific physical fitness are still insufficiently presented.

One of the mechanisms of function regulation and stimulation is the activation of the cardio-respiratory system (CRS) during exertion. A rapid, adequate, and complete response by athletes to an increase in physiological load stress is a crucial factor in the realization of the body's functional reserves. In cyclic sports, the increase in physiological load stress is associated with the development of hypoxia, hypercapnia, and lactate acidosis. An important regulatory factor is the neurogenic influence on the initial phase of the reaction, as well as the maintenance of reaction levels during the steady-state and fatigue compensation phases. Depending on the duration and intensity of the load, the impact of each factor differs significantly. Variations in physiological states create the conditions for the realization of neurohumoral stimuli, which shape the structure of the body's reaction to load depending on the structure of competitive activity and the athlete's individual physiological reactivity.

The study shows that the degree of influence of neurohumoral stimuli on reactions differs depending on the level of functional preparedness of the rowers. In rowers with a high level of functional preparedness, physiological states serve as stimuli for the development of functions and the mobilization of the body's functional reserves, in accordance with the requirements of functional support for specific work capacity. In

athletes with a low level of functional preparedness, or under conditions of incomplete recovery, these physiological states and the associated shifts in homeostasis lead to a reduced CRS and energy supply response, and under conditions of maximum load (critical power load), a reduction in the limits of reaction compared to the steady-state. This is manifested in a decreased speed of reaction deployment, reduced energy supply power, and a diminished capacity for fatigue compensation.

The problem lies in the fact that during competitive activity in academic rowing, physiological states are characterized by complex transitional processes such as load-induced hypoxia, load-induced hypercapnia, and lactate acidosis. It is impossible to separately isolate the degree of differentiated effects of neurogenic, hypoxic, and acidemic stimuli during the simulation of competitive activity.

A promising direction for specific analysis is the examination of competitive components that differ in their reaction structures and the degree of physiological load stress, corresponding to specific phases of the 2000 m race. These phases include: the initial part of the race, associated with fast kinetics of reactions; the middle segment, characterized by the steady state of functions; and the last part of the distance, marked by the active development and compensation of fatigue. Collectively, these phases form the integral structure of the functional support for specific work capacity, where each component has its own features of function stimulation and affects the mobilization of functional reserves in accordance with the overall demands of physiological load stress in competition.

The presented data provide grounds for further reflection and heuristic modeling of the functional support structure for the specific work capacity of rowers, based on the assessment of quantitative and qualitative characteristics of neurohumoral response stimuli.

The foundations for this modeling are provided by the works of MacDougall J., Wenger H., Green H. (1991), J. R. Lacour, L. Messonnier (2009), and Tomiak T., Mishchenko V., et al. (2014), who revealed the structure of functional support for rowers' specific work capacity through the analysis of functional capabilities and working performance parameters across different segments of the competitive distance [Lacour et al., 2009; Tomiak et al., 2014]. These include characteristics of anaerobic energy supply power and capacity [Diachenko et al., 2020; Hommel et al., 2019; Wang et al., 2019], the rate of reaction deployment (fast kinetics), and the power and stability of aerobic energy supply [Diachenko et al., 2021; Mishchenko & Suchanowski, 2010; Whipp et al., 2005], along with generalized characteristics of the CRS and energy supply during the development and compensation of fatigue [Kong et al., 2018; Mishchenko et al., 2007; Warren, 1987], registered during the functional realization at specific segments of the race.

As a result, a clear understanding has emerged that the foundation for realizing the integral structure of functional support for the specific work capacity of rowers is based on the "domino principle."

For the 2000 m distance, this means that a change in the first element of the chain — the fast kinetics of reactions — triggers a change in the adjacent element — the steady state of functions — followed sequentially by a change in fatigue compensation. In this model, the high degree of realization of fast kinetics plays a particularly crucial role, serving as a stimulus for reaching the limits and stability of reactions throughout the competitive activity.

The results presented in the study confirm the findings of Y. Liu, J. M. Steinacker, M. Stauch (1995), S. A. Ward, N. Lamarra, B. Whipp (1996), O. Ozkaya, G. A. Balci et al. (2021), and A. Diachenko, Guo P. et al. (2021) regarding the mechanisms of stimulation of fast kinetics and substantiate its role in the realization of functional support for specific work capacity [Diachenko et al., 2021; Liu et al., 1995; Ozkaya et al., 2021; Whipp et al., 2005]. Of particular interest are generalized data that justify considering the characteristics of the ratio between CO₂ partial pressure and pulmonary ventilation response (PaCO₂ test 10 s and PaCO₂ test 30 s) as important components for evaluating the reactive properties of the CRS.

The works of R. L. Warren (1987), R. T. Withers, G. Ploeg, J. P. Finn (1993), B. J. Whipp, S. A. Ward et al. (2005), and C. Cleuziou, S. Perrey et al. (2005) substantiated the standard conditions of load-induced hypoxia, hypercapnia, and lactate acidosis, which stimulate fast kinetics, anaerobic power, and the respiratory compensation response to metabolic acidosis [Cleuziou et al., 2005; Warren, 1987; Whipp et al., 2005; Withers et al., 1993].

The problem is that the conditions for realizing stimuli and their combinations exhibit a distinctly differentiated character. This allowed for the resolution of specific issues related to the functional preparedness of athletes. For example, using work parameters under submaximal and maximal hypoxia conditions to develop VO₂ max [Billat et al., 2001; Withers et al., 1993], employing hypercapnia and progressive lactate acidosis to develop stability and the respiratory compensation response for metabolic acidosis [Mishchenko & Suchanowski, 2010], and mobilizing functional reserves during the critical power load phase [Melbo, 1996; Wang et al., 2019].

The issues related to improving the efficiency of the functional support for specific work capacity have not been fully resolved. This is largely due to the absence of a normative framework for components of functional preparedness that address the regulation of functions and their stimulation under conditions of high competitive load stress.

The lack of a normative basis for physiological stimuli of reactions reduces the possibilities for assessing the functional support of specific work capacity in rowers over a 2000-meter distance. This, in turn, limits the ability to develop a specialized orientation for specific physical fitness, as well as to design training parameters and criteria for evaluating training effectiveness.

The data presented in this study provide a qualitative and quantitative characterization of the physiological mechanisms regulating functions and stimulating the reaction limits of functional support for the specific work capacity of rowers. It is demonstrated that reaching the limits of anaerobic and aerobic power is observed in rowers who possess highly reactive properties of the cardio-respiratory system (CRS) and energy supply mechanisms.

The stimulus for increasing the functional response is the development of acidosis, manifested during the race as an increase in CO₂ partial pressure, CO₂ elimination, and lactate acidosis. The impact of these reaction components differs across different segments of the race. Accordingly, the structure of reactions and the composition of neurohumoral stimuli indicators vary:

- For fast kinetics: PaCO₂ test 10 s, PaCO₂ test 30 s, and VCO₂ test 30 s;
- For steady-state: EQCO₂ ST, VCO₂ ST, and La VO₂ max;
- For fatigue compensation: EqCO₂ CrP, La test 30 s / La CrP (%), EqO₂ ST / EqO₂ CrP, and EqCO₂ ST / EqCO₂ CrP.

The functional response to neurohumoral stimuli indicates a higher or lower capacity for reaching the limits of CRS and energy supply functions at the beginning, middle, and latter parts of the race.

The practical applications of the research findings are related to the implementation of monitoring, modeling, enhancing functional specificity, and individualizing specific physical fitness regimes.

Monitoring results can be analyzed based on the principles of modeling specific physical fitness. For high-level rowers, the normative characteristics of reactions were found within $\pm S$ (according to the three-sigma rule [Pukelsheim, 1994]). Reaction characteristics within $\pm S$ correspond to the normative parameters of generalized models representing the main group of rowers. Reaction characteristics with $n > \pm S$ relate to individual preparedness models and indicate unique aspects of the rowers' functional readiness.

Decreased reaction characteristics provide grounds for correcting specific physical fitness. Specialized literature presents a wide range of training load regimes that simulate physiological states and stimulate functions depending on the direction and physiological load stress [Billat et al., 2001; Tomiak et al., 2014; Vilaça-Alves et al., 2016; Withers et al., 1993].

In the system of stimulating athletes' functional capacities, the recovery system plays an important role. Data show the possibilities of using non-training methods that increase the CRS sensitivity threshold to hypoxia and decrease it to hypercapnia [Mischenko et al., 2007]. Such interventions optimize pre-start readiness, enhance the ability to mobilize functions, and reduce the risk of early fatigue development.

In addition, new possibilities for improving CRS reactive properties may be associated with simulating types of load that mimic the conditions for the realization of key components of functional support for specific work capacity. This mainly refers to the realization of anaerobic and aerobic energy supply structure components.

For rowing, specific test work regimes—where the parameters presented in this article were registered—can be used. This allows for the control of training work parameters and volume according to individual response levels, optimizing the "dose-effect" ratio of training loads.

Thus, new opportunities are shown for developing a specialized orientation and realizing specific physical fitness for high-level rowers based on optimizing the reactive properties of the CRS and energy supply mechanisms over the 2000-meter distance. The presented data represent a conceptual model for managing the specific physical fitness of elite rowers based on studying the structure of functional support for specific work capacity and improving the mechanisms of function regulation, stimulation, and the mobilization of the body's functional reserves.

Conclusions

It has been found that rowers who are able to reach anaerobic and aerobic power limits typically have higher cardiorespiratory system (CRS) and energy supply mechanism reactivity.

Stimuli contributing to the enhanced functional response include elevated CO₂ partial pressure, CO₂ emission, and the development of lactic acidosis

These responses are affected differently at different stages of the race. This leads to differences in the structure of the "stimulus-response" and in the composition of the neurohumoral stimulus indexes:

- For fast kinetics: PaCO₂ test 10 s (test 30 s) and VCO₂ test 30 s;
- For steady-state: EQCO₂ ST, VCO₂ ST, La VO₂ max;
- For fatigue compensation: EqCO₂ CrP, La test 30 s / La CrP (%), EqO₂ ST / EqO₂ CrP, and EqCO₂ ST / EqCO₂ CrP.

Functional “stimulus-response” responses to specific physiological states of hypoxia, hypercapnia and lactic acidosis reveal differences in the ability of athletes to reach the limits of the cardiorespiratory system and energy supply responses in the early, middle and late phases of a race.

Conflicts of interest - If the authors have any conflicts of interest to declare.

The authors declare that no artificial intelligence (AI) tools were used in the collection, analysis, or interpretation of the study data. AI-assisted tools were used solely for language editing and grammatical refinement during manuscript preparation. All scientific content, study design, statistical analysis, and interpretation of results were performed solely by the authors.

References

- Billat, V. L., Slawinski, J., Bocquet, V., Chassaing, P., Demarle, A., & Koralsztejn, J. P. (2001). Very short (15 s–15 s) interval training around the critical velocity allows middle-aged runners to maintain VO_2max for 14 minutes. *Sports Medicine*, 22(3), 201–208.
- Bompa, T., & Buzzichelli, C. (2018). *Periodization: Theory and methodology of training* (6th ed.). Human Kinetics.
- Cleuziou, C., Perrey, S., Lecoq, A. M., Candau, R., Courteix, D., & Obert, P. (2005). Oxygen uptake kinetics during moderate and heavy intensity exercise in humans: The influence of hypoxia and training status. *International Journal of Sports Medicine*, 26(5), 356–362.
- Diachenko, A., Pengcheng, G., Yevpak, N., Rusanova, O., & Kiprych, S. (2021). Neurohumoral components of rapid reaction kinetics of the cardiorespiratory system of kayakers. *Sport Mont*, 19(S2), 29–33.
- Daniels, J. (2001). Aerobic capacity for endurance. In B. Foran (Ed.), *High-performance sports conditioning: Modern training for ultimate athletic development* (pp. 193–213). Human Kinetics.
- Filippov, M. (2019). Conditions for carbon dioxide formation and transfer in the course of muscular activity. *Science in Olympic Sport*, 4, 17–23.
- Garnacho-Castaño, M. V., Albasa-Albiol, L., Serra-Payá, N., Bataller, M. G., Felú-Ruano, R., Cano, L. G., Cobo, P. E., & Maté-Muñoz, J. L. (2019). The slow component of oxygen uptake and efficiency in resistance exercises: A comparison with endurance exercises. *Frontiers in Physiology*, 10, Article 357. <https://doi.org/10.3389/fphys.2019.00357>
- Guo, P., Rusanova, O., Huang, Z., Diachenko, A., Rusanov, A., & Kiprych, S. (2023). Programming modes of training sessions of qualified kayakers specializing in the 1000 m distance. *Journal of Physical Education and Sport*, 23(1), 32–40. <https://doi.org/10.7752/jpes.2023.01004>
- Diachenko, A., Guo, P., Wang, W., Rusanova, O., Kong, X., & Shkrebtii, Y. (2020). Characteristics of the power of aerobic energy supply for high-qualified paddlers in China. *Journal of Physical Education and Sport*, 20(Suppl. 1), 312–317. <https://doi.org/10.7752/jpes.2020.s1043>
- Herda, T. J., & Cramer, J. T. (2015). Bioenergetics of exercise and training. In G. G. Haff & N. T. Triplett (Eds.), *Essentials of strength training and conditioning* (pp. 43–64). Human Kinetics.
- Hommel, J., Öhmichen, S., Müller, U. M., et al. (2019). Effects of six-week sprint interval or endurance training on calculated power in maximal lactate steady state. *Biology of Sport*, 36(1), 47–54.
- Korobeynikov, G., Korobeynikova, L., Potop, V., Nikonorov, D., Semenenko, V., Dakal, N., & Mischuk, D. (2018). Heart rate variability system in elite athletes with different levels of stress resistance. *Journal of Physical Education and Sport*, 18(2), 550–554.
- Lacour, J. R., Messonnier, L., & Bourdin, M. (2009). Physiological correlates of performance: Case study of a world-class rower. *European Journal of Applied Physiology*, 106(3), 407–413.
- Kong, X., Rusanova, O., Diachenko, A., & Kosticova, S. (2018). Functional support of special performance throughout the race distance in well-trained rowers in China. *Journal of Physical Education and Sport*, 18(4), 2324–2330.
- Liu, Y., Steinacker, J. M., & Stauch, M. (1995). Does the threshold of transcutaneous partial pressure of carbon dioxide represent the respiratory compensation point or anaerobic threshold? *European Journal of Applied Physiology*, 71(4), 326–331.
- Lysenko, O. (2015). Physiological reactivity and the stimulus–reaction ratio under physical exertion of various nature. *Physical Education, Sport and Health Culture in Modern Society*, 2(30), 136–143.
- Melbo, J. (1996). Is the maximal accumulated oxygen deficit an adequate measure of anaerobic capacity? *Canadian Journal of Applied Physiology*, 21, 370–383.
- Maté-Muñoz, J. L., Domínguez, R., Barba, M., Monroy, A. J., Rodríguez, B., Ruiz-Solano, P., & Garnacho-Castaño, M. V. (2015). Cardiorespiratory and metabolic responses to loaded half-squat exercise at lactate threshold intensity. *Journal of Sports Science & Medicine*, 14(3), 648–656.
- Mishchenko, V. S., & Bulatova, M. M. (1993). Effect of endurance training on cardiorespiratory reactive features. *Journal of Sports Medicine and Physical Fitness*, 33(2), 95–106.
- Mischenko, V., & Monogarov, V. (1995). *Fisiología del deportista*. Paidotribo.
- Mishchenko, V. S., Lysenko, E. N., & Vinogradov, V. E. (2007). *Reactive properties of the cardiorespiratory system as a reflection of adaptation to intense physical training*. Naukovyi Svit.

- Mishchenko, V., & Suchanowski, A. (2010). *Athlete's endurance and fatigue characteristics related to adaptability of specific cardiorespiratory reactivity*. AWFIS.
- Miyamoto, Y., Nakazono, Y., & Yamakoshi, K. (1987). Neurogenic factors affecting ventilatory and circulatory responses to static and dynamic exercise in humans. *Japanese Journal of Physiology*, 37(3), 435–446.
- Ozkaya, O., Balci, G. A., As, H., & Yildiztepe, E. (2021). A new technique to analyse threshold intensities based on time-dependent change-points in ventilatory variables. *Respiratory Physiology & Neurobiology*, 294, Article 103735.
- Pukelsheim, F. (1994). The three sigma rule. *The American Statistician*, 48, 88–91.
- Puype, J., Van Proeyen, K., Raymackers, J. M., Deldicque, L., & Hespel, P. (2013). Sprint interval training in hypoxia stimulates glycolytic enzyme activity. *Medicine & Science in Sports & Exercise*, 45(11), 2166–2174.
- Salazar-Martínez, E., de Matos Tomé, P. R., Arrans, P., et al. (2018). Ventilatory efficiency response is unaffected by fitness level, ergometer type, age or body mass index in male athletes. *Biology of Sport*, 35(4), 393–398.
- Tabata, I., Irisawa, K., Kouzaki, M., Nishimura, K., Ogita, F., & Miyachi, M. (1997). Metabolic profile of high-intensity intermittent exercise. *Medicine & Science in Sports & Exercise*, 29, 390–395.
- Tomiak, T., Mishchenko, V., Lysenko, E., Diachenko, A., & Korol, A. (2014). Effects of moderate and high-intensity training on cardiopulmonary chemosensitivity in elite paddlers. *Baltic Journal of Health and Physical Activity*, 6(3), 218–228.
- Vilaça-Alves, J., Freitas, N. M., Saavedra, F. J., Scott, C. B., dos Reis, V. M., Simão, R., & Garrido, N. (2016). Comparison of oxygen uptake during resistance and ergometer exercises matched for intensity. *Journal of Human Kinetics*, 53, 179–187.
- Wang, W., Rusanova, O., & Diachenko, A. (2019). Control of functional safety in highly qualified kayak and canoe paddlers. *Theory and Methodology of Physical Education and Sports*, 2, 92–100.
- Warren, R. L. (1987). Oxygen uptake kinetics and lactate concentration during exercise in humans. *American Review of Respiratory Disease*, 135(5), 1080–1084.
- Whipp, B. J., Ward, S. A., & Rossiter, H. B. (2005). Pulmonary O₂ uptake during exercise: Conflating muscular and cardiovascular responses. *Medicine & Science in Sports & Exercise*, 1574–1585.
- Withers, R. T., Ploeg, G., & Finn, J. P. (1993). Oxygen deficits during 45–90 s maximal cycling. *European Journal of Applied Physiology*, 67(2), 185–191.