

Specific Intensity of Physiological Costs during Cyclic Operation of Different Power

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Abstract—The aim of the study is the search for heart rate criteria of the rate of energy consumption during intense cyclic work. In the first part of the study, nine athletes (qualified athletes, age 18.3 ± 1.5 years, weight 72.2 ± 8.04 kg), specializing in BMX (Bicycle MotoX), performed on different days a series of five all-out exercises on a cycle ergometer at a maximal power output and fixed durations of 10, 30, 60, 120 and 360 s. In the second part of the study, eight road racers (qualified athletes, age 21.3 ± 3.4 years, weight 72.9 ± 11.3 kg) performed two exercises on the cycle ergometer at the aerobic threshold and at the anaerobic threshold, each trial lasting 30 min. We observed a high correlation ($p < 0.05$, $R^2 > 0.9$) between the paired values of the specific intensity of physiological costs (SIPC), calculated from oxygen consumption ($SIPC_{O_2}$) and heart rate sums ($SIPC_{fH}$). This correlation was present throughout the whole range of exercise intensities—from the aerobic threshold to maximum anaerobic power. Thus, it is possible to use the $SIPC_{fH}$ parameter in training practice for assessing the rate of energy consumption during exercise.

Keywords: limit and non-limit exercises, intensity of energy consumption, heart rate indices, athletes cyclists

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INTRODUCTION

It is known that loads of different power cause physiological costs of different intensity and structure, which was postulated by V.S. Farfel in his concept of “relative power zones” and was further confirmed by the results of biochemical studies [1]. In each of these zones, different tools and indices are used to characterize the load. For example, in the zones of moderate and high load power (according to Farfel), a linear dependence of the heart rate (HR) and oxygen consumption on the load power is used, whereas in the submaximum and maximum power zones it is necessary to use nonlinear characteristics. An example of the latter is the “pulse debt accumulation rate” (PDAR) parameter [2], which was proposed in the mid-1980s and makes it possible to assess the intensity of physiological costs of the body during the maximum duration of work under conditions of active anaerobic energy supply.

However, the level (intensity) of physiological costs is one of the most important parameters that are taken into account during the formation of training programs and methods. In recent decades, many studies by Russian and foreign authors have been devoted to

the development of different methods for its assessment [3–11].

In laboratory conditions, the exercise intensity is usually determined using the level of oxygen demand and the parameters of its components [12–20].

In training practice, the intensity of load and its regulation are usually assessed using the absolute HR values, as well as various methods based on the relative HR values (e.g., the method for calculating the relative working increase in the HR [3, 4], the method for calculating the PDAR [2], etc.). However, in all these cases, tools for solving particular problems of assessing physiological costs in a certain power range are proposed.

One of the methods used to assess the load intensity is to calculate the ratio of the level of oxygen demand of the exercise to the maximum oxygen consumption, which the authors of this idea called the units of the maximum metabolic rate (MMR) [19]. This method makes it possible to assess the relative exercise intensity over the entire range of physical loads up to maximum anaerobic power by the level of oxygen demand normalized with respect to MMR.

However, measurements and calculations of parameters of oxygen demand and its components require expensive equipment and high-level physiologists. Such measurements can be performed only in specialized laboratories. This significantly narrows the availability of these methods for monitoring the athlete's condition in the training process.

The aim of this study was to search for the pulsometric criteria of intensity during intense cyclic work to quantitatively assess the level of energy consumption and normalize physical exercise performed by an athlete in the range from the aerobic threshold (AeT) to maximum anaerobic power.

METHOD

The experimental work was performed on the basis of the Center for Sports Innovative Technologies and Training of National Teams of Moskomspor (Moscow). The study consisted of two parts. In the first part, $SIPC_{th}$ was developed and its information content was tested in the anaerobic range, from the critical to maximum anaerobic power. In the second part, the informativeness of $SIPC_{th}$ was tested in aerobic exercises, at the AeT power and at the anaerobic threshold (AnT) power.

The study involved two groups of athletes. In the first part of the study, a group of nine athletes (first-grade and sub-master athletes, age 18.3 ± 1.5 years, weight 72.2 ± 8.04 kg), specializing in BMX (Bicycle MotoX), consistently performed a series of maximum exercises on an Lode Excalibur Sport cycle ergometer (Netherlands) with a maximum power and fixed duration of 10, 30, 60, 120, and 360 s, with 1–2 days of rest between tests. The athletes performed exercises to failure lasting 10 and 30 s in the “all-out” mode, and the non-exhaustive exercises lasting 60 and 120 s were performed with the intention to show the highest possible performance according to their working capacity at the time of test start. In the exercises lasting 360 s, the athletes were instructed to work with critical power, which was recorded in the test with steadily increasing power to failure (ramp test), with the intention to show maximum performance. All exercises were performed on different days.

In the second part of the study, a group of eight athletes (first-grade and sub-master athletes, age 21.3 ± 3.4 years, weight 72.9 ± 11.3 kg), specializing in road racing, on different days consecutively performed a series of two non-exhaustive exercises on a cycle ergometer with AeT power and with AnT power, each lasting 30 min.

Before each test, athletes performed a standard warm-up on a cycle ergometer (power 60 W, duration 5 min). After the warm-up completion, the athlete remained “in the saddle” (5 min), and the prestart level of functional indices was recorded. Functional indices were also recorded during the performance of

the work and at the end of the exercise, during the recovery process, when the subject remained in the sitting position on the cycle ergometer for 10 min.

Two to three days before the start of the series of all-out tests, each athlete preliminarily performed a ramp test on a cycle ergometer to determine the maximum oxygen consumption (MOC) according to a single protocol: the initial pedaling power was 60 W, the power steadily increased by 15 W/min, and the pedaling speed was 70–75 rpm. In all cases, work continued to failure. Failure was recorded individually on demand of the subject or with a decrease in the pedaling speed by 30%. The aerobic and anaerobic thresholds were determined by the dependence of the concentration of lactate on the work power during testing. The aerobic threshold power corresponded to the start of deviation of the lactate concentration from its linear increase [21]. The anaerobic power threshold corresponded to the start of a rapid increase in the blood lactate concentration detected by the D-max procedure [22].

During the study, the heart rate was recorded using Polar H10 sensors (Finland). Oxygen consumption, carbon dioxide evolution, and pulmonary ventilation were determined using a Cosmed Qark gas analyzer (Italy), which was calibrated before each study. The data were averaged over 5-s intervals.

To determine the pulse cost of an exercise, the pulse sums during the exercise implementation and 5 min of recovery were calculated.

The lactate concentration was determined with a Biosen C-Line automatic analyzer (EKF-Diagnostic GmbH., Germany) before the exercise, immediately after the end of the work, and then 3, 5, 7, and 10 min after the end of the work. The maximum concentration of lactate in blood (La_{max}) was usually recorded on the 3rd or 5th min of recovery.

Data were statistically processed using R medium (version 3.5.1) and MS Excel. The strength of correlation between indices was estimated using the Spearman correlation analysis. The normality of distribution was confirmed by the Shapiro–Wilk method and by visual assessment of the distribution histograms and their quantile–quantile plots.

The calculated indices included:

$\min VO_2$ is the oxygen consumption in the state of relative rest before the start (L/min).

$\sum RO_2$ is the oxygen demand of the exercise (L), which is calculated as the sum of oxygen arrival and oxygen debt:

$$\sum RO_2 = \sum O_2 + \sum O_{2d}, \quad (1)$$

where $\sum O_2$ is oxygen arrival (L), the volume of oxygen consumed above the prestart level, which is calculated during the exercise; $\sum O_{2d}$ is the oxygen debt of the exercise (L), the volume of consumed oxygen in excess

of the prestart level, which is calculated for 10 min of recovery.

VRO_2 is the rate of oxygen demand formation (L/min), which is calculated as the ratio of the oxygen demand to the work duration:

$$VRO_2 = \sum RO_2 / t, \quad (2)$$

where $\sum RO_2$ is the oxygen demand of the exercise (L) and t is the work duration (min).

$SIPC_{O_2}$ is the specific intensity of physiological costs by oxygen, which was calculated as the ratio of the rate of oxygen demand formation to the individual level of maximum oxygen consumption above the initial level. One unit of $SIPC_{O_2}$ corresponds to the level of oxygen demand equal to the value of the individual MOC minus the pre-start level of oxygen consumption (2):

$$SIPC_{O_2} = VRO_2 / \Delta VO_{2max}, \quad (3)$$

where VRO_2 is the rate of oxygen demand formation in the exercise (L/min) and ΔVO_{2max} is the individual maximum oxygen consumption minus the initial level (i.e., the difference between the maximum oxygen consumption and $minVO_2$ (L/min)).

ΔLa_{max} is the rate of lactate accumulation (mmol/L/min), which is calculated as the ratio of the difference between the recorded maximum and initial lactate concentration to the work duration:

$$\Delta La_{max} = \Delta La_{max} / t. \quad (4)$$

$\sum \Delta fh_{tot}$ is the total pulse cost of the exercise (beats), which was calculated as the sum of the pulse arrival during work and pulse debt for 5 min of recovery:

$$\sum \Delta fh_{tot} = \sum \Delta fh_p + \sum \Delta fh_r, \quad (5)$$

where $\sum \Delta fh_p$ is the pulse arrival (beats), i.e., the pulse sum over the prestart level, calculated during the exercise; $\sum \Delta fh_r$ is the pulse debt (beats), i.e., the pulse sum over the prestart level, calculated for 5 min of recovery.

Δfh_{tot} is the rate of accumulation of the pulse cost of the exercise (bpm), which was calculated as the ratio of the total pulse cost of the exercise to the work duration:

$$\Delta fh_{tot} = \sum \Delta fh_{tot} / t, \quad (6)$$

where $\sum \Delta fh_{tot}$ is the total pulse cost of the exercise (beats).

$SIPC_{fh}$ is the specific intensity of physiological costs by the heart rate during the work in the exercise (a. u.), which was calculated as the ratio of the rate of formation of the pulse cost of the exercise to the maximum increase in the heart rate (pulse reserve):

$$SIPC_{fh} = \Delta fh_{tot} / \Delta HR_{max}, \quad (7)$$

where Δfh_{tot} is the rate of accumulation of the pulse cost of the exercise (bpm) and Δfh_{max} is the pulse reserve (bpm), i.e., the difference between the HR_{max}

determined in the ramp test and the initial HR level in the test.

In our study, the exercise power was often higher than the critical one. After the end of the work, despite the fact that the heart rate recovered much longer than for 5 min, the most rapid changes in HR after the end of the load were completed by the 5th min of recovery. In view of this, the pulse debt sum was calculated for 5 min. If an athlete during recovery reached the prestart level earlier than for 5 min according to the HR dynamics or 10 min according to the oxygen consumption dynamics, then the oxygen and pulse debts were calculated for the actual recovery time.

RESULTS

Table 1 shows the anthropometric and maximum functional indices of the subjects that were obtained in the ramp test on the cycle ergometer.

The indices calculated by the pulse sums and by the oxygen consumption in exercises with the maximum power of different durations are summarized in Table 2.

The SIPC indices in the exercises with the maximum power of various durations, calculated both by pulse sums and by oxygen consumption, are strongly related to the exercise power, maximum lactate accumulation rate, oxygen demand formation rate, and to each other (Table 3).

The indices calculated by the pulse sums and by the oxygen consumption in the series of non-exhaustive exercises at a fixed duration (30 min) with different power (at the aerobic threshold (W_{AeT}) and anaerobic threshold (W_{AnT}) levels) are presented in Table 4.

The indices in the non-exhaustive exercises calculated both by pulse sums and by oxygen consumption are strongly related to the exercise power, the maximum lactate accumulation rate, the oxygen demand formation rate, and to each other (Table 5).

DISCUSSION

It is known that the pulse cost of an exercise and its components are strongly related to O_2 demand, O_2 arrival, and O_2 debt [23]. The plots constructed on the basis of oxygen consumption and heart rate data equally reflect the rate of metabolic processes during the maximum power exercise (the data are averaged over the group, $n = 9$, Fig. 1).

Thus, the intensity of the energy consumption of an exercise can be estimated by the pulse sums of work and recovery. Volkov et al. [23] compared the rate of pulse demand formation with the power of exercise, the rate of lactate formation, the rate of oxygen demand formation, and the load intensity index expressed in MMR units in exercises of different fixed duration and maximum power in the power range from critical to maximum anaerobic. Then, they

Table 1. Anthropometric and maximum functional indices of participants in the 1st and 2nd series of studies based on the results of the ramp test

Parameter	Study series 1	Study series 2
	$M \pm \sigma, n = 9$	$M \pm \sigma, n = 8$
Age, years	18.3 \pm 1.5	21.3 \pm 3.4
Body weight, kg	72.2 \pm 8.04	72.9 \pm 11.3
Body length, cm	177 \pm 12	181 \pm 11
MOC _{abs} , L/min	3.29 \pm 0.49	4.136 \pm 0.61
MOC _{rel} , mL/min/kg	45.9 \pm 7.00	57.01 \pm 6.84
HR _{max} , bpm	188 \pm 11	188 \pm 6
Abs. W _{max} , W	296 \pm 33	371 \pm 53
Rel. W _{max} , W/kg	4.11 \pm 0.35	5.14 \pm 0.66

MOC_{rel}—maximum oxygen consumption, relative values; MOC_{abs}—maximum oxygen consumption, absolute values; HR_{max}—maximum heart rate value recorded in the test; Abs. W_{max}—absolute maximum power achieved in the test; Rel. W_{max}—relative maximum power achieved in the test.

Table 2. Ergometric and physiological indices obtained in exercises with maximum power of various duration ($M \pm \sigma, n = 9$)

Indices	Maximum exercise duration, s				
	10	30	60	120	360
W _{mean} , W	775 \pm 111	722 \pm 92	561 \pm 62	414 \pm 53	305 \pm 39
Rel. W _{mean} , W/kg	10.72 \pm 0.57	10.00 \pm 0.61	7.78 \pm 0.50	5.55 \pm 0.58	4.43 \pm 0.82
SIPC _{O₂} , a. u.	10.81 \pm 1.52	4.41 \pm 0.65	3.12 \pm 0.59	2.04 \pm 0.37	1.40 \pm 0.24
SIPC _{fh} , a. u.	10.10 \pm 2.75	4.81 \pm 1.08	3.23 \pm 0.44	1.94 \pm 0.20	1.29 \pm 0.10
Σ O ₂ , L	0.11 \pm 0.07	0.63 \pm 0.32	1.94 \pm 0.31	4.79 \pm 0.49	16.95 \pm 1.22
Σ O _{2d} , L	5.31 \pm 0.86	6.08 \pm 1.52	7.34 \pm 0.82	7.15 \pm 1.36	8.18 \pm 2.05
Σ RO ₂ , L	5.42 \pm 0.85	6.71 \pm 1.40	9.28 \pm 0.86	11.94 \pm 1.80	25.14 \pm 2.35
$\Sigma\Delta$ fh _p , beats	5 \pm 2	24 \pm 14	66 \pm 15	131 \pm 30	483 \pm 60
$\Sigma\Delta$ fh _r , beats	159 \pm 44	213 \pm 71	247 \pm 61	232 \pm 40	238 \pm 49
$\Sigma\Delta$ fh _{tot} , beats	164 \pm 44	237 \pm 75	313 \pm 69	357 \pm 34	721 \pm 93
La _{max} , mmol/L	8.83 \pm 3.26	15.97 \pm 2.70	17.56 \pm 2.5	16.31 \pm 2.94	14.59 \pm 2.61

Here and in Tables 3–5, for designations see the section Method (Calculated indices).

deduced the regression dependence of the rate of pulse demand formation on these indices and concluded that, on the basis of this dependence, a strict quantitative assessment of the applied training loads and their strict classification become possible.

This is fully confirmed in our study. However, in different athletes performing the same work, pulse

demands may vary greatly in magnitude, and this variation is not necessarily related to working capacity. To understand at what level of intensity the work is performed and to individually assess the physiological response of each athlete to the standard load in the power range from AeT to maximum anaerobic power, we used the SIPC_{fh} index (formula (8)), which is the

Table 3. Correlation matrix of calculated indices ($p < 0.05, n = 45$)

Indices	W _{mean}	W _{mean/kg}	VRO ₂	V Δ La _{max}	SIPC _{O₂}	SIPC _{fh}
SIPC _{O₂}	0.92	0.93	0.97	0.95	1.00	0.94
SIPC _{fh}	0.92	0.95	0.95	0.97	0.94	1.00

Table 4. Ergometric and physiological indices obtained in a series of two non-exhaustive exercises in the aerobic power range ($M \pm \sigma, n = 8$)

Indices	WAeP	WAnT
$W_{\text{mean}}, \text{W}$	153 ± 29	250 ± 27
Rel. $W_{\text{mean}}, \text{W/kg}$	2.09 ± 0.23	3.47 ± 0.44
$\text{SIPC}_{\text{O}_2}, \text{a. u.}$	0.52 ± 0.04	0.80 ± 0.08
$\text{SIPC}_{\text{fh}}, \text{a. u.}$	0.51 ± 0.06	0.82 ± 0.09
$\Sigma\text{O}_2, \text{L}$	58.0 ± 8.7	88.4 ± 10.4
$\Sigma\text{O}_2\text{d}, \text{L}$	2.47 ± 1.33	4.51 ± 1.14
$\Sigma\text{RO}_2, \text{L}$	60.5 ± 9.2	92.9 ± 10.9
$\Sigma\Delta\text{fh}_p, \text{beats}$	1744 ± 297	2412 ± 353
$\Sigma\Delta\text{fh}_r, \text{beats}$	138 ± 53	219 ± 42
$\Sigma\Delta\text{fh}_{\text{tot}}, \text{beats}$	1882 ± 344	2631 ± 381
$\text{La}_{\text{max}}, \text{mmol/L}$	0.90 ± 0.29	4.78 ± 2.19

Table 5. Correlation matrix of calculated indices in a series of two non-exhaustive aerobic exercises ($p < 0.05, n = 16$)

Indices	W_{mean}	$W_{\text{mean}}/\text{kg}$	VRO_2	La	SIPC_{O_2}	SIPC_{fh}
SIPC_{O_2}	0.75	0.87	0.75	0.79	1.00	0.91
SIPC_{fh}	0.83	0.81	0.80	0.86	0.91	1.00

rate of pulse demand accumulation normalized by the pulse reserve value ($\Delta\text{fh}_{\text{max}}$).

In fact, SIPC_{fh} is an exact analogue of the index proposed by Volkov et al. [19], expressed in MMR units (formula (3)): the SIPC_{fh} index is the ratio of the pulse demand of the exercise to the pulse reserve of the athlete. The pulse demand is closely related to the O_2 demand of the exercise [23], and the pulse reserve

value, according to Uth et al. [24], is interrelated with MOC. The SIPC_{fh} index unites the approaches by Karvonen [3] (assessment of the intensity of aerobic processes) and PDAR [2] (assessment of the intensity of anaerobic processes) and is a numerical expression of the *specific* intensity of physiological costs (since it is normalized by the individual pulse reserve) during performance of almost any cyclic exercise.

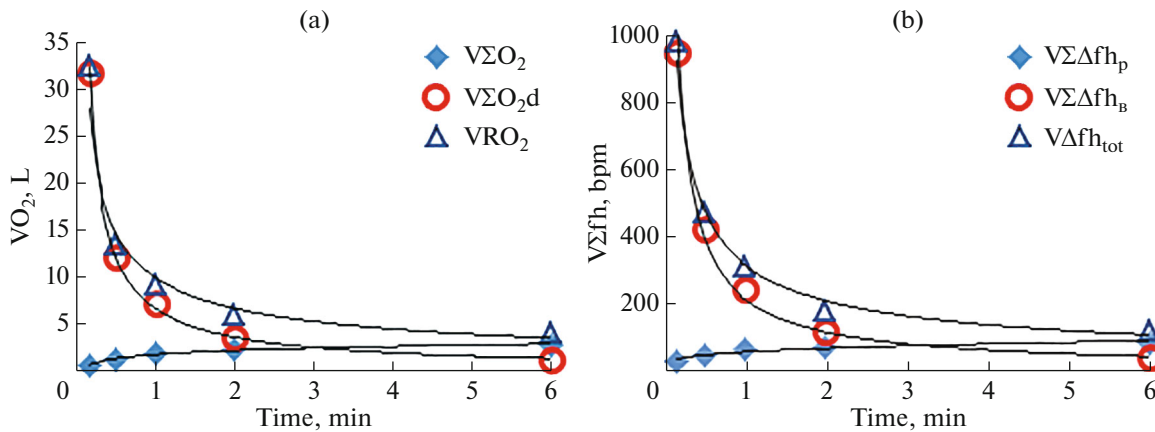


Fig. 1. Dependence of the rate of formation of the oxygen demand and its components (a) and the rate of formation of the pulse demand and its components (b) on the maximum exercise duration. The abscissa axis shows the maximum exercise duration, min; the ordinate axis shows the gasometric (a) and pulsometric (b) components of the oxygen and pulse demand when performing the exercise to failure.

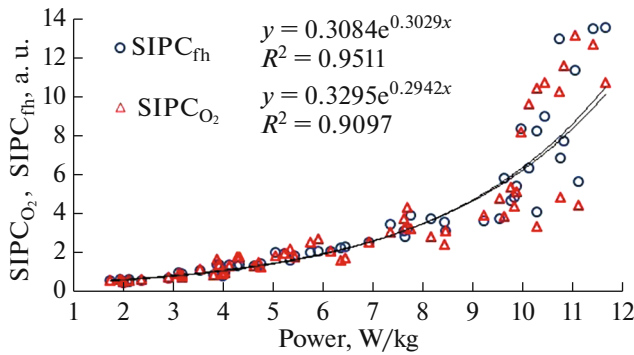


Fig. 2. Dependence of $SIPC_{fh}$ and $SIPC_{O_2}$ values on the load power in the entire range of loads from the aerobic threshold to maximum anaerobic power.

This is confirmed by the results of our study both in the exercises performed in the range from the critical (corresponding to VO_2 max) to maximum anaerobic power and in the aerobic exercises performed at the level of AeT and AnT.

Using the data obtained in the second series of studies, in the non-exhaustive exercises lasting 30 min that were performed by road racers at a power at the level of AeT and AnT, we constructed the plots of the dependence of $SIPC_{fh}$ and $SIPC_{O_2}$ (Fig. 2) and the diagram of the dependence of $SIPC_{fh}$ (Fig. 3) on the load power for all measurements ($n = 61$) in the load range from AeT to maximum anaerobic power.

As can be seen in Fig. 2, $SIPC_{fh}$ and $SIPC_{O_2}$ values show a very strong exponential dependence on power in the entire range of loads from AeT to maximum anaerobic power. A strong linear dependence was

revealed between the $SIPC_{fh}$ and $SIPC_{O_2}$ indices in the entire range of loads ($n = 61, p < 0.05; R^2 > 0.9$).

The results shown in Fig. 3 make it possible to evaluate the quantitative characteristics of different power zones by the $SIPC_{fh}$ value, which may have a direct applied value for arranging the training process.

Thus, the full interchangeability of pulsometric and gasometric indices of integrated functional costs of the body in performing exercises in the range from AeT to maximum anaerobic power is shown. This opens up broad prospects for the practical use of the proposed $SIPC_{fh}$ index in the work of coaches and sports doctors.

CONCLUSIONS

(1) The $SIPC_{fh}$ index in the entire range of loads from AeT to maximum anaerobic power shows a strong exponential dependence on the exercise power ($n = 61, p < 0.05; R^2 > 0.95$). A linear dependence with high coefficients of determination ($p < 0.05; R^2 > 0.9$) between the $SIPC_{O_2}$ and $SIPC_{fh}$ values is observed in the entire studied range of values from AeT to maximum anaerobic power. This fact testifies to the complete interchangeability of pulsometric and gasometric indices for determination of the intensity of functional costs.

(2) The $SIPC_{fh}$ index can be used for quantitative assessment of the level of energy consumption when athletes perform training loads in the range from AeT to maximum anaerobic power.

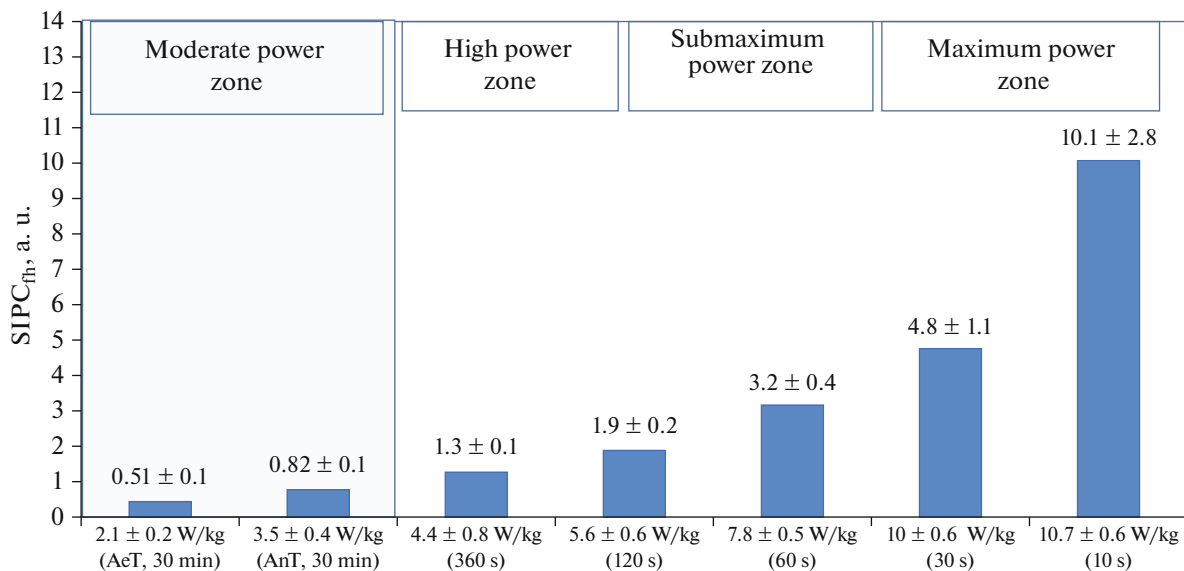


Fig. 3. Diagram of the dependence of $SIPC_{fh}$ values on the load power in the entire range of loads from the aerobic threshold to maximum anaerobic power.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interest. The authors declare that they have no obvious and potential conflicts of interest related to the publication of this article.

Statement of compliance with standards of research involving humans as subjects. All studies were conducted in accordance with the principles of biomedical ethics formulated in the 1964 Declaration of Helsinki and its subsequent amendments and approved by the local bioethical committee of the Center for Sports Innovative Technologies and Training of National Teams of Moskomspor (protocol no. 12 dated January 27, 2020, Moscow). Each study participant provided a voluntary written signed informed consent after explaining the potential risks and benefits, as well as the nature of the upcoming study.

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