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Physiological Criteria in Defining the Standards for Training and Competition Loads in Elite Sports

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Abstract—Adaptation to training loads can be quantitatively described by a dose–effect dependence, with the gain in the training function over a certain period regarded as the effect and the dose expressed as a product of the energy spent during exercise and the stimulus duration. The duration combines the periods of exercises, pauses, and recovery needed to compensate for the fast fraction of the oxygen debt. In addition to direct measurements of the energy spent, quantitative assessment of the load intensity can be based on the total pulse cost of exercise, which accurately reflects the changes in the oxygen demand and the energy cost of the physical load. To quantitate and standardize training and competition loads, we suggest the use of correlations found between the pulse and energy costs of exercises and their relative power determined in critical modes of muscle activity: at the anaerobic threshold; the critical power, associated with the maximum oxygen consumption; the alactic anaerobic threshold; the power of exhaustion, when blood lactic acid reaches its maximum; or at maximum aerobic power, when the muscle reserves of ATP and creatine phosphate are the most depleted.

Adaptation to training loads can be quantitatively described by a dose–effect dependence (Fig. 1, [1]). A gain in the training function over a certain period is regarded as the effect, and the dose is expressed as a product of the energy spent during exercise and the total duration of training. The duration combines the periods of exercises, pauses, and recovery needed to compensate for the fast fraction of the oxygen debt. The absolute pulse rate, usually used in sports to assess the energy expenditures of exercise, depends linearly on the anaerobic energy supply only within a limited range of physical loads of a subcritical power, when the maximum oxygen consumption is achieved. Within a wider range, it seems more proper to use generalized pulse criteria, such as the pulse sum of work, pulse debt, and pulse cost of exercises, which can be derived from the pulse rate kinetics recorded during work and recovery [2, 3].

This study was designed to test how useful the pulse sum and the energy cost of exercise might be for quantitating and standardizing training and competition loads.

METHODS

Twenty-six highly qualified swimmers, middle-distance runners, and speed skaters (age 18–24 years, height 162–186 cm, and weight 62–83 kg) performed a series of single bicycle ergometer tests with duration limits of 10, 30, 60, 120, and 360 s. In addition, they were tested according to our standard laboratory program, the results of which allowed an integrated assessment of their anaerobic and aerobic working capacities at the critical intensity of muscle activity. This program consisted of the following tests: the stepwise load increase test, assessing the maximum oxygen consumption and critical power [4, 5]; the single-time lim-

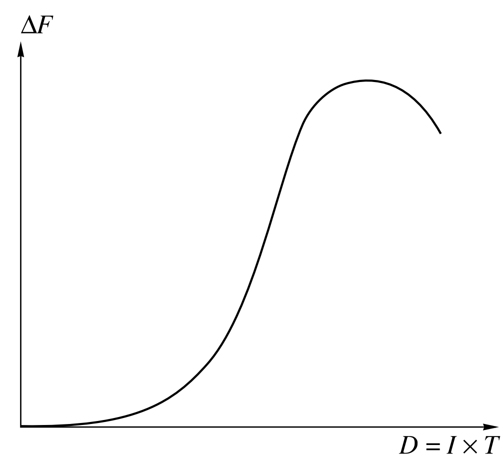

Fig. 1. Dose–effect dependence for training-induced changes in performance. The ordinate shows an increase in the training function (Δ*F*); the abscissa shows the dose (*D*) of the training stimulus (physical load). The dose is calculated as the product of load intensity (*I*, MMR units = $\mathring{R}O_2$/max $\mathring{V}O_2$) and training time (*T*; the total duration of exercise, pauses, and fast recovery).

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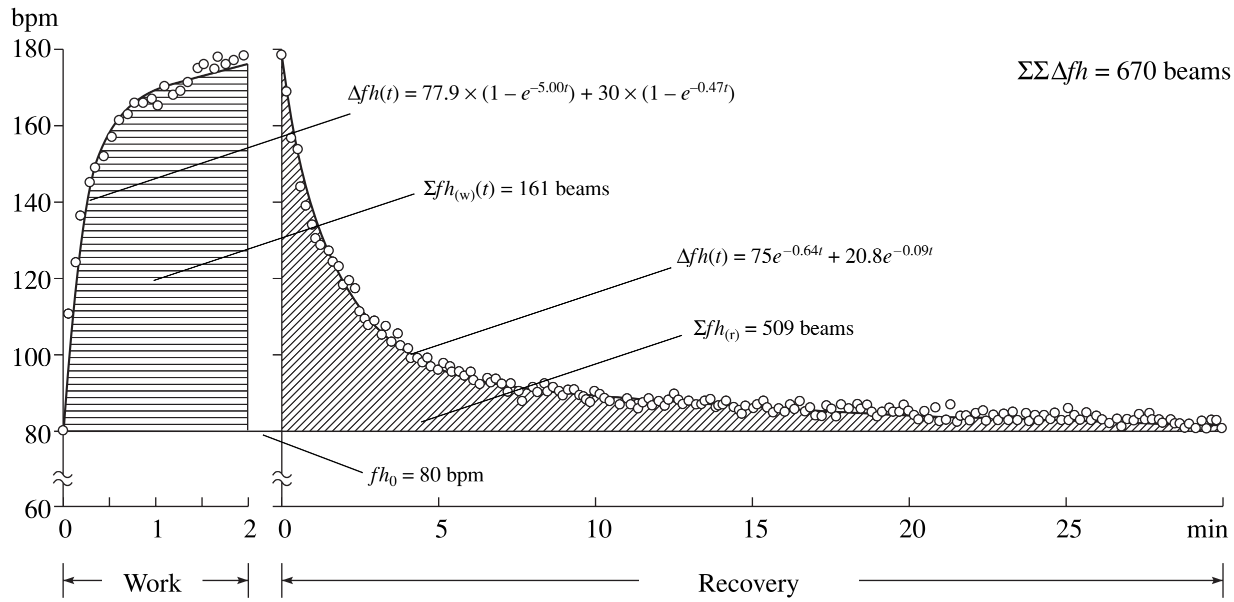

Fig. 2. Changes in the heart rate during work and recovery and a calculation of the total pulse cost of exercise. Ordinate: heart rate, bpm; abscissa: time, min. The crosshatched area within the work period corresponds to the pulse sum of work ($\Sigma\Delta fh_w$); the shaded area under the recovery curve corresponds to the pulse sum of recovery ($\Sigma\Delta fh_r$); and the total pulse sum of exercise ($\Sigma\Sigma\Delta fh$) is determined by adding $\Sigma\Delta fh_w$ to $\Sigma\Delta fh_r$.

iting work test (the Wingate test), assessing the anaerobic glycolytic power and capacity [6, 7]; and the maximum anaerobic power test, assessing the alactic anaerobic power [8, 9]. Exercises were performed without any preliminary warm-up.

Respiratory volumes and the composition of the exhaled air were monitored with a SensorMedics Vmax 29C apparatus. A special computer program calculated the O_2 debit, debt, and demand and the energy supplied aerobically and anaerobically during exercise tests. Lactate in the blood was measured using a microphotometric method developed by Lange [10]. Parameters of the acid–base equilibrium of the blood were measured with an IL-213 microanalyzer of blood pH and gases (Instrumentation Laboratory, United States). The heart rate was continuously recorded during exercise and recovery with a Team Polar pulse monitor (Polar, Finland) and transferred to a computer via an infrared interface. The standard Statistica and Microsoft Excel programs were used for graphical processing and statistical analysis of the data [11].

RESULTS

Figures 2 and 3 show examples of pulse curves recorded during single and repeated exercises. The biexponential expressions in these figures were used for calculating the work and recovery pulse sums ($\Sigma\Delta fh_w$ and $\Sigma\Delta fh_r$, respectively) and the total pulse cost of an exercise ($\Sigma\Sigma\Delta fh$). The pulse costs rates were calculated by dividing the corresponding pulse sums by the exercise duration.

Table 1 shows the group-averaged pulse sums and energy costs for exercises of different powers and duration limits. Figures 4a and 4b show how the pulse sums change with the duration limit of exercise.

The total pulse cost rapidly increases during brief exercise (Fig. 4a) and grows much slower after a 2-min time limit. Within these ranges of rapid or slow growth, its changes are determined mainly by changes in the recovery or work pulse sums, respectively.

The plot of the exercise pulse cost rate versus time limit (Fig. 4b) shows that, within the range studied, the pulse cost rate is determined mainly by the recovery pulse sum, associated with the anaerobic contribution to the total energy supply during exercise.

The curves in Figs. 4a and 4b are very similar to curves in Figs. 4c and 4d, where oxygen debit, debt, and demand are plotted versus time limits of exercises performed at the corresponding relative powers.

Still more evident is the similarity between changes in the oxygen demand and the pulse exercise cost. Figures 5a and 5b show their linear growth within a wide range of relative exercise power. This growth is determined mainly by shifts in anaerobic metabolism,

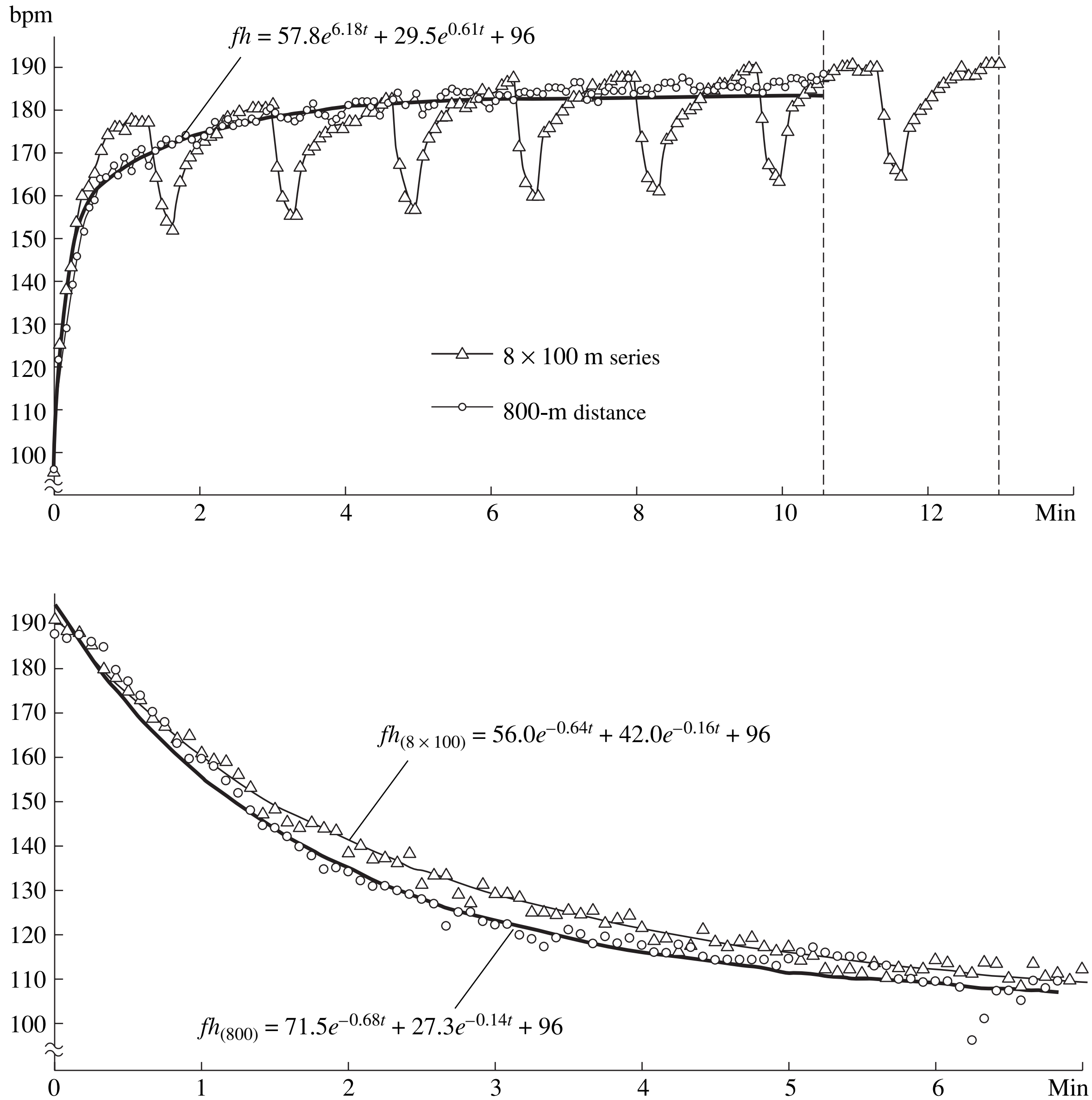

Fig. 3. Changes in the heart rate during single limiting and repetitive exercises of the same volume. Ordinate: heart rate, bpm; abscissa: time, min.

reflected in changes in the oxygen debt and recovery pulse sum.

More precisely, the correlation between the exercise pulse cost and the energy spent during exercises of different powers and time limits was calculated by means of regression analysis. The regression plot (Fig. 6) shows that this correlation is strictly linear. This plot can be used to determine the energy production rate during an exercise with a known pulse cost. In addition, with known energy costs and pulse sums of critical muscle activity (as in Table 2), this plot allows a strictly quantitative rating and classification of training loads.

It seems unlikely that, in the near future, Russian trainers and sports doctors will have an opportunity to directly determine the energy costs by means of gasometric techniques. Hence, a simultaneous determination of the pulse costs and blood lactate appears more realistic [12]. The dependences of the exercise-associated lactate accumulation rate on the relative power of exercise and on the O_2-demand rate are shown in Fig. 7. With known values of O_2-demand rate and relative power of critical muscle activity, this plot makes it easy to determine the limits for the lactate production rate for various ranges of physical loads with various training stimuli. The pulse costs of critical physical loads

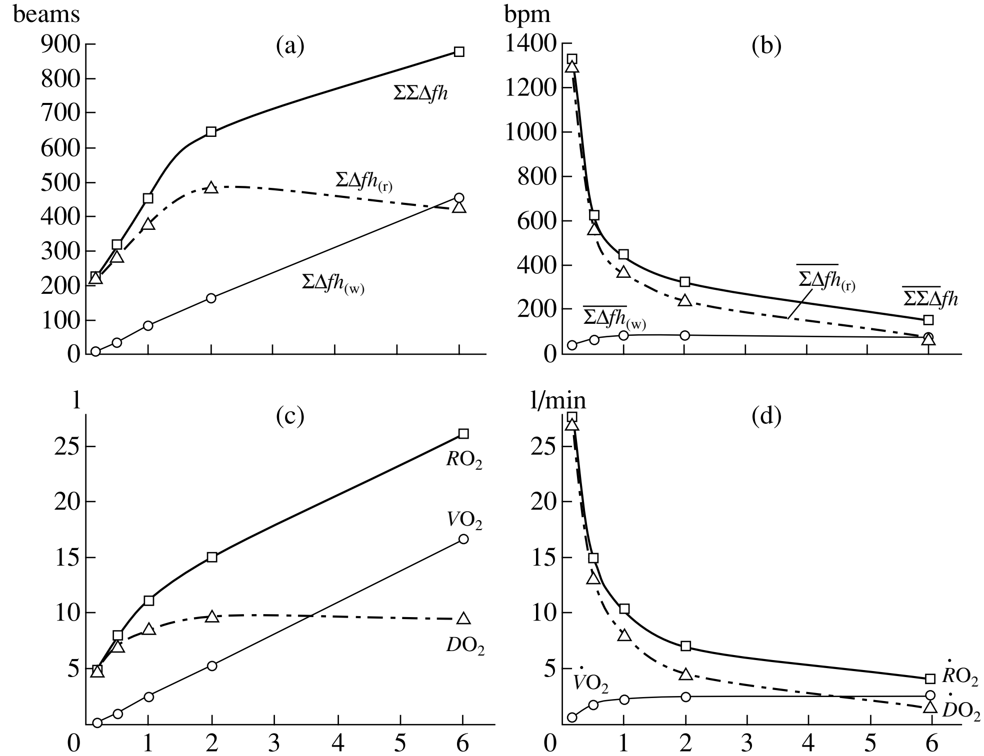

Fig. 4. Changes in (a) pulse cost (beats), (b) pulse cost rate (bpm), (c) O_2 demand, (l), and (d) O_2-demand rate (l/min) with the time limit of exercise (abscissa, min).

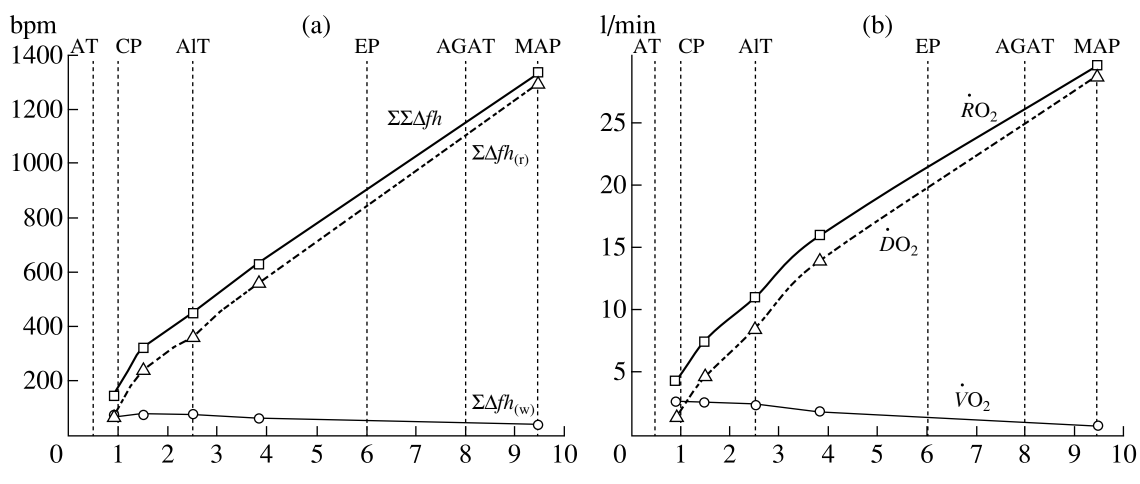

Fig. 5. Changes in (a) pulse cost rate (bpm) and (b) O_2-demand rate (l/min) with relative power of exercise (abscissa, MMR units). Here and in Fig. 11: AT, anaerobic threshold; CP, critical power; AlT, alactic threshold; EP, exhaustion power; AGAT, alactic–glycolytic anaerobic transition; and MAP, maximum anaerobic power.

(Table 2) may be used in defining optimal training programs [13].

Figure 8 shows that the rate of lactate accumulation in the blood and the relative power of an exercise linearly correlate with its pulse cost (both for swimming and bicycle-ergometer tests). A greater slope of the regression line observed in the swimming test indicates that, since the work is less efficient because of the need to overcome water drag and a significant energy loss caused by the high thermal conductivity of water, increases in the O_2 cost and relative power are accompanied by a significantly stronger increase in the pulse

Table 1. Pulse sums and energy costs determined for exercises of different power and duration limit (mean ± *SD*)

Parameter	Designation	Unit	Duration limit of exercise, s				
			10	30	60	120	360
Power	$\mathring{W}$	W	850 ± 108	490 ± 48	380 ± 37	290 ± 28	170 ± 14
Maximum metabolic rate (MMR)	$\mathring{R}O_2/\max\mathring{V}O_2$	MMR unit	9.45 ± 2.61	3.82 ± 0.63	2.51 ± 0.38	1.48 ± 0.19	0.913 ± 0.126
Pulse sum of work	$\Sigma\Delta fh_w$	beats	7	33	80	160	450
			2	6	22	37	83
Pulse sum of recovery	$\Sigma\Delta fh_r$	beats	215 ± 54	280 ± 65	370 ± 105	480 ± 112	420 ± 97
Pulse cost of exercise	$\Sigma\Sigma\Delta fh$	beats	222 ± 59	313 ± 69	450 ± 136	640 ± 174	870 ± 182
Rate of the pulse sum of work	$\overline{\Sigma\Delta fh}_w$	beats per minute	42 ± 12	66 ± 13	80 ± 22	80 ± 18	75 ± 14
Rate of the pulse sum of recovery	$\overline{\Sigma\Delta fh}_r$	beats per minute	1290 ± 322	560 ± 131	370 ± 105	240 ± 57	70 ± 16
Rate of the pulse sum of exercise	$\overline{\Sigma\Sigma\Delta fh}$	beats per minute	1332 ± 355	626 ± 138	450 ± 16	320 ± 88	145 ± 31
Maximum oxygen consumption	$\mathring{V}O_2$	l/min	1.27 ± 0.14	2.83 ± 0.2	4 ± 0.13	4.5 ± 0.24	4.68 ± 0.31
O_2 debit	ΣVO_2	l	0.12 ± 0.05	0.97 ± 0.04	2.5 ± 0.19	5.3 ± 0.93	16.6 ± 2.15
O_2 debt	DO_2	l	4.6 ± 1.05	7.02 ± 1.07	8.54 ± 1.09	9.65 ± 1.71	9.4 ± 0.98
O_2 demand	ΣRO_2	l	4.7 ± 0.33	7.98 ± 0.84	11.04 ± 0.94	14.95 ± 2.01	26.3 ± 1.96
O_2-demand rate	$\mathring{R}O_2$	l/min	32.4 ± 5.2	16.01 ± 2.1	11.01 ± 1.28	7.42 ± 0.63	4.4 ± 0.34
Maximum lactate accumulation in the blood	max*HLa*	mmol/l	8.63 ± 1.93	11.57 ± 0.82	15.11 ± 0.96	18.67 ± 1.37	15.67 ± 1.49
Total lactate production	Σ*HLa*	g/kg	0.61 ± 0.07	0.78 ± 0.29	1.02 ± 0.21	1.39 ± 0.31	7.3 ± 0.51
Total energy production	E_{tot}	J/kg	923 ± 51	1540 ± 80	2345 ± 99	3273 ± 131	6605 ± 53.6
Energy production rate	$\mathring{E}_{tot}$	J/kg min	5572 ± 275	3084 ± 147	2345 ± 141	1638 ± 83	1102 ± 65.3

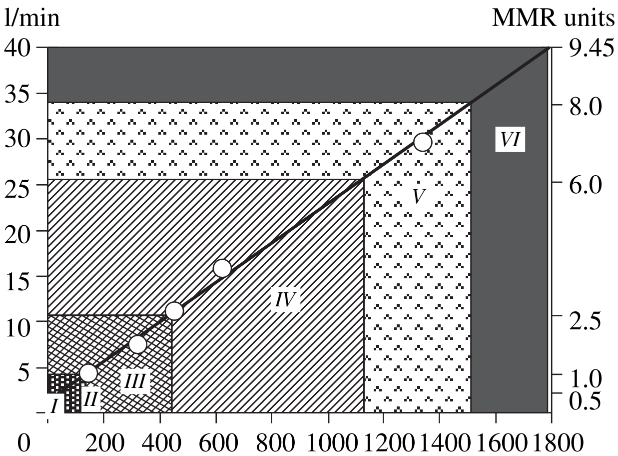

Fig. 6. Correlation between O_2-demand rate and pulse cost rate of exercise. The left-hand and right-hand ordinates show the O_2-demand rate (l/min) and the relative power (MMR units), respectively. The abscissa shows the rate of the exercise pulse cost (bpm). Here and in Fig. 7, cross-hatched patterns indicate zones of loads with different physiological effects: (*I*) predominantly aerobic; (*II*) combined aerobic–anaerobic; (*III*) combined anaerobic–aerobic; (*IV*) glycolytic anaerobic; (*V*) combined alactic–glycolytic; and (*VI*) alactic anaerobic.

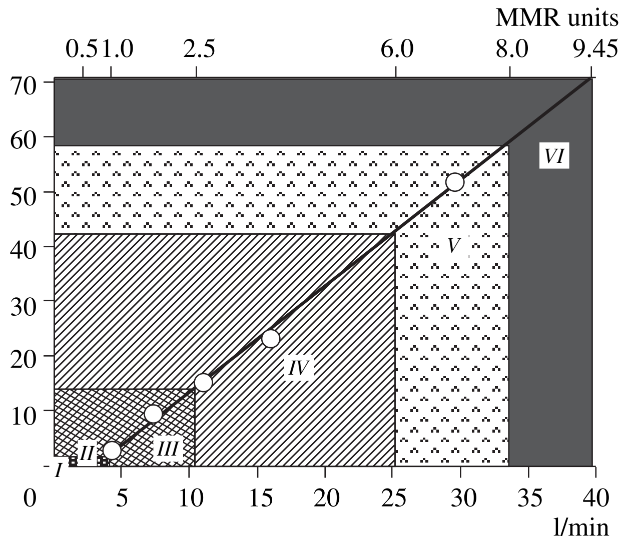

Fig. 7. Correlation between the lactate accumulation rate in the blood and the O_2-demand rate of exercise. The ordinate shows the lactate accumulation rate (mmol/min). The bottom and top abscissas show the O_2-demand rate (l/min) and the relative power (MMR units), respectively.

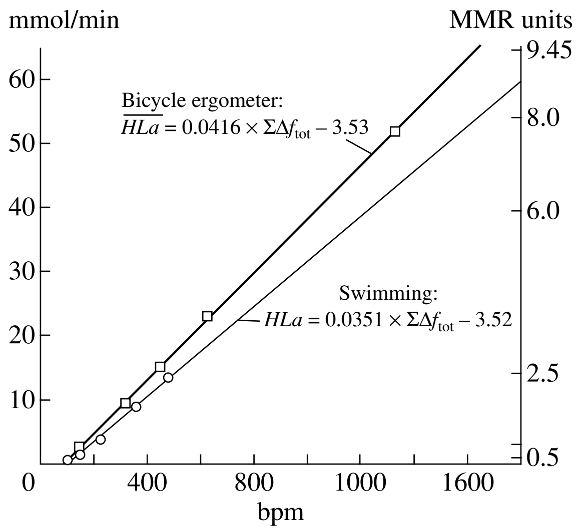

Fig. 8. Dependences of the lactate accumulation rate in the blood and the relative power of exercise on the exercise pulse cost rate. The left-hand and right-hand ordinates show the lactate accumulation rate (mmol/min) and the relative power (MMR units), respectively. The abscissa shows the exercise pulse cost rate (bpm).

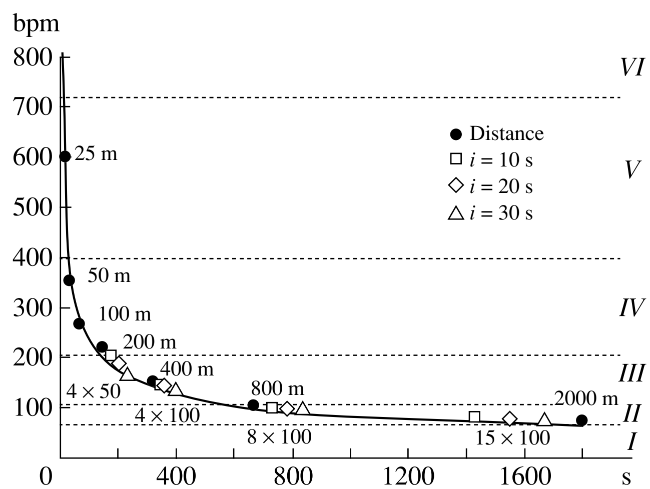

Fig. 9. Pulse cost rates determined for variable-distance swimming at limit velocities and for repetitive exercises of the same volume performed with different rest pauses. Ordinate: the exercise pulse cost rate, bpm; abscissa: time limit of exercise, s.

cost. Therefore, this method of quantifying the critical muscle load should be used only with a strictly determined pulse cost and an experimentally found O_2 demand (or rate of lactate production).

As indicated by changes in pulse cost observed for different swimming distances and for different training loads performed repetitively with different rest pauses (Fig. 9), the regimens with repetitive exercises are associated with significantly lower exercise pulse costs.

DISCUSSION

Our results show that the exercise pulse cost can be used to quantitate and standardize training and compe-

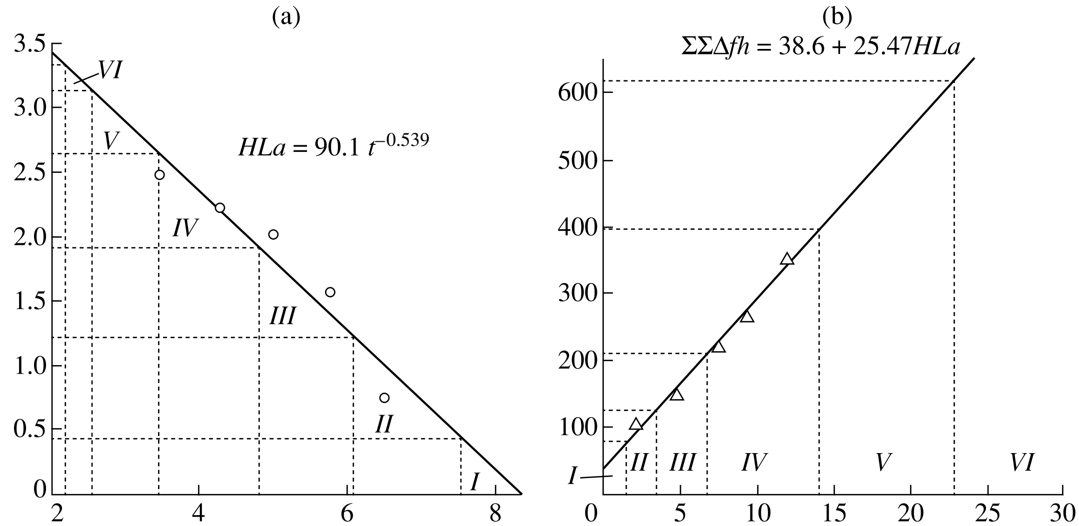

Fig. 10. Determination of individual limits for load ranges of different physiological effects according to (a) the lactate accumulation rate in the blood and (b) the exercise pulse cost rate (master of sports S.A.). (a) Ordinate: natural logarithm of the lactate accumulation rate, mmol/min; abscissa: logarithm of the load limit time, min. (b) Ordinate: the exercise pulse cost rate, bpm; abscissa: the lactate accumulation rate, mmol/min.

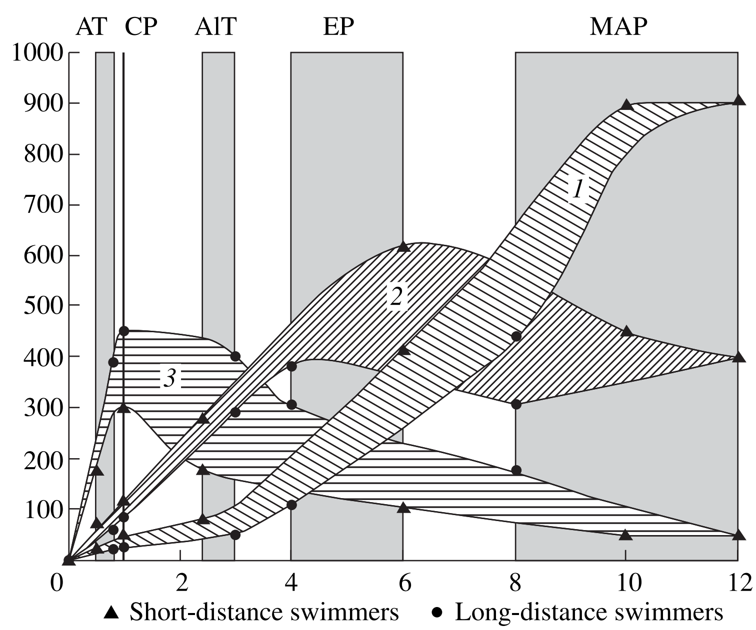

Fig. 11. Contributions of different mechanisms of energy production to the total energy balance of exercises performed by swimmers specializing in different distances. Ordinate: energy production rate, cal/kg min; abscissa: relative power, MMR units.

tition loads for elite athletes. However, its wide use for physiological monitoring of training processes requires data banks specific to different sports and exercises selected. As an example of an individualized approach to defining standard training loads, Figure 10 shows changes in the rate of lactate accumulation in the blood and the total pulse sums recorded for the master of sports S.A. at various load ranges. These data differ appreciably from the group-averaged values shown in Table 2. Still more dramatic differences can be seen when the energy production rates in critical modes of muscle work by short- or long-distance swimmers are matched with the corresponding relative power of physical exercise. Such data are shown in Table 3 and Fig. 11.

In Fig. 11, the vertical lines delineate the variation ranges of the relative power observed in swimmers of

Table 2. Energy and pulse costs determined for critical modes of exercises

Parameter and its unit	Aerobic threshold	Critical power	Exhaustion power	Maximum anaerobic power
Relative power, MMR units	0.5	1.0	5.5	10–12
Energy cost rate, J/kg min	450	1100	1650	5550
O_2 debit, ml/kg	45	70	55	25
O_2 debt, ml/kg	45	90	200	125
O_2-demand rate, l/min	3.2	4.5	7.5	30.0
Lactate concentration, mmol/l	4	15.0	>20	10.0
Maximum pH shift, arb. units	0.15	0.40	>0.55	<0.55
Pulse sum of work, beats	1200	900	600	250
Pulse sum of recovery, beats	250	410	430	220
Pulse cost rate of exercise, beats per minute	40	150	900	1350

different specializations during different training loads. As can be seen, these ranges grow wider with growing energy costs. Hence, in defining the standards for different training loads, trainers should select exercises according to the pulse and energy costs differentially for athletes of different qualifications and specializations [13, 14].

CONCLUSIONS

(1) The pulse cost parameters (such as the pulse sum of work, pulse sum of recovery, and total pulse sum of exercise) are similar to the oxygen demand and energy cost of exercise in the character of dependence on the relative power and duration limit of work.

(2) Calculations of exercise pulse costs allow precise and specific selection of training loads for each athlete.

(3) The standards for training and competition loads based on parameters of exercise pulse costs should be defined differentially for athletes specializing in different sports with different training regimens.

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Table 3. Energy production rates during muscle activity in critical modes in short- and long-distance swimmers (SDS and LDS, respectively)

Energy production rate	Critical modes of exercise									
	anaerobic threshold		critical power		alactic threshold		Exhaustion power		Maximum anaerobic power	
	SDS	LDS	SDS	LDS	SDS	LDS	SDS	LDS	SDS	LDS
Alactic anaerobic, cal/kg min	50	40	60	45	80	60	415	110	910	440
Glycolytic anaerobic, cal/kg min	80	60	110	90	270	260	620	380	450	305
Aerobic, cal/kg min	170	380	300	450	180	400	105	305	50	175
Total energy production rate, cal/kg min	300	480	470	585	530	720	1140	795	1410	920
Rate of relative energy cost, MMR units	0.5	0.8	1	1	2.4	3	6	4	10	8

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