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Physiological Effects of an Ultra-Marathon Run

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Abstract—Autonomic functions of the body and gas exchange have been studied in one athlete (master of sports in skiing, aged 27 years, with a maximal oxygen consumption of 67 mL/(min kg)); during a 6-h indoor ultra-marathon race; at an average speed of 2.7 m/s. Continuous monitoring of the heart rate was carried out using a Polar RS 800 heart rate monitor. Gas analysis of the exhaled air and recording of the parameters of external respiration were carried out during the first hour with subsequent repetitions during 20–30 minutes each hour, using a Metamax mobile device (Germany) mounted on the subject throughout the race. Before and after the subject passed the intervals of a distance when these parameters were measured, the blood lactate content was measured. Our data demonstrate a number of features that accompany fatigue at the final stage of the race, such as a decrease in efficiency of body functions, which is expressed by an increased heart rate and oxygen usage, an activation of anaerobic glycolysis path of energy production, and intensification of the external respiration. In addition, the methods of correlation and regression analysis revealed the changes (increase and decrease) of the relationship between the functions depending on whether muscular performance is at the stage of warming up, sustainably high performance, or in at a stage of extreme fatigue. These findings suggest interference of the effects of the central and tissue mechanisms of fatigue on the organization of oxygen transportation in the body. Apparently, in the instance of an ultra-marathon run, i.e., a prolonged performance of moderate power, autonomic functions, rather than the energy resources of the body, play the role of the main limiting factor.

Keywords: ultra-marathon run, fatigue, moderate work load, pulse and oxygen costs, blood lactate, interaction of autonomic functions, gas analysis, correlation and regression analyses

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Extreme activities enable physiological mechanisms to be most fully involved. An ultra-marathon race is a prime example of an extreme activity. It is particularly interesting because a moderate load, typical for it, lasts for hours, which enables multiple physiological measurements to be carried out. This feature has been often used by researchers, who recorded a variety of physiological characteristics of ultra-marathon and marathon running [1, 2]. In this case, studies are most often focused on the energy supply and the problems of maintaining temperature homeostasis [3, 4]. At the same time, interaction between the physiological functions providing a prolonged adequate oxygen supply of the body is of great interest [5, 6]. Modern instrumental techniques provide new opportunities for the study of these processes directly in the course of running, which is what we have used in this study. The unique experimental situation suggests that the data obtained from the only subject in the experiment can provide new information about the organization of the interaction of cardiorespiratory functions at different stages of an extremely long load of relatively constant intensity.

The goal of this study was to evaluate the dynamic changes of the components of cardiorespiratory function in an athlete during a prolonged run at a constant speed. The research objectives were (1) to compare the dynamics of the parameters of oxygen transportation in the body and the running speed during a 6-hour-long ultra-marathon race and (2) to estimate the features of interaction between the autonomic systems of the body at different stages of an ultra-marathon run.

EXPERIMENTAL

The subject of our study was a regularly training master of sports in skiing, aged 27 years; body weight (at the start), 70 kg; body height, 170 cm; maximum oxygen consumption (MOC), 67 mL/(min kg). The subject had signed his informed consent to participate in the experiment. The study protocol was approved by the Ethics Committee of the All-Russian Research Institute of Physical Culture and Sports.

The experiment was carried out during a 6-h indoor Championship of Moscow, the ultra-marathon Passatore cup, in February 2009. The race started at 10:00 p.m. and ended at 4:00 a.m. The track length was 229 m. The subject consumed water (a total amount of about 2.5 L), chocolate, dried fruit, and bread during the race.

The time spent on each circle was recorded by special timekeepers. On the basis of these data, the speeds on different parts of the distance were then calculated. The heart rate (HR) was recorded continuously using a PolarRS 800 HR monitor (Finland). Gas analysis of the exhaled air and recording of the parameters of external respiration were performed during the first hour with the following repetitions during 20–30 min each hour, using a Metamax mobile device (Germany)

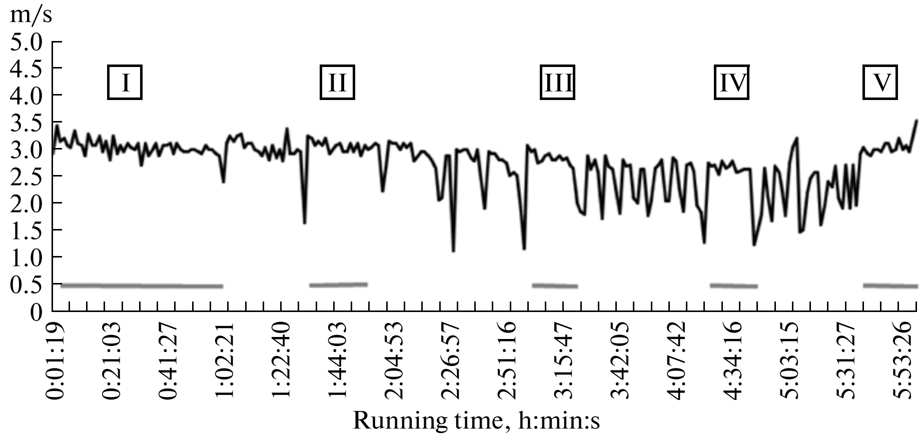


Fig. 1. Running speed for 6 hours. The intervals of the distance when the parameters of gas exchange were measured.

mounted on the subject throughout the race. The device was calibrated with a standard gas mixture shortly before the experiment. The protocol of the parameters of gas exchange during the race is schematically shown in Fig. 1. Before and after the subject passed the intervals when these parameters were measured, the blood lactate content was measured using a Biosen C-line analyzer (EKF Diagnostics, Germany). The error of lactate measurements was $\leq\pm1.5\%$ for 12 mM. The stability was $\leq\pm3\%$ for ten samples with values of 12 mM.

Data processing was performed by standard methods using the STATISTICA (version 8.0) software.

RESULTS AND DISCUSSION

During 6-h running, the subject covered a distance of 56.211 km, with an average speed of 2.7 m/s. As seen in Fig.1, during the first 120 min of running, the speed remained almost constant (on average, 3.0 m/s). Then, the speed slowly decreased during 3.5 h (on average, 2.5 m/s); and only in the last 30 min, it began to increase, reaching its initial values in the final circles of the marathon. From 2.5 h to 5.5 h, there was a sharp, abrupt decrease in the running speed. This was due to the alternation of the subject's running and walking. Note that the subject did not walk during the measurements of gas exchange.

Table 1 shows the average values of the external respiration, gas exchange, HR, blood lactate levels, and the average running speed on five separate intervals of the ultra-marathon race when the parameters of external respiration and gas exchange were being measured. Table 1 also shows correlation diagrams demonstrating the strength and sign of the correlations between the parameters measured in each distance interval.

The average running speed in intervals I and II, is almost the same; however, in the middle of the distance, i.e., in intervals III and IV, the speed markedly decreased. In the final interval V, the average running speed goes back to high values due to a finishing spurt made by the subject (Fig. 1).

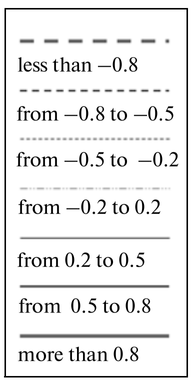
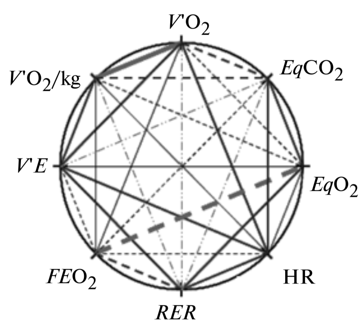
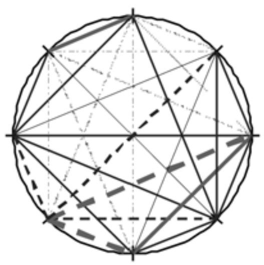
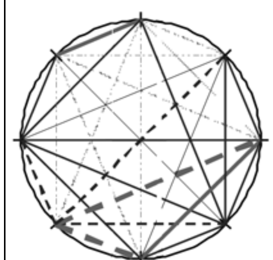
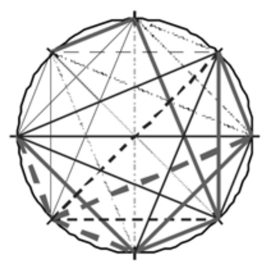
The changes in lactate content in the peripheral blood indicate the unequal difficulty of various intervals of distances. In interval I, which is characterized by an urgent adaptation to stress, the level of lactate was reduced from the beginning to the end of the interval, reflecting the high activity of aerobic metabolism. In intervals II and III, lactate levels were stable, which suggests that the subjects reached a state close to sustainable. However, by the beginning of the interval IV, the lactate levels begin to increase. This increase continues throughout this and the next interval, ultimately reaching the values close to the anaerobic threshold. Thus, according to the dynamics of lactate, it can be assumed that intervals IV and V are characterized by a growing fatigue. Probably, this is also indicated by a significant decrease in the running speed in interval IV.

At the same time, the values of HR do not indicate fatigue. The HR values in interval IV are lower than that in interval III; however, this is combined with slower running in this interval. In other words, the HR parameters under such loads are not sufficiently sensitive to indicate a degree of stress of the body. Much the same can be said about the values of oxygen consumption. The ratio of these parameters, i.e., the oxygen pulse, also demonstrates the constancy of its average values at various stages of an ultra-marathon race despite the changes in the ergometric characteristics of the load.

Pulmonary ventilation, which is much higher on the final distance interval compared with the previous intervals studied, can serve as a relatively more sensitive indicator in terms of diagnosis of fatigue. A significant increase in the respiratory coefficient on the final interval of the marathon may be due to the intensification of lung ventilation and to the causes of metabolic nature, as it is combined with a sharp increase in lactate levels in the peripheral blood.

The dynamics of two simultaneously measured parameters of the functional stress of the body, oxygen consumption (OC) and HR during the 6-h race, are shown in Fig. 2. Note that no strict parallelism is observed between OC and HR; the curves depicting

Table 1. Averaged physiological parameters measured while passing different distances and correlation diagrams of the parameters of gas exchange, external respiration, and pulse rate

Distance segment measured	I (circles 1–48)	II (circles73–87)	III (circles 135–148)	IV (circles 186–198)	V (circles 229–246)
Average running speed in an interval, m/s	3.02	3.06	2.83	2.64	3.03
HR, bpm/min	153	161	163	159	166
OC, mL/(min kg)	39	40	40	37	42
PV, L/min	66	67	66	65	76
RC, arb. units	0.87	0.94	0.91	0.91	0.96
OP/kg, mL/(min kg bpm)	0.26	0.25	0.24	0.24	0.25
Correlation diagram 					
lactate at the beginning of the interval, (mM)	1.41	1.25	1.24	1.40	2.10
lactate at the end of the interval, (mM)	1.15	1.25	1.22	1.57	3.68

Note: HR, heart rate; OC, oxygen consumption; PV, pulmonary ventilation; RC, respiration coefficient; OP, oxygen pulse.

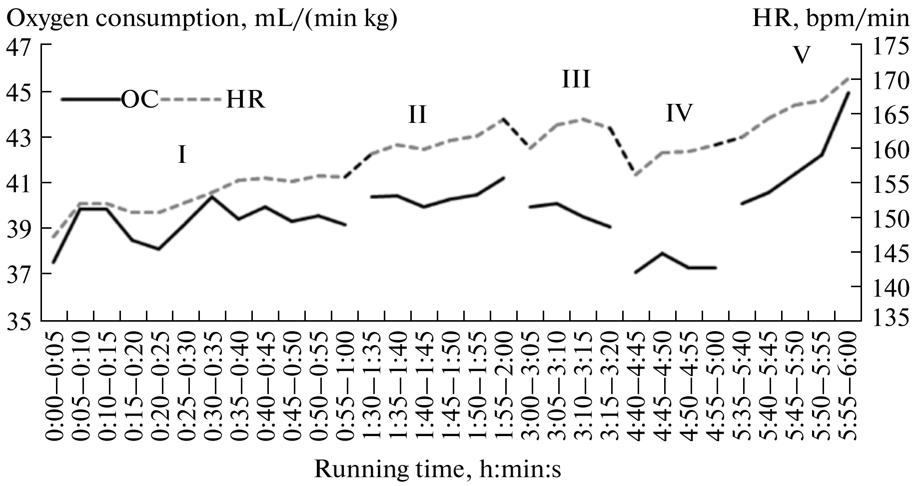


Fig. 2. Dynamics of OC and HR during running (5-min averages). I, II, III, IV, V are the intervals of the distance when the parameters of gas exchange were measured.

these functions sometimes converge and then diverge. This shows that the HR does not fully characterize oxidative metabolic stress during a prolonged cyclic physical performance with relatively constant power. The functional state of the body, apparently, greatly modulates the extent of the correlation between the requests for oxygen in the body tissues and oxygen delivery to consuming structures. Throughout intervals I and II (0–1 and 1.5–2 h of running), an uneven gradual increase in these parameters was observed. The highest degree of synchronization in the changes of these parameters was recorded in interval II, when, probably, the physiological functions were close to their optimal values for prolonged cyclic activity of moderate power. This particular interval was characterized by the highest average running speed, no episodes of changing to walking mode, and stable low blood lactate levels.

The third interval (from 3 to 3.33 h of running) was characterized by a reduced running speed compared to the previous intervals. Against this background, a decrease in OC and HR were recorded. This decrease was not detected at the level of the average values; however, it can be clearly seen on the graph (Fig. 3). The dynamic changes in OC and HR at this period of running are asynchronous, and even have the opposite sign at times. This may be the first sign of an imbalance in the oxygen supply system of the body.

This trend is expressed even stronger in interval IV (from 4.66 to 5 h of running). The parameters measured often had opposing trends. For example, against the background of a decrease in or stable values of OC, the HR almost constantly increased. This can be explained by the fact that with the growth of fatigue, the efficiency of the cardiorespiratory system declines. Note that in interval IV, the running speed was relatively stable, with no sudden accelerations or decelerations (Fig. 1); however, it declined, on average, during the fourth interval compared to the third one.

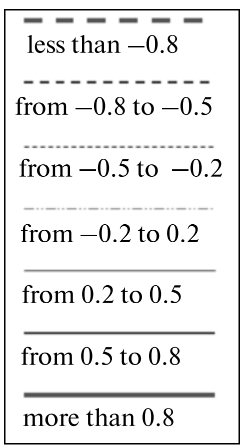
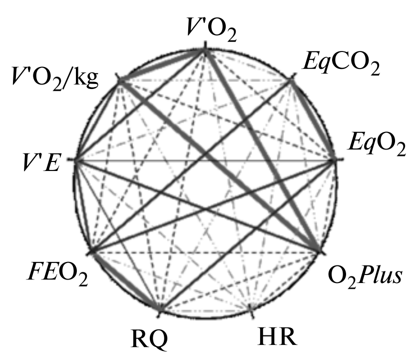
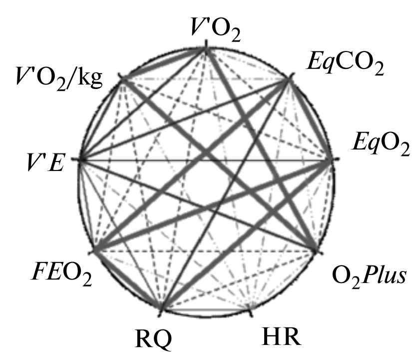
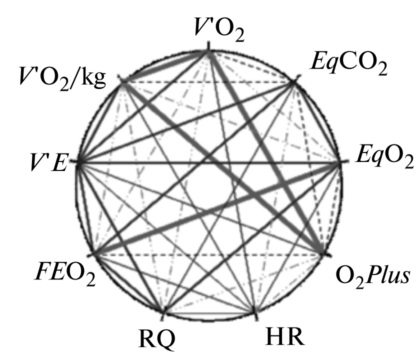
At the last (final) interval of the run, the running speed slightly increased, which was immediately reflected in an increase in the average values of OC and HR.

There is a well-known view that, with the growth of fatigue (body stress), the relationships between autonomic functions vary and generally become more stringent [6]. We calculated the correlation coefficients between the main parameters of the cardiorespiratory system obtained on five intervals of the ultramarathon distance (Table 1). The correlation diagram presented shows that the minimum number and strength of relationships were recorded in interval II, when the body seems to function optimally. Subsequently, the number of reliable relationships and their strength gradually increase, reaching the highest values at interval V corresponding to the end of the ultramarathon.

All these findings suggest that, with an increase in fatigue, the changes in the interaction of the body functions related to the OC take place; and, ultimately, the efficiency of the cardiovascular system declines. We assume that this process is combined with an increase in the central regulatory effects on the activity of autonomic functions.

The mechanical power (intensity) of the work is one of the most important factors modulating the activity of physiological functions. In our study, it was not constant throughout the race, which can significantly distort the true relationships between the components of the cardiorespiratory system. In order to better analyze these processors, we have identified three 5-min intervals at various stages of the ultramarathon distance, where the running speed (i.e., the power output of the mechanical work) was almost the same; and a synchronous recording of gas exchange and HR was carried out. Such intervals occurred during the first, second, and sixth hours of running. The results of this analysis are shown in Table 2 and Fig. 3.

Table 2. Physiological characteristics of the intensity of performance of the cardiovascular system while passing different intervals of the ultra-marathon distance with the same running speed

Distance interval	I (circles 8–12)	II (circles 81–85)	V (circles 237–241)
Time of running, h:min	0:10–0:15	1:40–1:45	5:45–5:50
Stage of performance	Warming up	Optimum	Fatigue
Average running speed, m/s	3.07	3.02	3.03
HR ($M \pm$ s), bpm/min	152 ± 2.5	160 ± 1.6	166 ± 1.7
$V'O_2$/kg ($M \pm$ s), mL/(min kg)	38.9 ± 2.6	39.8 ± 2.6	41.4 ± 1.3
$V'E$ ($M \pm$ s), L/min	65.6 ± 4.9	66.2 ± 4.4	77.8 ± 3.3
RER ($M \pm$ s), arb. units	0.88 ± 0.03	0.94 ± 0.03	0.98 ± 0.02
VO_2/HR ($M \pm$ s), mL/beat	17.95 ± 1.30	17.47 ± 1.16	17.46 ± 0.51
Pulse cost of 1-m distance, bmp/m	0.825	0.883	0.913
Oxygen cost of 1-m distance, mL/m	14.8	15.4	15.9
Correlation diagrams 			

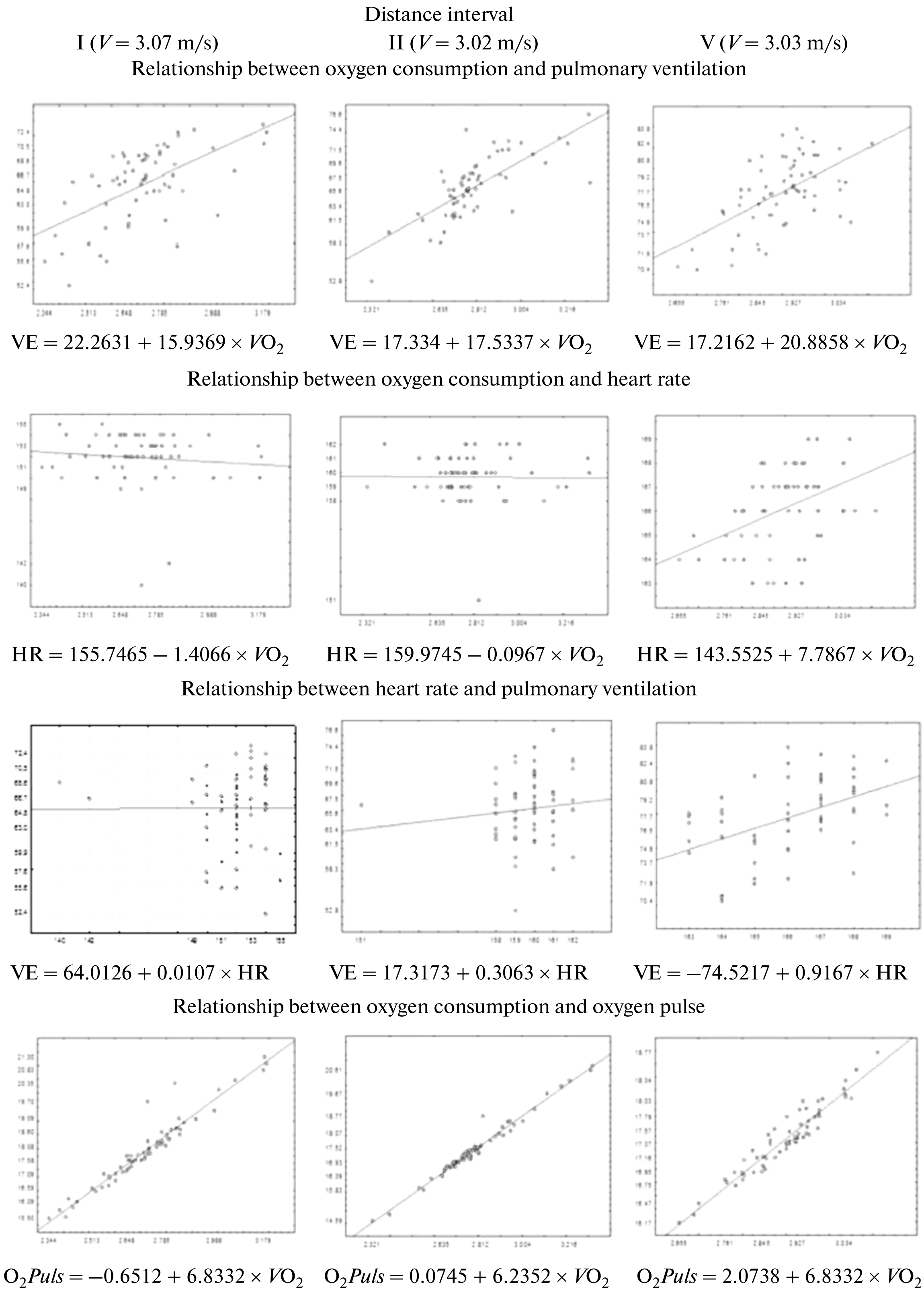
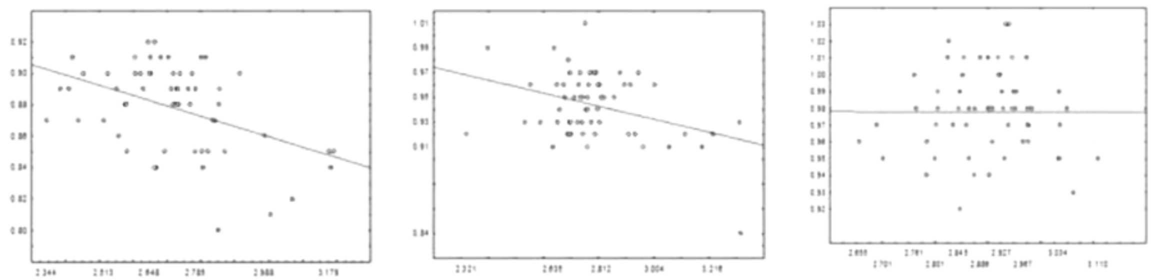


Fig. 3. The relationships between the parameters of the cardio-respiratory system during different intervals of the ultra-marathon distance with the same running speed.

Distance interval

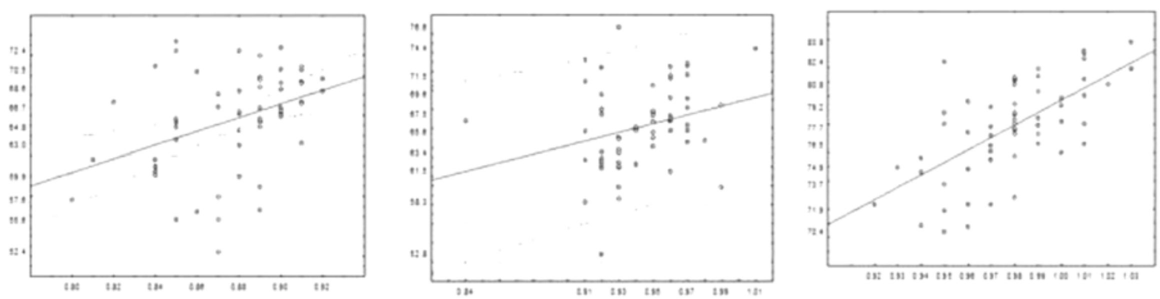
I ($V = 3.07$ m/s) II ($V = 3.02$ m/s) V ($V = 3.03$ m/s)

Relationship between oxygen consumption and respiration coefficient



RQ = 1.0563 – 0.0656 VO_2 RQ = 1.0896 – 0.0524 VO_2 RQ = 0.9794 – 0.0005 VO_2

Relationship between respiration coefficient and pulmonary ventilation



VE = 6.0179 + 67.9161 × RQ VE = 23.0557 + 45.7742 × RQ VE = –8.3016 + 88.012 × RQ

Fig. 3. (Contd.)

The pulse rate, oxygen consumption, and pulmonary ventilation increase (significantly in the comparison of the first and the third intervals, $p < 0.05$) during the periods from the first to the second interval and from the second to third distance interval, which indicates a decrease in the efficiency of muscular work. This is also confirmed by an increase in the value of pulse and oxygen costs of passing a 1-m distance. The oxygen pulse shows a downward trend during the transition from the stage of warming up to the optimum stage; however, it demonstrates no further changes. The respiratory rate increases, particularly, at the early stages of the race; this probably reflects the gradual involvement of carbohydrate resources in the substrate supply of physical activity. However, the change in the ventilation–perfusion relationships, especially in the final stage of the marathon, when the sharp increase in pulmonary ventilation (17% compared to the second stage) was significantly greater than the increase in the pulse rate (3.75%) may also be the reason for an increase in the respiratory rate. Since, against the background of fatigue, a significant increase in the beat ejection could hardly be expected, the increase in the blood flow rate is also likely to be low. This irregularity can cause a noticeable increase in the respiratory coefficient. At the same time, at the final stage of the race, a sharp increase in lactate levels in the peripheral blood was recorded; this acidification of the internal media can cause both an increase in the respiratory coefficient and an intensification of pulmonary ventilation.

It is interesting to analyze the correlations between the parameters of activities of the components of the cardiorespiratory system at various stages of an ultramarathon distance. As the intervals described in our instance, are characterized by stable and almost the same running speed (i.e., the power of the external mechanical work), the differences found in the structure of the correlation diagrams are related solely to the differences in the functional state of the body. In the initial period, the number of strong relationships is relatively small. At the stage of the optimal load, the total number of significant relationships increases; some of them become noticeably stronger. At the final stage, against the background of accumulated fatigue, a decrease in the number of strong relationships and the change in correlation foci are recorded. Thus, at the first and second stages of the run, the respiratory coefficient was an important focus, and HR did not show strong relationships with other functions; while in the phase of fatigue, the relationships of the respiratory coefficient with other parameters weakened, and the HR was one of the main focuses of the correlation diagram. It is difficult to interpret the changes found;

however, it is clear that the state of optimum performance is characterized by the well-coordinated interaction of various functions of the body, while fatigue is characterized by the weakening and alternation of the pattern of correlations within the cardiorespiratory system.

Given these results, the analysis of binary interactions between various parameters of the performance of the cardiorespiratory system, taking into account the functional state of the body, is of particular interest. These results are shown in Fig. 3.

The OC and pulmonary ventilation show the most obvious nature of the relationship and its changes. In the initial period, the binary data cloud is of low density, though the parameters are clearly and significantly correlated to each other. At the stage of optimum performance, the point cloud becomes denser, which indicates the intensification of the interaction between the parameters, whereas against the background of fatigue, the low density of the point cloud and the weakening of relations between the traits are recorded.

The results of the analysis of the relationships between OC and HR were surprising. It turned out that, at the initial stage of performance, as well as at the stage of optimal performance, no statistically significant correlations were found between these seemingly strongly functionally related parameters. Only against the background of fatigue, a relatively strong relationship, albeit, characterized by a diffuse cloud of points on the regression diagram, was found. The reason for this unexpected result could be that the individual data obtained at relatively the same moderate loads were analyzed. In this case, the factors causing a strong relationship of OC and HR in the mode of alternating loads, when both factors are dependent on the load, did not work. This result indicates that there are degrees of freedom in these two important parameters by which we usually estimate the severity of the load and its power supply; and these degrees of freedom are not always taken into account. These results result in doubts about the accuracy of such suggestions, at least, under the conditions of moderate loads.

Similar relationships were found between the HR and pulmonary ventilation; significant relationships between these parameters are formed only against the background of fatigue.

The relationship between the OC and oxygen pulse is characterized by the narrow range of scatter of the data at all stages of the race. However, at the stage of optimal performance (interval II), the strength of this relationship is particularly high; against the background of fatigue, it decreases.

In the initial period of the race, the relationship between the OC and oxygen pulse is weak and negative. Apparently, in this case, the respiratory coefficient reflects the metabolic structure of the energy production. The fluctuations of the respiratory coefficient to some extent depend on the fluctuations of the ratio between the aerobic and anaerobic glycolysis paths of energy production in the muscles. In the state of optimal performance (interval II), the pattern described persists; and the density of the points around the regression line even slightly increases. However, at the final stage, the pattern changes; the relationship between the parameters disappears, and the scatter of data significantly increases. This can be explained by the fact that, at this stage, the changes in the respiratory coefficient are not related to the metabolic structure of energy production, but depend on other factors, such as the ratio of the alveolar ventilation and the blood flow. It is clear that our data allow us to only approximately describe the effect of these physiological mechanisms.

However, the following group diagram can be an indirect confirmation of this suggestion. It reflects the relationship between the respiratory coefficient and pulmonary ventilation. The strength of this relationship decreases from the initial to the second stage; however, at the final stage, it markedly increases. Of course, it is not clear why this happens and what the consequences are; i.e., whether the pulmonary ventilation increases under the action of the same factors (acidification) as the respiratory coefficient, or vice versa, the respiratory rate increases as a result of an increase in the ventilation–perfusion ratio. At this stage, acidification occurs (as shown above), as well as an increase in the ventilation-perfusion ratio. In any case, a significant increase in the respiratory rate can be considered as a sign of fatigue accumulated during the race and as an indication of desynchronization between the functions of the components of the cardiorespiratory system.

CONCLUSIONS

Our data have demonstrated a number of obvious and predictable features that accompany fatigue during prolonged muscular work of moderate intensity. The first feature consists in a decrease in efficiency, which results in increased HR and the oxygen used. The second feature consists in the activation of the anaerobic glycolysis path of energy production. Since the simultaneous increases in the activity of aerobic and anaerobic glycolytic energy production occur against the background of fatigue, actual energy consumption increases very considerably; this shows an increasing imbalance in the mechanisms of energy production and utilization. The third feature consists in the intensification of the respiratory function; which is, probably, partly due to acidification of the internal media of the body and, thus, is a consequence of metabolic changes.

In addition, we recorded some features that are not obvious. They reflect the mechanisms of the interaction between functions, which are subtle, varying in dependence of the current functional state, and poorly understood. They are expressed in the changes (increase or decrease) in the relationships between the functions, depending on whether the work is at the stage of warming up, sustainably high performance, or at the stage of considerable fatigue. It seems that with the development of fatigue, the functional system, that meets the needs of an organism in oxygen, goes through a set of stages. At the initial stages, the degree of interaction between the functions increases, which creates an optimal background for muscular performance; while at the final stages, this interaction weakens and its pattern partially changes. Probably, these changes have a central origin, and lead to the decrease in the efficiency of muscular performance observed against the background of constant mechanical efficiency.

Our comprehensive data suggest the combined effect of the central and tissue mechanisms of fatigue on oxygen transportation in the body.

The lack of strong relationships between the HR and OC when the load is constantly moderate, outside of the fatigue zone, is unexpected and seemingly strange. This is probably due to the variety of functions of blood circulation; along with the delivery of oxygen and substrates to the working tissues, it solves various tasks, such as thermoregulation and detoxification. Apparently, under the conditions of the constant load of moderate intensity, the cardiovascular system has many possible ways of functioning, which is expressed, in particular, in the significant variability of the HR. Oxygen consumption is also not constant and varies continuously over a wide range. This is confirmed by the values of the standard deviations of both parameters (Table 2), which significantly decrease by the end of the distance, compared to the initial period. Under the conditions of warming up and optimal performance, the HR and OC are often not synchronized. However, under the conditions of fatigue, the synchronization of the functions is forced to increase; this is similar to an increase in the tension index against the background of stress [7]. In this situation, the interdependence between these two parameters dramatically increases. All this findings show the feasibility of using tools that can assess the variations in the patterns of physiological functions in order to study the mechanisms of the autonomous support of muscular work. These attempts have been recently undertaken [8].

Analyzing the mechanisms of fatigue, which limit the athlete's physical abilities and athletic performance, researches often consider four types of models: energy, strength, biomechanical, and psychological [9]. Probably, in the instance of ultra-marathon running, that is, in the case of an extremely long performance of moderate power, the autonomic system rather than the energy of the body is the main limiting factor. The balance and concurrency of the functions may be the main limiting factor under these conditions; while the changes in the pattern of their interaction can be an informative sign of fatigue starting. However, further research is required in order to identify the indicators and criteria of developing fatigue.

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