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Original Article

Optimization of functional adjustments of the oxygen supply system in the body of young skilled athletes during long-term athletic training

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Abstract
Purpose: to establish generalized regularities of the cumulative impact of training the formation of a "functional base" in the dynamics of body growth and development. Material & methods: 263 young athletes (79 kayakers, 88 canoeists, 96 cyclists) of different ages (12-20 years) and sports qualification were examined. The studies were conducted from 2010 to 2017. The tests were performed at rest after an overnight fast and under different modes of strenuous muscular work on a cycle ergometer, as well as in natural training conditions. A complex technique was used to determine the level of functional fitness. It included the registration of the main parameters of gas exchange, external respiration, blood, the cardiovascular system at maximum one-minute and stepwise loads, at standard load and work at a critical power level, performed on a cycle ergometer attachment to a bike or a rowing machine. **Results:** After 15-16 years the increase of special work capacity and efficiency of the respiratory system is accompanied by a decrease in the specific weight of development of the *power* of functional systems and their mobility. At the same time, a natural tendency to increase *stability*, *economy,* and degree of *realization* of gas transport system capacities is noted. The later the specific weight of *power* and *mobility* factors in the total efficiency of the respiratory system decreases, the greater the final level of its development in the dynamics of long-term training. The combination of high training loads, the process of enhanced body growth and development can earlier than usual realize the development potential of the respiratory system. Thus it can be argued that the way of the respiratory system adaptation of young athletes in the process of long-term training should be channeled into creating optimal conditions for stimulation of maximum functional reactions of the process of oxygen delivery to working organs. In this case, a directed deepening of the tendency to tolerate ("endure") a lack of oxygen and an excess of underoxidized metabolic products should be avoided (up to the age of 17-18 years). Oxygen debt accumulation and internal environment shifts should be used only in those working conditions and to the extent that they are an additional stimulus for maximizing functional responses. **Conclusions:** The degree of response sensitivity decrease reflects an increase in the potential of the respiratory system reserve capacity. The decrease in functional reactivity reflects the degree of the respiratory system potential realization. It is understood as a possibility of its efficiency further increase as a result of training at the given level of system potential. Such criteria in case of their further applied development allow approaching the quantitative estimation of such hardly quantifiable factors, as a degree of system potential realization, reserve capacities for deepening the influence of the further training on the respiratory system**.** Deviations from optimal training regimes (based on the notions of great plasticity of the growing body, lesser reliability of functional systems) in the presence of "sensitive" periods of development, have a great and yet insufficiently clear mechanism of negative significance for the complete realization of the respiratory system potential of the body by a mature age.
Keywords: young rowers, young cyclists, respiratory system, age-related changes

Introduction

The functional state is an integral characteristic of those human functions and qualities that directly or indirectly determine the efficiency of performing a particular activity (Camara et al., 2012; Orlov et al., 2017). The training status in sport reflects one of the highest degrees (stages) of adaptation to muscular activity and covers a wide range of issues. Functional fitness is one of these issues (Pryimakov, 2012). Functional fitness is a pivotal question for cyclic sports events and reflects the part of an athletic capacity provision, which is conditioned by the capabilities of key functional systems (Dahmen, 2012; Takaishi et al., 1998). For cyclic sports events, this is the oxygen transport system (in other terminology, the oxygen supply system) or the respiratory system (in the broad sense of the terms). Quantitative and qualitative manifestations of these system

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activities are one of the most important objects of control and criteria of functional fitness diagnostics in the dynamics of the training process (Emanuele et al., 2012; Thakur et al., 2008).

There are numerous publications on studies with a complex approach to assessing the functional state of the body of skilled athletes and differentiation of functional fitness various aspects (Abramovich et al., 2015; Bini & Rossato, 2014; Fudin et al., 2015; Wangerin et al., 2017).

Some authors note that functional fitness is a number of multicomponent in their structure qualities (Mornieux et al., 2010). Functional fitness analysis is connected with the necessity to take into account an integral “vegetative portrait” of an athlete, with a multicomponent cause of work capacity limitation in the absence of any limited weak link (Castronovo et al, 2012; Ericson, 1988) or in its presence (Podstawski et al., 2020). Degallier & Ijspeert (2010), Wael et al. (2021) suggested using several energy criteria - power, capacity, and efficiency - to characterize metabolic states.

The majority of works deal with generalizations and structural analysis within one functional system. Especially many important studies in this direction concern the activity of the cardiovascular system. The most complete elaborations refer to the analysis of changes in the “oxygen regime” of the athletes’ bodies (Dedieu et al., 2020; Dorel et al., 2009; Hug et al., 2009).

Training in endurance sports events contributes to the possibility of age-related development of the respiratory system during the whole period of sports engagement (Antonov et al., 2017; Miller et al., 2019). The peculiarities of its adjustment reflect the adaptation of a number of other systems that provide high efficiency of bioenergetic processes and speed of athlete movement in specific conditions of sports activity (Monogarov & Bratkovsky, 1979).

While analyzing the literature data on the impact of sports training on the growing body, several physiological peculiarities in the response of the oxygen transport system (OTS) of children, adolescents, and young men to physical loads may be noted. They are due to the physiological immaturity of various body systems (Hug et al., 2008; Theurel et al., 2011).

However, so far there are no data that would allow developing physiological basis to analyze the optimality of long-term adaptation of a growing body OTS to strenuous muscular training.

In this regard, the task of our study was to analyze and substantiate possible approaches to examining physiological criteria of optimality of long-term training general direction for young athletes specialized in cyclic sports events.

The purpose consisted in establishing generalized regularities of cumulative influence of training formation of “functional base” in the dynamics of body growth and development on the basis of a complex study of the respiratory system.

Materials & methods

Participants. 263 young athletes (79 kayakers, 88 canoeists, 96 cyclists) of different ages (12-20 years) and sports qualification were examined.

Organization of the study. The studies were conducted from 2010 to 2017. The tests were performed at rest after an overnight fast and under different modes of strenuous muscular work on a cycle ergometer (rowing machine), as well as in natural training conditions.

A complex technique was used to determine the level of functional fitness (Kolumbet et al., 2019). It included the registration of the main parameters of gas exchange, external respiration, blood, the cardiovascular system at maximum one-minute and stepwise loads, at standard load and work at a critical power level, performed on a cycle ergometer attachment to a bike or a rowing machine.

We determined interrelated parameters of gas exchange, external respiration - frequency, depth, minute respiratory volume, alveolar ventilation, O_2 and CO_2 content in exhaled and alveolar air, main pulmonary volumes; indices of diffusion conductivity - respiratory and circulatory components; blood circulation – cardiac output according to Defar modified by V.S. Mishchenko, systolic volume, pulse, arterial blood pressure, amount of venous blood admixture; blood respiratory function – blood oxygen content, hemoglobin content, blood O_2, and CO_2 tension, arterialized blood O_2 tension according to Astrup, arterial blood oxygen saturation by oxyhemometry using special calibration method; body temperature of an athlete; indices of arterial blood acid-base balance, blood lactic acid and glucose content.

The study of the oxygen transport system of the athletes' body under physical load envisaged the analysis of oxygen and carbon dioxide parameters in parallel with the analysis of the activity of the major functional systems that determine them. Quantitative and qualitative assessment of the ratios between indices of work capacity and O_2 consumption - CO_2 excretion, other oxygen, and carbon dioxide parameters and functional indices were investigated.

Statistical analysis. During experimental data processing, we determined the average values of indices and their errors (M±m), the degree of difference of averages, and the significance of differences (t, p).

While conducting complex pedagogical, biomechanical, and biological surveys with the participation of athletes, the legislation of Ukraine on health care, the 2000 Helsinki Declaration, Directive No. 86/609 of the European Society regarding people’s participation in biomedical research were adhered to.

Results & Discussion

The methodology of the analysis envisaged quantitative determination of the key functional properties (factors) that influenced the threshold efficiency of the respiratory system. The generalized data of such analysis of the system physiological properties are shown in Figure 1. As seen in Figure 1, there are regular age-related changes in the specific weight of various factors in the formation of young athletes' functional fitness.

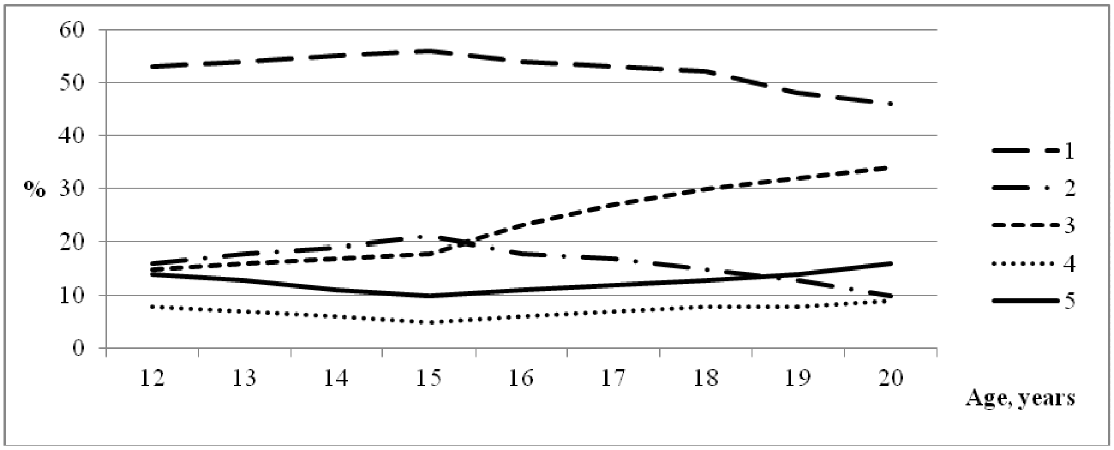

Fig. 1. Dynamics of the factors of functional fitness structure (their specific weight in % of the total sum of factors) in the process of age-related development of athletes (n=84)
Legend: 1 – power; 2 – mobility; 3 – stability; 4 – economy; 5 - realization

After 15-16 years the increase of special work capacity and efficiency of the respiratory system is accompanied by a decrease in the specific weight of development of the *power* of functional systems and their mobility. At the same time, a natural tendency to increase *stability*, *economy,* and degree of *realization* of gas transport system capacities is noted. The later the specific weight of *power* and *mobility* factors in the total efficiency of the respiratory system decreases, the greater the final level of its development in the dynamics of long-term training.

We had to find out:

- to what extent the dynamics of the key physiological properties of the body systems of young athletes is optimal for the full realization of development potential by the age of the highest athletic achievements?
- what are the optimality limits of the decrease of response sensitivity to the complex of adequate stimuli for the oxygen transport system for different periods of body growth and development?
- what are the rates of decrease in sensitivity of responses to a complex of adequate stimuli for the oxygen transport system at different ages of intensive training onset?

Some of the answers to these complex questions are discussed below.

One of the adequate criteria reflecting the cumulation of training impacts on the respiratory system is the degree of the training economizing influence (in the morning at rest) on energy metabolism and the oxygen transport system functions, as well as the state of receptor formations involved in the regulation of pulmonary ventilation and central hemodynamics (sensitivity, thresholds, general efficiency of their responses to adequate humoral and "neurogenic" stimulus).

The study of training impact depth in terms of economization at rest (close to the conditions of the basal metabolism) demonstrated that in some cases already at the age of 14-16 very high (as in mature athletes) degrees of reduction of O_2 consumption specific values, pronounced hypoventilation, and (or) hypocirculatory phenomena are observed. These phenomena usually coincide with cases of especially high training volume of young athletes, and some of them achieve significant sports success in their age group. At the same time, a decrease in the sensitivity of responses to a complex of adequate stimuli for the oxygen transport system is noted.

The group of young athletes (with the lowest values of O_2 consumption per kg of body mass) tends to have the slowest rate of respiratory system efficiency increase (Fig. 2).

Of particular interest is the issue of the rate of training economizing effect, which reflect the cumulation of its effects at different age of the beginning of active sports engagement. Figure 3 schematically shows the impact of training on cardiac output (Q) and alveolar ventilation (VA) at different ages of the beginning of sports specialization. As seen in this figure, a significant degree and higher rates of its economizing effect may be observed at the early onset of active sports training. In these cases, the impact of training increases only slightly in the subsequent years.

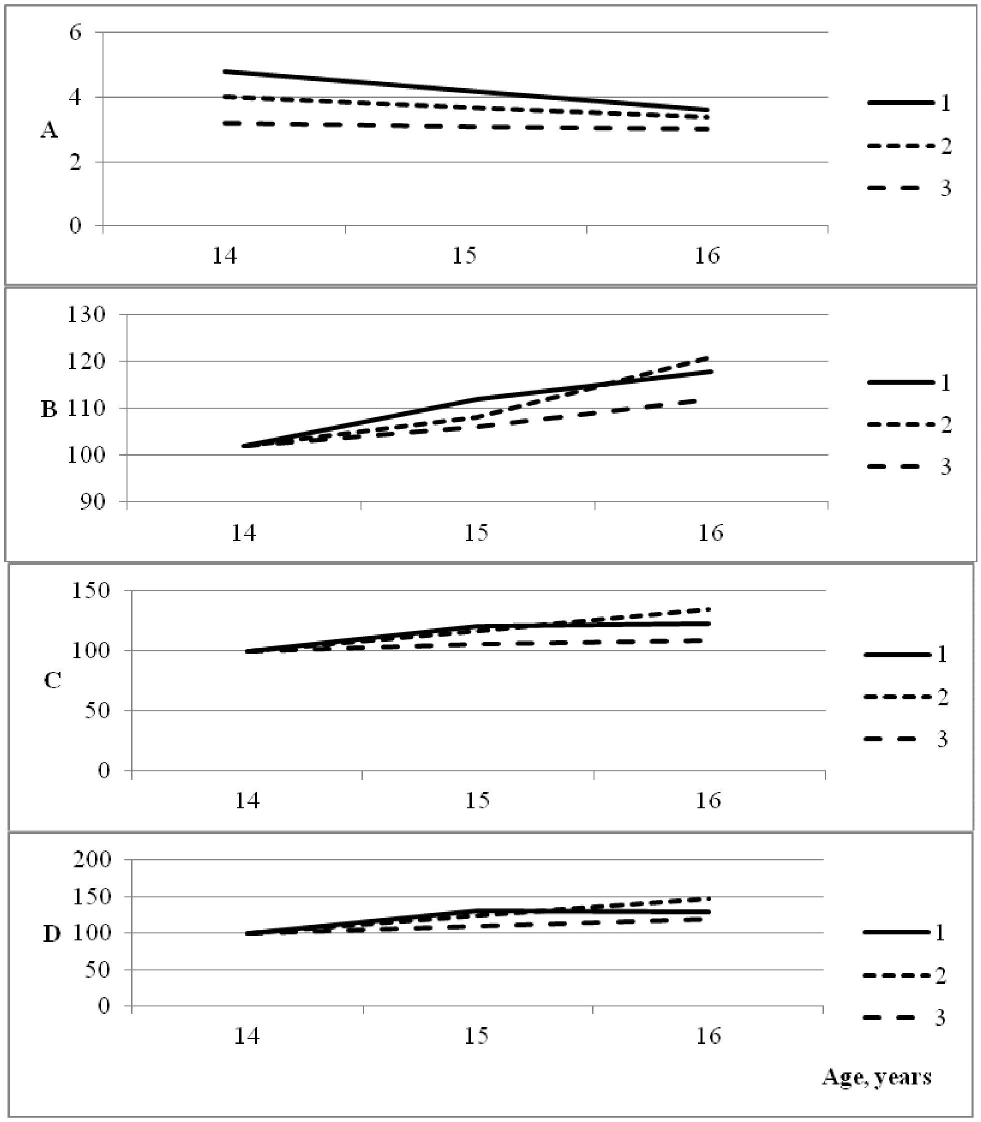

Fig. 2. Dynamics of specific oxygen consumption (**A**), body surface (**B**), power of functional responses of external respiration and central circulation during critical power work (**C**), sports result (**D**) in different age periods.
Legend: 1 - athletes with a high level of specific oxygen consumption; 2 - athletes with an average level of specific oxygen consumption; 3 - athletes with a low level of specific oxygen consumption

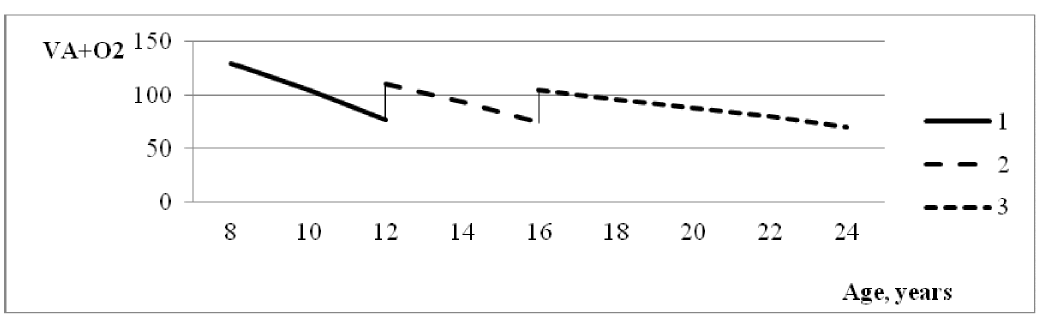

Fig. 3. The degree of athletic training influence on the respiratory system of young athletes at different age of sports specialization onset
Legend: 1 – specialization onset at the age of 8; 2 – specialization onset at the age of 12; 3 – specialization onset at the age of 16

With regard to the growing body, the optimality of early and such profound shifts requires special analysis. Some physiological mechanisms of this process are revealed (Fig. 4) when analyzing the sensitivity of ventilation and heart rate responses to the increased degree of hypoxia, designated as A and HR/SaO_2, respectively, and baroreceptor sensitivity.

The optimality of such influence depth at different stages of young athlete long-term training may be estimated by the degree of correspondence of the age-related changes in the main indices of resting economization, the decrease in sensitivity of responses, and parameters of the maximum efficiency of the functional reaction during special work (Ajiboye et al., 2009; Fudin et al., 2015). Deviations from optimal dynamics of the relationship between the mentioned parameters are noted when the deepening of economization is accompanied by a less pronounced increase in maximum efficiency of external respiration, central circulation, and O_2 transport. Individual ratios are established for each athlete in the process of long-term physiological control (Hebisz et al., 2019).

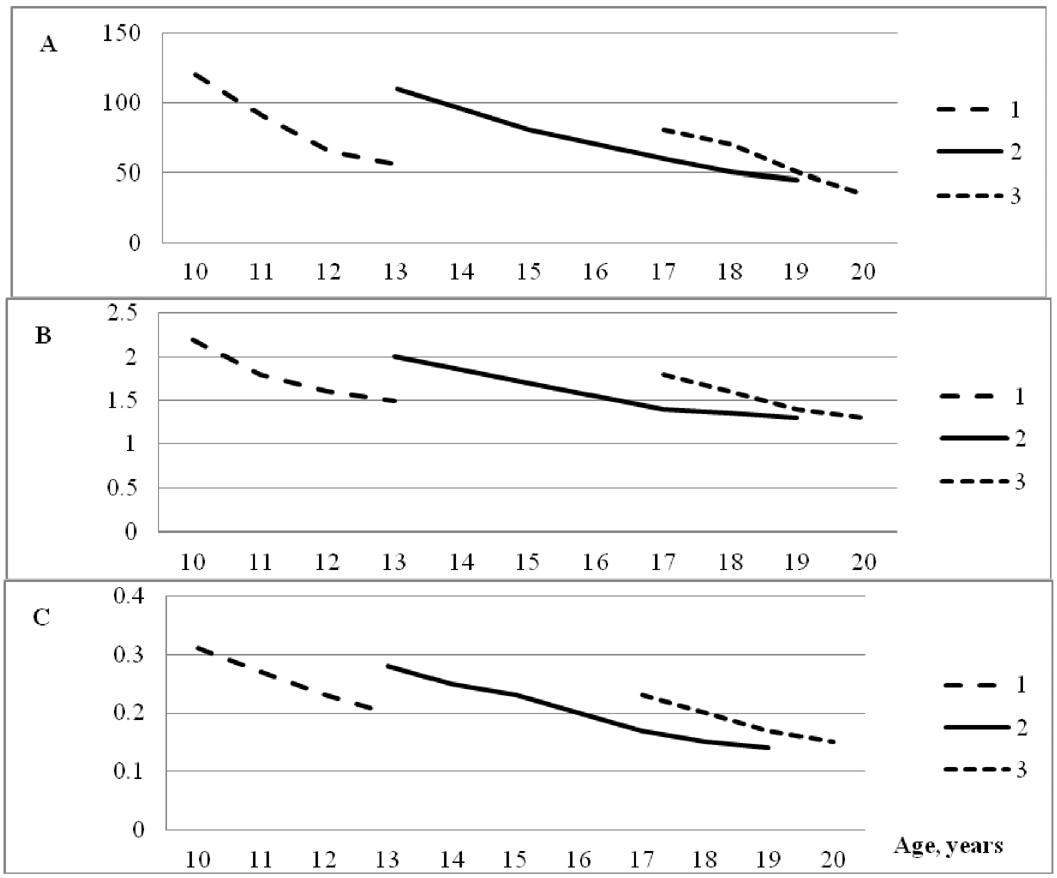

Fig. 4. Levels and dynamics of the decreased sensitivity of ventilation, pulse, and baroreceptor response to hypoxia in young athletes
Legend: 1, 2, 3 – time of active sports engagement; **A** – *A* per sq.m. of body surface; **B** – $\Delta HR/\Delta SaO_2$; **C** – $\Delta HR/\Delta P$

With the increased role of the utilization factor, more complete O_2 usage from the alveolar air and arterial blood, the shifts of the internal milieu inevitably deepen and the least training effect on the executive organs of respiration and O_2 transport is observed. Over the years, this leads to a lag in the development rate of operational properties of the entire system of respiratory gas transport, the capabilities of the executive organs in the "drive for oxygen" (Barratt et al., 2016; Tupin et al., 2011).

The combination of high training loads, the process of accelerated body growth and development can earlier than usual realize the development potential of the respiratory system (Ya-weng Tseng et al., 2006). Thus it can be argued that the way of the respiratory system adaptation of young athletes in the process of long-term training should be channeled into creating optimal conditions for stimulation of maximum functional reactions of the process of oxygen delivery to working organs (Boyles et al., 2012). In this case, a directed deepening of the tendency to tolerate ("endure") a lack of oxygen and an excess of underoxidized metabolic products should be avoided (up to the age of 17-18 years). Oxygen debt accumulation and internal environment shifts should be used only in those working conditions and to the extent that they are an additional stimulus for maximizing functional responses (Ambrosini et al., 2012).

Obtained data on the presence of the "habituation" effect are indicative of the importance of these issues (Castellini, 2013; Vardar et al., 2007). A significant decrease in functional reactivity to the shifts of the internal milieu of athletes was established. The degree of participation of functional reactivity decrease was revealed in 25-40% of athletes being the members of junior national teams (Zameziati et al., 2006).

The growing body is more sensitive to both "neurogenic" and humoral factors of the respiratory system stimulation (Hirai et al., 2015). Elements of "habituation" to shifts in the internal milieu lead to a relative decrease in the general functional response of the respiratory system and speed of their deployment (Tomiak et al., 2015).

These shifts may be interpreted as an increase of resistance to them. At the same time, the value of a fast ("purely") neurogenic component of the response may also decrease (Proske et al., 2012). The comparative analysis of functional indices of young track-and-field athletes (runners) with a different experience of using special endurance development means in training is presented in Table 1.

Table 1. Comparison of the levels of functional responses and shifts of the internal milieu at the critical level of work power in young athletes with relatively higher (age 16.7 years) and lower (age 16.5 years) specific weight of training means for the development of anaerobic (lactate) capacity

№№	Indices	Age	
		16.5 years	**16.7 years**
1	Body mass, kg	63.2	64.1
2	pH of arterial blood, mg%	7.281	7.202
3	Blood lactic acid content, mg%	71	86
4	Pco_2 of mixed venous blood, mmHg	60.5	68.0
5	Pulmonary ventilation, $l.min^{-1}$	124	102
6	Heart rate, $beats.min^{-1}$	196	184
7	Respiration rate, $breath.min^{-1}$	51.1	43.2
8	Cardiac output, $l.min^{-1}$	25.5	23.1
9	Pulse pressure, mmHg	121	100
10	Diastolic pressure, mmHg	50	75
11	T_{50} of V_E response, s	21.0	24.3
12	T_{50} of HR response, s	25.0	27.4

Young athletes with higher anaerobic capacity (at a similar critical power of work) are characterized by a lesser functional response at high shifts in the internal milieu (De Oliveira, 2002). A stronger stimulus is required to induce the same level of functional response of the respiratory system to a training load (Hug et al., 2010). That is, loads continuously increase along with the improvement of athletes' training status. In young athletes, the efficiency of the functional response (during the competitive period of training) to most stimuli of the respiratory system significantly decreases with age (Table 2a, Table 2b).

Table 2a. Age dynamics of some properties of the respiratory system regulation in young skilled athletes

Indices	Age, years					
	14.9±0.26		**16.9±0.24**		**21.6±0.8**	
	X	**m**	**X**	**m**	**X**	**m**
Functional response sensitivity (chemoreceptors)						
$S\Delta V_E/\Delta P_{ACO2}$	1.51	0.08	1.21	0.02	1.10	0.09
S/kg	0.238	0.02	0.17	0.01	0.138	0.01
S/VC	0.320	0.02	0.240	0.03	0.183	0.02
$\Delta V_E/\Delta SaO_2$(A)	0.89	0.09	0.62	0.11	0.39	0.08
$\Delta HR/\Delta SaO_2$	1.58	0.08	1.37	0.13	1.25	0.09
S•A	1.350	0.14	0.751	0.13	0.429	0.10
ΔHR/ΔP	0.243	0.01	0.195	0.01	0.145	0.01
Pulmonary stretch receptors						
M	22.7	0.8	19.5	0.92	17.9	1.1
60K/M	0.360	0.09	0.618	0.09	0.875	0.08
HR_{84}	98.1	1.5	92.6	2.7	76.2	2.1
V_{E84}	23.1	1.0	19.7	1.2	12.8	1.1

Legend: V_E – pulmonary ventilation; P_{ACO2} - CO_2 tension in alveoli; S – sensitivity to hypercapnia; S_{aO2} – arterial blood oxygen saturation; HR – pulse; A – sensitivity to hypoxia

Table 2b. Age dynamics of some properties of the respiratory system regulation in young skilled athletes

Indices	Age, years **14.9±0.26**		**16.9±0.24**		**21.6±0.8**	
	X	**m**	**X**	**m**	**X**	**m**
Response thresholds						
B (CO_2 threshold)	30.3	1.1	31.2	1.0	35.1	1.2
K (lung receptors)	0.12	0.01	0.18	0.01	0.26	0.03
Functional response efficiency						
0.5(50-B) V_{60}	383	5	285	8	136	6
ΔSP of initial hypercapnia	15	3.0	11	3.2	43	2.8
Pulse pressure at P_{ACO2}=50 mmHg	53.2	2.0	50.5	3.4	43.0	2.8
Pulse pressure at S_{aO2} = 84%	48.0	2.4	45.0	3.0	41.0	2.9
V_{50} of hypercapnia	38.3	1.0	30.2	1.6	18.2	1.2
V_E at $V_{T=2l}$	43.0	1.8	36.1	1.6	30.8	1.4
FSR of CO_2 per kg of weight	1.62	0.25	1.39	0.30	0.96	0.15
HR_{84}	98.1	1.5	92.6	2.7	76.2	2.1
V_{E84}	23.1	1.0	19.7	1.2	12.8	1.1
Functional response stability						
P_{ACO2} of HR(%) hypercapnia decrease onset	46.1	1.0	48.8	1.3	53.1	1.6
Δ of pulse pressure during hypoxia of initial	-5.0	3.5	-4.0	3.0	+5.0	2.6
S_{aO2} of HR(%) hypoxia decrease onset	92.3	1.6	90.2	1.8	87.3	2.0
HR(%) of hypoxia S_{aO2}=84%, %	3.0	0.35	5.9	0.30	9.3	0.30
Parameters reflecting vegetative balance of sympathetic and parasympathetic impacts and regulation						
Resting HR	62.1	1.1	54.6	1.3	46.4	1.2
Resting f	15.1	0.9	13.3	0.9	10.6	0.8
V_{O2}/kg of body mass	3.95	0.09	3.70	0.09	3.31	0.10
Resting P_{AO2}	106.0	1.2	104.3	1.1	98.2	1.3
Resting HR(%), %	4.6	0.3	6.6	0.3	8.0	0.4
Maximum hypercapnia HR(%), %	8.3	0.4	10.1	0.3	13.5	0.3

Legend: V_{50} – ventilation at P_{ACO2}=50 mmHg; SP – systolic pressure; FSR – CO_2 fast storage rate; HR_{84} – pulse at SaO_2=84%; HR(%) – pulse respiratory arrhythmia

Conclusions

The degree of response sensitivity decrease (for instance, the S value for hypercapnic sensitivity) reflects an increase in the respiratory system potential of its reserve capacity. The decrease of functional reactivity (for hypercapnia it is an increase in response threshold at the same S value) reflects the degree of the respiratory system potential realization. It is understood as a possibility of its efficiency further increase as a result of training at the given level of system potential. Such criteria in case of their further applied development allow approaching the quantitative estimation of such hardly quantifiable factors, as a degree of system potential realization, reserve capacities for deepening the influence of the further training on the respiratory system**.**

Deviations from optimal training regimes (based on the notions of great plasticity of the growing body, lesser reliability of functional systems) in the presence of "sensitive" periods of development, have a great and yet insufficiently clear mechanism of negative significance for the complete realization of the respiratory system potential of the body by a mature age. With further detailing and development, these regularities of functional fitness dynamics may lay the foundation for the elaboration of normative dynamics of the functional fitness structure.

Conflict of interest

The authors declare that there is no conflict of interests.

References

Abramovich, T.I., Vereshchaka, I.V., Tal'nov, A.M., Gorkovenko, A.V., Dornowski, M., & Kostyukov, A.I. (2015). Coordination of activity of the shoulder belt and shoulder muscles in humans during bimanual synchronous two-joint movements. *Neurophysiology*, 47, 310–321. doi: 10.1007/s11062-015-9538-6

Ajiboye, A.B, & Weir, R.F. (2009). Muscle synergies as a predictive framework for the EMG patterns of new hand postures. *Journal of Neuralogy & Engineering, 6*, 036004.

Ambrosini, E., Ferrante, S., Ferrigno, G., Molteni, F., & Pedrocchi, A. (2012). Cycling induced by electrical stimulation improves muscle activation and symmetry during pedaling in hemiparetic patients. *IEEE Trans. Neural Syst. Rehabil. Engineering, 20*, 320–330.

Antonov, S., Briskin, Y., Perederiy, A., Pityn, M., Khimenes, K., Zadorozhna, O., Semeryak, Z., & Svystelnyk, I. (2017), Improving technical preparedness of archers using directional development of their coordination skills on stage using the specialized basic training. *Journal of Physical Education & Sport, 17*(1), 39, 262-268.

Barratt, P.R., Martin, .C., Elmer, S.J., & Korff, T. (2016). Effects of pedal speed and crank length on pedaling mechanics during submaximal cycling. *Medicine & Science in Sports & Exercise*, *48*(4), 705-13.

Bini, R.R., & Rossato, M. (2014). *Kinetics and pedaling technique biomechanics of cycling*. Springer International Publishing Switzerland.

Boyles, J., Panzer, S., & Shea, C.H. (2012). Increasingly complex bimanual multi-frequency coordination patterns are equally easy to perform with on-line relative velocity feedback. *Experimental Brain Research, 216*, 4, 515-525.

Camara, J., Maldonado-Martin, S., Artetxe-Gezuraga, X., Vanicek, N., & Camara, J. (2012). Influence of pedaling technique on metabolic efficiency in elite cyclists. *Biology of Sport, 3*(29), 229-233.

Castellini, C., & van der Smagt, P. (2013). Evidence of muscle synergies during human grasing. *Biol. Cybern*. 107, 233–245. doi: 10.1007/s00422-013-0548-4

Castronovo, A.M., De Marchis, C., Bibbo, D., Conforto, S., Schmid, M., & D'Alessio, T. (2012). Neuromuscular adaptations during submaximal prolonged cycling. Conf. Proc. IEEE *Medicine Engineering & Biology Society*, 3612-3615.

Dahmen, T. (2012). Optimization of pacing strategies for cycling time trials using a smooth 6-parameter endurance model. Pre-Olympic Congress on Sports Science and Computer Science in Sport (IACSS2012). Liverpool: UK.

Dedieu, P., Pelaez, M., Poirier, E., & Zanone, P-G. (2020). Effects of saddle height on muscular pattern and interlimb coordination in cycling. *Journal of Physical Education & Sport, 20*(1), 29, 222-228.

Degallier, S., & Ijspeert A. (2010). Modeling discrete and rhythmic movements through motor primitives: a review. *Biological Cybernetics, 103*, 4, 319-338.

De Oliveira, S.C. (2002). The neuronal basis of bimanual coordination: recent neurophysiological evidence and functional models. *Acta Psychology, 110,* 2/3, 139-159.

Dorel, S., Drouet, J.M., Couturier, A., & Champoux, Y. (2009). Changes of pedaling technique and muscle coordination during an exhaustive exercise. *Medicine & Science in Sports & Exercis*e, *41*(6), 1277-1286.

Emanuele, U., Horn, T. & Denoth, J. (2012). The relationship between the freely chosen cadence and optimal cadence in cycling. *International Journal of Sports Physiology & Performance, 7*, 375-381.

Ericson, M.O. (1988). Mechanical muscular power output and work during ergometer cycling at different workloads and speeds. *European Journal of Applied Physiology and Occupational Physiology, 57*, 382-387.

Fudin, N.A., Klassina, S.Y., Pigareva, S.N., & Vagin, Y.E. (2015). Muscular and cardiovascular system indices in persons engaged in physical culture and sport during failure to perform intensive physical load. *Theory & Practice of Physical Culture, 11*, 18-20.

Fudin, N.A., Klassina, S.Y., & Pigareva, S.N. (2015). Relationship between the parameters of muscular and cardiovascular systems in graded exercise testing in subjects doing regular exercises and sports. *Human Physiology, 41*(4),412-419.

Gorkovenko, A.V., Sawczyn, S., Bulgakova, N.V., Jasczur-Nowicki, J., Mishchenko, V.S., & Kostyukov, A.I. (2012). Muscle agonist-antagonist interactions in an experimental joint model. *Experimental Brain Research*, *222*, 399–414. https://doi.org/10.1007/s00221-012-3227-0.

Hebisz R., Hebisz P., Borkowski J., & Zaton, M. (2019). Effects of concomitant high-intensity interval training and sprint interval training on exercise capacity and response to exercise-induced muscle damage in mountain bike cyclists with different training backgrounds. *Isokinetics & Exercise Science, 1*(27), 21-29. https://doi.org/10.3233/IES-183170.

Hirai, H., Miyazaki, F., Naritomi, H., Koba, K., Oku, T., Uno, K., et al. (2015). On the origin of muscle synergies: invariant balance in the co-activation of agonist and antagonist muscle pairs. *Front. Bioeng. Biotechnol*. 3:192. doi: 10.3389/fbioe.2015.00192

Hug, F., & Dorel, S. (2009). Electromyographic analysis of pedaling: a review. *Journal* of *Electromyografy & Kinesiology, 19*, 182–198.

Hug, F., Drouet, J.M., Champoux, Y., Couturier, A., & Dorel, S. (2008). Interindividual variability of electromyographic patterns and pedal force profiles in trained cyclists. *European Journal of Applied Physiology, 104*, 667–678.

Hug, F., Turpin, N.A., Guevel, A., & Dorel, S. (2010). Is interindividual variability of EMG patterns in trained cyclists related to different muscle synergies? *Journal of Applied Physiology, 108*, 1727–1736.

Kolumbet, A.N., Dudorova, L.Y., Dovgych, A.A., Ivaschenko, E.A., Melnik, A.A., Nichiporenko, I.V., & Suprunenko, M.V. (2019). Improvement of cyclist pedaling technique by studying their individual differences. *Journal of Physical Education & Sport, 19*(3), 229, 1577-1584. https://doi.org/10.7752/jpes.2019.03229.

Miller, M.C., Fink, P.W., Macdermid, P.W. & Stannard, S.R. (2019). Quantification of brake data acquired with a brake power meter during simulated cross-country mountain bike racing. *Sports Biomechanics, 18*(4), 343-353. https://doi.org/10.1080/14763141.2017.1409257

Monogarov, V.D., & Bratkovsky, V.K. (1979). *Coordination motions of sportsmen in the period of the compensated fatigue during muscular work of cyclic character*. Kiev.

Mornieux, G., Gollhofer, A., & Staperlfeldt, B. (2010). Muscle coordination while pulling up during cycling. *International Journal of Sports Medicine, 31*, 843–846.

Mornieux, G., Zameziati, K., Rouffet, D., Stapelfeldt, B., Gollhofer, A., & Belli, A. (2006). Influence of pedaling effectiveness on the interindividual variations of muscular efficiency in cycling. *Isokinetic Exercise & Science, 14*, 63–70.

Orlov, V.A., Fudin, N.A., Fetisov, O.B., Strizhakova, O.V., & Novikova, I.N. (2017). Indicators of functional reserves of cardiovascular and respiratory systems of human body. *Harold of New Medical Technologies, 1*, 179-185.

Podstawski, R., Boryslawski, K., & Boraczynski, M. (2020). The physiological effect of sauna and rowing on former elite athletes with hypertension. *Journal of Physical Education & Sport, 20*(3), 204, 1481-1490.

Proske, U., & Gandevia, S.C. (2012).The proprioceptive senses: their roles in signaling body shape, body position and movement, and muscle force. *Physiol. Rev*. 92, 1651–1697. doi: 10.1152/physrev.00048.2011

Pryimakov, A.A. (2012). Activity and relationships of muscular and cardiovascular systems in different states during muscular activity in athletes. *Physical Education of Students, 6*, 93–99. https://doi.org/10.6084/m9.figshare.96576.

Takaishi, T., Yamamoto, T., Ono, T., Ito, T., & Moritani, T. (1998). Neuromuscular, metabolic, and kinetic adaptations for skilled pedaling performance in cyclists. *Medicine and Science in Sports & Exercise, 30*, 442-449.

Thakur, P.H., Bastian, A.J., & Hsiao, S.S. (2008). Multidigit movement synergies of the human hand in an unconstrained haptic exploration task. *Journal of Neuroscience, 28*, 1271–1281. https://doi.org/10.1523/jneurosci.4512-07.2008.

Theurel, J., Crepin, M., Foissac, M., & Temprado, J.J. (2011). Effects of different pedalling techniques on muscle fatigue and mechanical efficiency during prolonged cycling. *Scandinavian Journal of Medicine & Science in Sports*, *22*, 714-721.

Turpin, N.A, Guével A., Durand, S., & Hug, F., (2011). Fatigue related adaptions in muscle coordination during a cyclic exercise in humans. *Journal of Experimental Biology, Article in Press*. https://doi.org/10.1242/jeb.057133.

Tomiak, T., Gorkovenko, A.V., Tal'Nov, A.N., Abramovych, T.I., Mishchenko, V.S., Vereshchaka, I.V., et al. (2015). The averaged EMGs recorded from the arm muscles during bimanual "rowing" movements. *Front Physiol*., 6:349. doi: 10.3389/fphys.2015.00349

Vardar, S.A., Tezel, S., Ozturk, L. & Kaya, O. (2007). The relationship between body composition and anaerobic performance of elite young wrestlers. *Journal of Sports Science & Medicine, 6*, 34-38.

Wangerin, M., Schmitt, S., Stapelfeldt, B., & Gollhofer, (2017). A inverse dynamics in cycling performance. *Advances in Medical Engineering*, *114*, 329-334.

Wael, R., Chrysovalantou, X., Refaat, M., Amr, S., & Sandra, A.B. (2021). Effect of wearing an alevation training mask on physiological adaptation. *Journal of Physical Education & Sport, 21*(3), 170, 1337-1345.

Ya-weng Tseng, Y., Scholz, J.P., & Valere, M. (2006). Effects of movement frequency and joint kinetics on the joint coordination underlying bimanual circle drawing. *Journal of Mot. Behav., 38*, 5, 383-404.

Zameziati, C., Mornieuxm, G., Rouffet, D., & Belli, A. (2006). Relationship between the index of effectiveness indexes and the increase of muscular efficiency with cycling power. *European Journal of Applied Physiology, 96*, 274–281.