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Physiological Features of Motor Coordination Formation Based on Training with Biological Feedback

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Abstract—The aim of this study was to study the physiological features of the formation of balance and coordination abilities based on training with biofeedback for various parameters. The study involved 60 girls aged 18–20 years, not engaged in sports and included in the main medical group (health group 1). The difference in the results of testing carried out for the selection of participants in the three groups was insignificant. Twenty girls were trained according to a program that included a set of exercises to develop the sensitivity of the vestibular analyzer and proprioceptive sensitivity. Twenty girls were trained on a Stabilan 01-2 computer stabiloanalyzer using feedback for the "projection position of the center of gravity" parameter. The remaining 20 subjects studied on a HUBER apparatus using feedback for the "applied efforts" parameter. Classes were held 3 times a week for a month, 12 workouts in total. Before the start of the training course, as well as after it, the girls underwent comprehensive testing using the methods of electromyography, stabilometry, EEG, and dynamometry on the HUBER apparatus. It was found that training with biofeedback contributes to the accelerated formation of the skill of maintaining balance, allows faster development of proprioceptive sensitivity, the ability to differentiate applied efforts without the participation of a visual analyzer, as well as to improve intermuscular coordination and muscle memory. A characteristic feature of the bioelectrical activity of the lower leg muscles while maintaining static balance after training with biofeedback for the "projection position of the center of gravity" parameter is an activation of the lower leg muscles in the static mode (simultaneous activation of antagonist muscles with commensurate indicators of bioelectrical activity). At the same time, after training with biofeedback according to the "applied efforts in the position of seeking dynamic balance" parameter, the lower leg muscles are activated in a dynamic mode (with a synchronized change in periods of tension and relaxation in the antagonist muscles). There is a more pronounced effect of training with biofeedback on the EEG frequency and power characteristics in comparison with traditional training. The results also make it possible to formulate a number of practical recommendations. All the methods studied here, both with biofeedback and without biofeedback, are aimed at the formation of coordination abilities and balance; therefore, they can be used in those sports that make increased demands for these qualities. It is advisable that these methods be used at different stages of sports improvement.

Keywords: biofeedback, movement regulation, coordination, balance, intermuscular interactions, muscular-articular feeling

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INTRODUCTION

The problem of finding new approaches to improving the motor skills and physical abilities of athletes remains relevant. Currently, the possibilities of traditional approaches are largely exhausted. The rigidity of anti-doping rules significantly limits the possibilities of pharmacological support for athletes. Under these conditions, the attention of researchers is attracted by the prospect of using information technologies and technical devices [1, 2]. Particularly effective are methodological techniques aimed at providing additional information, biofeedback (BFB) or biocontrol; in English literature, the term "biofeedback" is used [3, 4].

Bernstein [5], describing the physiological mechanisms of maintaining balance, was the first to point out the feedback system for maintaining balance referred to as "sensory correction." At present, the BFB concept has been confirmed in the study of the mechanisms of postural control and their disturbances under conditions of weightlessness and in several diseases [6–9]. Therefore, the search for new methodological approaches for correcting the maintenance of balance is of great practical importance.

The range of applications of BFB technology in sports activities is quite wide, from optimizing loads and ensuring peak performance of skeletal muscles to teaching relaxation and recovery after loads [10, 11]. Feedback allows us to perform physical work balanced in terms of strength, coordination of movements, and postural control. The BFB method also makes it possible, using multimedia capabilities, to provide high emotional interest and non-standard conduct of classes [12–14].

Training with BFB is carried out according to various parameters: the frequency and structure of heart contractions [15, 16], the frequency of electroencephalogram (EEG) rhythms [17], respiratory parameters, etc. A promising direction is also the use of BFB in the development of coordination as the ability to coordinate muscle tension in accordance with the intended motor program, since self-control exercised on the basis of distinct motor concepts is important for controlling the movement system, and one of the ways to improve it is to develop the accuracy of perception and reproduction of one's own efforts manifested in solving motion tasks of various directions [18–20].

In recent years, a large number of studies have been published that analyze the use of various types of training with BFB. The main direction of using BFB for the purpose of conscious regulation of body functions remains physical rehabilitation (including after sports injuries) [11, 21]. However, many studies have been conducted in relation to the issues of improving sportsmanship [2, 11, 18]: the effectiveness of urgent feedback in ensuring the perfection of sports performance by improving the skill to differentiate and evaluate the main specific parameters of movements in the chosen sports specialization has been proven [10, 22].

At the same time, studies aimed at developing physical qualities through a combination of various types of BFB training are much less common; the comparative effectiveness and mechanisms for implementing the effects of various types of training in solving this problem have not been studied in detail.

The aim of the study was to investigate the physiological features of the formation of balance and coordination abilities based on training with BFB under various settings.

MATERIALS AND METHODS

The study involved 60 girls aged 18–20 years who are not engaged in sports and are included in the main medical group (health group 1), i.e., without deviations in the state of health and physical development, having a good functional condition, and age-appropriate physical fitness. The conclusion about the state of health of the girls was made based on historic data, the results of the study of the level of health and the functional state of the body, as well as medical examination that allowed the subjects to go in for physical education in the main medical group. When drawing up the research plan, the menstrual cycle phases of the subjects were taken into account. Studies of girls were carried out in the postmenstrual phase of the cycle.

Girls with a standard body type were selected for the study; students of high or short stature and with a nonstandard body length to legs ratio were excluded. The presence of diseases of the cardiovascular, neuromuscular, and musculoskeletal systems, neurological diseases incompatible with physical activity, injuries, diseases in the acute period, deficient (body mass index (BMI) below 18.5) or excessive (BMI above 25.0) body weight, obesity (BMI above 30.0), and the state of overexertion were also exclusion criteria. Participants who had experience in sports aimed at developing coordination were not included in the group either.

As a result of the selection, three groups of girls were formed so that the difference between the results of the testing of the participants in the three groups during the selection was insignificant. Twenty girls (the control group, or the Exercise group) trained according to the program, which included a set of exercises to develop the sensitivity of the vestibular analyzer and proprioceptive sensitivity. Twenty girls (the first experimental group, or the Stabilan group) practiced on a Stabilan-01-2 computer stabilizer (ZAO OKB Ritm, Russia) using feedback for the "projection position of center of gravity" parameter. The remaining 20 subjects (the second experimental group, or the HUBER group) exercised on a HUBER apparatus (LPG SYSTEMS, France) using feedback for the "applied effort" parameter. Classes were held 3 times a week for a month, a total of 12 workouts.

Before the start of the training program, as well as after it, the following types of studies were conducted with the girls for 4 days from 10:00 a.m. to 12:00 a.m.

Day 1—study using the NS Psychotest (methods "Tapping test" and "Contact coordinatiometry according to the profile"), determination of muscle accuracy using a dynamometer. These techniques are designed to assess the coordination of movements and coordination of motor actions of the subjects in space.

When performing the Tapping test, the subject was asked to make as many strokes with a "pencil" on a special platform as possible within a given time interval. The number of strokes, the average frequency of strokes (Hz), the level of manual asymmetry (s), and the average interstroke intervals for the right and left hands (s) were taken into account.

The "Contact coordinatiometry by profile" technique from the research catalog of the NS-Psychotest computer complex was used to diagnose the accuracy of the movements of the subject's hand when solving motor problems and, consequently, her ability to coordinate movements. The subject was asked to insert an aluminum rod through one of the holes of a special platform with a labyrinth at the beginning of the labyrinth to a depth of 2–3 mm and, holding the arm in the air, move the end of the rod to the end of the labyrinth as quickly as possible, trying not to touch the edges of the hole. The duration of testing (s), the number of touches (total and per second), and the total and average touch time (s) were recorded.

A muscle accuracy test was used to assess proprioceptive sensitivity. The test consisted of two stages. The first stage is the compression of the spring dynamometer by the hand to the maximum possible value. Then, the subject had to repeat the compression of the spring by a force of 50% of the initial force with closed eyes three times. The result was evaluated as a deviation from the given force (in kg).

Day 2—stabilography and EEG. Stabilographic studies were carried out using a Stabilan-01-2 computerized stabiloanalyzer with a BFB system (ZAO OKB Ritm, Russia).

The Triangle test was used to assess the level of short-term motor memory and proprioceptive sensitivity. Centering was done before recording. During testing, it was not allowed to take the feet off the platform. The test was performed using visual modality feedback. This test consists of two stages. At the analysis stage, the subject, using the maximum possible deviation of the center of pressure (CP) in three directions (forward, right-backward, left-backward) without taking their feet off the platform, had to set an acceptable location of markers, the triangle vertices, on the monitor screen. Then, within 1 min, the subject had to move her CP sequentially from one vertex to another, as the set markers would light up red describing the "triangle" figure. At the second stage, the subject also had to describe this "triangle" figure for 2 min, but without the help of the feedback function.

After the study, the deviations of the CP movement trajectory of the subject from the "triangle" figure obtained at the training stage were calculated as average systematic and random errors in the frontal and sagittal planes (mm).

An EEG was performed using a Neiron-spectr 4/P hardware–software complex (OOO Neirosoft, Russia) in the system of 10–20 leads in 8 channels (even on the right, odd on the left): frontal (Fp_1, Fp_2), area of the central sulcus (C_3, C_4), temporal (T_3, T_4), occipital (O_1, O_2) electrodes and mounting with a combined ear electrode. EEG was recorded during the following tests with closed eyes:

(1) Background recording (in a state of relative rest with closed eyes)—180 s.

(2) Test 1—a simple Romberg test with eyes closed (the subject stands without shoes with her eyes closed, her feet put tightly together, arms stretched forward, fingers relaxed and slightly apart)—10 s.

(3) Test 2—a complicated Romberg test with closed eyes (the subject's legs are on the same line (the toes of the left foot rest on the heel of the right foot). The arms are stretched forward, the fingers are relaxed and slightly apart)—10 s.

(4) Test 3—Biryuk test with closed eyes (the subject stands in a closed stance on her toes, arms up and maintains this position)—10 s.

The EEG analysis included an assessment of parameters, such as the amplitude of the spectrum and the spectral power of α- and β-rhythms. EEG symmetry was understood as a significant coincidence of the amplitudes of the homotopic divisions of both hemispheres of the brain, the difference is less than 50%.

Day 3—electromyography (EMG) on the Neiro-MVP-4 computer complex. Biopotentials of skeletal muscles were led off and registered according to the generally accepted method using a multifunctional Neiro-MVP-4 computer complex (Russia). The bioelectrical activity of the anterior tibial (*m. tibialis anterior*) and gastrocnemius (*m. gastrocnemius*) muscles of both legs was studied. The registration of the bioelectrical activity of the muscles was carried out when performing the following tests:

— a simple Romberg test—the subject stands without shoes, her feet put tightly together, arms stretched forward, fingers relaxed and slightly apart, first with open (10 s), then with closed (10 s) eyes;

— a complicated Romberg test—the subject's legs are on the same line (the toe of the left foot rests on the heel of the right). The arms are stretched forward; the fingers are relaxed and slightly apart. The subject performs the test first with open (10 s), then with closed (10 s) eyes;

— Biryuk test—the subject stands in a closed stance on toes, arms up and maintains it first with open (10 s), then with closed (10 s) eyes.

Day 4—dynamometry on the HUBER apparatus. To test the proprioceptive sensitivity of girls under conditions of additional vestibular load, a multifunctional HUBER apparatus was used. The peculiarity of the apparatus lies in the multisensory effect on proprioception, exteroception, and the patient's sense organs during isotonically isometric effort in various versions of the motor task: the speed and amplitude of the support platform movement change.

The apparatus is a motorized movable platform attached to a vertical dynamic column with built-in multi-sector handles containing sensors for measuring the applied force; interactive display for feedback with the trainee and self-regulation of motor activity in relation to various muscle groups directly involved in movement performance; coordination board for displaying information about the degree of synchronization (coordination) of the motor activity of muscles of the right and left sides of the body of the trainee when movement is performed.

The girls were then trained 3 times a week for 4 weeks, depending on the group according to one of the three programs. The performance of exercises in each program was regulated. The volume, dosage, duration, and intensity were adjusted to the load response of the body and the level of functional and technical readiness. The intensity of training increased from session to session until the middle of the course and decreased by the end of the course.

The Exercise group trained according to a program that included a set of exercises to develop the sensitivity of the vestibular analyzer and proprioceptive sensitivity without feedback. The duration of the session was 1 h.

The Stabilan group was engaged in the program of developing the sensitivity of the vestibular analyzer on a Stabilan-01-2 stabiloanalyzer by adjusting the CP movement trajectory on the support plane. The duration of the session was 30 min and consisted of stabilographic computer games of varying complexity included in the software of the apparatus and played using the BFB method. The CP position on the support plane conditionally taken as a projection of the common center of gravity of the body was the control parameter of BFB training. The proportion of time out of the total training time, in which the subject held the CP within the specified limits, served as a criterion for evaluating the effectiveness of the training. The training was assessed as successful if the specified value was 80% or more.

The HUBER group was engaged in the program of the motor analyzer (MA) development on a HUBER apparatus by adjusting the force applied to the force-measuring elements of the apparatus. The duration of the session was 1 h. The magnitude of the applied effort (bench press or deadlift) was the control parameter of BFB training. The average difference between the reference and applied effort for the period of training served as a criterion for evaluating the effectiveness of the training. The training was assessed as successful if the specified value was 80% or more of the reference effort.

The subjects from the experimental groups who could not provide the above level of training success by the fifth training session were excluded from the study.

Statistical data were processed using the Statistica 8.0 for Windows software package (Statsoft, United States). Descriptive analysis included the determination of the arithmetic mean, error of the mean "mean ± error of mean" ($X \pm m$). The Kolmogorov–Smirnov test was used to test the nature of distribution of the feature of the data obtained. Since the data did not obey the parametric distribution law, the analysis was performed using the Kruskal–Wallis ANOVA test. Data are presented as Xav ± SE. Differences in data were considered statistically significant at $p < 0.05$. To assess the relationship between the values of the bioelectrical activity of different muscle groups, the Spearman rank correlation coefficient (ρ) was used.

RESULTS

The results indicate the presence of significant features in the implementation of the effects of various types of training aimed at the formation of coordination abilities and balance in athletes.

According to the results of the Tapping test, after the course of training there was a significant decrease in the manual asymmetry value (i.e., the difference in the interstroke intervals of the right and left hands) in the first and third groups, the exercises in which included, among other things, work with the upper limbs (for strength, endurance, and proprioceptive sensitivity) (Fig. 1d).

When testing was performed according to the "Contact coordinatiometry for the profile" method in the Stabilan group, a decrease in such indicators as the number of touches was observed after a course of training. At the same time, the average touch time significantly decreased. Thus, we can state an increase in the speed of correcting errors that occur in the Stabilan group subjects after a course of training, which may indicate an improvement in the nervous regulation of movements (Fig. 1b).

Testing according to the "Dynamometry" method after a course of training revealed a significant decrease in the mean error in the Stabilan and HUBER groups during testing with the left hand and the eyes closed (Fig. 1a). This may indicate an improvement in the visibility of the applied efforts without the participation of a visual analyzer and their more correct dosing after training with BFB in the Stabilan and HUBER groups. The same index for the Exercise group also decreased, but only slightly. Training without the use of BFB appeared to be the least effective in this aspect.

Figure 2 shows the results of the stabilographic analysis of the Triangle test performance. In all groups, there is a significant decrease in the indicators of displacement of the common center of gravity (CCG) in the frontal plane and the average speed of the CP movement, the value of the average random error in the frontal and sagittal planes at the analysis stage in comparison with the training stage. After training in the Exercise group, a significant increase was noted in the average systematic error in the frontal plane at the analysis stage in comparison with the training stage. The subjects from the Stabilan and HUBER groups showed a significant decrease in this value at the stages of training and analysis in comparison with the results shown before the training course.

To test the proprioceptive sensitivity of girls under additional vestibular load conditions, the multifunctional HUBER apparatus was used.

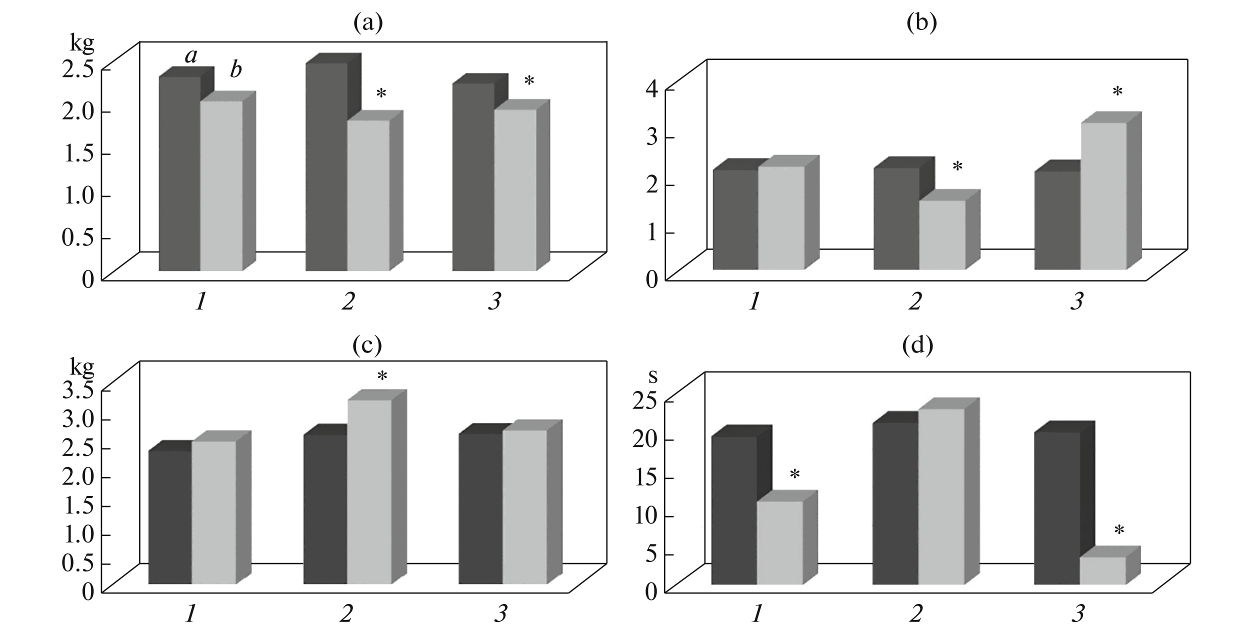

Fig. 1. The results of psychophysiological testing of athletes after various types of training. (a) Dynamometry: average error for the left hand, kg. (b) Contact coordinatiometry for the profile: the number of touches per second. (c) Dynamometry: average error for the right hand, kg; (d) Tapping test: manual asymmetry index, s. (*1*) Exercise group; (*2*) Stabilan group; (*3*) HUBER group. (*a*) Before the training course; (*b*) after. *, significance of differences with the results before the course of training ($p < 0.05$).

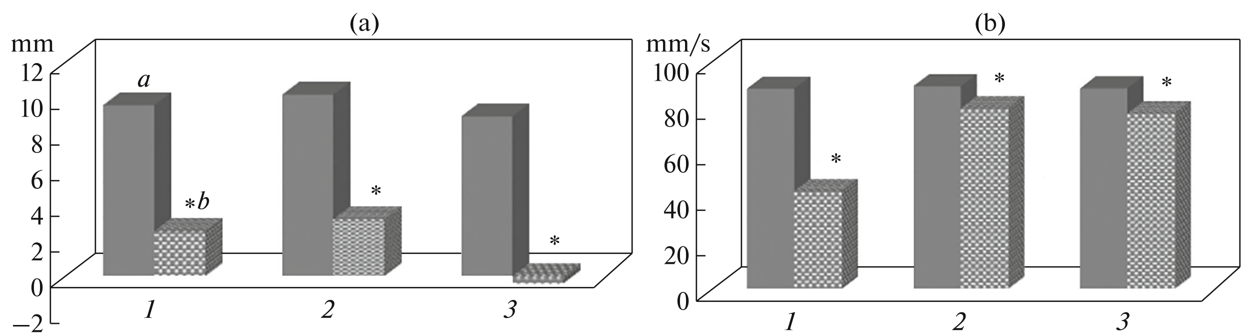

Fig. 2. Stabilographic indicators of the Triangle test before and after the course of training. (a) Displacement of the common center of gravity (CCG) in the frontal plane. (b) The average speed of CCG movement. (*1*) Exercises group; (*2*) Stabilan group; (*3*) HUBER group. Dark bars, before the training course; shaded bars, after the training course. *, significance of differences with the result before the training course, $p < 0.05$.

The most balanced efforts to reproduce the reference effort and the same work of both hands in the "Press" and "Deadlift" exercises from the "arms parallel, legs parallel" position were shown by the HUBER group, which indicates the development of proprioceptive sensitivity.

The least balanced in terms of the degree of compliance with the reference effort and the uniform work of both hands, especially in the "Press" exercise, were the results shown by the Stabilan group, in which, despite a more developed sense of dynamic balance (judging by the results of testing on the stabiloplatform), muscle sensitivity and endurance, especially of the upper limbs, did not attain an appropriate level of development during training (Fig. 3). In the Exercise group, despite significant differences between the reference and reproduced results shown by testing after training, in comparison with the results before the training course, an increase was noted in the average time to reproduce the reference result, an indicator on the basis of which the level of coordination of the subject's work is assessed.

Various types of training also contribute to the formation of various muscle stereotypes, which are realized when tests for balance and coordination are performed (Fig. 4, Table 1). During training without the

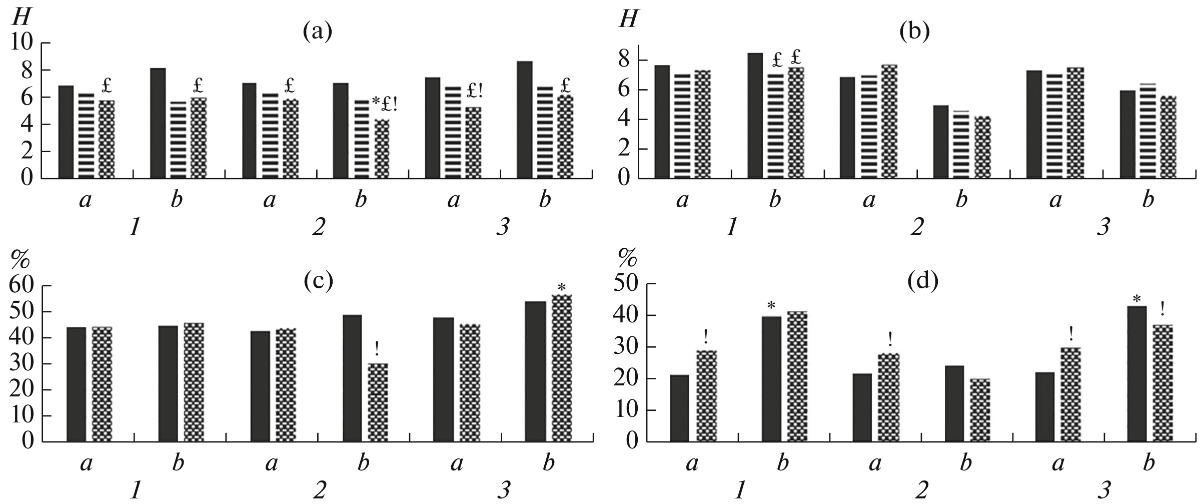

Fig. 3. The results of the exercise performed by the girls from the "hands parallel, legs parallel" position on the HUBER simulator before and after training. (a) The efforts shown during the bench press. (b) The efforts shown during the deadlift. Dark columns are the reference result, horizontal shading is the reproduced result (left hand), and mesh shading is the reproduced result (right hand). (c) The average reference duration of reproduction of the reference effort during the bench press. (d) the average reference duration of reproduction of the reference effort during deadlift. Dark bars are the left hand; shaded bars are the right hand. (*1*) Exercise group; (*2*) Stabilan group; (*3*) HUBER group. (*a*) Before the training course; (*b*) after the training course. * Is the significance of differences with the result before the course of training, $p < 0.05$. £ is the significance of differences in the group between the reference value and the reproduced result, $p < 0.05$. ! is the significance of differences in the group between the right and left hand parameters, $p < 0.05$.

use of BFB technologies, the stereotypes of muscle activity remained practically unchanged.

When the Romberg test with open eyes was performed before the course of training, the posture in about 80% of cases was maintained due to the active tension of the calf muscles; in about half of the cases, the right and left calf muscles were not equally involved (Spearman's rank correlation coefficient $\rho = 0.87$; $p < 0.05$). In the remaining 20% of cases, the main bioelectrical activity was observed in the right leg muscles ($\rho = 0.15$; $p > 0.05$), which may indicate an uneven distribution of weight between the legs. Greater involvement of the calf muscles in the work may indicate that the body is kept from tipping forward and the weight is transferred more to the forefoot.

When this test was performed with closed eyes, the bioelectrical activity of the muscles under consideration was higher in about 60% of cases than with open eyes; a uniform distribution of weight between the feet of both legs was observed in about 60% of cases ($\rho = 0.82$; $p < 0.05$); the greatest involvement of the gastrocnemius muscles was noted in about 20% of cases ($\rho = 0.21$; $p > 0.05$); and in 20%, alternating weight transfer from foot to foot, which was expressed in the corresponding bursts of EMG activity. Thus, we observed a nonuniform distribution of the load between tense muscles, as well as inconsistent activation of the muscles in the work. After a course of training, all three groups showed an increase in the degree of coordination in the work of the calf muscles during Romberg test performance, and the most pronounced rise was in the HUBER ($\rho = 0.87$; $p < 0.05$) and Stabilan ($\rho = 0.83$; $p < 0.05$) groups due to the specifics of the types of training.

A distinctive feature of the results in the Exercise group after the course of training was the predominance of the pattern of selective activity of individual motor units not synchronized with the muscles under study. The Stabilan group was characterized by a greater proportion of the posture maintenance pattern over the entire duration of the test, as well as more coordinated work of the muscles involved in maintaining this posture, which was expressed in the simultaneous appearance or disappearance of the static effort maintenance pattern during the task ($\rho = 0.79$; $p < 0.05$). In the HUBER group, there was consistency in the work of the gastrocnemius muscles in the format of reciprocal interaction of antagonist muscles ($\rho = 0.76$; $p < 0.05$); the proportion of the posture maintenance pattern during the test was less than in the Stabilan group, and, in addition to the static effort maintenance patterns, there were patterns of selective activity of individual motor units, which can be considered as one of the feedback-based mechanisms for movement correction [22].

When performing a complicated Romberg test with closed eyes after traning, a decrease in the amplitude and frequency of impulses was noted in all groups. In the Stabilan and HUBER groups, the static tension retention pattern was more uniform and without significant amplitude and frequency bursts, and muscle

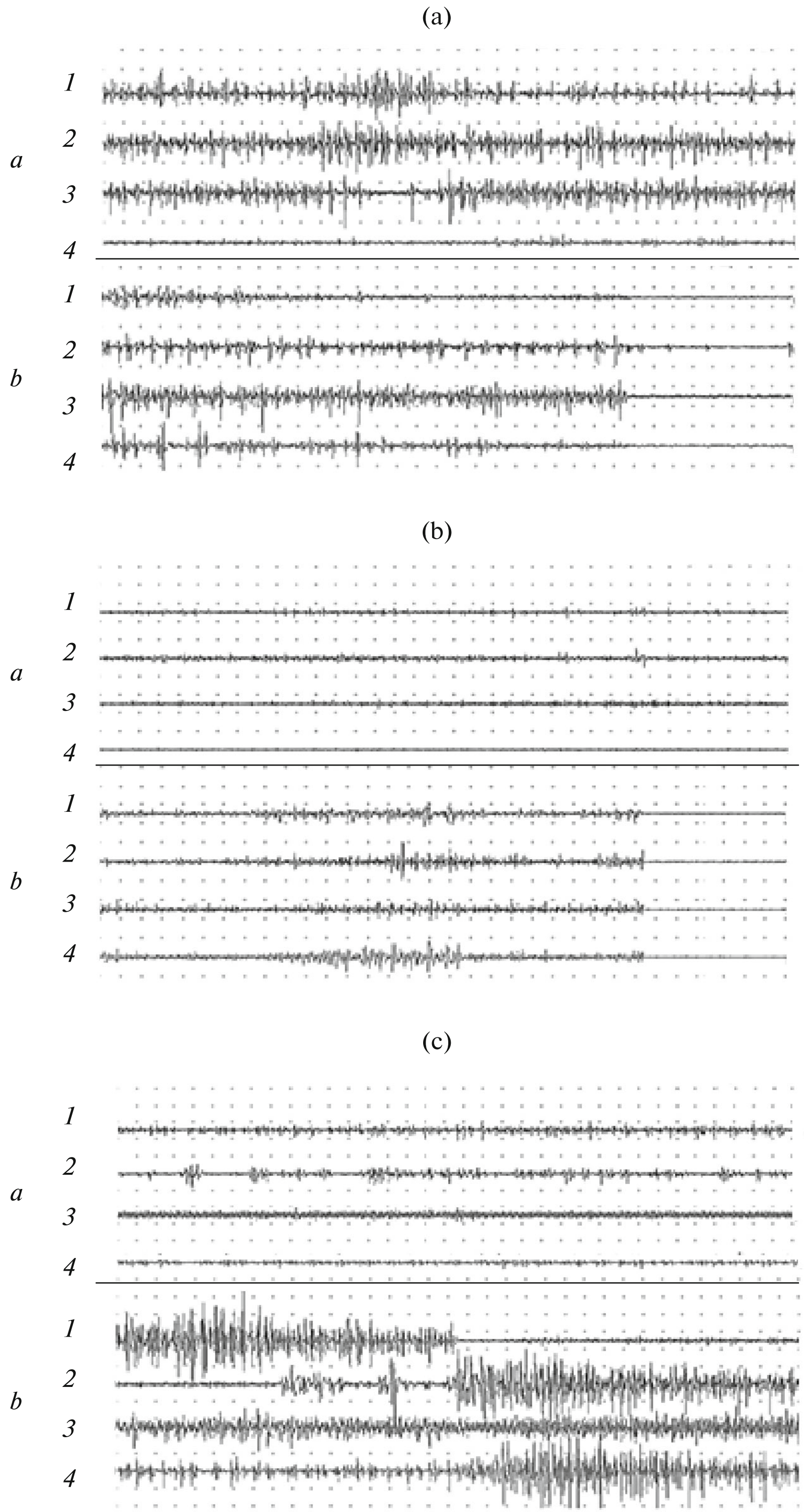

Fig. 4. Surface electromyography (EMG) during the execution of Biryuk test. (a) Exercise group; (b) Stabilan group; (c) HUBER group. (*a*) Before training; (*b*) after training. *1*, Left anterior tibial muscle; *2*, left gastrocnemius muscle; *3*, right gastrocnemius muscle; *4*, right anterior tibial muscle. The time mark is 0.25 s; the amplitude mark is 50 μV.

Table 1. Characteristics of the average amplitude of muscle bioelectrical activity, μV during balance tests, $M \pm m$

Test	Muscles	Exercises group		Stabilan group		HUBER group	
		before training course	after training course	before training course	after training course	before training course	after training course
Simple Romberg test with eyes open	Left anterior tibial	142.4 ± 28.1	179.8 ± 80.9	136.2 ± 22.9	33.4 ± 5.6$^{*, £}$	137.3 ± 35.6	38.0 ± 4.8$^{*, £}$
	Left gastrocnemius	239.2 ± 20.3	291.2 ± 12.5	242.7 ± 22.2	53.0 ± 11.8$^{*, £}$	233.7 ± 39.0	95.4 ± 12.9$^{*, £, \#}$
	Right gastrocnemius	640.4 ± 41.0	550.4 ± 55.2	598.3 ± 22.0	120.1 ± 18.7$^{*, £}$	556.9 ± 34.4	140.2 ± 15.2$^{*, £}$
	Right anterior tibial	207.6 ± 19.2	280.2 ± 19.9*	212.5 ± 18.4	42.1 ± 12.4$^{*, £}$	198.1 ± 7.5	32.5 ± 5.2$^{*, £}$
Simple Romberg test with eyes closed	Left anterior tibial	430.4 ± 43.3	450.6 ± 49.4	427.7 ± 24.6	156.8 ± 25.7$^{*, £}$	404.9 ± 55.6	207.0 ± 32.9$^{*, £}$
	Left gastrocnemius	403.8 ± 38.8	413.4 ± 46.4	413.1 ± 24.0	183.8 ± 18.3$^{*, £}$	397.37 ± 10.5	38.0 ± 9.8$^{*, £, \#}$
	Right gastrocnemius	741.4 ± 37.4	793.0 ± 29.9	720.7 ± 73.0	85.2 ±9.5$^{*, £}$	684.9 ± 33.0	201.2 ± 19.8$^{*, £, \#}$
	Right anterior tibial	134.7 ± 12.46	138.2 ± 11.7	131.6 ± 18.4	140.8 ± 25.6	127.9 ± 18.5	51.2 ± 9.5$^{*, £, \#}$
Complicated Romberg test with eyes open	Left anterior tibial	453.2 ± 35.3	462.0 ± 56.1	448.5 ± 73.67	150.6 ± 36.1$^{*, £}$	425.8 ± 22.7	190.2 ± 22.9$^{*, £}$
	Left gastrocnemius	217.4 ± 56.5	160.7 ± 46.9	210.7 ± 38.3	127.6 ± 27.0*	199.4 ± 40.7	117.2 ± 29.6*
	Right gastrocnemius	555.6 ± 44.7	527.0 ± 79.7	468.3 ± 23.4	29.2 ± 19.4$^{*, £}$	443.5 ± 198.3	129.7 ± 17.4$^{*, £}$
	Right anterior tibial	190.2 ± 13.7	196.4 ± 60.2	186.9 ± 18.4	161.0 ± 17.4	184. 3 ± 20.6	82.2 ± 11.4$^{*, £, \#}$
Complicated Romberg test with eyes closed	Left anterior tibial	663.6 ± 36.3	695.4 ± 40.89	642.5 ± 32.6	251.0 ± 21.7$^{*, £}$	582.4 ± 259.6	273.2 ± 19.9$^{*, £}$
	Left gastrocnemius	398.2 ± 34.7	374.3 ± 83.6	349.1 ± 47.5	240.8 ± 18.5$^{*, £}$	357.4 ± 29.3	148.7 ± 33.2$^{*, £, \#}$
	Right gastrocnemius	645.2 ± 25.7	553.0 ± 68.8	617.4 ± 82.6	170.0 ± 12.7$^{*, £}$	632.2 ± 22.5	232.7 ± 48.7$^{*, £}$
	Right anterior tibial	315.0 ± 45.3	322.2 ± 33.8	310.5 ± 37.6	220.4 ± 15.5$^{*, £}$	321.6 ± 24.0	172.5 ± 29.6$^{*, £}$
Biryuk test with eyes open	Left anterior tibial	188.6 ± 61.2	166.6 ± 16.9	195.2 ± 63.1	399.8 ± 17.1$^{*, £}$	191.7 ± 18.0	177.5 ± 14.8$^{\#}$
	Left gastrocnemius	308.5 ± 33.7	293.8 ± 26.0*	321.4 ± 29.6	251.0 ± 32.5*	301.8 ± 31.4	141.5 ± 30.9$^{*, £, \#}$
	Right gastrocnemius	374.0 ± 19.6	307.0 ± 38.9*	387.3 ± 28.4	178.6 ± 23.1$^{*, £}$	357.4 ± 47.3	253.1 ± 49.3*
	Right anterior tibial	311.7 ± 82.3	314.6 ± 12.4	309.4 ± 76.7	333.0 ± 50.7	337.1 ± 88.6	252.7 ± 68.5
Biryuk test with eyes closed	Left anterior tibial	301.0 ± 32.2	295.4 ± 7.7	313.1 ± 31.9	223.0 ± 24.2$^{*, £}$	296.1 ± 37.1	226.7 ± 28.5$^{£}$
	Left gastrocnemius	351.0 ± 23.4	292.6 ± 25.8	366.3 ± 38.4	239.7 ± 27.2*	323.9 ± 64.1	157.5 ± 36.5$^{*, £, \#}$
	Right gastrocnemius	375.5 ± 34.7	352.80 ± 43.7	389.4 ± 43.9	179.0 ± 13.6$^{*, £}$	367.9 ± 44.3	296.5 ± 71.7$^{\#}$
	Right anterior tibial	403.7 ± 54.3	379.2 ± 29.4	397.4 ± 57.4	367.5 ± 75.8	384.9 ± 64.8	307.0 ± 80.8

*, significance of differences with the results before the training course, $p < 0.05$; $^{£}$, significance of differences with the Exercise group, $p < 0.05$; $^{\#}$, significance of differences between the Stabilan group and the HUBER group values, $p < 0.05$.

tension and relaxation were more consistent ($\rho = 0.84$ and $\rho = 0.81$, respectively; $p < 0.05$) than in the Exercise group ($\rho = 0.72$; $p < 0.05$). At the same time, while the Stabilan group demonstrated a simultaneous activation of all the muscles, which is typical of static work, in the HUBER group, there was a reciprocal activation in the work of antagonist muscles, which may indicate a method for solving the problem of maintaining static balance through a more dynamic body weight movement over the support than in the Stabilan group.

When performing the Biryuk test with closed eyes after a course of training, a decrease in amplitude and frequency parameters was recorded in all the groups under study, especially in the Stabilan and HUBER groups. In these groups, the fluctuations in bioelectrical activity were more smoothed and had more marked periods of voltage rise and fall, which indicates a well-coordinated activation of the work of motor units. In addition, in all the groups (especially in Stabilan and HUBER), periods of synchronized muscle impulse activity are clearly defined.

In the Exercise group, when the Biryuk test was performed with closed eyes after a course of training, periods of coordinated work of the lower leg muscles were recorded ($\rho = 0.65$; $p < 0.05$), but they were less pronounced than in other groups and also included both periods of maintaining balance through the simultaneous tension of all calf muscles and periods of maintaining balance in the reciprocal work mode. In the Stabilan group, either simultaneous tension of all studied muscles ($\rho = 0.75$; $p < 0.05$) or weight transfer with a slight increase in amplitude from one leg to the other with simultaneous tension of the ipsilateral muscles were observed. In the HUBER group, in addition to the uniform distribution of tension between the studied muscles ($\rho = 0.80$; $p < 0.05$) and the simultaneous tension of the muscles of one leg, both anterior tibial or gastrocnemius muscles, as well as the anterior tibial and gastrocnemius muscles of contralateral legs, were brought into work simultaneously. In contrast to the Exercise group, coordination in the work of muscles in the HUBER group was more clearly defined ($\rho = 0.89$; $p < 0.05$), without excessive impulse activity of individual motor units during test performance.

In the group of subjects who trained without the use of BFB, in most cases there was no marked localization of the average spectral power of the EEG α- and β-ranges in one or another area of the cortex during test performance; all areas of the cortex were involved approximately equally; changes in the amplitude of the EEG spectrum from test to test, as well as changes in the power of the EEG spectrum, were least pronounced.

Differences were also recorded along with similar effects after training with BFB (increased α-activity mainly in the occipital region of the cortex and activation of high-frequency EEG β-activity in the occipital leads). If after training, using the "projection position of the center of gravity" parameter as a BFB channel, we observed a decrease (desynchronization) in the activity of the EEG α- and β-ranges in comparison with the results before the training course, a consistent increase in the EEG α- and β-activity during the gradual complication of the task, and rare changes in the spatial localization of rhythms from trial to trial, then training using the "applied efforts" parameter as a BFB channel, on the contrary, contributed to an increase in the average power of EEG α-activity in the central region of the cortex, an increase in the activity of EEG rhythms in various areas of the brain, significant interhemispheric asymmetry of EEG rhythms, and frequent spatial change of localized EEG patterns on the convexital surface from test to test (Figs. 5 and 6).

DISCUSSION

Trainings with the use of BFB for the "projection position of the center of gravity" and "efforts applied in the position of searching for dynamic balance" parameters allow us to develop proprioceptive sensitivity, distinguishability of the applied efforts, to diminish the significance of the visual analyzer (in the group of those who trained with BFB for the "efforts applied in the position of searching for dynamic balance" parameter), as well as to improve intermuscular coordination and muscle memory, over a relatively short time (1 month) more noticeably than during training without BFB.

After training with BFB in terms of the "projection position of the center of gravity" parameter, the development of a sense of balance occurs due to the improvement of the neuromuscular control over the CP position when performing dynamic tests, which shows up in the increase in the degree of stability (the ability to keep balance over a larger area relative to the support) [23, 24]. This, in addition to the coordination of muscle work, is manifested by an increase in the degree of concentration and by the ability to maintain this concentration for a long time while keeping balance [22], which is reflected in the parameters of bioelectrical activity in the cerebral cortex [2].

A characteristic feature of the formation of a sense of balance and coordination after training with BFB in the "applied efforts in the position of search for dynamic balance" parameter is the development of the ability to maintain static stability during distraction to perform parallel mental operations, to coordinate the work of muscles of the whole body, and to correctly dose the applied efforts. Similar results were obtained by the authors when using the HUBER system in the practice of physical rehabilitation [25] and in assessing the psychophysiological status [26]. In the available literature, we did not find works containing an analysis of the results of using the HUBER simulator for improving the skills of athletes. However, the

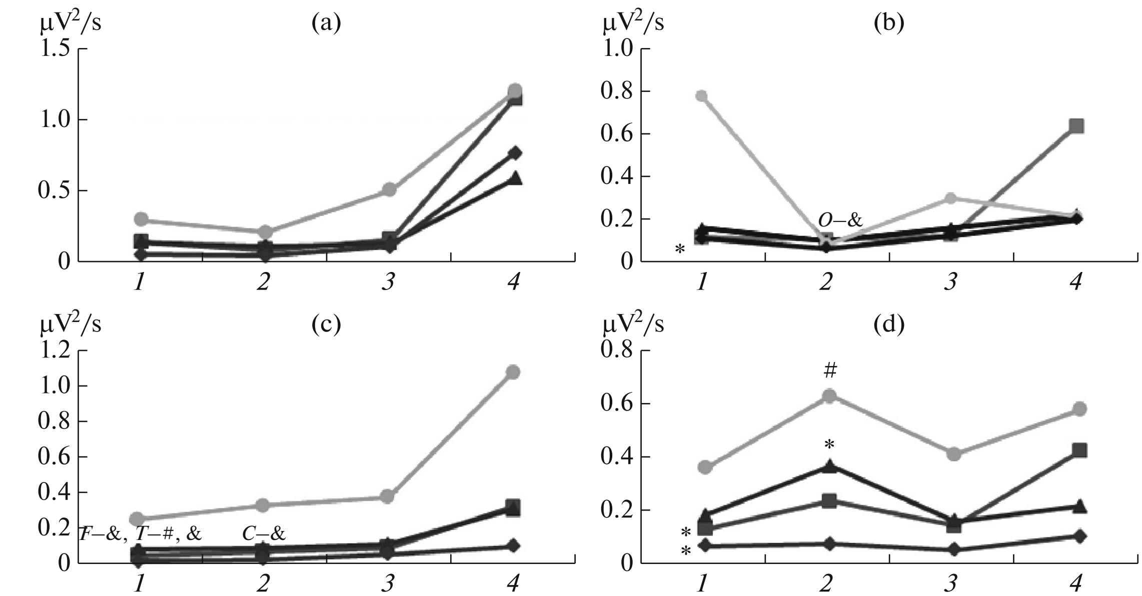

Fig. 5. The average power of the electroencephalogram (EEG) α-activity spectrum before and after the training course, μV^2/s. (*1*) Indicators of background recording; (*2*) indicators during the execution of a simple Romberg test; (*3*) indicators during the execution of a complicated Romberg test; (*4*) indicators during the execution of Biryuk test. Leads: squares, *F*; triangles, *C*; circles, *O*; diamonds, *T*. (a) Before the course of training; (b) after the course of exercises; (c) after the course of training with BFB on the Stabilan apparatus; (d) after the course of training with BFB on the HUBER apparatus. #, statistically significant differences between indicators when compared with the Exercises group ($p < 0.05$); *, statistically significant differences between indicators when compared with group 2, ($p < 0.05$), &, statistically significant differences between indicators when compared with group 3 ($p < 0.05$).

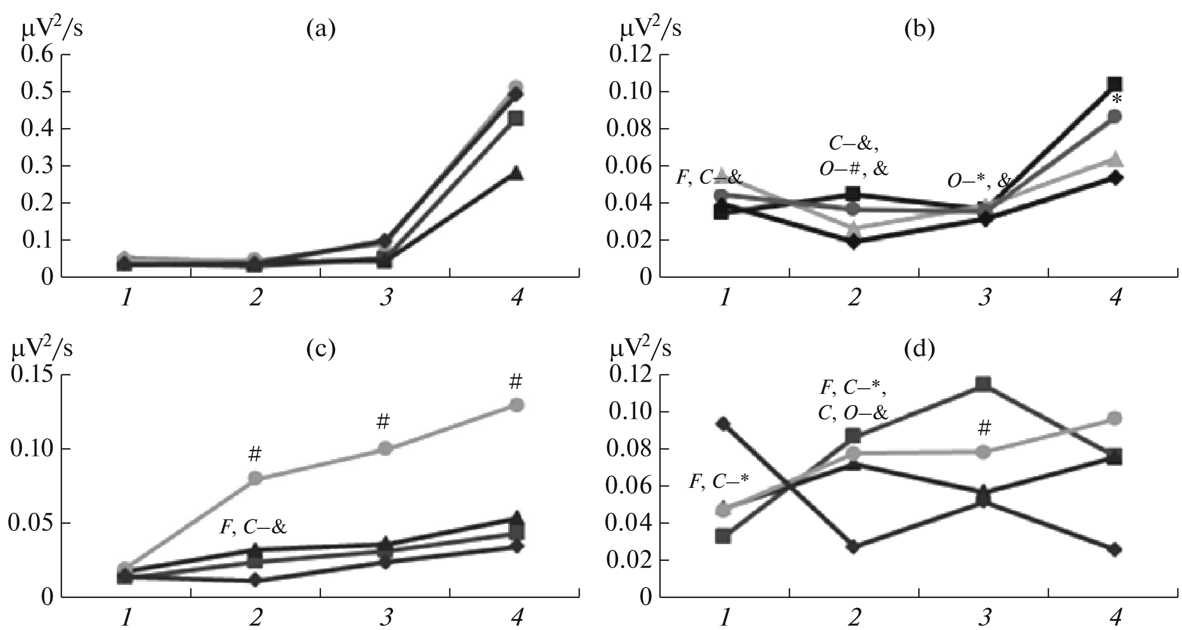

Fig. 6. The average spectral power of the electroencephalogram (EEG) low-frequency β-activity before and after the training course, μV^2/s. See Fig. 5 for designations.

existing experience of teaching the differentiation of applied efforts using special exercises [27] is indicative of the promise and high efficiency of this approach.

It can be thought that the mechanism of maintaining balance after training with BFB for the "efforts applied in the position of searching for dynamic balance" parameter is characterized by a constant change in the foci of concentration of bioelectrical activity in the cerebral cortex and frequent movement of body weight over the support in the process of keeping static balance without visual control, which is noted during fixation of the bioelectrical activity of muscles. One can talk about a more dynamic process of searching for a stable balance in comparison with training with BFB for the "projection position of the center of gravity" parameter.

The data obtained on the highest efficiency of biocontrol in terms of the "applied efforts in the position of searching for dynamic balance" parameter can be explained from the standpoint of the theory of functional systems by P.K. Anokhin [28]. One of the key elements of this theory is the need for feedback and current corrective actions to ensure the optimal nature of the motor action. Of the three methods of training used in our study, it is this type of training that involves the largest number of analyzers in the work providing a significant amount of urgent information in the process of movement performance, which, in turn, provides the best opportunity for learning to correct motor actions.

Various types of training also contribute to the formation of various muscle stereotypes that are implemented when balance and coordination tests are performed. When training was performed without the use of BFB technologies, the stereotypes of muscle activity remained practically unchanged. These results are consistent with literature data indicating that the restructuring of muscle stereotypes is a long process that requires targeted approaches [29]. At the same time, the formation of new patterns of muscle activity is one of the mechanisms for improving the level of proficiency of an athlete [30, 31].

A characteristic feature of the bioelectrical activity of the lower leg muscles while maintaining static balance without visual control after training with BFB for the "projection position of the center of gravity" parameter is their activation in a static mode (simultaneous activation of antagonist muscles with commensurate indicators of bioelectrical activity), which may testify to maintaining balance with minimal fluctuations of the CP relative to the support.

At the same time, a feature of the bioelectrical activity of the lower leg muscles while maintaining static balance without visual control after training with BFB in terms of the "efforts applied in the position of search for dynamic balance" parameter is their activation in the dynamic mode (with a synchronized alternation of periods of tension and relaxation in the agonist and antagonist muscles), which may provide evidence of the preservation of balance due to more pronounced CP movements relative to the support than in the group trained with BFB according to the "projection position of the center of gravity" parameter.

This stereotype is the most difficult in terms of its formation [32]. According to the theory of N.A. Bernstein, alternate synchronous movements are provided by higher levels of regulation and require the involvement of more complex mechanisms. Simultaneous muscle contractions are realized at lower levels of motion control. Therefore, it can be concluded that training with BFB for the "efforts applied in the position of search for dynamic balance" parameter contributes to the activation of such movement control mechanisms that are provided by the overlying divisions of the central nervous system.

It is necessary to note the specificity of the EEG rhythm patterns for each of the groups in the process of test performance to maintain balance. The possibility of such rearrangements of the bioelectrical activity of the brain has been described for various methods of biocontrol [33].

The results of the study of the bioelectrical activity of the cortex are in good agreement with the data of E.V. Krivonogova et al. [34], who revealed the presence of different types of EEG changes during training with BFB for heart rhythm. The types they discovered reflect variants of neuron integration in functional systems to optimize the balance of sympathetic and vagotropic mechanisms, which can be accompanied by multidirectional changes in the power of the EEG α-, β-, and θ-components in all parts of the brain.

According to the concept of G.G. Knyazev [35], various aspects of control of motor reactions (preparation, execution and inhibition of movement, "motor attention," and others) are associated with the activity of various oscillatory systems of the brain. In particular, there is a specific relationship between β-activity and the inhibition of motor reactions, which confirms mutual independence of the processes that ensure the activation and inhibition of movements. The results obtained by us are in good agreement with this concept, it may be suggested that the BFB option for the "applied efforts in the position of searching for dynamic balance" parameter involves the oscillatory systems of the brain to the greatest extent, thereby contributing to the optimal combination of excitation and inhibition processes due to which the best training results are ensured.

There is no consensus in the literature concerning the interpretation of the physiological significance of different ranges of bioelectrical activity of the cerebral cortex. At the same time, there is evidence of a relationship between its certain patterns and the formation of motor skills [36]. Obviously, the use of traditional forms of training in our case did not allow us to achieve noticeable neurophysiological changes during the study period. This is also evidenced by the results obtained by L.P. Cherapkina [2]: she showed that during traditional types of training, differences in the characteristics of the background EEG between groups of athletes can be recorded even in cases when load efficiency was the same. On the contrary, the use of simulators with BFB led to significant changes in EEG parameters. The activation of high-frequency β-activity in the occipital leads characteristic of both methods of BFB training is interpreted as a sign of tension, a focus on the performed action and is associated with the formation of sportsmanship. A similar picture is described in several studies [37, 38] that show the possibility of the formation of specific EEG patterns during training of various directions.

The situation looks contradictory in relation to the α-range activity [35, 39]. On the one hand, high activity is more often characterized by a decrease in this EEG component, which can be interpreted as a manifestation of the desynchronization effect, an increase in cortical tone and activity of the reticular formation desynchronizing the main EEG rhythm. On the other hand, there is evidence of an increase in the α-range activity when physical activity is combined with cognitive task performance. In this case, there is a decrease in cortical tension, an emphasis on increased activity of median, diencephalic structures, a transition to the mode of internal focus on visceral sensations, and activation of attention processes [40]. It may be suggested that exercise performance with BFB for the "efforts applied in the position of search for dynamic balance" parameter requires greater involvement of neuronal ensembles responsible for the processes of proprioceptive perception, autonomic regulation, attention concentration, as well as for the formation of an adaptive individual strategy of biocontrol.

Apparently, the result of the identified features of the mechanisms for implementation of the effects of training with BFB in various parameters is the difference in the effectiveness of these trainings, in the success of the formation of several important skills in athletes. The results allow us to determine the differences in the mechanisms underlying the strategy for solving problems of balance and coordination, which is formed in the subjects after various types of training, including training with BFB (Fig. 7). BFB during training contributes to the accelerated formation of skills for solving problems of keeping balance through the development of a system of neuromuscular regulation of movements: the appearance of clearly defined foci of concentration at the level of the cerebral cortex and synchronized work of the muscle groups involved in maintaining balance. There is also an increase in the sensitivity of the proprioceptive analyzer, which allows one to perform movements more accurately.

CONCLUSIONS

The results allow us to conclude that training with BFB contributes to the accelerated formation of the balance maintenance skill. After training with BFB for the "efforts applied in the position of searching for dynamic balance" parameter, there is a more rapid development of the ability to maintain static stability during distraction to perform parallel mental operations than in training with BFB for the "projection position of the center of gravity" parameter, which characterizes this variant of training as more effective, especially in the eyes closed position.

Training with the use of BFB allows one to quickly develop proprioceptive sensitivity, the ability to differentiate applied efforts without the participation of a visual analyzer, as well as to improve intermuscular coordination and muscle memory. After training with BFB for the "projection position of the center of gravity" parameter, the development of a sense of balance occurs due to an increase in the efficiency of control over the CP position, while after training with BFB for the "applied efforts in the position of searching for dynamic balance" parameter, the ability to maintain static stability during distractions to perform parallel mental operations, to coordinate the work of muscles, as well as to correctly dose the applied efforts, is more successfully formed.

A characteristic feature of the bioelectrical activity of the lower leg muscles while maintaining static balance after training with BFB in terms of the "projection position of the center of gravity" parameter is the activation of the lower leg muscles in the static mode (simultaneous activation of antagonist muscles with commensurate indicators of bioelectrical activity). At the same time, after training with BFB for the "efforts applied in the position of searching for dynamic balance" parameter, activation of the calf muscles in the dynamic mode (with a synchronized change in periods of tension and relaxation in the antagonist muscles) is observed.

A more marked effect of training with BFB on the EEG frequency and power characteristics is observed in comparison with traditional training. Training with BFB according to the "projection position of the center of gravity" parameter is accompanied by a decrease in EEG power as a reflection of the effect of nonspecific generalized desynchronization and structural rearrangement of EEG rhythms in comparison with BFB training according to the "applied efforts in the position of search for dynamic balance" parameter, which contributed to EEG activation, more specific in frequency characteristics and spatial localization, which reflected more differentiated and directed structural changes in the activity of the cerebral cortex.

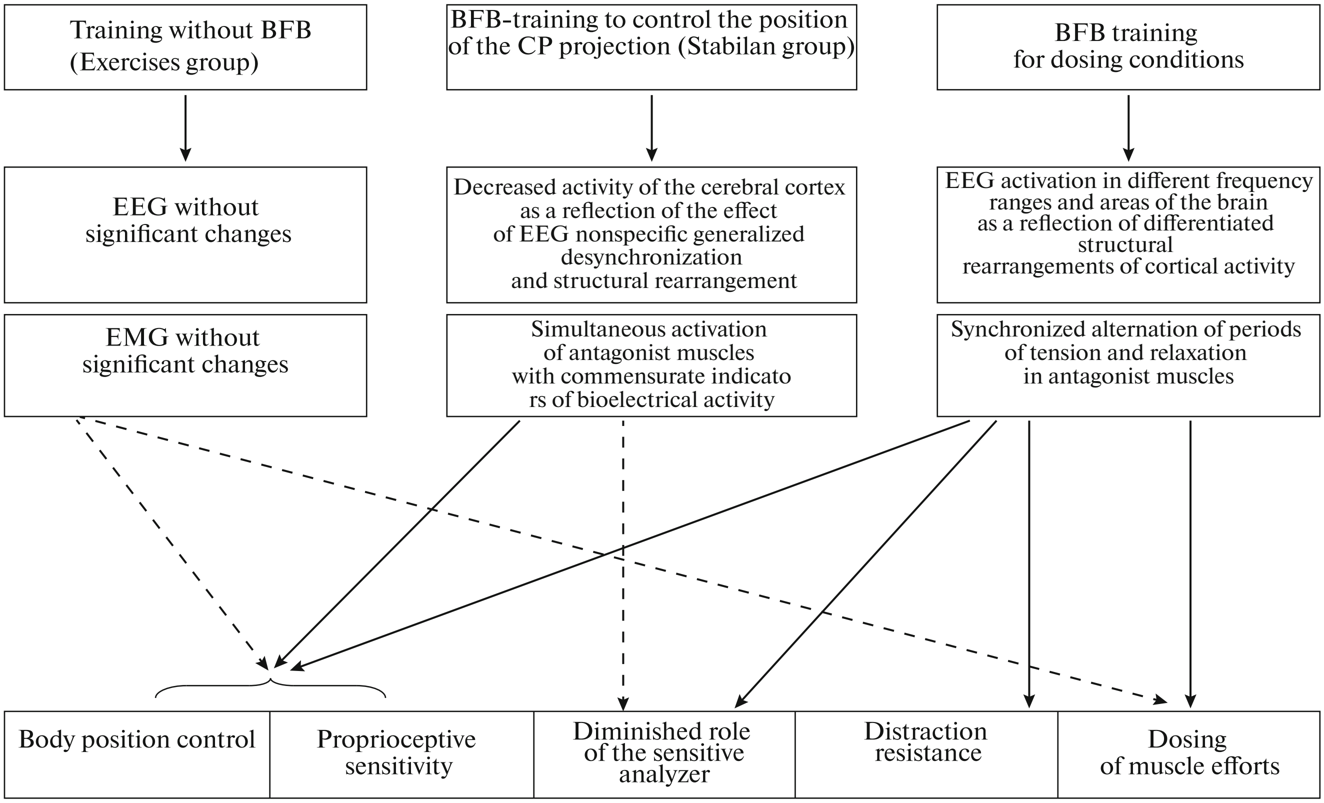

Fig. 7. The physiological characteristics and the effectiveness of various types of training.

The results also allow us to formulate several practical recommendations. All the methods studied, both with BFB and without BFB, are aimed at the formation of coordination abilities and balance; therefore, they can be used in those sports that place high demands for these qualities. These are, first of all, martial arts, many team sports, gymnastics, acrobatics, etc. It is advisable to use these methods at different stages of sports improvement. At the initial stages, it is worth starting with regular exercises without BFB, this option is more effective for the formation of entry-level skills. At the intermediate level, it is possible to use BFB on a stabiloplatform, and for more qualified athletes it is advisable to use HUBER, this technique contributes to the formation of higher-level skills and to a greater extent involves the resources of the overlying parts of the nervous system in their formation.

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COMPLIANCE WITH ETHICAL STANDARDS

All procedures performed in studies involving human participants were in accordance with the biomedical ethics principles formulated in the 1964 Helsinki Declaration and its later amendments and approved by the local bioethical committee of the Biological Institute of the National Research Tomsk State University (Tomsk).

Conflict of interests. The authors declare that they do not have a conflict of interest.

Informed consent. Each study participant provided a voluntary written informed consent signed by him after explaining to him the potential risks and benefits, as well as the nature of the upcoming study.

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