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ESTIMATION OF ATHLETE COORDINATION ABILITIES BASED ON THE REPRODUCIBILITY ANALYSIS OF THE ELECTROMYOGRAPHIC PATTERNS OF COMPLEX COORDINATION MOVEMENTS

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Abstract. Coordination abilities are the integral components in estimation of an athlete's physical preparedness and movement capabilities. The paper describes an original approach to the estimation of athletes coordination abilities based on the construction and analysis of electromyographic patterns of complex coordination movements. The maximum informative test exercises with a complex motion structure are recommended. Reproducibility analysis of the electromyographic patterns of motion tests under the influence of external destabilizing factors is proposed. The following factors were chosen as external perturbing ones: disabling the visual and disabling the sound analyzer of a person. The coefficients describing the individual informative components of the athletes' coordination abilities are presented: the coefficient of influence of the visual analyzer (γ) and the coefficient of influence of the sound analyzer (τ) on the stability of reproduction of the movements with a complex coordination structure. Research of the coordination abilities of young athletes, specializing in tennis and figure skating, are presented. For young athletes, specializing in figure skating, the coefficient of influence of the visual analyzer is $\gamma = 2.09 \pm 0.49$, the coefficient of influence of the sound analyzer is $\tau = 1.98 \pm 0.58$. For young tennis players, the coefficient of influence of the visual analyzer is $\gamma = 1.97 \pm 0.48$, the coefficient of influence of the sound analyzer is $\tau = 2.12 \pm 0.61$. In addition, a significant correlation between the age of the athlete and the coefficient of the influence of the visual analyzer has also been established. The Pearson correlation coefficient for skaters is $r = -0.63$, and for tennis players – $r = -0.62$. These indicates about the improvement of such component of coordination abilities with age. The recommendations on the practical use of the research results for young athletes are given.

Keywords: *coordination abilities, multichannel electromyography, electromyographic motion pattern, digital signal processing, statistical analysis.*

I. Introduction

Estimation of human coordination abilities is the pressing problem for various areas: physical education, sports, work and military activities, sports and diagnostic medicine [1-3].

Coordination abilities of the human are understood as preparedness for optimal control of the motion action and regulation of it [4]. Basic coordination abilities have a wide range of applications and include: the ability to orientate in space, differentiate muscular sensations and regulate the degree of muscle tension, respond to signals from the external environment, the ability to keep static and dynamic balances, a sense of rhythm [5].

The efficiency of the implementation of complex coordination actions depends on a number of factors, as well as on their combination and interaction between them [6]. The level of technical preparedness largely determines the realization of the athlete's accumulated capabilities and other components of training, such as physical, tactical and coordination capabilities of the athlete [7].

The functional complexity and multi-component organization of the human motor system determines the need for a multipurpose approach to the study of complex coordination movements of human body. The concept of such approach is to consider jointly both external motion characteristics (biomechanical parameters of motion) and internal control mechanisms (electrophysiological parameters of motion) [8,9].

The main diagnostic method of electrophysiological study of the human neuromuscular system is the surface electromyography. Electromyography is based on the registration of total bioelectrical activity of aggregated motor units of a muscle with the help of skin electrodes and qualitative-quantitative analysis [10]. This method found the greatest application in clinical practice, rehabilitation and research of diseases of the motor system [11-15].

Electromyographic (EMG) pattern of a movement is a spatial-temporal model that indicates the direction, level and sequence of activities of the muscles involved in the movement [8,16]. Recognition of EMG patterns of movements is a perspective goal and today is being developed towards biocontrol by external devices (prostheses, exoskeleton, human-machine interfaces) [17-20]. There are also works devoted to the analysis of EMG patterns of sports movements [21-23].

The goal of the paper is to analyze the reproducibility of EMG patterns of complex coordination movements under external destabilizing factors in order for further estimation of the coordination abilities of the athletes.

II. Research Methods

The coordination abilities of the athletes were studied at the Department of "Sports Engineering" of the Belarusian National Technical University (Minsk, Belarus).

Subjects

The study involved young athletes, engaged in specialized sports sections (tennis and figure skating). Sixteen athletes (12 male, age, 8 to 13 years; 4 female, age, 8 to 13 years) volunteered to participate in the study. For all subjects were previously explained the essence of the research and showed the test exercises. The subjects were in full health and did not report any feelings of pain when performing the tests.

The test tasks with a complex motion structure [24] were developed for legs (Figure 1) and arms (Figure 2) in the following sequence: test 1 - with open eyes; test 2 - with closed eyes; test 3 - cross-coordination performed in rhythmic cadence (Figure 3); test 4 - cross-coordination performed without rhythmic cadence.

Test exercises with a complex motion structure selected for the estimations made are the most informative ones for the study of the components of coordination abilities.

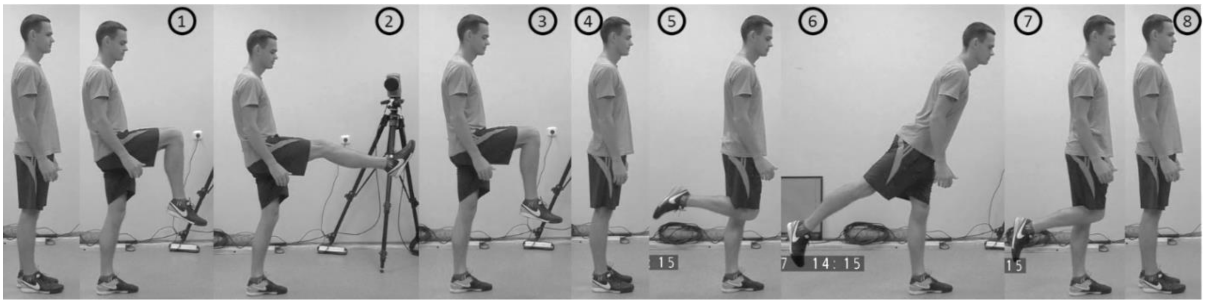


Figure 1. Motion test for the legs.
1 - flexion in the hip and knee joints at straight angles; 2 - straightening in the knee joint, the leg is horizontal; 3 - flexion in the knee joint at straight angles; 4 - starting position; 5 - flexion in the knee joint back at a straight angle; 6 - semi-inclined forward at an angle of 45 °, the leg and body constitute a straight line; 7 - flexion in the knee joint back at a straight angle; 8 - starting position.

Figure 2. Motion test for the arms.
1 - maximal flexion in elbow joints without application of additional force; 2 - straightening in the elbow joints, arms are horizontal; 3 - flexion of the arms in the elbow joints, arms are in front of the thorax horizontally; 4 - straight arms are to the sides, horizontally; 5 - flexion of the arms in the elbow joints, arms in front of the thorax horizontally; 6 - maximal flexion in elbow joints without application of additional force; 7 - straightening in the elbow joints, arms are horizontal; 8 - starting position.

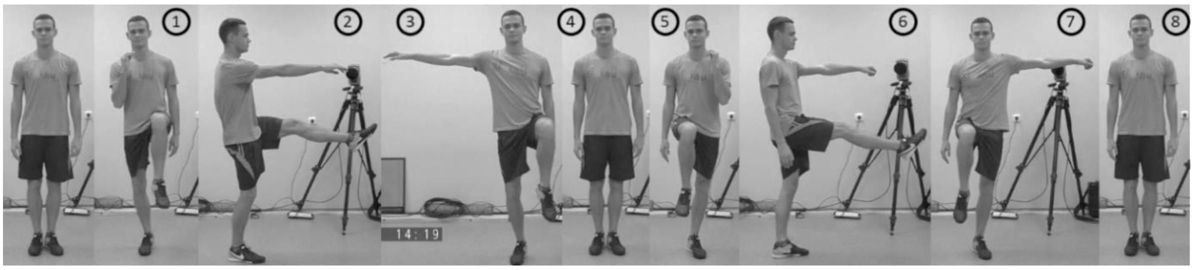


Figure 3. Motion test for the cross-coordination.
1 - flexion of the right arm in the elbow joint and flexion of the left leg in the hip and knee joints at a right angle; 2 - straightening of the limbs forward horizontally; 3 - swerve of the straight right arm to the side and flexion of the left leg in the knee joint at right angles; 4 - starting position; 5-8 - the same with other limbs.

For the study, seven large muscle groups of the arms and legs were chosen [25]. The complex coordination motions are not possible without control movements of the limbs, which have a sufficiently large number of degrees of freedom and mobility in comparison with the body (Figure 4, Table 1).

Table 1

Chosen muscles and their functions

Muscle name (Latin)	Location and function
m. rectus femoris	It is located on the front of the thigh. Unbends the leg in the knee joint, flexes the hip in the hip joint.
m. biceps femoris	It is located on the back of the thigh. Flexes the leg in the knee joint, unbends the leg in the hip joint.
m. gastrocnemius lateralis m. gastrocnemius medialis	These are located on the back of the shin. Flex the foot, help in the flexing of the leg in the knee joint.
m. tibialis anterior	It is located on the front of the shin. Unbends the ankle joint and lifts the medial edge of the foot.
m. biceps brachii	It is located on the front surface of the forearm. Flexes the shoulder in the shoulder joint and the forearm in the elbow joint.
m. triceps brachii	It is located on the back surface of the forearm. Unbends the forearm in the elbow joint, helps in unbending the shoulder.

Data Collection

Registration of EMG signals of muscles were realized a TrignoTM Wireless System (Delsys Inc., Boston, USA) and surface EMG electrodes, TrignoTM Wireless Sensor (Delsys Inc., Boston, USA) [26]. Each EMG sensor has a built-in triaxial accelerometer, a transmission range of 20 m and a rechargeable battery lasting a minimum of 7 hours (TRIGNO Wireless System User's Guide, 2013).

Fixation and positioning of sensors on the studied muscles, orientation relative to motor fibers, the quality of skin surface preparation for recording of surface EMG were carried out in accordance with the recommendations of SENIAM [27].

The EMG signals were acquired using 14 active electrodes (DelSys®, Inc., Boston, MA, USA) that provided a EMG signal bandwidth 20- 450 Hz, EMG signal sampling rate of 2000 samples/sec, EMG baseline noise of <750 nV RMS, CMRR > 80dB, 16-bit EMG signal resolution (Trigno™ Wireless System User's Guide, 2013).

The EMG and accelerometer signals were recorded using Delsys EMGWorks Acquisition software [26]. For further analysis, the data was exported to MATLAB using Delsys EMGworks COM interface.

Data Processing

To estimate the coordination abilities of a person, based on the analysis of the reproducibility of EMG patterns of complex coordination movements, the following stages were offered:

- Preliminary processing of EMG signals of muscles for removing noise from the spectrum of useful signal.
- Analysis of the spatio-temporal structure of the complex-coordination movement to find the phases of motion exercises.

- Analysis of the amplitude-time characteristics of EMG-signals of muscles in accordance with the spatio-temporal structure of motion.
- Quantitative estimation of the athletes' coordination abilities based on the analysis of the reproducibility of EMG patterns of motion tests.
- Construction of individual motion profiles of athletes, characterizing their preparedness and coordination abilities.

Using mathematical programming system MatLab R2017, a special program called "Motion analyzer" (Figure 5) was developed to analyze multichannel electromyograms of muscles and motion accelerometry. The program substantially simplifies and speeds up data processing.

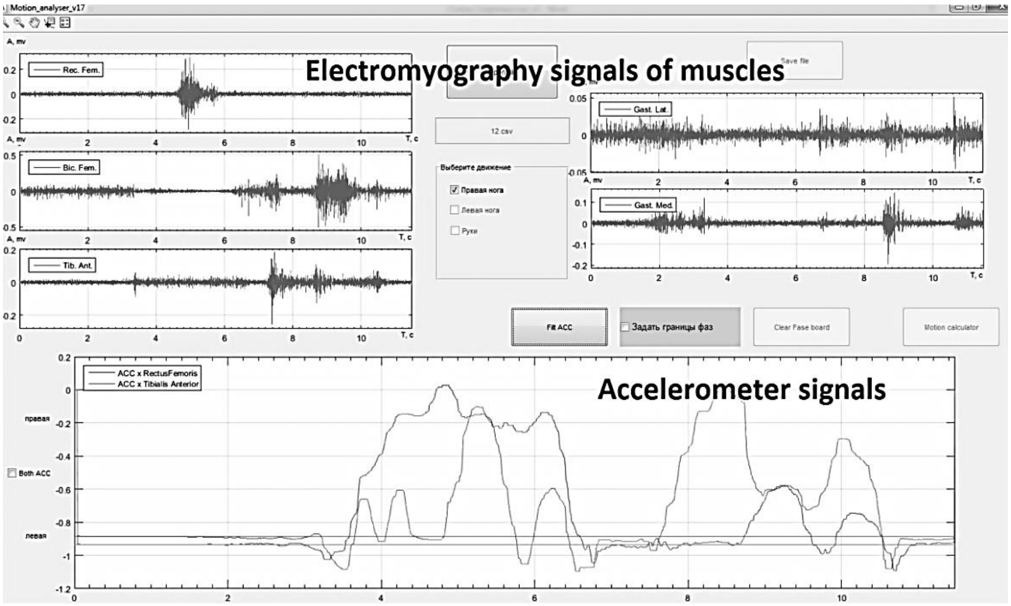


Figure 5. Interface of the program "Motion analyzer".

III. Results and Discussions

Stage 1. Preliminary Processing of EMG Signals of Muscles

When working with biomedical signals, including EMG signals, the reliability of the results is determined by the quality of the recorded signal. Motion artifacts, high-frequency noise, power supply frequency interference and crosstalk of different biomedical signals, introduce some significant distortions into useful signals. Improving the identification quality of needed biomedical signals is possible through the use of digital filtering methods which precede the subsequent analysis of signals [28].

In the reported investigation, the EMG signals have been filtered by using a Chebyshev high-pass digital filter with a cutoff frequency of 10 Hz (for removing motion artifacts), a 50 Hz Butterworth digital notch filter (for removing power supply frequency interference). Also, a constant component in the spectrum of the useful signal has been deleted.

Stage 2. Analysis of the Spatio-Temporal Structure of the Complex-Coordination Movements

The analysis of accelerometric signals with clear structural patterns was used to determine the phases of the complex coordination test movement. For motion tests under investigation, the accelerometer signals of the muscles Rectus Femoris and Biceps Femoris were chosen for legs' exercises while right and left Biceps Brachii were used for arms' exercises.

Figure 6 shows an example of the analysis of the spatio-temporal pattern of a test exercise for the legs. The accelerometer signals of the muscles Rectus Femoris and Biceps Femoris made it possible to determine the following phases of motion:

Phase 1 - flexion of the leg in the hip and knee joints at a right angle;

Phase 2 - extension of the leg in the knee joint to the horizontal position, then flexion in the knee joint at a right angle;

Phase 3 - return of the leg to the start position;

Phase 4 - start position;

Phase 5 - flexion of the leg at the knee joint backward at right angles, knees are at the same level;

Phase 6 - semi-incline forward 45 °, leg and body make a straight line, then return to the previous position;

Phase 7 - return of the leg to the start position.

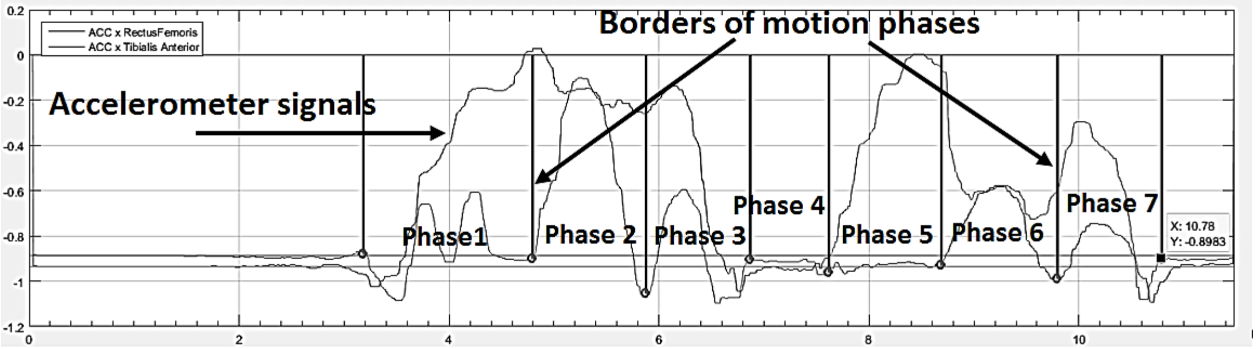


Figure 6. The determination of the motion phases using the accelerometer signals of the muscles Rectus Femoris and Biceps Femoris.

Stage 3. Analysis of the Amplitude-Time Characteristics of EMG-signals of Muscles in Accordance with the Spatio-Temporal Structure of Motion

The analysis of the EMG pattern of motion is based on the study of multichannel EMG signals of working muscles in the time domain. It is essential to compare the muscle innervation pattern with the spatio-temporal characteristics of the performed actions.

The works devoted to the amplitude-time analysis of EMG signals, as a rule, use the average or peak amplitude of the EMG signal during the selected period of time as the main informative parameter [29-32].

The presented work proposes the analysis of EMG signal energy inside the found phases of motion exercises (Figure 7). Since significant energy in the EMG signals an indicator of force generation in a specific muscle, a high value for may be used to suggest that movement may be taking place [12, 33]. In works [34,35] on biomechanics the connection between muscle force and the number of motor fibers involved in the process of muscle contraction is shown. This approach to EMG analysis makes it possible to quantitatively estimate the distribution of muscular effort in phases during the test movements.

For each muscle (m), the energy of the EMG signal (E_m) is calculated as follows:

$$E_m = \sum_{i=1}^{n} E_m[i] = \sum_{i=1}^{n} \frac{(x_m[i])^2}{n}, \tag{1}$$

where ***m*** is the muscle number;

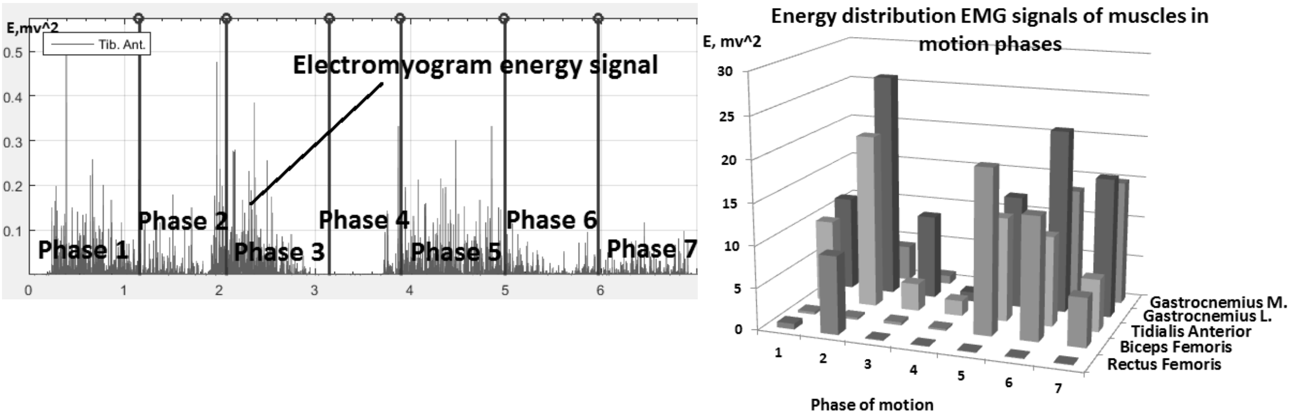
$E_m[i]$ is the *i*-th discrete sample of the energy signal of the *m*-th muscle's EMG;

$x_m[i]$ is the amplitude of the *i*-th discrete sample of the EMG signal of the *m*-th muscle;

n is the number of discrete samples of the EMG signal.

Similarly, for each muscle (*m*), the energy of the EMG signal is calculated inside each phase (*f*) of the motion under investigation.

Figure 7a shows an example of the EMG-signals' energy of the muscle Tibialis Anterior of the right leg when doing the motion test 1. Figure 7b shows an example of the energy distribution of the EMG signals of the right leg's muscles in the phases of movement during the motion test 1.



a) b)

Figure 7. Amplitude-time analysis of EMG signals of muscles: a - EMG-signals' energy of the muscle Tibialis Anterior of the right leg when doing the motion test 1; b - the energy distribution of the EMG signals of the right leg's muscles in the phases of movement during the motion test 1.

Stage 4. Analysis of the Reproducibility of EMG Patterns of Motion tests.

Quantitative estimation of the athletes' coordination abilities is based on the analysis of the reproducibility of EMG patterns of motion tests under the action of external destabilizing factors. The following external destabilizing factors were chosen: disabling the visual analyzer (test 2 is done with the closed eyes) and disabling the sound analyzer (test 4 is done without counts).

The method of estimating the reproducibility of the motion skills of a person [8] was used as the basis for the proposed estimation of the athletes' coordination abilities.

The initial data for the analysis are the energy of the EMG signal of the studied muscles (Eq.(1)) and the percentage distribution of the energy of the EMG signal of each muscle in the phases of motion of the total energy of the signal:

$$E_{m,f}^{\%} = \frac{E_{m,f}}{E_m} \times 100\%, \tag{2}$$

where **m** is the muscle number;

f is the motion phase number;

$E_{m,f}$ is the energy of the EMG signal of the *m*-th muscle in the *f*-th phase;

E_m is the total energy of the digital EMG signal of the *m*-th muscle.

The percentage distribution of the energy of the EMG signal of muscles over the phases of motion shows, first of all, the localization of muscular forces in different phases of movement, irrespective of the strength of the test exercise.

Figure 8 a, b shows examples of the percentage distribution of the energy of the EMG signals of the muscles under investigation in the phases of movement for test exercises 1 and 2.

Then, for the initial motion test and the test involving the influence of the external factor, the deviation of the phase shares of the EMG signals' energy for all the muscles is calculated:

$$\Delta E_{m,f}^{\%} = \left| E_{m,f,2}^{\%} - E_{m,f,1}^{\%} \right|, \tag{3}$$

where $\boldsymbol{E_{m,f,1}^{\%}}$ is the energy share of the EMG signal of the *m*-th muscle in the *f*-th phase of the initial motion;

$\boldsymbol{E_{m,f,2}^{\%}}$ is the energy share of the EMG signal of the *m*-th muscle in the *f*-th phase of motion under the action of the external factor.

The deviation of the energy share of the EMG signal ($\Delta E_{m,f}^{\%}$) of the muscles, in all phases of the motion, characterizes the degree of variability in the distribution of muscular effort over the phases of the motion under the action of the external destabilizing factor.

Figure 8 c shows the example of the deviation in the percentage distribution of energy of the muscles' EMG signals in the phases of the motion between the motion tests 1 and 2.

To estimate the reproducibility of human movement as a whole, it is necessary to consider the degree of each muscle's contribution to the formation of the movement under investigation, because the muscles are involved in the process of the motion realization differently. Besides, it is necessary to consider the significance of each phase of the movement, because the distribution of muscular efforts in the motion phases is not uniform.

For each muscle, the significance coefficient (Eq.(5)) is determined as the share of the average energy of the EMG signal of each muscle (Eq.(4)) of the total energy of the EMG pattern of the motion:

$$E_m^{\text{cp}} = \frac{E_{m,1} + E_{m,2}}{2}, \tag{4}$$

where $\boldsymbol{m}$ is the muscle number;

$\boldsymbol{E_{m,1}}$ and $\boldsymbol{E_{m,2}}$ are the energies of the EMG signal of the muscle *m* of the initial motion (1) and the motion under the action of the external factor (2).

$$k_m = \frac{E_m^{\text{cp}}}{\sum_{m=1}^{M} E_m^{\text{cp}}}, \tag{5}$$

where $\boldsymbol{M}$ is number of the muscles under investigation;

$\boldsymbol{E_m^{\text{cp}}}$ is the average energy of the EMG signal of each muscle (*m*).

The coefficient of muscle significance (km) lies within the range [0 … 1].

Figure 8 d shows an example of the calculated significance coefficients of the muscles under investigation for the test motion.

For each phase of the motion, the significance coefficient (Eq.(7)) is determined as the share of the average energy of all EMG signals of the muscles in the phase of motion (Eq.(6)) of the total energy of the EMG pattern of motion:

$$E_f^{\text{cp}} = \sum_{m=1}^{M} \frac{E_{m,f,1} + E_{m,f,2}}{2}, \tag{6}$$

where $\boldsymbol{E_{m,f,1}}$ и $\boldsymbol{E_{m,f,2}}$ are the energies of the EMG signal of the *m*-th muscle in the *f*-th phase of the initial motion (1) and motion under the action of the external factor (2).

$$k_f = \frac{E_f^{\text{cp}}}{\sum_{m=1}^{M} E_m^{\text{cp}}}, \tag{7}$$

where $\boldsymbol{f}$ is motion phase number;

$\boldsymbol{E_f^{\text{cp}}}$ is the average energy of all EMG signals of the muscles in the phase (f) of the motion.

The coefficient of significance of the motion phases (kf) lies within the range [0 ... 1].

Figure 8 e shows an example of the calculated phase significance coefficients for the test motion.

The coefficient of variability of motion (Kv) with the influence of the external perturbing factors is calculated as the sum of the weighted deviations of the percent share of the energy of EMG signal of the investigated muscles in all phases of the motion:

$$K_v = \sum_{m=1}^{M} \sum_{f=1}^{F} k_m \times k_f \times \Delta E_{m,f}^{\%}, \tag{8}$$

where $\boldsymbol{F}$ is the number of motion phases.

Figure 8 f shows an example of the weighted (considering the importance of the muscles and the motion phases) deviation in the percentage distribution of the energy of EMG signals of muscles in the phases of motion between the motion tests 1 and 2.

The coefficient of influence of the visual analyzer (γ) is calculated as the coefficient of variability (Eq.(8)) for the motion tests 1 and 2. In other words, by doing the test task without using the visual analyzer relative to the test, where the exercise is performed with open eyes.

The coefficient (τ), characterizing the reproducibility of the structure and the speed of motion, is calculated as the coefficient of variability (Eq.(8)) for motion tests 3 and 4. In other words, by doing the test task without counts relative to the test, where the exercise is performed with counts.

Stage 5. Construction of the Individual Motion Profiles of Athletes

The final stage in the estimation of human coordination abilities based on the analysis of the reproducibility of EMG patterns of complex coordination motions is the construction of individual motion profiles of athletes. The individual motion profiles are based on the calculated coordination coefficients γ and τ (Figure 9), that characterize the preparedness and coordination abilities of a person.

The smaller values of these coefficients indicate about the high level of development of the individual components of coordination abilities. This is due to the fact, that the coefficients of influence of the visual and sound analyzers characterize the stability of reproduction of complex coordination movements under external destabilizing factors. In the ideal case, with the complete overlap of the EMG-structure of the motion before and after introducing of the destabilizing factor, these coefficients are equal to 0. This information provides a visual representation of the current state and the possibility of the further development the athlete's coordination abilities.

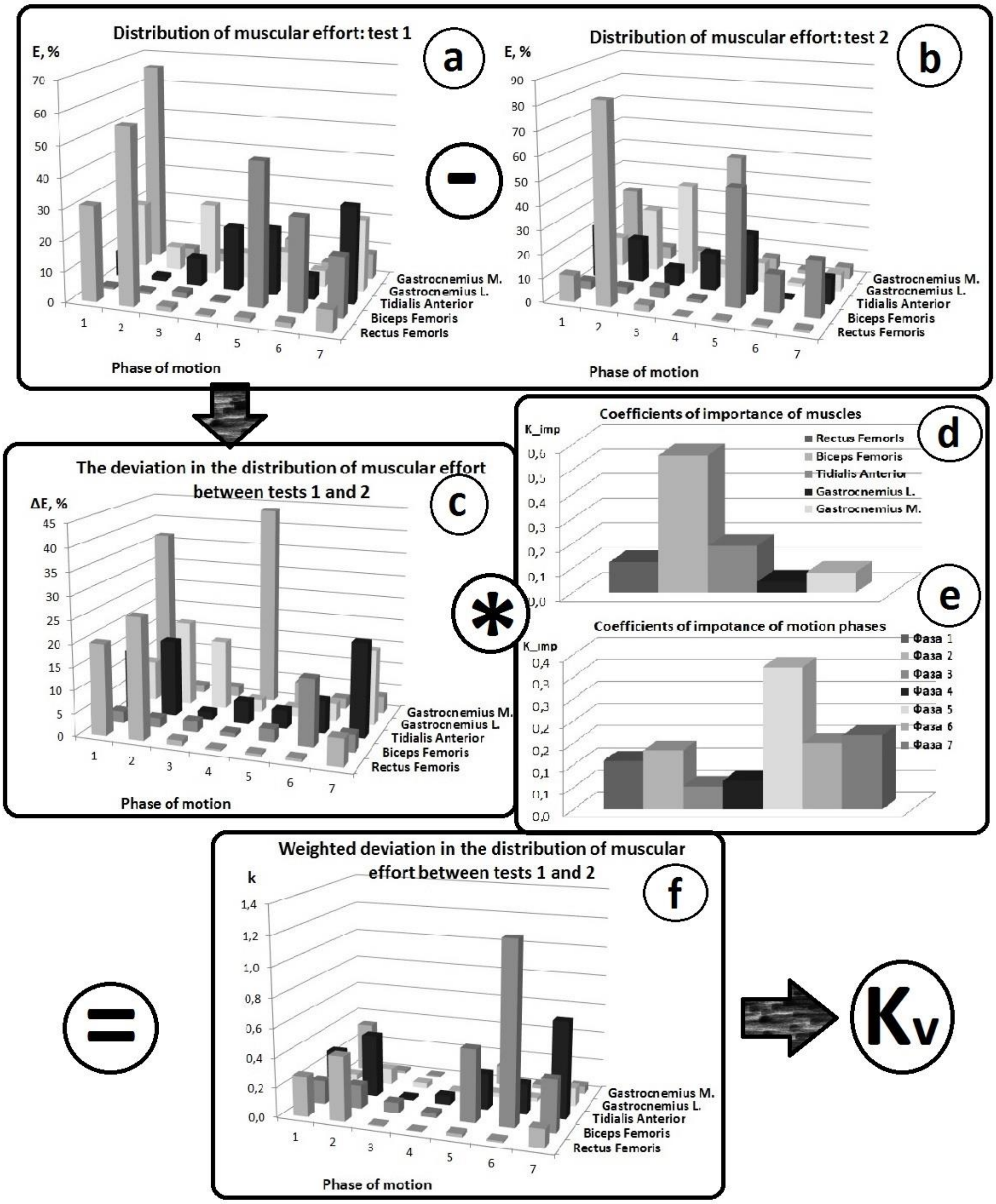
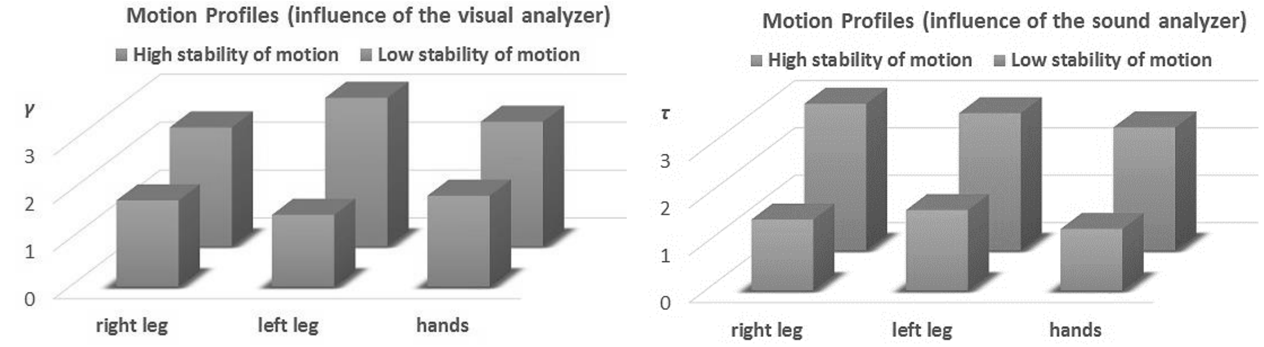


Figure 8. The stages of the estimation of the reproducibility of electromyographic patterns of motion with the influence of the external disturbing factor in the example of tests 1 and 2 for the left leg: a, b - the percentage distribution of the energy of EMG signals of the muscles in the motion phases for motion tests 1 (a) and 2 (b); c - the deviation in the percentage distribution of the energy of EMG signals of the muscles in the motion phases between the motion tests 1 and 2; d - coefficients of the muscle significance, e - coefficients of significance of the motion phases; f - weighted deviation in the percentage distribution of the energy of EMG signals of the muscles in the phases of motion between the motion tests 1 and 2



a) b)

Figure 9. Comparison of the individual profiles of athletes: a - influence of the visual analyzer; b - influence of the sound analyzer.

Results

The research involved 16 athletes of different gender and ages 8 to 16 years, specializing in tennis and figure skating. Table 2 presents the results of estimation of the coordination abilities of young athletes based on the authors' method. The total coefficients of the influence of the visual and sound analyzer on the stability of reproduction of complex coordination movements were calculated.

Table 2

Results of the research

Athlete	Kind of sport	Gender	Age	γ	τ
1	figure skating	male	11	2,75	2,50
2	figure skating	female	13	1,88	1,18
3	figure skating	female	11	2,33	2,48
4	figure skating	male	13	1,28	2,19
5	figure skating	male	11	1,77	2,53
6	figure skating	female	9	2,44	1,30
7	figure skating	male	9	2,22	1,68
8	tennis	male	15	1,69	2,37
9	tennis	male	13	2,15	3,14
10	tennis	male	16	1,40	1,51
11	tennis	male	8	2,57	1,55
12	tennis	male	11	1,56	3,00
13	tennis	male	11	2,17	1,72
14	tennis	male	11	1,93	2,01
15	tennis	female	8	2,77	2,12
16	tennis	male	9	1,49	1,65

As the result of the research, the influence of the visual analyzer and the influence of the sound analyzer on the stability of reproduction of the movements with a complex coordination structure were shown. So for young athletes, specializing in figure skating, the coefficient of influence of the visual analyzer is $\gamma = 2.09 \pm 0.49$, the coefficient of influence of the sound analyzer is $\tau = 1.98 \pm 0.58$. For young tennis players, the coefficient of influence of the visual analyzer is $\gamma = 1.97 \pm 0.48$, the coefficient of influence of the sound analyzer is $\tau = 2.12 \pm 0.61$.

A significant correlation between the age of the athlete and the coefficient of the influence of the visual analyzer was established. So the Pearson correlation coefficient for skaters is r = -0.63, and for tennis players – r = -0.62. These indicates about the improvement of such component of coordination abilities with age.

Conclusions

The paper proposes a new approach to the estimation of athlete coordination abilities based on the analysis of the reproducibility of EMG patterns of complex coordination motions under the action of external destabilizing factors. The following factors were chosen as external perturbing ones: disabling the visual and disabling the sound analyzer of a person.

Test exercises with a complex motion structure selected for the estimations made are the most informative ones for the study of the components of coordination abilities.

Recognition and analysis of EMG patterns of the test exercises with complex motion structure include the following steps:

- Preliminary processing of EMG signals of the muscles under investigation.
- Detection of phases of the complex coordination motions.
- Analysis of the amplitude-time characteristics of EMG signals of the muscles in accordance with the spatio-temporal structure of the motion.
- Analysis of the reproducibility of EMG patterns of motion tests under the action of external destabilizing factors.
- Construction of the individual motion profiles of athletes, characterizing their coordination abilities.

According to the proposed method in the ideal case (with the complete overlap of the EMG-structure of the motion before and after introducing of the destabilizing factor), the value of the coefficient of influence of the visual and sound analyzer will be zero. However, real research shows the dispersion of the values of these coefficients from 1.28 to 3.14. Analysis of these coefficients allows identifying the athletes with high coordination abilities and giving recommendations for young athletes about promotion in a particular sport. Therefore, for example, the value of the coefficient of influence of the visual analyzer are important for choosing the sports that require high visual concentration: some game sports (tennis, badminton), target shooting and biathlon.

In this way, the proposed method can be used for objective monitoring of the levels of individual components of the athletes' coordination abilities.

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