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AMPLITUDE-TIME ANALYSIS OF BIOMECHANICAL PATTERNS OF HUMAN MOTIONS

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Abstract. Biomechanical analysis of motions solves the tasks of efficiency estimation of movement realization, search of technique optimal variants and tactics of motion performance, definition of a degree and reasons of not matching real movement action to optimal one. Today, inertial measurement devices based on microelectromechanical sensors (MEMS) are becoming more and more popular for biomechanical analysis of human motions. The paper describes an algorithm for estimation of the biomechanical pattern of human motions based on amplitude-time analysis of inertial gyroscope signals. The presented algorithm allows to quantitatively estimate spatial, temporal and spatio-temporal parameters of motion, symmetry of left and right limbs motions and reproduction stability of the motion biomechanical pattern. The specific feature of the algorithm is its universality for the study of symmetrical and asymmetrical motions.

Keywords: *biomechanics, motion pattern, inertial gyroscope, digital signal processing.*

Introduction

Biomechanics of human motions solves the following tasks: 1) development of biomechanical methods of efficiency estimation of motions; 2) development of new variants of motion techniques and estimation of their efficiency; 3) estimation of the existing technique correctness and identification of problems which can lead to injuries [1].

Biomechanical methods of human motions study are focused on getting data about the processes underlying the motion structure. These methods are based on registration of external motion events - kinematic and dynamic motion parameters [2].

Today, inertial measurement units (IMU) based on MEMS are becoming more and more popular for biomechanical analysis of human motions. These devices include an accelerometers and gyroscopes. At the same time, acceleration sensors (accelerometers) are used for measuring the parameters of forward motion and angular velocity sensors (gyroscopes) - for parameters measuring of rotational motion [3].

As a basic structural unit of the whole system of movements is the concept of motion stereotype (image, pattern). Motion stereotype means a constant individual complex of unconditional reflexive motion reactions realized in a certain sequence providing postotonic functions [4]. The individual motion stereotype is formed under the influence of various factors of the external and internal environment associated with the creation of human motion (the whole complex of motion capabilities) [5]. In its turn, a stable motion stereotype, characterized by certain kinematic and dynamic parameters, can be considered as a biomechanical pattern of human motion [6].

The paper presents the estimation algorithm of biomechanical pattern of human motions based on amplitude-time analysis of inertial gyroscope signals. The algorithm allows to quantitatively estimate spatial, temporal and spatio-temporal parameters of motion, symmetry of left and right limbs motions and reproduction stability of motion biomechanical pattern. The specific feature of the algorithm is its universality for the study of symmetrical and asymmetrical motions.

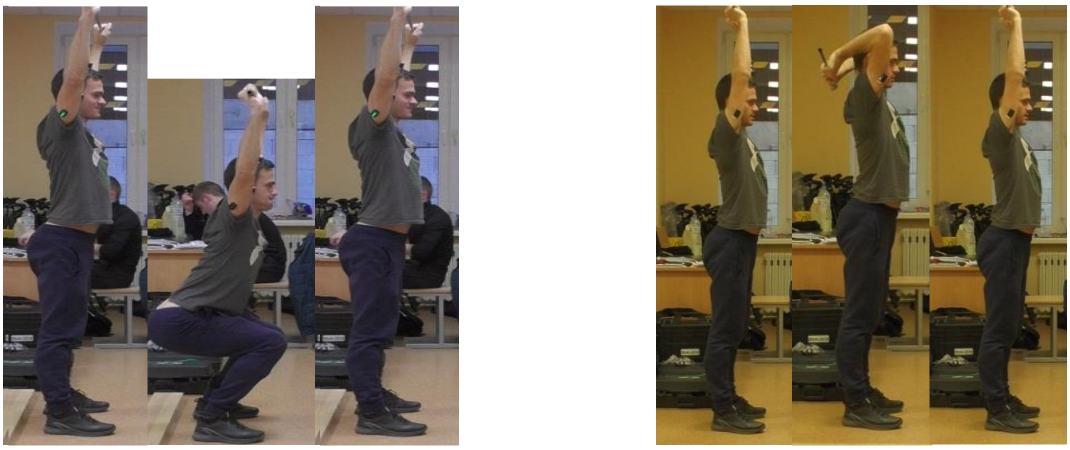
Subjects

In terms of biomechanics any motion is a complex of elements of dynamic posture and control movements. The element of dynamic posture is joint fixation, and the controlling motion is the change of the joint angle [2].

In the majority of competitive exercises of any kinds of sports (cyclic, complex coordination, playing, combat sport) there are bending and unbending motions in joints. In the present study the following exercises were chosen as test movements:

1. Squatting with raised arms (figure 1 a).

This exercise is used to estimate symmetrical and functional mobility of hip, knee and ankle joints. The bodybar above the head estimates symmetrical mobility of shoulder joints and thoracic spine [7].



a) b)

Figure 1. Test symmetrical acyclic motions: a – squatting with raised arms; b – bending in the ulnar joints.

2. Bending in the ulnar joints (figure 1 b).

Bending in ulnar joints is performed with a bodybar or lightweight dumbbells and is used to estimate the intermuscular coordination of the upper limbs [8].

While performing squats and bending in ulnar joints, the muscles of the right and left limbs should be activated and relaxed synchronously and symmetrically.

3. Running on a treadbana (figure 2).

Running on a treadbana is used to estimate a person's physical performance, endurance, coordination abilities [9]. This movement is cyclic, and the muscles of the right and left limbs should be activated and relaxed in antiphase (asymmetric motion).

Data Collection

The registration of multichannel biomechanical signals is based on the inertial method of detection of object position and orientation. MEMS-sensors of gyroscopes are used to measure angular velocity by Coriolis force. This method makes it possible to analyze kinematic characteristics of motions [10].

The kinematic characteristics allow to analyze motions in time and space. They are separated into spatial, temporal and spatial-temporal [11].

Figure 2. Test cyclic asymmetric movement (running on a treadbana).

Signals from inertial gyroscope are given as projections of angular velocity vector across on axis associated with the object [12]. Figure 3 shows an example of gyroscope signals for each axis of the local coordinate system during the study of running motions (the sensor is located on the lower limb).

Registration of gyroscope signals of motion were realized by TrignoTM Wireless System (Delsys Inc., Boston, USA) and TrignoTM Wireless Sensor (Delsys Inc., Boston, USA) [13]. Each sensor has a built-in triaxial gyroscope (sampling rate – 741 sa/sec, resolution – 16 bit), a transmission range of 20 m and a rechargeable battery lasting a minimum of 7 hours (TRIGNO Wireless System User's Guide, 2013).

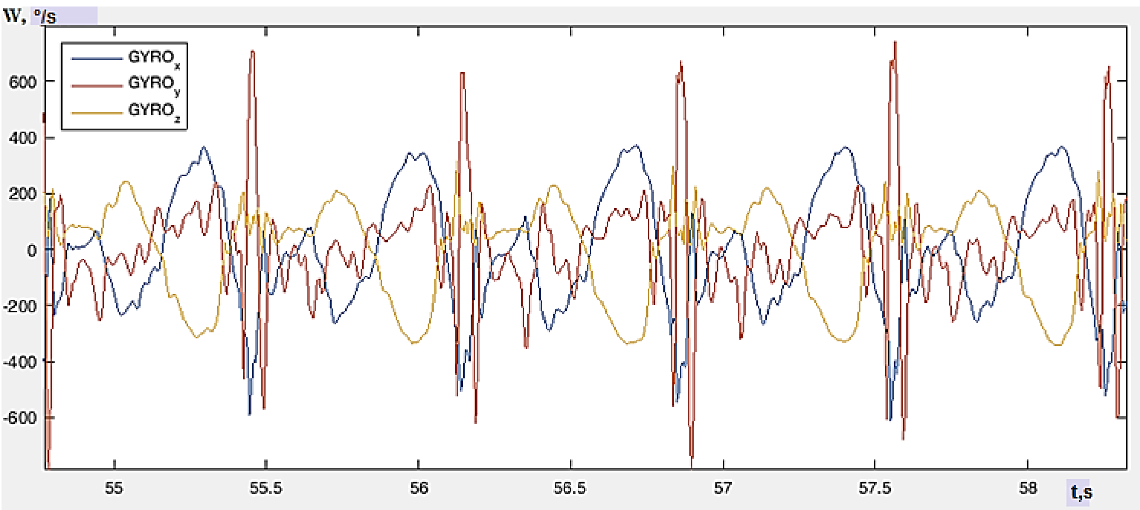


Figure 3. Example of gyroscope signals across the three axes of coordinates during the study of running motions.

The gyroscope signals were recorded using Delsys EMGWorks Acquisition software [13]. For further analysis, the data was exported to MATLAB using Delsys EMGworks COM interface.

Data Processing

The paper presents the estimation algorithm of biomechanical pattern of human motions (figure 4) based on amplitude-time analysis of inertial gyroscope signals.

The algorithm includes the following stages:

1. Choosing of the target signals of gyroscope.
2. Filtration of the signals.
3. Finding of isoline signals.
4. Determining the motion phases.
5. Calculating the spatio-temporal symmetry of the left and right limbs.
6. Analysis of reproducibility of motion biomechanical pattern.

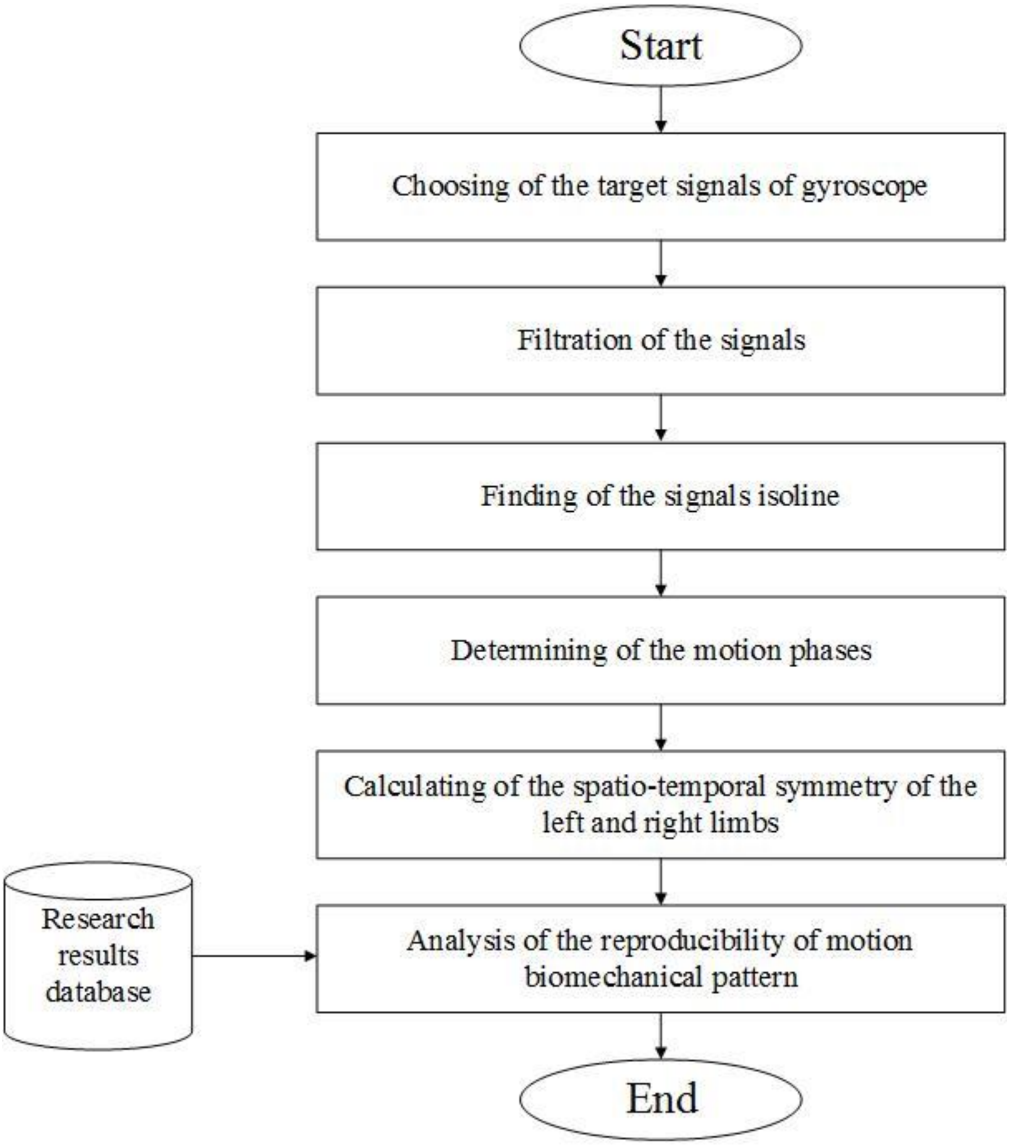


Figure 4. The analysis algorithm of the biomechanical pattern of motions.

1. Choosing the target signals of gyroscope

The task of target signals choice of gyroscope for each motion is solved individually and depends on the type and structural complication of the investigated motion.

The location of inertial sensors and axes orientation towards the body's general orientation system determine the precision of kinematic characteristics of movements [14]. Inertial sensors are usually fixed to that part of the body which motion is studied. For example, IMU fixed to the ankle and shin is used to study leg movements during walking, and IMU fixed to the wrist is used to study limb tremor in Parkinson's disease. In many applications, when it is necessary to study total motion in space, the IMU is located as close to the center of body mass as possible, for example, on the sternum or in the lumbosacral area [15].

Thus, the location of sensors on the human body should correspond to the studied motion. For motions performed by the lower limbs, it is reasonable to analyze the signals of the sensors located on the lower limbs (Figure 5 a). For motions performed by the upper limbs, it is reasonable to analyze the sensor signals located on the upper limbs (Figure 5 b).

In the present paper the task of determining motion phases is set. In this view, one gyroscope channel for each limb is chosen for the following analysis.

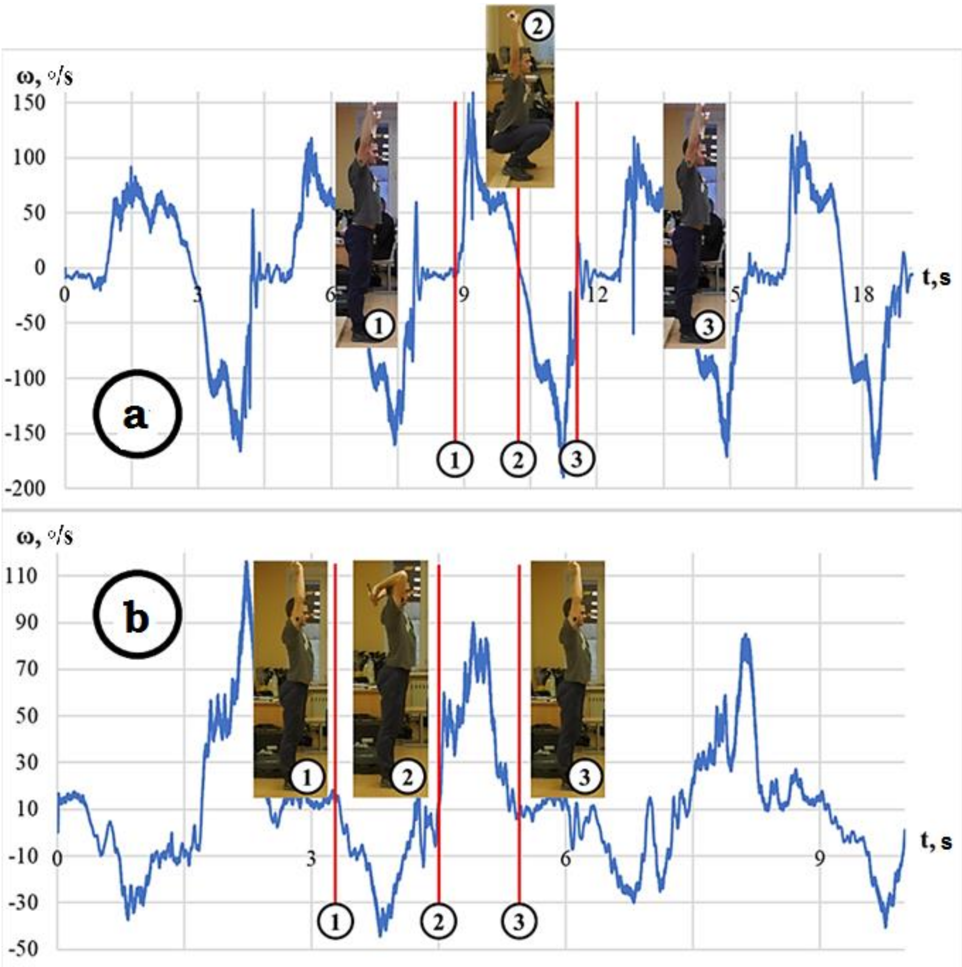


Figure 5. Gyroscope signals from sensors located on the lower and upper limbs: a - signal from the gyroscope located on muscle "Rectus Femoris" during the squatting; b - signal from the gyroscope located on muscle "Extensor Carpi Ulnaris" during the bending of arms in the elbow joints.

2. Filtration of the signals

A sliding average (median) filter is used to filter the signals of inertial sensors. This filter is optimal to minimize random noise while keeping the precision of the signal edges in the time domain [16].

Median filter averages a few points from the input signal to calculate each point in the output signal (Eq.(1)).

$$y[i] = \frac{1}{M}\sum_{j=0}^{M-1} x[i+j], \tag{1}$$

where M – number of points for averaging (filter window);

x[i+j] – input signal;

y[i] – output signal.

Figure 6 shows the examples of filtration of gyroscope signals for different motions.

As illustrated by the example, the 100-points slide averaging filter is optimal for squatting, while the 50-points slide averaging filter is optimal for running. It gives enough smoothing signal with minimal distortion in the time domain.

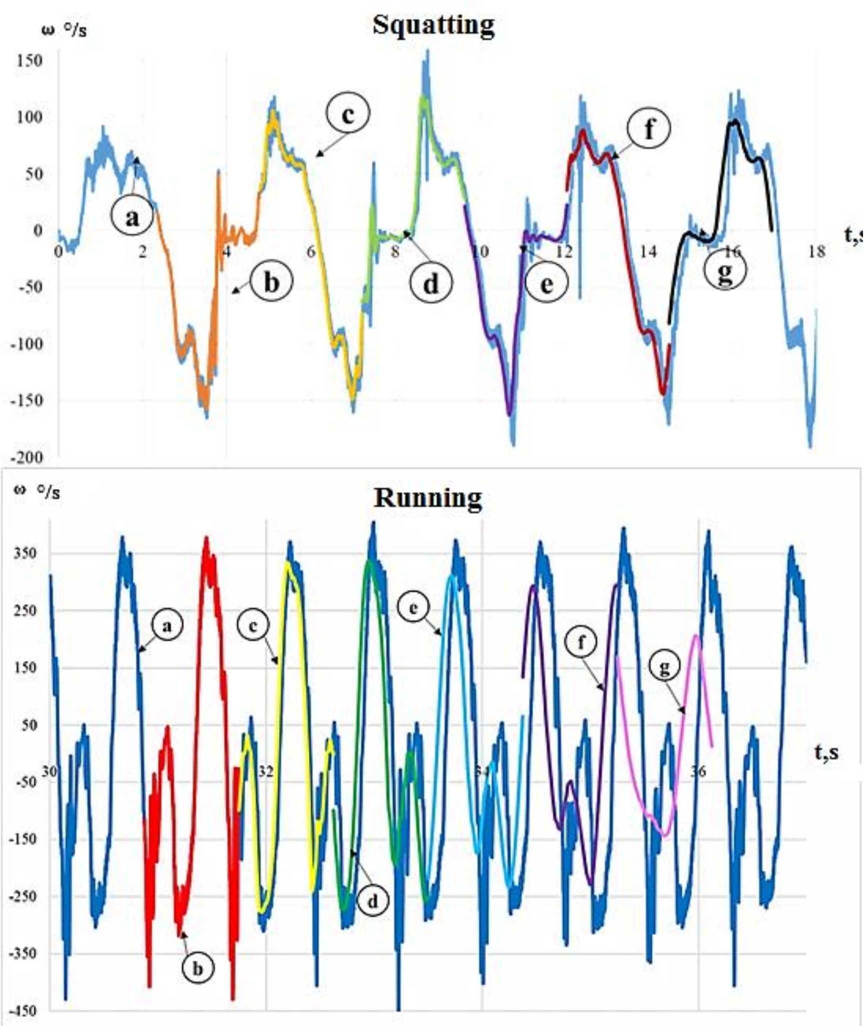


Figure 6. Gyroscope signals for squatting and running using a sliding average filter with different window widths: a - gyroscope signal without filtration; b - window 10 points; c - window 50 points; d - window 100 points; e - window 150 points; f - window 200 points; g - window 300 points.

3. Finding the isoline signals

The basic problems that give an incorrect MEMS sensor measurement are the initial offset and the drift of the zero line (isolines). Note that the errors have systematic and random components. Only a systematic component can be solved algorithmically, while a random component will determine the error value [17].

The initial zero offset in the gyroscope signals is caused by the unorthogonality of the sensor axes. When inertial sensors are manufactured, the producer cannot ensure that the sensor axes match the instrument body. As a result, the sensors have installation errors or unorthogonality of the axes.

Errors caused by installation inaccuracies have a constant offset effect under the condition of a continuously influencing value (such as free falling acceleration or Earth's rotation velocity) [18].

The estimation of constant component for the digital signal is an arithmetic mean of N samples [16]. The initial isoline offset in gyroscope signals is constant and can be calculated using the formula (Eq.(2)):

$$\delta = \frac{\sum_{i=1}^{N} x[i]}{N}, \tag{2}$$

where $x[i]$ – digital signal from a gyroscope sensor that contains N points.

Figure 7 shows the example of gyroscope signal isoline for squatting detection.

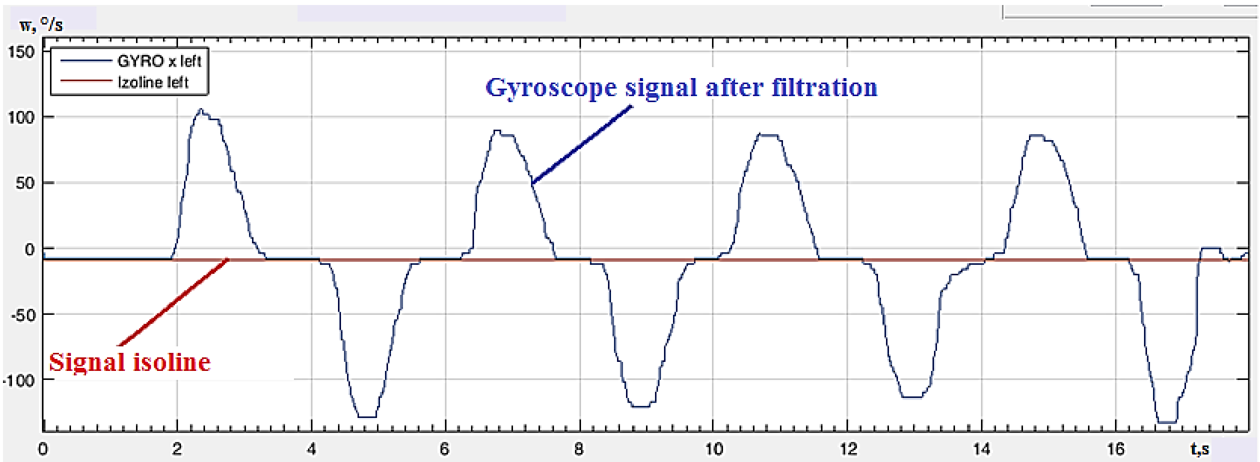


Figure 7. The detection of gyroscope signal isoline for squatting.

The gyroscope signal with zero offset correction is calculated by formula (Eq.(3)):

$$y[i] = x[i] - \delta, (3)$$

where $x[i]$ – input signal,

δ – initial isoline offset.

The physical reason of zero drift is the resizing of silicon elements and the pressure inside the capsule because of temperature variations. These factors modify the proper frequency of gyroscopes and, consequently, their output values [19]. Temperature variations depend on the influence of external temperature and internal heating of the sensor because of close location of the components [20]. Note, the drift of gyroscope signal isoline has a significant influence only during a long observation. A lowpass filter (LPF) with a large time constant can be used for compensation of the gyroscope zero drift [21].

4. Determining the motion phases

The motion phases are determined by analysis of the chosen gyroscope channels. According to the type of motion, the criteria of phases detection can be local extremes of the signal (which corresponds to a change of direction of a body part motion) or signal crossing with the isoline (which corresponds to a stop of a human body part in a certain position).

The $\mathbf{i_{max}}$ point is called the point of local maximum of the function **X(n)**, if for all **i** from the area around this point will be true the following inequality (Eq.(4)):

$$x[i] < x[i_{max}] \tag{4}$$

The $\mathbf{i_{min}}$ point is called the local minimum of the function **X(n)**, if for all **i** from the area around this point will be true the following inequality (Eq.(5)):

$$x[i] > x[i_{min}] \tag{5}$$

Figure 8 shows the example of the determination of motion cycles by local signal extremums for running on a treadbane.

The $\mathbf{i_{cross}}$ point is the crossing point of two **X(n)** and **Y(n)** signals, if the following condition (Eq.(6)) is true:

$$X(i_{cross}) - Y(i_{cross}) = 0 \tag{6}$$

Figure 9 a shows the example of phase detection by crossing the gyroscope signal with the isoline for squatting.

The marked points in the figure correspond to the boundaries of the motion phases: the phase of sub-squat, the phase of keeping sub-squat, the phase of rising out of sub-squat (figure 9 b) [22].

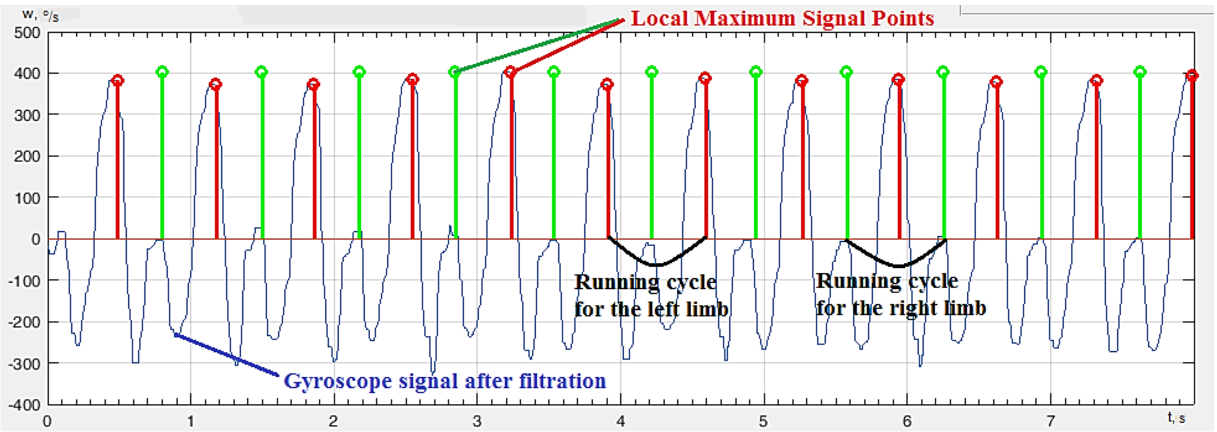


Figure 8. Determining the running cycles.

5. Calculating the spatio-temporal symmetry of left and right limbs

The formation of athletes' movement skills is followed by different participation of right and left hemispheres of brain in motion regulation, which leads to asymmetry in the motion functions of left and right limbs [23].

Estimation of the spatio-temporal symmetry of left and right limbs during the performance of motions is based on the correlation analysis of gyroscope signals of the different limbs. Such analysis allows to find out asymmetry in motion functions of the left and right limbs.

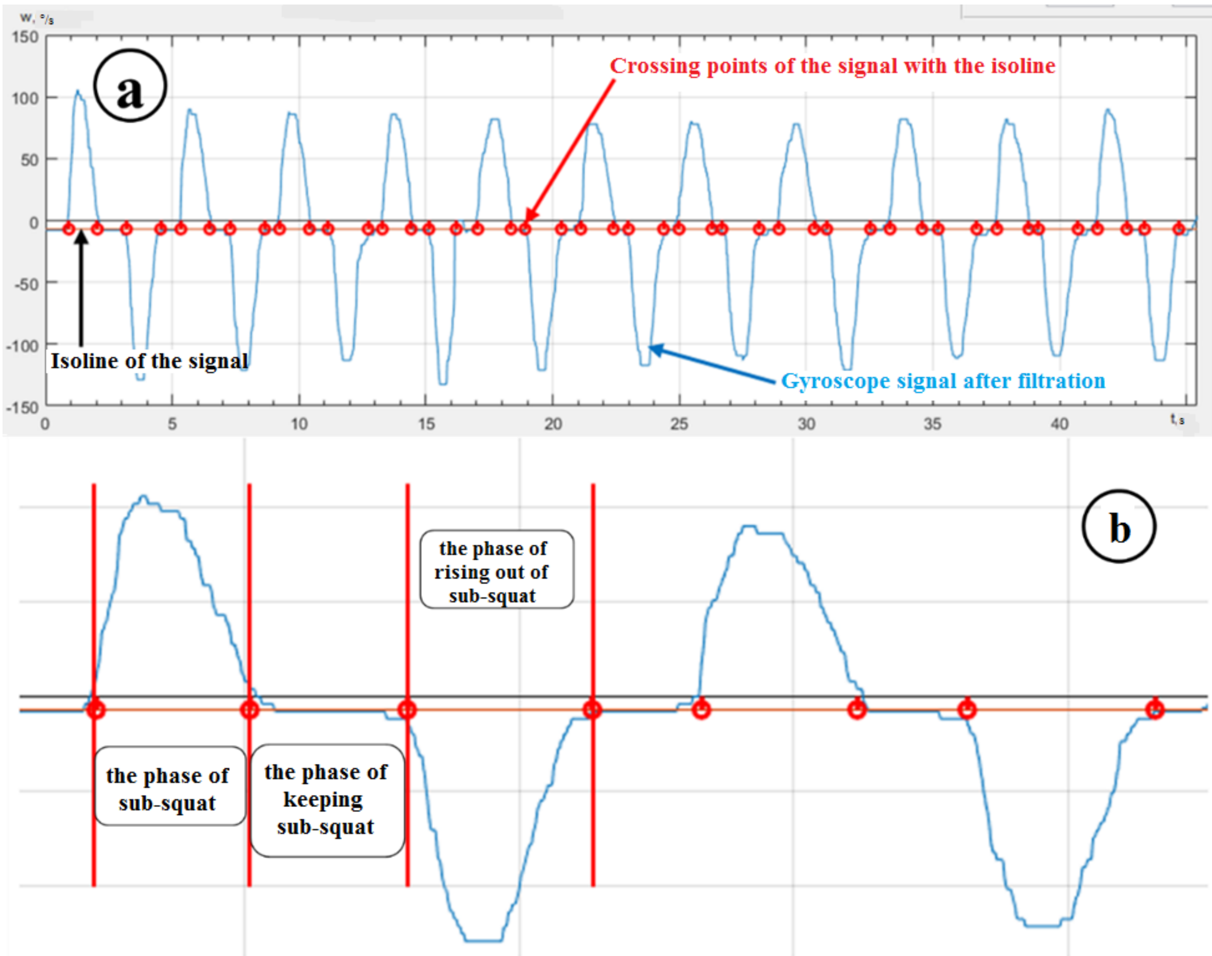


Figure 9. Determining the squatting phases: a - the points of gyroscope signal crossing with the isoline (the gyroscope signal of the sensor fixed to the muscle "Rectus Femoris" of the left leg); b - the determined motion phases.

The coefficient of correlation between two signals is calculated using formulas (Eq.(7)) and (Eq.(8)) [24].

$$\rho_{12}(j) = \frac{r_{12}(j)}{\frac{1}{N}\left[\sum_{n=0}^{N-1} x_1^2(n) * \sum_{n=0}^{N-1} x_2^2(n)\right]^{1/2}}, \tag{7}$$

where r_{12} – cross-correlation of signals:

$$r_{12}(j) = \frac{1}{N}\sum_{n=0}^{N-1} x_1(n) * x_2(n+j), \tag{8}$$

where $x_1(n)$и $x_2(n)$– digital signals with N elements,

j – shift value between signals$x_1(n)$ and $x_2(n)$.

The value of the cross-correlation coefficient always is between "-1" and "+1", where "+1" means 100% positive correlation, "-1" means 100% negative correlation (such as antiphase signals). A value of "0" indicates a zero correlation. It means that the signals are completely independent, for example, if one of the signals is absolutely random. Small values of $\rho_{12}(j)$ indicate a slight correlation [24]. The cross-correlation coefficient of gyroscope signals of the different limbs allows to estimate the degree of their spatio-temporal symmetry. At the analysis of symmetric motions, the delay j is equal to 0 for calculation of the cross-correlation coefficient (figure 10 a). At the analysis of asymmetric motions, the delay j is equal to $t_{cycle}/2$ for calculation of the cross-correlation coefficient because motions of different limbs are performed in antiphase (Figure 10 b).

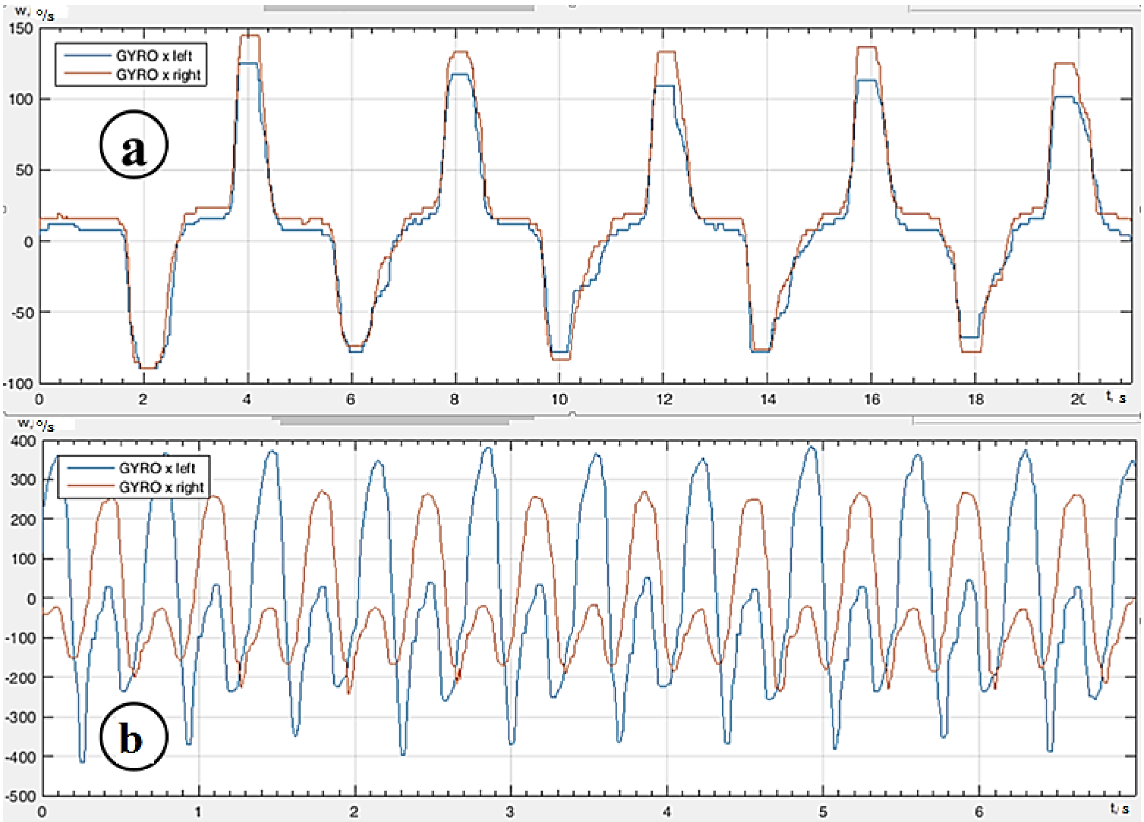


Figure 10. The examples of gyroscope signals of the different limbs: a - symmetrical movement (bending of arms in elbow joints); b - asymmetrical movement (running).

6. Analysis of motion biomechanical pattern reproducibility

The variability of biomechanical characteristics of a motion skill is an indicator of its defectiveness, because it shows the increase of muscle energy costs for correction and keeping of a motion stereotype [25]. The task of stability estimation of movement performance or reproducibility of motion skill is relevant for sports and can be solved by analysis of significant biomechanical parameters of the studied motion repeating several times [2, 26]. The reproducibility estimation of biomechanical pattern is based on the analysis of the target gyroscope signals for the motion repeated over a given number of times. The maximum angular velocity in phases (ω^{max}) and the duration of motion phases (t) are selected for analysis (Figure 11).

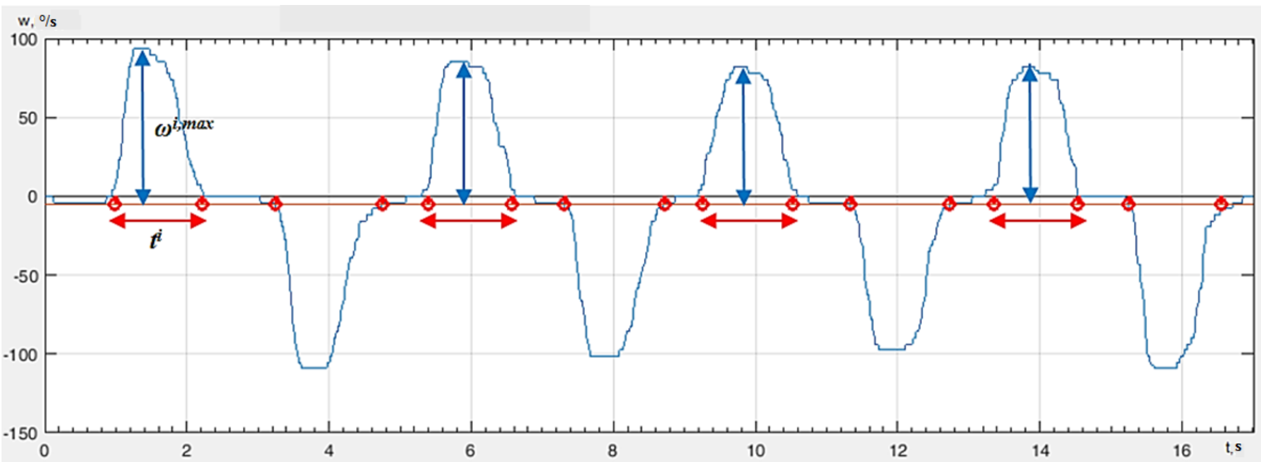


Figure 11. The example of stability estimation of sub-squat phase biomechanical parameters.

The stability coefficient of the biomechanical pattern is calculated according to the following algorithm:

1. For each phase of motion, the mean value of the maximum angular velocity W_f^{cp} (Eq.(9)) and the phase duration T_f^{cp} (Eq.(10)) are calculated using multiple repetitions.

$$W_f^{\text{cp}} = \frac{\sum_{i=1}^{N} \omega_f^{i,max}}{N}, \tag{9}$$

where N – number of attempts of the investigated motion;

i – attempt number;

f – motion phase number;

$\omega_f^{i,max}$ – maximum angular velocity in the f- th phase of the motion for the i-th attempt.

$$T_f^{\text{cp}} = \frac{\sum_{i=1}^{N} t_f^i}{N}, \tag{10}$$

where t_f^i – duration of the f-th phase of the motion for the i-th attempt.

2. For each phase of motion, the standard deviation of the maximum angular velocity σ_f^W (Eq.(11)) and the phase duration σ_f^T (Eq.(12)) are calculated using multiple repetitions.

$$\sigma_f^W = \sqrt{\frac{\sum_{i=1}^{N} (\omega_f^{i,max} - W_f^{\text{cp}})^2}{N}} \tag{11}$$

$$\sigma_f^T = \sqrt{\frac{\sum_{i=1}^{N} (t_f^i - T_f^{\text{cp}})^2}{N}} \tag{12}$$

The standard deviation of the maximum angular velocity in the phases and the duration of the motion phases characterize the variability degree of motion biomechanical parameters.

3. For each phase of motion, the stability coefficient of maximum angular velocity k_f^W (Eq.(13)) and the stability coefficient of phase duration k_f^T (Eq.(14)) are calculated:

$$k_f^W = \left(1 - \frac{\sigma_f^W}{W_f^{\text{cp}}}\right) \times 100~\% \tag{13}$$

$$k_f^T = \left(1 - \frac{\sigma_f^T}{T_f^{\text{cp}}}\right) \times 100~\% \tag{14}$$

The stability coefficient of maximum angular velocity in phases and the stability coefficient of phase duration characterize the degree reproducibility of motion biomechanical parameters.

4. The stability coefficient calculation of biomechanical pattern.

Integral stability coefficient of biomechanical pattern K is calculated as an average of all obtained stability coefficients of maximum angular velocity in phases and stability coefficients of phase duration according to the formula (Eq.(15)).

$$K = \sum_{f=1}^{F} \frac{\left(k_f^W + k_f^T\right)}{2} / F, \tag{15}$$

where F – number of the motion phases.

The stability coefficient of the motion biomechanical pattern has a value in the range [0...100 %].

Conclusions

The paper presents the estimation algorithm of biomechanical pattern of human motions based on amplitude-time analysis of inertial gyroscope signals. The algorithm allows to quantitatively estimate spatial, temporal and spatio-temporal parameters of motion, symmetry of left and right limbs motions and reproduction stability of motion biomechanical pattern. The specific feature of the algorithm is its universality for the study of symmetrical and asymmetrical motions.

The proposed algorithm to analyze the biomechanical pattern of human motion can be used for: development of biomechanical methods of motion efficiency estimation; development of new variants of motion techniques and estimation of their efficiency; estimation of the existing technique correctness and problem identification which can lead to injuries.

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