High resolution miniature MET sensors for healthcare and sport applications

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***Abstract* — A device has been developed for determining the motion parameters of the human body and lower limbs intended for use in orthopedic healthcare facilities, treatment and prevention of musculoskeletal system disorders, sports medicine. The layout of a miniature detector of movement parameters, consisting of six miniatures high precision molecular-electronic technology (MET) sensors (three linear motion sensors and three angular motion sensors) designed to be fixed on human lower limbs and body, was developed and constructed. Data processing algorithms have been developed to define, in addition to the provided instrumentally accurate data on linear and angular motion parameters at sensor fixation points, the major phases of motion corresponding to the periods of rest, start and end of the motion, as well as the actual movements of human limbs and body.**

Keywords — acceleration, motion parameters, miniature sensor, molecular electronics, algorithms, low noise, sport, wearable sensors, high resolution

I. Introduction

The current state of microelectronics, coupled with a huge breakthrough in information technology, opens up the possibility of innovative approaches to a number of tasks that have become already classical, such as the definition of motion parameters of human body and limbs. The urgency of the problem is underlined by a large number of potential applications, such as medical research on orthopaedics, analysis of human propulsion activities for detection of musculoskeletal system disorders and their degrees, sports medicine, including monitoring of motion parameters of sportsmen. Peculiarity of the current stage of development of the systems of the above-mentioned assignment is that the high accuracy requirements of the motion measurement systems are combined with severe restrictions on mass, dimensions, consumption and cost.

This study has developed a miniature 6-component measuring module, optimized in its characteristics to accurately define the angular characteristics, accelerations and time-related parameters of motion phases of body and lower limbs, as well as the development of algorithms to process and complexing data provided by sensors.

Physical activity sensors, also based on motion measurement using microaccelerometers and microgyroscopes [1,2], are fairly well represented on the market. An example is OMRON Walking Style Pro HJ-720-I [3] small devices developed by OMRON. In particular, devices of the kind allow to control the calorie outtake, including the use of energy to monitor children activity. At the same time, the functionality of such devices is very limited, because both the characteristics of the sensors used and the related software do not imply a precise measurement of the motion parameters, but rather detect the mere fact of motion and, let's say, distinguish walking and running. At the same time, the development of substantially more accurate systems that may emerge as soon as possible, is very active. In particular, works [4, 5, 6] present researches on the analysis of the walk using accelerometer methods. In particular, methods are being considered to detect violations of the walk, especially among older people, which may lead to sudden falls. The parameters of human lower limbs and body motion when the person sits or rises from the sitting position are investigated in works [7, 8, 9]. Monitoring of motion parameters changes in human body and lower limbs caused by orthosis disorders, the Parkinson's disease, as well as monitoring of the rehabilitation of the patients using motion microsensors are considered in works [10, 11, 12].

Analysis of these publications shows that interest in such research in clinical practice and sports medicine is very high [13, 14, 15], so a number of commercial products that provide accurate motion measurements and effective algorithms algorithms to process and complexing data is likely to appear [16,17].

II. Experimental Section

A. Experimental set.

This study has developed and constructed the layout of a miniature detector of motion parameters, consisting of six miniature sensors (three linear motion sensors [18, 19] and three angular motion sensors [20]) based on the molecular-electronic transfer (MET) technology Fig. 1, designed to be fixed on human lower limbs and body.

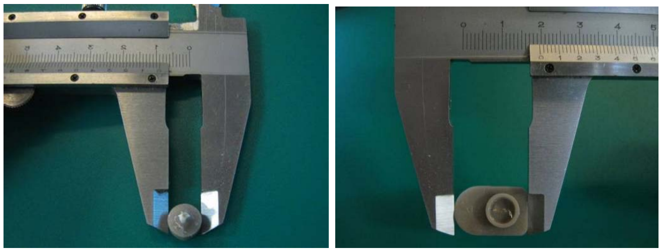

Fig. 1. Dimension parameters of developed rotation and linear motion sensors

On the laboratory stands have been measured technical parameters of the linear and angular motion sensors: frequency response, self-noise, Alan variance, sensitivity, temperature stability and operating range, power consumption etc.

The miniature MET sensors self-noise has been shown at Fig. 2, and Fig. 3

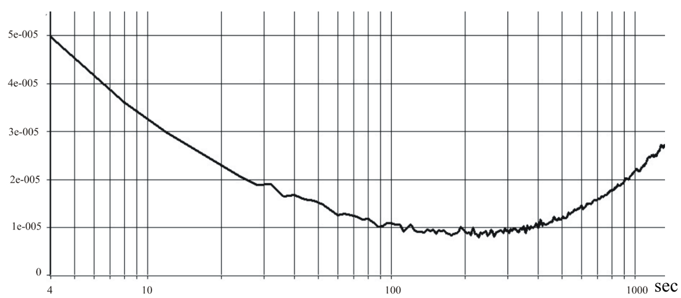

Fig. 2. Allan variance of miniature MET sensor of angular acceleration in rad/sec^2. Averaging time on X axis.

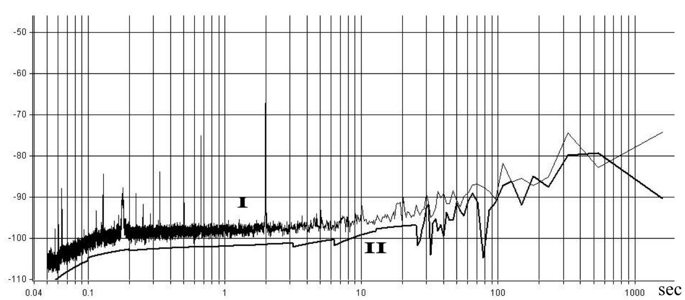

Fig. 3. Power Spectral Density (PSD) of miniature MET sensor of linear acceleration. **I** – signal PSD in low ambient noise conditions, **II** – noise level PSD in dB at 1 m/sec^2/√Hz. Periods on X axis.

With the help of the laboratory benches Fig. 4 the specific motions of human lower limbs and body were modeled, which reaffirmed the ability to measure motion parameters, such as acceleration and inclination angles with accuracy better than 1% and 1° respectively [21].

Fig. 4. One-axle motion simulator ST1144C with thermal camera 750T30/4 Climats in the horizontal position with 3 rotative and 3 linear components fixed for technical parameters testing.

TABLE 1. CHARACTERISTICS OF ROTATION MOTION SENSORS

Dimensions, mm	d 9x7
Weight, grams	0.8
Consumption, mA	1.5
Temperature range, °C	-50 +65
Temperature stability of the scale factor, %/°C	≤0.23
Service band, Hz	0.02 – 50
Time to prepare for operation, sec	1
Scale factor, V/rad/sec^2	0.5
Bias stability, rad/sec^2	10^{-5}, see fig 1b

TABLE 2. CHARACTERISTICS OF LINEAR MOVEMENT SENSORS

Range of input signals	2 g
Temperature drift of the scale factor, %	<2 in operating range
Noise spectral density, dB at 1 m/sec^2/√Hz	-102, see Fig 1c
Range of operating temperatures, °C	-50 +65
Current consumption, mA	1.5
Weight, grams	3.4
Dimensions, mm	20×10×6
Scale factor, V/m/sec^2	0.3

The task solution of calculating motion parameters of human body and lower limbs can be divided into the instrumental part and the development of data processing algorithms. The instrumental part is the creation of devices with an output signal proportional to the external mechanical impact and the direct measurement of angular and linear acceleration at sensor fixation points on human body and lower limbs. By integrating the instrumental part data, you can directly calculate the motion parameters as linear and angular velocity, rotations and displacements. The data processing algorithms, in turn, should define the phases of movement.

B. Algorithms

Experimental data were obtained during the preliminary tests of the complex as a recording of the sensor reading, depending on time and on the fixation points on the lower limbs.

The analysis of experimental data resulted in a processing algorithm that allows to determine the parameters of human limbs movements and to search walking phases. To explain the algorithm's work, let's consider the reading of one of the linear acceleration sensors, located on the human foot during the walking process, and consider the algorithm's work in stages:

1) For each sensor, the noise level of "x" shall be calculated. Then a filter is applied to the entire record, which identifies the sections where the noise level is higher than the signal level. The signal recorded at these sections is accepted as zero. The result of the filter action is shown in Fig. 5

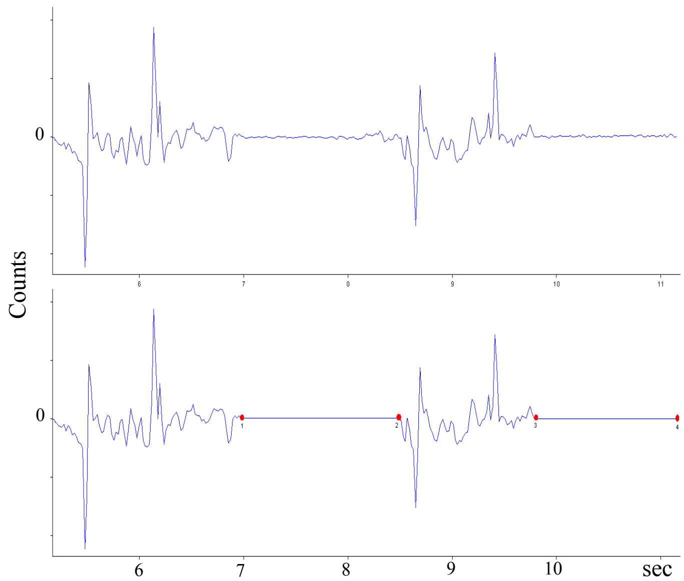

Fig. 5. On the top of the diagram there is a primary record, and record after the first step of the algorithm – on the bottom. Sections between numbers 1 and 2 and 2 and 4 were replaced by zero.

2) Presence of resting areas of the foot. Since the smooth movement of the pedestrian's foot is actually never realized in practice, it can be assumed that if the recorded acceleration is equal to zero, then the pedestrian's foot in the current timespan rests relatively to the floor. Thus, the rest phase of the foot (sections between numbers 1 and 2 and 2 and 4) and the motion phase of the foot (sections before number 1 between numbers 2 and 3) is calculated in Fig. 5. The motion phase can be divided into the following phases: motion start, foot movement in the air and foot slowdown phase.

3) Identification of the walking start phase. After the foot rest phase, the motion start phase begins. If in a gap of 0.1 seconds the signal has changed more than several times, we believe that the foot takeoff has occurred and the motion start phase is over. The filter's work is illustrated in Fig. 6.

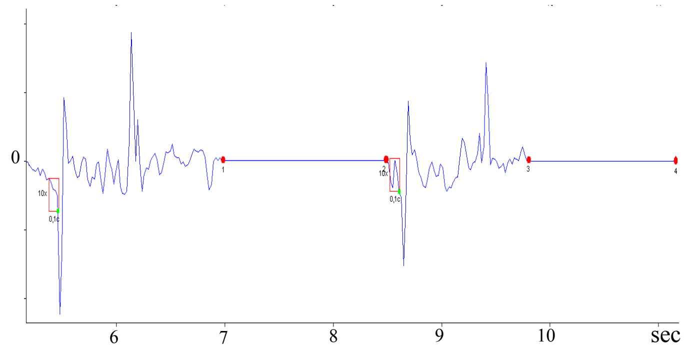

Fig. 6. The moments when the signal value changes more than 10x times are marked by green points.

4) Immediately following the motion start phase, the displacement phase of the foot in the air occurs.

5) The slowdown phase starts in the following two conditions: a) The acceleration of the foot is terminated, i.e. the boundaries of the filter gap of the point (3) are no longer intersected on the top and bottom (these moments are illustrated by black points in Fig. 5), b) from the moment mentioned in paragraph a) from the interval of 0.1 seconds the signal value changed more than "20x" times ("15x" for the rotational acceleration sensor) (these moments are illustrated by blue points in Fig. 7). The slowdown phase terminates with a phase of the complete peace of the foot, which was found in paragraph (4).

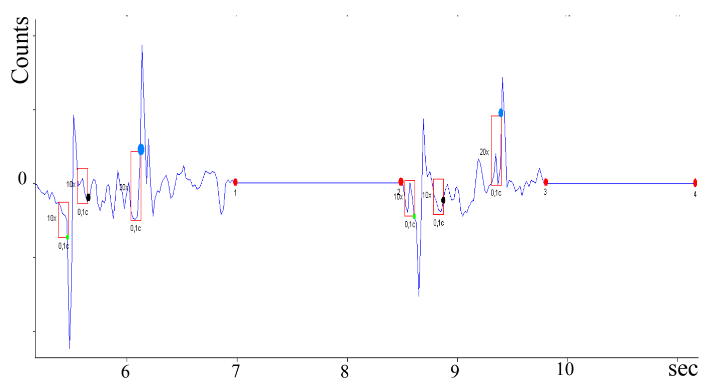

Fig. 7. The result of operation of the 5th paragraph of the algorithm.

6) The slowdown phase terminates at the beginning of the next peace phase found in paragraph (2).

7) For the data received from each of the two sensors fixed on foot, paragraphs 1-6 are implemented. It then averages the time phases according to the data received from each sensor (for example: t_1 – is the time moment of the full stop of foot obtained from the linear sensor data, t_2 – is the same time moment, but obtained from the rotational acceleration sensor data, then the result of the algorithm is the temporary coordinate of the full foot stop is: $t=(t_1+t_2)/2$).

Thus, the implementation of the algorithm developed can be presented in the following flowchart Fig. 8.

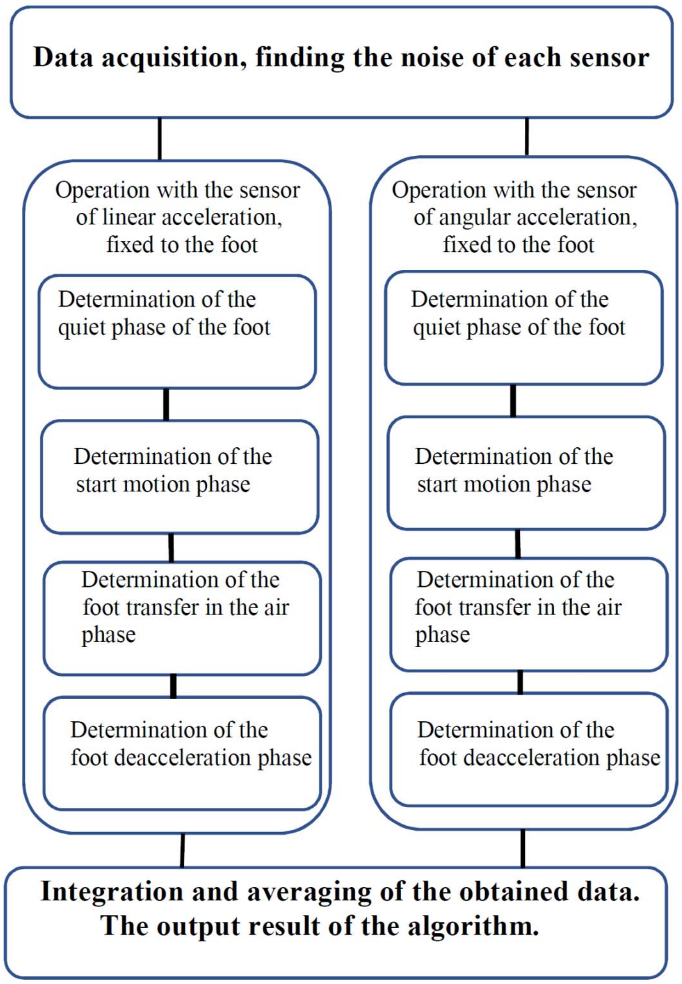

Fig. 8. Flowchart of time parameters calculation of walk phases

C. Natural experiment

In the course of the tests, the output signal of all the channels of the miniature detector was recorded to the computer of the data collection system, with the simultaneous recording of the experiment by a digital video camera synchronized in time with the data collection system. In the course of the experiment, the readings of the miniature detector sensors fixed on the lower limbs of the pedestrian as he moves along the rectangle marked in line with Fig. 9, were investigated. The footing at each step of the elevation plots was made according to the layout. The received records were processed in the off-line mode using the algorithm described above.

The processing of the experimental data using the algorithm described above makes it possible to establish a clear correspondence with a series of experiments and to highlight the walking phases of a pedestrian, namely the rest of the foot on the floor, the phase of the start of the resumed motion, phase corresponding to the direct movement in space, the end-of-motion phase Fig. 10.

Thus, as a result of the implementation of the relevant paragraph of the tests, the complex steadily demonstrated that the parameters of the human lower limbs movement can be determined and that the time parameters of the walking phases are registered.

The processing of recorded sensor signals showed that the strongest signal is demonstrated by angular and linear acceleration sensors fixed on the foot. The sensitivity axis of these sensors was directed to register the angle of the foot rise. The records clearly show all the phases of human walking as an example in Fig. 8, a detailed analysis of the recording of the accelerometer's signal, located on human's foot at slow speed, using the developed data processing algorithm. The records of the three consecutive steps taken by the linear and angular motion sensors in the slow, normal and fast walking speeds are presented in Fig. 9, 10, 11. Table 3 shows the main parameters of the human foot movement derived from these records.

Fig. 9. Angular motion and linear acceleration sensors fixed on foot of the examiner

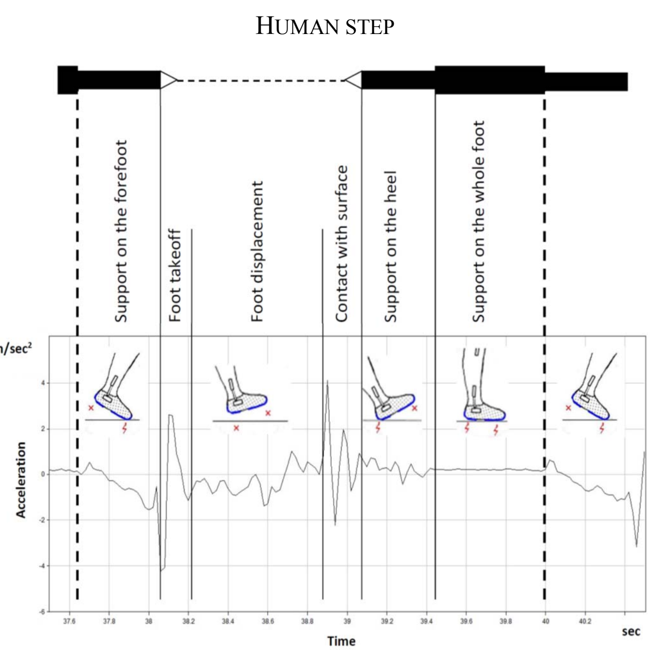

Fig. 10. A signal recorded by a linear accelerometer during human walking

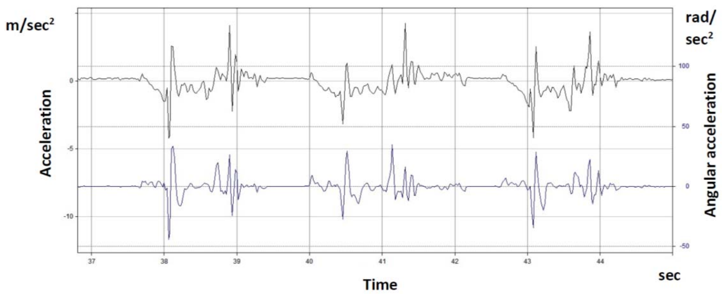

Fig. 11. Three consecutive steps, signals from the angular and linear accelerometers, slow walking speed.

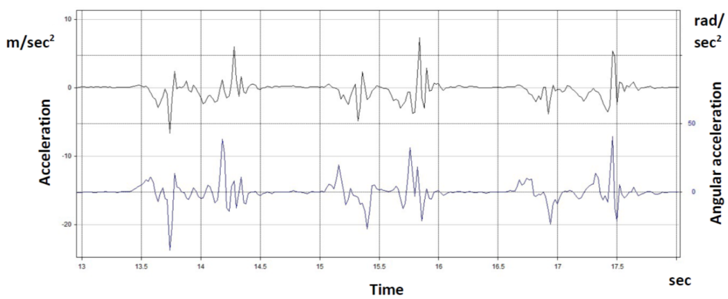

Fig. 12. Three consecutive steps, signals from the angular and linear accelerometers, normal walking speed.

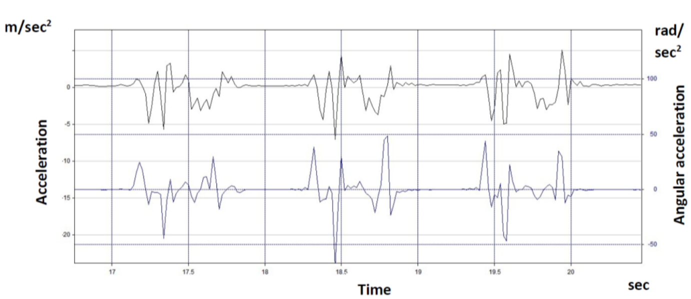

Fig. 13. Three consecutive steps, signals from the angular and linear accelerometers, fast walking speed.

TABLE 3. SOME PARAMETERS OF THE HUMAN FOOT MOVEMENT

Walking speed	Slow	Normal	Fast
Support on the forefoot	0.36 s	0.24 s	0.12 s
Foot displacement	0.84 s	0.54 s	0.38 s
Support on the heel	0.52 s	0.28 s	0.14 s
Support on the whole foot	0.6 s	0.58 s	0.48 s
Step duration	2.32 s	1.5 s	1.16 s
Maximum linear acceleration	4.28 m/sec^2	7.21 m/sec^2	19 m/sec^2
Maximum angular acceleration	44 rad/sec^2	40.8 rad/sec^2	48.5 rad/sec^2

It is clear from the table that the time of partial support and the takeoff is significantly reduced as the walking speed increases, while the length of the rest of the foot is much smaller. Similarly, the maximum linear acceleration increases almost 4.5 times, but the angular acceleration is almost unchanged.

Next, let's look at the sensors on the human's lower leg. The signals of two pairs of sensors were recorded – one pair was fixed on the front of the lower leg, the other – on the side Fig. 7. Fig. 14 and 15 show records of three steps taken by these sensors. As you can see, when removing a signal from the lower leg, the walking phases are also clearly visible. It should be noted that the best results are provided by the angular acceleration sensor located on the side of the lower leg (the axis of sensitivity is directed at the bend axis of the human knee) and the linear acceleration sensor located at the front of the lower leg (the sensitivity axis is directed vertically). The maximum linear acceleration values are 6.5 and 5 m/s^2 of sensors located on the side and front respectively. For angular acceleration, they are equal to 15 and 26.5 rad/s ^{2}.

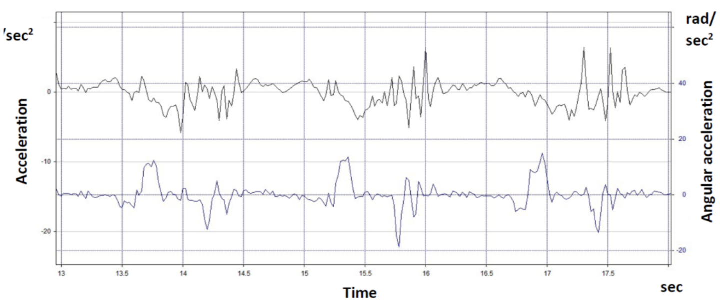

Fig. 14. Signals record of linear and angular sensors fixed on the side of the lower leg. Normal walking speed.

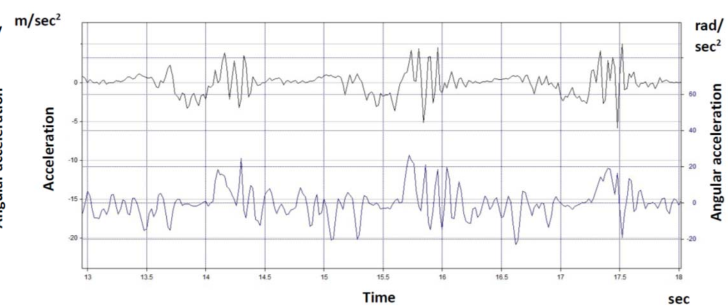

Fig. 15. Signals record of linear and angular sensors fixed on the front of the lower leg. Normal walking speed.

In the field tests, the reading of the sensors did not exceed the operating range. The algorithm was also set up to work reliably under conditions of straightforward motion. At rotation, the algorithm does not always work and needs to be redesigned in a proper way. Fig. 16 shows the schedule of the rotation acceleration sensor when the examiner is rotated by 90 degrees.

Fig. 16 shows that there is no second spike corresponding to the start of the slowdown phase. The algorithm has been finalized, a paragraph (6.1) has been added between paragraphs (6) and (7), the meaning of which is to identify the slowdown phase of the foot by the angular acceleration sensor. If the slowdown phase is found, paragraph (7) of the algorithm remains unchanged, if the slowdown phase of the angular acceleration sensor has not been detected, in paragraph (7), for the start of the slowdown phase of the foot, instead of averaging the temporary intervals of the two types of sensors, the values obtained from sensor data of linear accelerations are taken.

Thus, the work resulted in the creation of a sextuple complex to measure walking and motion of human lower limbs, and the algorithm for the registration of walking and lower limbs was developed and refined, and the following accuracy and other characteristics were experimentally reached Table 4:

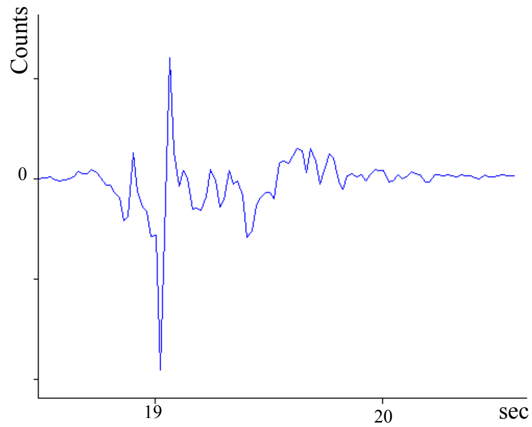

Fig. 16. Data obtained at the dismissal of the experimenter for the rotational acceleration sensor, on the ordinate axis of the ADC.

TABLE 4. EXPERIMENTALLY PROVEN CHARACTERISTICS OF THE MINIATURE DETECTOR AND SENSORS

Precision of angular characteristics determination	No worse than 1 °
Accuracy of temporary characteristics determination	No worse than 0.01 s
Precision of acceleration determination	No worse than 0.01 g

III. CONCLUSION:

The developed data processing algorithms allow to define, in addition to the provided instrumentally accurate data on linear and angular motions parameters at sensor fixation points, the major phases of motion corresponding to the periods of rest, start and end of the motion, as well as the actual movements of human limbs and body.

By analyzing the totality of the output parameters, such as noise level, the dynamic range on one side and the mass of sensors that are part of a detector, with other types of sensors, especially those constructed on solid technologies, one can conclude that the developed devices in a miniature sensor class of up to 3-4 g range, provide the highest output parameters in order of magnitude and more than the devices that have been selected for comparison [22,23]. However, comparable or better parameters are provided only by significantly more overall (and expensive) devices. The experimental study demonstrated the high signal resolution of angular and linear MET sensors. Thus, it can be concluded that the most promising applications of the developed miniature detector are those that are crucial for measuring relatively weak motions or motion features on the background of strong enough signals such as neurological and orthopedic medicine, sport science and others.

ACKNOWLEDGEMENTS:

This work was supported by the Russian Foundation of Basic Research #17-07-01334, 17-20-02183, 16-07-01081 and Russian ministry of science project ID #14.578.21.0243

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