Algorithm for Monitoring the State of the Musculoskeletal System in Scoliosis

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***Abstract*—In the work considers an algorithm for analyzing a person's gait based on the accelerometer readings of mobile devices. The proposed algorithm, in contrast to the previously known ones, performs processing not in the frequency domain, but in the time domain, and makes it possible to estimate the difference in the duration of the steps with the right and left legs of a person. The algorithm can be used to build a system for the rehabilitation of patients with scoliosis. The following system components have been developed: data collection using a special application on a mobile phone; their processing by the subsequent algorithm.**

I. Introduction

According to the dissertation by Shcherbina S.L. [1] scoliosis is a three-plane spinal deformity. Flat feet in children are often combined with scoliosis. In most cases, one of the pathologies leads to the appearance of the other. So, the wrong structure of the foot significantly increases the load on the spine, contributing to the disruption of its normal growth and the occurrence of curvature. Spinal curvature disrupts the balance of gravity and causes disharmony with the load on the feet, which leads to lateral flatfoot in children and the rapid progression of foot deformity in adults. developing foot, it is necessary prophylactic use of children's individual orthopedic insoles.

Gait recognition systems can be divided into two categories:

- Assessment using special equipment and scales.
- Wearable sensors (accelerometers).

In work by Shcherbina S.L. [1] describes a method for detecting scoliosis using electromyographic (EMG), stabilometric, metrological (centimeter tape) and palpatory methods. These methods investigate the state of the paravertebral muscles and the balance of equilibrium, as a result of which they decide on the absence or presence and degree of scoliosis in a patient. The described method of diagnosing scoliosis is not suitable from the point of view of the mobility of the test subject, you will have to constantly meet with the doctor for identification and subsequent monitoring, which takes a lot of time.

Also, there are methods for analyzing a person's gait using computer vision. A person's gait is recorded on a video camera, then image processing algorithms and video sequences are used. Basically, the algorithms are arranged as follows - the background is removed from the image, and then the human silhouette is extracted and analyzed [2], [3], [4], [5]. Their main disadvantages are price and stationarity. To monitor the progress of recovery, the patient will have to personally come to the clinic personally and undergo an examination that will spend a large amount of time and money.

Another way to diagnose scoliosis is the method described in work [6] a method for detecting scoliosis using an accelerometer in a mobile phone and a special algorithm based on Fourier transform and working in the frequency domain.

Let us consider in more detail - in this work, the subject attaches a mobile phone to the body and travels a certain distance, then the algorithm processes the data obtained. Due to diseases of the musculoskeletal system, the frequency in the spectrum may vary, for example, the appearance of peaks at higher frequencies. The program catches these changes and makes its decision. Detection of scoliosis with the help of this symptom does not allow to monitor the dynamics of the disease or the rehabilitation of the patient. This algorithm can only make a decision whether the subject has scoliosis, or there is none. When implementing this system, there is a problem of taking data at the exact moment of time (with the same frequency), since this program works under the control of the android system, significant distortions are introduced, the discretization goes with unequal steps and the algorithm [6] may not work correctly.

Thus, the actual question is the development of an algorithm that is not subject to this kind of distortion.

In our work, we will present a method for diagnosing scoliosis, with the help of which it is possible to trace the dynamics of recovery or the patient's condition deterioration.

The algorithm below will also determine the correcting ability of the insole for the treatment of scoliosis described in the work of the aforementioned Shcherbina S.L.

II. Descriptions of the Developed Solution

It has been proven that a person with scoliosis has a big difference in the length of steps, due to this, two nonsynchronous oscillations appear during walking (the step of the left and right legs are not the same), whereas in a healthy person the length of the left and right steps are on average equal.

Based on this nonsynchronous movement of the legs (one step is longer than the other), disease can be detected.

When developing the system, a well-known fact was used [7] that when walking, the movement of its hip (TBS) joint is close to a sinusoid (Fig. 1, Fig. 2).

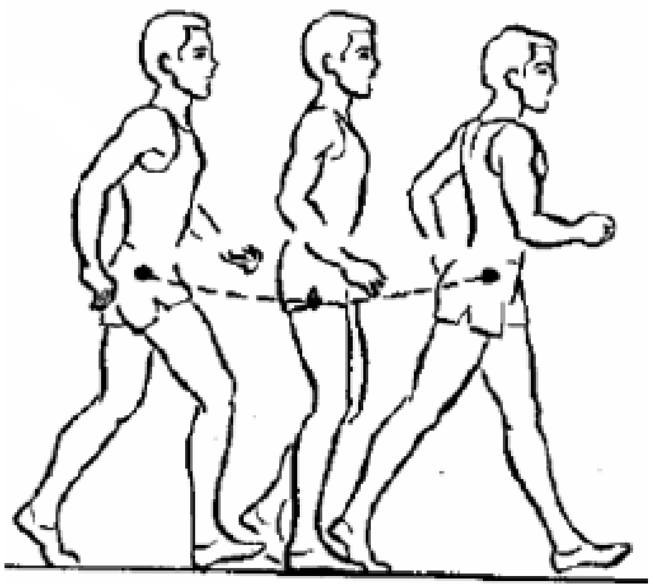

Fig. 1. Moving the common center of gravity during normal walking. [7]

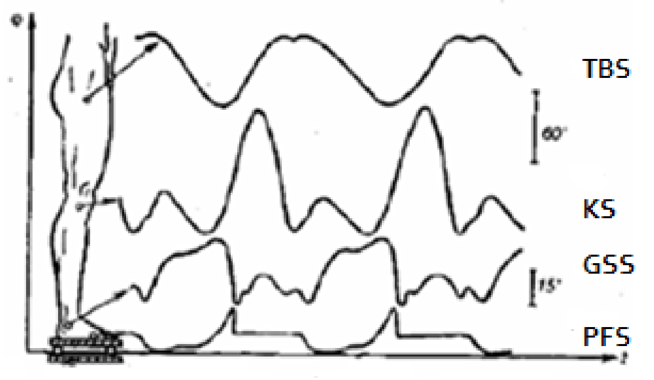

Fig. 2. Charts of interstitial angles and support reactions when walking in normal, TBS, KS, GSS, PFS - respectively hip, knee, ankle, metatarsophalangeal joints. [7]

The phenomenon can be seen in the implemented algorithm.

On the Fig. 3, dash-dotted line shows the time function of the acceleration recorded by the accelerometer of the mobile device, thick line is the result of double differentiation, thereby moving into the time domain. Therefore, according to the accelerometer, we can restore the trajectory of the hip joint

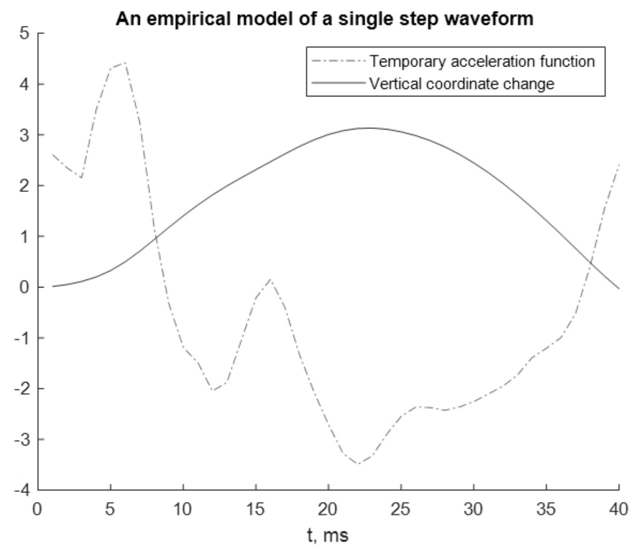

Fig. 3. An empirical model of a single step waveform

Having twice integrated the accelerometer readings, we can restore the pelvic trajectory and determine the steps. In practice, devices are introduced significant distortions in the data and double integration is an error accumulates. Further processing becomes impractical. Therefore, our work uses a different approach. Detection of steps occurs when working immediately with acceleration without the need for double integration, thereby avoiding the accumulation of error.

The system consists of two parts, hardware (application on the smartphone, which takes the data from the sensors and sends them to the server) and server (the program that processes the received data and issues a solution).

The hardware works as follows, the smartphone is mounted on the belt of the test. This place was not chosen by chance, because during the experiments it was proved that when the smartphone was moved to the right or left side of the body, the amplitude of oscillations of one leg greatly exceeds the amplitude of the opposite one, as a result, when the signal is segmented into steps, the two steps merge into one and further work with the data meaningless. If the phone is installed in the middle of the patient's torso, it detects separate, not paired ones, as a result of which it is possible to distinguish both steps with further data processing. Below are pictures proving this.

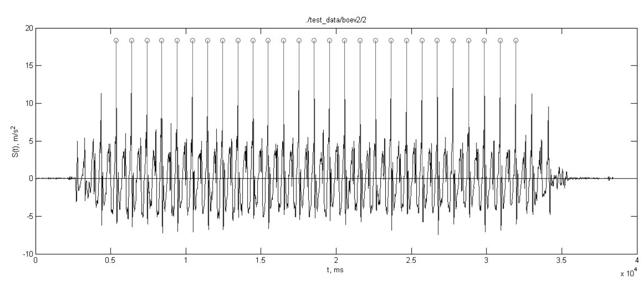

Fig. 4. Experiment timing diagram, where the phone is placed on the patient's belt on the left

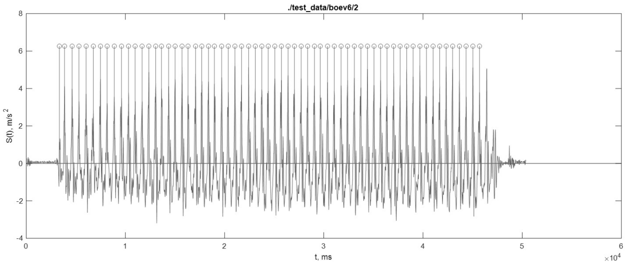

Fig. 5. Experiment timing diagram, where the phone is placed on the patient's belt in the middle

On the Fig. 4 and Fig.5, the difference is clearly visible, the number of peaks (where each peak corresponds to one step) is not equal, on the Fig. 5 they are twice as large. Experimental conditions for schedule 4 and 5 were exactly the same, the only difference was only in the location of the phone, it follows from this that the phone must be located in the center for more accurate data collection. Most likely this phenomenon is due to the fact that the mount of the smartphone on the hip from either side does not take into account oscillations from the opposite side due to the physics of the step.

Next, the patient must go with the device in a natural step along a straight path on a flat surface, while the program takes readings from the accelerometer. Accelerometer readings represent acceleration along the three axes X, Y, Z. The algorithm analyzes the Y axis, since it is along this axis that the body oscillates during walking.

Data from it is taken from the maximum for the smartphone software frequency of about 50 - 100 Hz. Then the data is sent to the program on the server for further processing.

A. *Taking data from the accelerometer sensor*

The task is to implement a program that, through the api operating system (in the case of android), will take the sensor readings and record the file for further processing. The only difficulty at this stage is to take readings as often as possible for a more truthful result. Ideally, this algorithm is designed for a continuous periodic signal, but in practice we have a deterministic, not taken at strict points in time, then the greater the frequency of taking the report, the better the result we get at the output.

This collection is carried out on the y-axis since it records the maximum fluctuations during walking.

The data on this axis will be processed in the following algorithm.

B. *Pre-processing*

While taking data from the device, an element of randomness is also added to the "clean" data. There are quite a few such elements here, for example, different steps during walking, which are also found in healthy people, floating sampling intervals, noise of the sensor itself, as well as the operating system through which we interact with the accelerometer.

Fig. 6 shows the original (not preprocessed signal) The initial and final values of the signal will be discarded as it either completes or begins walking and these values are most prone to error. These places correspond to the beginning and end of the movement, since the step at a given time is unstable, this data introduces more errors than helps to make the right decision.

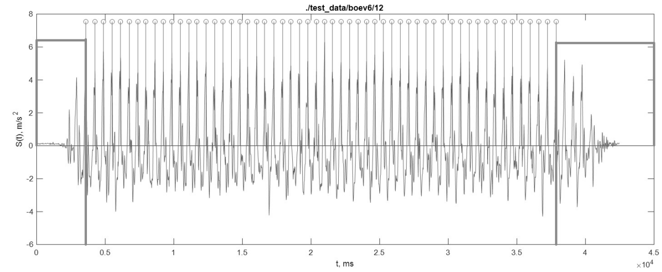

Fig. 6. Removing data from the edges of the signal

On average, data from the sensor (real data that is written to a file and is processed) is taken with a period of +- 15 milliseconds. This is a big error for the data that must come to the input of the segmentation algorithm steps, which is why the preprocessing stage is introduced in which the data passes the following processing:

- Removal of the constant component (acceleration of free fall).
- Ccorrected due to improper placement of the smartphone (if necessary), the case is considered when the phone is turned or turned.
- Remove data from the edge of the signal.

C. *Step segmentation*

The time function of the acceleration values undergoes segmentation into separate periods according to the maxima of the time function using the algorithm “Speech signal segmentation for automatic speech processing” [8], adapted to the signal taken from the accelerometer while walking. 5 periods are removed from the beginning and end of the signal (the period of time when the subject was motionless, or started or finished the experiment, at the given time the error is most likely).

Search for stepping cycles is performed by selecting local maxima in the signal and subsequent candidates for the limits of these maxima, which are specified with a number of additional conditions.

Algorithm 1 Algorithm of step segmentation

0: Allocation of local maxima.
1: Variable initialization.
2: Selection of a subset of local maxima.
3: Candidate for OT segment (maximum limits).
4: Selecting a new subset of local maxima and checking with other additional conditions.
5: Check maximum limits.
6: If found - exit, if not - clarification of the candidate for the border, the transition to the next.

Dividing timing chart into steps, we get the following result presented in the Fig. 7.

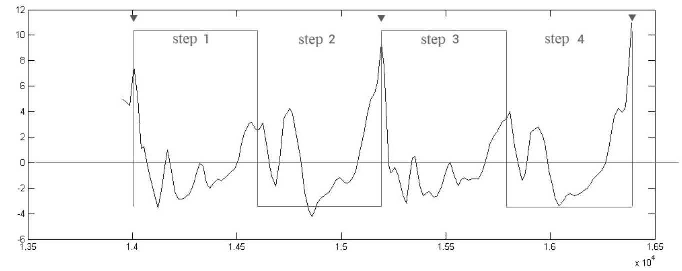

Fig. 7. Experiment timing diagram, where the phone is placed on the patient's belt in the middle

Approaching the timing diagram (Fig. 7), we will see 4 whole steps of the left and right legs.

This algorithm is sensitive to the following inaccuracies in the measurements of the input data - the effect of internal oscillations within a period that can be large enough to generate false elevations of the segment boundaries. Taking this fact into account, an appropriate adjustment must be made before the signal is fed to the input of the algorithm.

This inaccuracy is mainly due to the unequal time of taking reports in the accelerometer, as the program works on top of the existing android shell, which makes its corrections to its work

Further, the obtained results (vector of steps) become input data for the next algorithm, even and odd steps and their total difference are analyzed.

D. *Error accumulation*

Allocated periods are divided into two groups: odd periods refer to one leg, even periods to the second leg.

Then, using the period, the duration of each step and the average duration are calculated, then these values are compared between the left and the right foot.

Algorithm 2 Algorithm for calculating the final error

0: Calculating the difference of steps:

$$dT = Tl - Tr;$$

where *Tl, Tr* - vector of steps.

1: Error accumulation and normalization by N. The error is calculated integrally this accumulation is necessary for averaging the random effects I have described above on the original signal. Ideally, after this action we will receive only a useful contribution.:

$$D = \sum(dT) / N;$$

2: We get rid of negative values:

$$\textbf{if } D(end) < 0,\ D = -D;\ \textbf{end}$$

The result obtained is equal to the total difference of steps throughout the experiment. Ideally, this value should be close to zero, this will mean that the correction ability of the insole is maximum.

In practice, this value in rare cases will be zero, this is primarily due to the errors introduced into the algorithm, as well as the nature of human walking. A person is asymmetric in his walk and from a physiological point of view; therefore, even a healthy person's steps can sometimes differ slightly. In a person with scoliosis, these differences will be more significant. From this it follows that in this algorithm it is necessary to make a threshold, the minimum possible difference in the step length, which is recognized as the norm.

III. RESULTS OF EXPERIMENTS

The subject was asked several times to go through the same area of a flat surface, but with a number of changes.

1) An insole was additionally placed under the left foot. (Fig 8, 9, 10)
2) The insole was under two legs. (Fig 11, 12, 13)
3) The insole was located in the right shoe. (Fig 14, 15, 16)

The time function of the acceleration values *A(t)* undergoes segmentation into separate periods along the maxima of the time function. 5 periods are removed from the edges of the signal (noise fragments without movement, the beginning and end of movement).

Allocated periods are divided into two groups: odd periods refer to one leg, even periods to the second leg.

The graphs *Tn* (Fig. 9, Fig. 12, Fig. 15) show the durations of the individual steps of each leg (a variational series of the durations of the steps), the bold marker indicates the average duration of the step. In the upper semiaxis data on one leg, in the lower - on the other.

The graphs *T(n)* (Fig. 10, Fig. 13, Fig. 16) show the dependence of the step duration on the step number. The steps of one and the second leg are marked with different colors.

Graph *D (n / 2)* (Fig. 10, Fig. 13, Fig. 16) reflects the accumulation of the difference in the durations of adjacent steps of one and second legs, normalized by the number of steps and corrected to a positive.

Experiment 1. Insole under the left boot. The difference between the left and right steps is clearly visible.

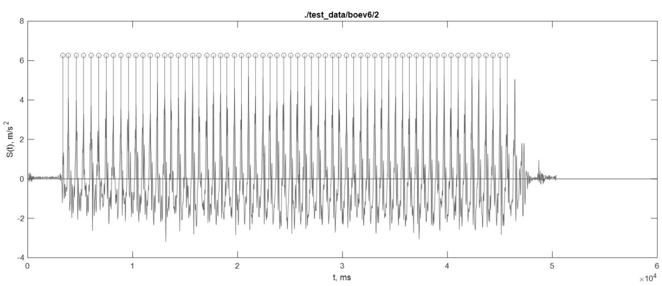

Fig. 8. Timing Chart

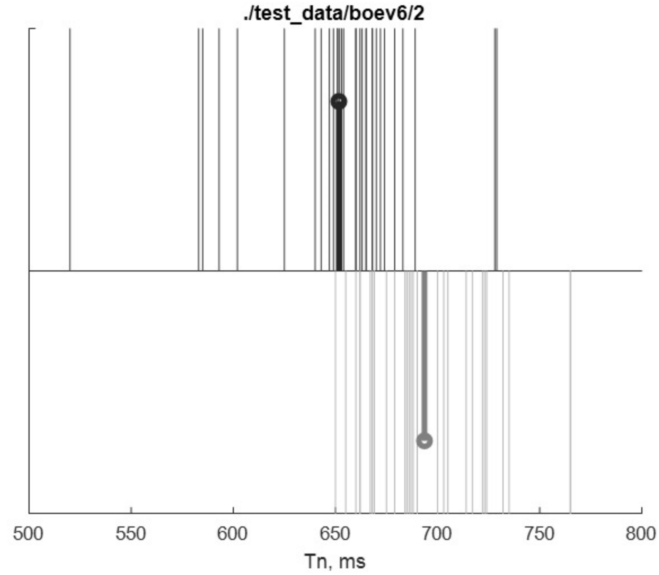

Fig. 9. Dependence of the step length from the number

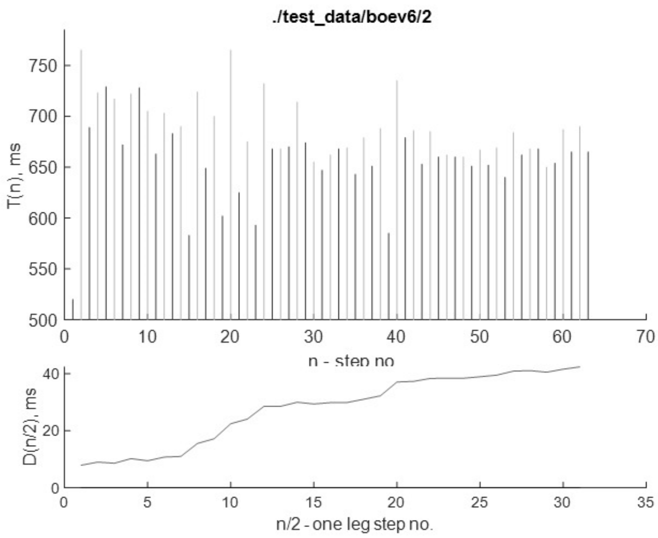

Fig. 10. Difference between adjacent steps

Experiment 2. The insole is under both shoes. The difference is also noticeable, however, the average error for the whole experiment is about zero.

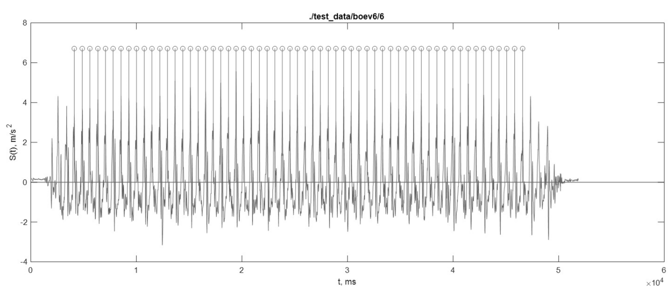

Fig. 11. Timing Chart

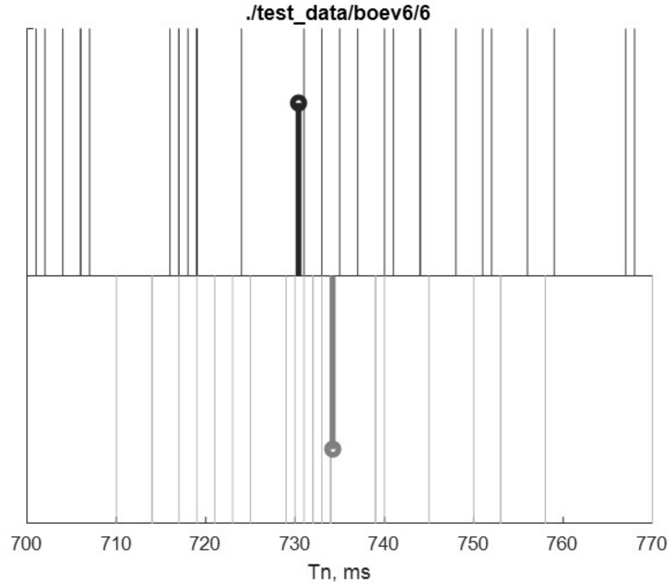

Fig. 12. Dependence of the step length from the number

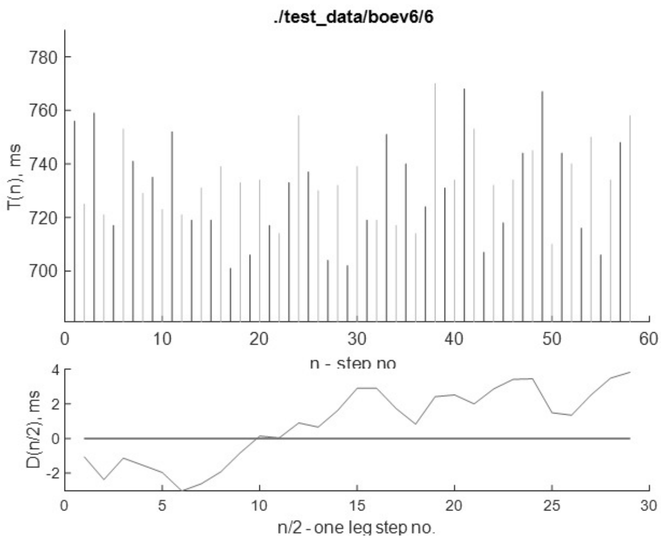

Fig. 13. Difference between adjacent steps

Experiment 3. The insole is under the left shoe the difference is almost not visible.

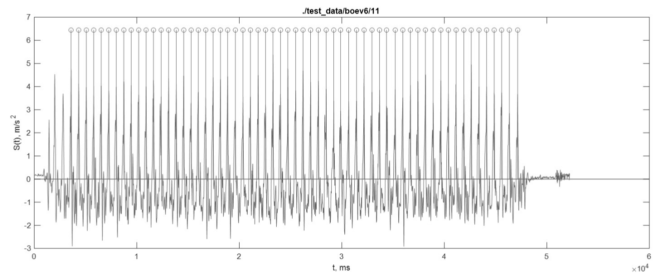

Fig. 14. Timing Chart

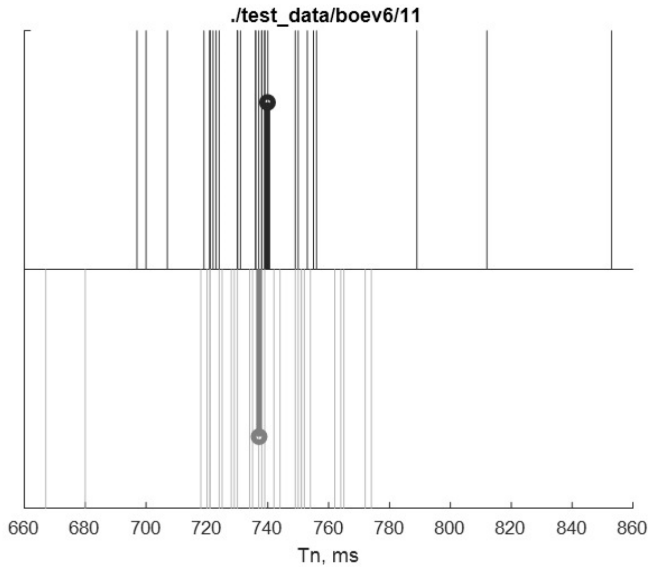

Fig. 15. Dependence of the step length from the number

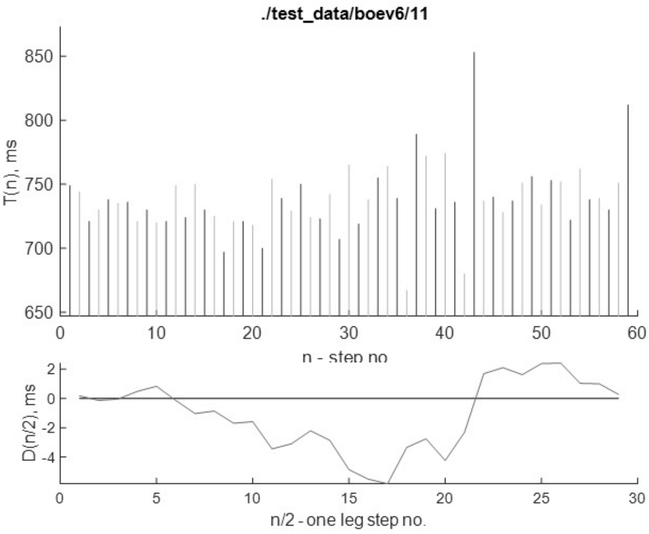

Fig. 16. Difference between adjacent steps

Analyzing the data obtained it is clear that when using the insole in experiment number 3 (the insole was located in the right shoe), the average length of the left and right steps are approximately equal, and the total error calculated for the entire experiment, tends to zero and the correcting ability of this insole is maximum. In experiment number 2 (in both boots there was an insole), the average length of the left and right steps was approximately equal, but still worse than in experiment number 3, the overall error estimate for all the time was close to zero, but higher than in experiment number 3. The worst corrective ability turned out to be in experiment number 1 (the insole was located in the left shoe) - the average step length of the left and right foot is maximum for all 3 experiments, and the average error estimate is ten times higher than in previous experiments. Hence the conclusion that this test subject has a curvature of the spine, but it has a low degree, as in the experiment with two insoles (experiment number 2) the step difference is small, but not zero. The insole has the highest corrective power in the 3rd experiment.

IV. Conclusion

In the work describes the algorithm for analyzing a person's gait based on the accelerometer readings of mobile devices. A comparison of this algorithm with previously known analogues is given. It is noted that due to the processing in the time, but not in the frequency domain, the algorithm allows to distinguish the difference in the duration of the steps of the right and left foot of a person. The algorithm can be effectively implemented on modern mobile devices, characterized by an unstable sampling interval of the accelerometer signal.

The novelty of this algorithm lies in the work of direct acceleration without a transition to vertical coordinates. Thereby we get rid of the procedure of double integration and accumulation of errors. Based on this, this method is more accurate and less error prone than its predecessors.

The paper describes the results of a series of experiments that show that this algorithm allows determining the change in the step length when adding removing a corrective insole with a thickness of about 3 mm.

The noted properties of the algorithm allow it to be used in building a system for the rehabilitation of patients with scoliosis.

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