Improving the Efficiency of the Human Spine Diagnostics Systems

Nikolay Dorofeev, Konstantin Podmasteriev, Oleg Kuzichkin, and Anastasia Grecheneva

Murom Institute (branch) Vladimir State University, Murom, 602200,
23 Orlovskaya st., Russia
DorofeevNV@yandex.ru
http://www.mivlgu.ru

Abstract. The paper proposes a method of recording and measuring the spatial mutual movement and positioning of the spine segments. As a basic method, an application of the accelerometer measuring method of the rotation angles and acceleration is proposed. The research results show that the use of accelerometer sensor significantly increases the flexibility of the system (scalability and ease of interfacing the accelerometric diagnostic and rehabilitation system of the spine with other diagnostic systems) and the accuracy of the results (thanks to additional digital processing of recorded signals) due to the small size and high precision of sensors. The proposed method is passive (does not use additional exposure, such as in an ultrasound, X-ray and tomography) and has no negative impact on patient.

Keywords: biomechanics, human spine, diagnostic system, goniometric control, accelerometery.

1 Introduction

One important area of medical technology is diagnostic and rehabilitation equipment, especially spinal diagnosis and rehabilitation system [1]. Various deviations in the relative position of the spine segments affect the functionality of the musculoskeletal system, internal organs, eventually triggering a “chain reaction” of disorders of organs and systems of the body as a whole [2, 3].

To figure out timely corrections of the deviations in the spine, and preventing the formation of irreversible pathological processes, a high accuracy primary diagnosis is required. It should be noted, that during the period of spinal rehabilitation to assess the treatment and recovery results, an investigation of patient’s motion is required.

2 The current state of medical diagnostics of the spine

In the existing medical diagnosis methods, the presence of pain syndrome is a key reason for the prescription of rehabilitation procedures [4]. Pain is the basis for hospitalization, medical appointments actions aimed at rehabilitation, and often for the adoption of expert solutions (diagnosis). Therefore, the prescriptions for rehabilitation are assigned to the patients that have a partial violation or substantial loss of functionality, *i.e.*, spine pathology with pain syndrome and neurological manifestations. In practice, this means one must carry out rehabilitation effects only on the patients with acute syndromes and during recovery periods.

Diseases of the spine are accompanied by impaired mobility of vertebral joints. For example, studies were carried out on soldiers of the Air Force of the Ministry of Defense of Russia. The soldiers' physical state were characterized by a high degree of physical fitness and health requirements. The results of the studies reveal a relatively high level of disorders of the spine functions in 56 % of the cases. The same violations of the biomechanics of the spine were revealed in 61.3 ± 3.5 % of the patients, with 19 % of the violations were of moderate to severe degree [5].

For this reason, an important part of solving the problem of diagnosis of spinal diseases and their treatment is the development of an automated method of goniometric spine control. The method are to provide a high accuracy and sensitivity, and must be easy applied in practice for estimation of the functionality of the spinal column.

3 The accelerometer method of geometric spine control

We propose to use accelerometer method of bending angle measurement for assessing spinal configuration and range of its motion in the sagittal, frontal and horizontal planes as a method of goniometry in the automated control system [6]. This instrumental method of the investigation of the curvature and mobility of the spine is built on the principle of measuring the full acceleration vector of two accelerometers attached to the vertebrae controlled spinal segments (Fig. 1).

The output of the four signals proportional to the acceleration of the general point of biokinematic pairs $\bar{a}$ are obtained as a result of measurement of the acceleration values of each accelerometer in two coordinate system.

$$\begin{array}{ll} a_x = K_{ax} a \cos(\varphi_A); & a_y = K_{ay} a \sin(\varphi_A); \\ b_x = K_{bx} a \cos(\varphi_B); & b_y = K_{by} a \sin(\varphi_B). \end{array} \tag{1}$$

where a_x, a_y, b_x, b_y are the acceleration values of the first and the second accelerometers in the plane 2D coordinate system; and φ_A, φ_B are the angle between the direction of the acceleration vector of a general point O about a pair of adjacent vertebrae $\bar{a}$ and measuring systems $(\bar{x}_A, \bar{y}_A)$ and $(\bar{x}_B, \bar{y}_B)$ the accelerometer, respectively; K_{ax}, K_{ay}, K_{bx}, K_{by} are transform coefficients of the corresponding accelerometers.

The goniometric angle $\varphi = \varphi_A - \varphi_B$ is determined on the basis of relations between the components of the linear acceleration vector in the spine movement and displacement of the accelerometers. The angle is described by the formulas:

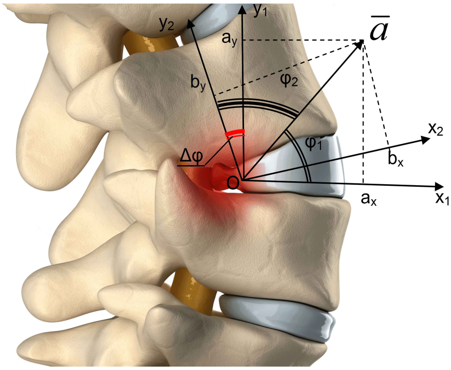

Fig. 1. The accelerometer method of geometric spine control

$$\varphi_A = \cos\left(\frac{(b_x a_x)/(K_{bx}K_{ax}) - (b_y a_y)/(K_{by}K_{ay})}{(a_x/K_{ax})^2 + (b_x/K_{bx})^2}\right) \quad (2)$$

$$\varphi_B = \sin\left(\frac{(b_x a_y)/(K_{bx}K_{ay}) - (b_y a_x)/(K_{by}K_{ax})}{(a_x/K_{ax})^2 + (b_x/K_{bx})^2}\right) \quad (3)$$

As a consequence, the desired value of the angle of rotation of the kinematic pair is determined from the expression

$$\varphi = arctg\left(\frac{a_y b_x - b_x a_x}{a_x b_x - a_y b_y}\right) \quad (4)$$

However, in the process of calculation the resulting error might increase due to a possible division by zero in the trigonometric arc tangent function argument. Such an error occurs due to the indeterminacy of the patient motion, and, consequently, it is a result of receiving different acceleration values, including zero.

The solution of the problem is to use a phase-measuring method [7], whose implementation is to compensate the multiplicative instability of the accelerometers branches. Signals from the two-component accelerometers is converted into the phase sine wave by multiplying the signals a_x, a_y, b_x, b_y on phase quadrature signals $\sin(\omega t)$ and $\cos(\omega t)$, whose frequency is a multiple of the frequency of the reference generator (RG). The obtained signals will be as follows:

$$\begin{array}{ll} a_x = U\sin(\omega t)K_{ax}a\cos(\varphi_A); & a_y = U\cos(\omega t)K_{ay}a\sin(\varphi_A); \\ b_x = U\sin(\omega t)K_{bx}a\cos(\varphi_B); & b_y = U\cos(\omega t)K_{by}a\sin(\varphi_B), \end{array} \quad (5)$$

where U and ω are the amplitude and the frequency of the quadrature phase signals.

Summing the signals in the adders for the object A and object B, respectively, we obtain:

$$a_A = UK_{ax} a \cos(\omega t + \varphi_A + \varphi_{Kax}); \quad a_B = UK_{bx} a \cos(\omega t + \varphi_B + \varphi_{Kbx}). \quad (6)$$

where φ_{Kax} and φ_{Kbx} are the phases of misaligment of the measuring branches.

From the relations (5) and (6), the signal value at the input of the main phase detector will be as follows:

$$\begin{aligned} U_A &= UK_{ax}(1 + \Delta K_1) a \cos(\omega t + \varphi_A + \varphi_{Kax}); \\ U_B &= UK_{bx}(1 + \Delta K_2) a \cos(\omega t + \varphi_B + \varphi_{Kbx}). \end{aligned} \quad (7)$$

Since the serial connection circuit is selected, the transform coefficients of accelerometers are $K_{ax} = K_{ay}$ and $K_{bx} = K_{by}$, respectively, hence the phase error of the measuring branches $\varphi_{K_{ax}} = \varphi_{K_{bx}} = 0$. As a result, phase detector generates a signal on the output. The signal is proportional to the angle of inclination of the pair of vertebrae, and it is finally independent of the instability influence of the coefficients of the measurement branches.

4 The algorithm of collecting and pre-processing the goniometric control data

Implementation the accelerometric method of rotation angle measuring in the goniometric control systems is based on an algorithm collecting dynamic data, which is based on the direct conversion of signals from two-component accelerometers in phase sine wave by multiplying the signal on the phase quadrature signals (PQS) with a frequency, which is a multiple of the reference oscillator frequency (RG) (Fig. 2) [8].

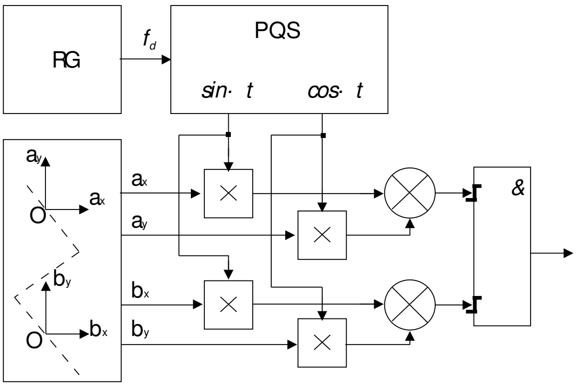

Fig. 2. The algorithm of collecting and pre-processing goniometric control data

According to the algorithm, the rotation angle of the biokinematic couples in the accelerometric goniometer is determined by the phase difference between the measured and the reference signals. Therefore, a signal proportional to the angle of biokinematic pairs without affecting instability coefficients transmitter branches is generated at the output by summing the received harmonic signal.

The multiplicative error is eliminated by means of hardware implementation of the phase-measuring method, namely, by limiting the signal level by a limiter circuit and following detection of the phase signal [9].

5 The error compensation method of the digital accelerometers

The measurement error is determined at the error measurement phase, which is a part of the application of the phase method for measuring turning angle in the accelerometric goniometer. The measurement is based on the direct conversion of signals from two-component accelerometers in the phase sine wave. A sampling error occurs since the phase measurement is conducted at the discrete time moments [10]. The sampling error is depended on the frequency ratio of the reference sine wave produced by programmable generator and the sampling frequency of the signal obtained from the accelerometric goniometer, with an algorithm of approximation of the target signal being applied between adjacent sample time moments. Figure 3 shows the sampling error data of the accelerometric goniometer signal.

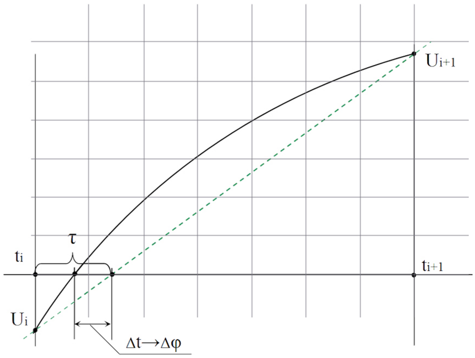

Fig. 3. The sampling error of the accelerometric goniometer signal

Traditionally, to calculate interval approximation between the samples U_i (at the time moment t_i) and U_{i+1} (at the next time moment t_{i+1}), algorithms of linear approximation are used:

$$U(t) = kt + b, \tag{8}$$

but the real process is described by

$$U(t) = U_m \cdot \sin(\omega t + \varphi), \tag{9}$$

where $\omega = 2\pi f$ is the frequency of reference oscillator, φ is a variable phase. The approximation coefficients are determined by the following relations:

$$k = \frac{U_{i+1} - U_i}{t_{i+1} - t_i}, \quad b = \frac{U_i \cdot t_{i+1} - U_{i+1} \cdot t_i}{t_{i+1} - t_i}, \tag{10}$$

The phase is determined on the base of the equation (10) by the time shift τ, forming an error of determination of the angle of accelerometric goniometer through the phase error $\Delta\varphi$:

$$k(t_i + \tau(\Delta\varphi)) + b = 0. \tag{11}$$

The time period expression that determines the measured phase on the base of n-periods of measurement is as follows:

$$T = \frac{(2\pi n + \varphi)}{\omega} = i \cdot \Delta t - \frac{U_i}{U_{i+1} - U_i} \cdot \Delta t, \tag{12}$$

where $f_d = 1/\Delta t$ is the sampling frequency.

Assuming that the frequencies are multiples of each other, the ratio of the oscillator and the sampling frequencies are defined by:

$$\frac{F}{f_d} = m. \tag{13}$$

From (12) and (13), the expression for phase determination, which is based on the linear approximation, takes the form

$$\varphi = 2\pi \left(m \cdot i - \frac{U_i}{U_{i+1} - U_i} \cdot m - n \right) \tag{14}$$

The rotation angle of the biokinematic pair in a accelerometric goniometer is measured by the difference of U_i and the reference phase signal U^0:

$$\alpha = \varphi - \varphi_0 = 2\pi \cdot m \left(\frac{U_i}{U_{i+1} - U_i} \cdot \frac{U_i^0}{U_{i+1}^0 - U_i^0} \right) \tag{15}$$

For this case, the error in the determination of the angle for the real values of phases is determined on the base of direct calculation

$$\begin{aligned} \alpha = \arctan &\left(\frac{U_i^0 \sin(2\pi m)}{U_{i+1}^0 - U_i^0 \cos(2\pi m)} \right) - \\ - \arctan &\left(\frac{U_i \sin(2\pi m)}{U_{i+1} - U_i \cos(2\pi m)} \right). \end{aligned} \tag{16}$$

In this case, the analytical expression for estimating the angle measurement error in the accelerometric goniometer is as follows:

$$max(\Delta\alpha/\alpha) = \frac{\sqrt{2\pi \cdot m - 1} - arctg(\sqrt{2\pi \cdot m - i})}{\pi \cdot m}. \tag{17}$$

As seen from the expression (17), the angle error can be reduced by increasing the sampling rate with respect to the oscillator frequency.

6 The system of goniometric spine control

In the standard spine goniometry, there are so-called the support points, which correspond to the ends of the spinous processes of S4, L4, Th7 and C7 vertebrae [11].

The following algorithm provides a differentiated picture of movements in the different parts of the spine. At same time, due to the small size and high precision of accelerometer sensors and system flexibility, the reliability of the results are significantly increased especially thanks to an additional digital processing the recorded signals. In addition, our proposed approach is passive, i.e., it does not use additional exposure, such as in ultrasound or X-ray method, and has no negative effects on human body. Moreover, the accelerometer module interface can be coupled with other system modules because of compactness of the accelerometer module.

Existing systems of biomechanics spine control measure only kinematic parameters of the skeletal system without taking into account the patient's neurophysiological parameters [12]. So, the process of diagnosis and rehabilitation is slower due to the absence of biofeedback data. Also, recording the parameters of evoked potentials makes it possible to determine the pain threshold more accurately, and to identify possible causes of motor neurophysiological abnormalities [13]. In general, the adaptive system of goniometric automated control can be represented as a block diagram shown in Figure 4.

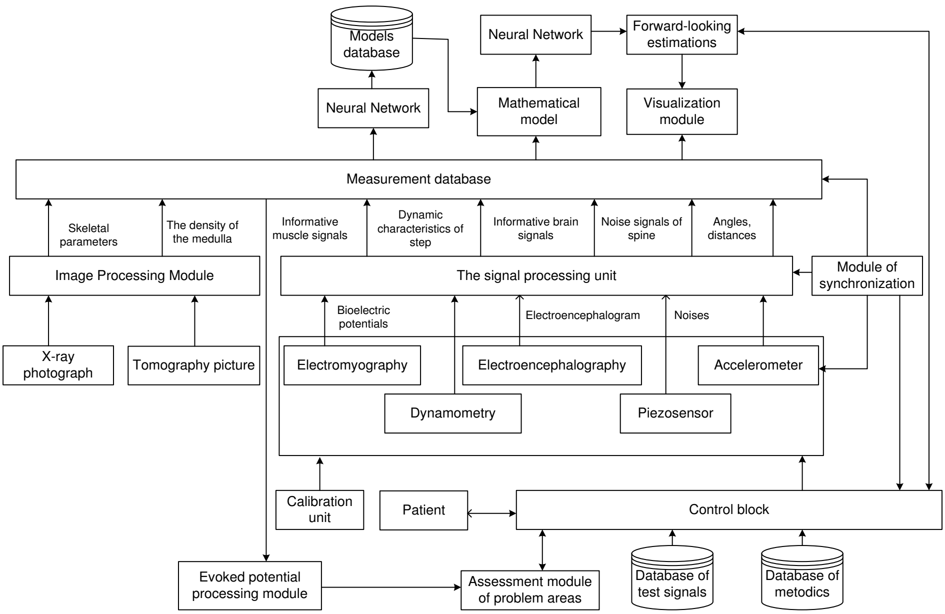

Fig. 4. The block diagram of hardware and software support of the automated goniometric control

After the synchronous processing, the recorded parameters form time series, which are visualized with various degree of detail.

The time series are the basis of a model of patient. The model is processed by a neural network and is stored in the model data base. The model that most closely matches the time series is instantiated. Pain thresholds and threshold of sensitivity of the patient for generating control signals to the actuators are determined by neural network algorithms. This is possible via a feedback method (patient's reactions to test stimuli). Based on the processed data, operation mode of the actuators is generated and selected from a database of test techniques.

It should be noted that the above adaptive system of goniometric control includes both stationary and mobile measuring systems. The number of monitored parameters is determined by the severity of the patient's pathology. In case of injuries or low severity of the scheduled examination, the use of portable goniometers alone is sufficient, as it guarantees the freedom of pationt's movements. If the presence of more serious violations in the musculoskeletal system functioning is suspected, the use of the accelerometric goniometer coupled with X-ray and tomography is recommended.

7 The choice of informative variables for constructing diagnostic models

The main problem of a model determination for diagnosis of the patient's health status is selection of informative variables.

In order to form adequate model instances, the sample data should be representative, the data should completely and correctly reflect the diagnostic object. The representativeness of the samples can only be achieved by selecting data objectively.

The sample data is represented as a matrix whose dimension is $N \times (n+1)$:

$$W_N = [X_n|Y_m], \tag{18}$$

where N is the number of cases (matrix rows); n is the number of independent informative input variables; m is the number of depended informative output variables; $X_n\{X_1, X_2, ..., X_i, ..., X_n\}$, $Y_m\{Y_1, Y_2, ..., Y_j, ..., Y_m\}$ are sets of vector values of inputs and outputs; $X_i\{x_{i,1}, x_{i,2}, ..., x_{i,N}\}$, $Y_i\{y_{j,1}, y_{j,2}, ..., y_{j,n}\} : x_{i,N}$, $y_{j,N}$ are i-th value of the input and j-th value of the output variable of N-row sample data matrix.

Each data row contains sample values of the input (information on chronic diseases, data from patient history) and output (current symptoms, the results of goniometry (accelerometry)) informative variables describing the dynamic state of a particular patient. Sampling should include a training data sample, which is used at the stage of model construction of the real diagnosed object. An important condition for the use of samples is that the stored learning sample data set and testing data set must be different. This ensures reliability of the diagnostic decisions.

The quality of the learning data samples obtained in the spine diagnostic systems is evaluated according to the following criteria: representativity, informativity, and reliability.

Table 1. Ranges of standards physiological fluctuations and degrees of spinal disorders in the goniometric studies

Position of the spine	Angle	Norm	Degree of functional disorders					
			slight		moderate		considerable	
			Less	More	Less	More	Less	More
Free vertical position,°	α	7-13	5-6	14-16	3-4	17-18	$\leqslant$2	$\geqslant$19
	β	10-15	8-9	16-18	6-7	19-20	$\leqslant$5	$\geqslant$21
	γ	9-14	7-8	15-17	5-6	18-19	$\leqslant$4	$\geqslant$20
Maximum flexion,°	α	60-80	51-59		41-50		$\leqslant$40	
	β	90-115	81-89	–	61-68	–	$\leqslant$60	–
	γ	130-155	121-129		111-120		$\leqslant$110	
Maximum extension,°	α	0-3	4-6		7-8		$\geqslant$9	
	β	35-52	25-34	–	17-24	–	$\leqslant$16	–
	γ	36-50	26-35		16-25		$\leqslant$15	
The slopes of the sides,°	bs	30-40	20-29	–	10-19	–	$\leqslant$9	–
	bd	30-40	20-29	–	10-19	–	$\leqslant$9	–

To determine the degree of correlation between the informative variables, *i.e.*, to assess the informativity of sample data, rank correlations are used. The degree of the relationship is determined by the value of the correlation coefficient, which can range from -1 to +1 inclusive.

To calculate the minimal sample size, the following formula is used:

$$N = n_{inf} \cdot (P \cdot \alpha/\eta^2), \tag{19}$$

where n_{inf} is the number of informative variables, P is the representativeness of the sample data; α is the required representativeness of the sample data; η is the resulting information content of the sample data.

The input sample data set consists of training and control subsets having the ratio of 2:1 and separated randomly to the subsets.

Usage of the accelerometer measurement method as a basis for the hardware and software system implementation of goniometric spine control requires continuous accounting assigned statistical range of physiological fluctuations of parameters with respect to the biokinematic norm and degrees of functional disorders of the spine (Table 1), as the system is intended to be used for optimization of medical biomechanical examination.

Selection of informative variables for the construction of multi-level diagnostic model is based on the medical reference book data(Table 2). These variables are to reflect the relations between the manifestations of a disease from the current symptoms and reported violations.

Table 2. Ranges of standards of physiological fluctuations and degrees of spinal disorders in the goniometric studies

Vertebra	Parameters of vertebra		Parameters of segment			Segment
	b, mm	Fb, °	Gb,°	Hd, mm	Db, mm	
C2	66,3±1,2	21,4±10,9	19,4±5,2	7,3±1,5	0,6±3,0	C2-C3
C3	23,1±10,1	2,4±5,5	4,4 ±2,0	7,3±3,2	1,6±3,0	C3-C4
C4	21,4 ±0,1	2,0 ±3,5	3,2 ±3,6	6,6 ±2,4	1,3 ±1,0	C4-C5
C5	19,3 ±0,1	5,2±0,1	1,7±7,8	7,4±1,2	0,7 ±1,4	C5-C6
C6	20,7 ±0,2	7,0 ±6,2	5,3 ±1,2	7,6 ±3,7	0,0 ±1,0	C6-C7
C7	24,4 ±0,2	12,2 ±6,7	–	–	–	C7-Th1

In Table 2, Fb is the body inclination angle to the vertical; Db is the body displacement of the overlying vertebra relative to the underlying one in the plane of the disc; Hd is the disc height; Gb is the angle between adjacent vertebrae.

8 Conclusion

The practical implementation of the proposed approach in the medical organization in goniometric spine control reveals new insights into the diagnosis and rehabilitation of the musculoskeletal system, particularly of the spine. The adaptability of the proposed approaches in early detection of motor function disorders, as well as its high accuracy, prevents the development of other diseases.

The proposed approach to automation of the spine diagnostics allows medical stuff to:

- continuously monitor the spine bending without attachment of patient to a stationary place;

- develop methods of evaluation of the degree of allowable deviation of the spine and vertebrae, accounting the age groups and possible bends of a healthy human spine, giving rise of the possibilities to automate the monitoring process that takes into account the patient's anatomy;

- derive estimations of quantities characterizing the tolerances segments of the spine of healthy individuals for each type of bending of the back, increasing the efficiency of diagnosis and rehabilitation of the spine;

- assess the degree of friction during movement of the vertebrae under the influence of physical activity, and to identify the critical decrease (changes) of the intervertebral discs;

- derive estimates of the spectral components of an acoustic signal produced by the friction of the vertebrae, providing means of improvement of the health automated diagnostic systems based on acoustic methods of control;

- reduce significantly the risk of injury at the time of rehabilitation;

- optimize the rehabilitation process on the basis of the patient's physical abilities and data control, allowing timely load adjustments, exclusion of the overloads and risks of injury.

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