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Principles of Constructing of Intellectual Systems for the Diagnostics and the Rehabilitation of the Human Spine

N.V. Dorofeev[a,]*, A.V. Grecheneva[b], O.R. Kuzichkin[b]

[a]*Vladimir State University, Gor’ky st.,87, Vladimir 600000, Russia*
[b]*Belgorod National Research University, Pobedy st., 85, Belgorod 308015, Russia*

Abstract

The article proposes general principles of the build of intelligent systems of the diagnostic and of the rehabilitation of the spine: a general structure scheme of the build, an individual neuro-mechanical model of the spine, and an algorithm for the constructing of the neuro-mechanical model. The neuro-mechanical model described in this work takes into account physiological characteristics (pathology and trauma) of the spine, as well as the pain sensitivity and pain threshold of the patient. The individual neuromechanical model is built on the basis of a basic model with the use of neural networks. The algorithm of adaptation of the individual model allows to identify pathologies in the patient's movement and to correct the model at all stages of the rehabilitation of the spine. The results of MRT, CT, EEG, EMNG and data of goniometric measurements are input data for the construction of the individual model of patient.

Keywords: diagnostics; rehabilitation; spine; neural network; fuzzy logic; accelerometer; goniometry; vertebra.

1. Introduction

Currently, the level of development of information technology means allows the implementation of sophisticated algorithms for intelligent data processing. This makes it possible to increase the efficiency of diagnostic and rehabilitation systems of the human spine. The article deals with the basic principles of constructing intelligent

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* Corresponding author.
E-mail address: DorofeevNV@yandex.ru

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systems for diagnosis and rehabilitation of the human spine. It is shown that the main problem of the existing automated systems of diagnostics and rehabilitation of the spine is the low accuracy of measuring the displacement of vertebrae in space, the absence of a neuromechanical model of the spine and low adaptation to the physiological characteristics of the patient [1]. In addition, the existing models of the stress-strain state of the spine, on the basis of which the effectiveness of rehabilitation techniques and mechanisms is predicted and studied, do not take into account the neuro-mechanic aspect of the motor actions of the patient, manifested in the compression effect of the spinal cord nerve roots [2]. The low accuracy of the measuring part affects the accuracy of controlling the actuators of automated systems in the process of rehabilitation of the spine, which serve to limit patient movements within acceptable limits (preventing the appearance of damage to human functional systems during its movement) and improving rehabilitation efficiency. The aim of the work is to develop the principles for constructing intelligent systems for diagnosing and rehabilitating the human spine based on the individual neuro-mechanical model of the patient and neural network approaches.

2. General block diagram of diagnostic and rehabilitation systems of the spine

Dependence of deviations from normal values of signals of neurons, reflexes and movements from pathologies of the neuromuscular system and injuries makes it possible to solve the inverse problem-to assess possible disorders of the neuromuscular apparatus from deviations in the space-time parameters of movements. Control of the parameters of movements with the subsequent evaluation of spinal pathology allows not only to carry out express diagnostics of the neuromuscular system, but also to develop management decisions in the rehabilitation of the spine with the use of exoskeletons. Increasing the effectiveness of diagnostic and rehabilitation systems of the spine and musculoskeletal system is achieved through the complex processing of heterogeneous data describing changes in the values of spatio-temporal parameters, acoustic, electrical and other signals of the neuromuscular system, through the use of an individual adaptive model of the patient capable of adapt to the physiological characteristics of the patient, and due to neural network algorithms for diagnosis, prediction and control [3,4].

It is obvious that for forming of the more accurate diagnosis and for forming of the right decisions during the rehabilitation the individual characteristics of the patient and his injury (illness) to estimate and to account necessary. For adaptation of the system of the diagnostics and of the rehabilitation under patients with different physiological characteristics and disorders of the spine and the musculoskeletal system as a whole neural network algorithms of the processing of accumulated data are offered to use join with the measurement of angles of the rotation and of the degree of the deviation of vertebrae by accelerometric transducers (Fig. 1).

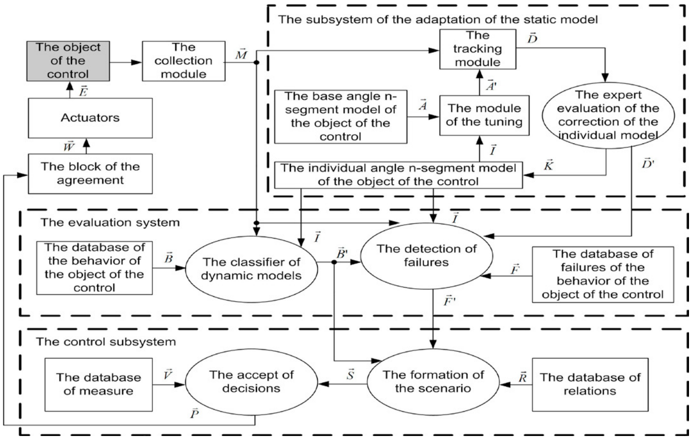

Fig. 1. General block diagram of diagnostic and rehabilitation systems of the spine.

At the time t the recorded data $\vec{M} = \{\vec{zv}_1,...,\vec{zv}_i,...,\vec{zv}_m\}$ (where $\vec{zv}_i = \{\alpha_i, \beta_i, \gamma_i\}$ is the vector describe the values of the angles α, β, γ of the deviation of the link i in the space relative to a reference point) is received in the subsystem of the adapting of the static model of the patient and the subsystem to the evaluation.

In the subsystem of the adapting of the static model of the patient, the individual angular n-segment model of the patient $\vec{I} = \{\vec{zv}_1,...,\vec{zv}_i,...,\vec{zv}_p\}$ is formed, where $\vec{zv}_i = \{\vec{\alpha}_i, \vec{\beta}_i, \vec{\gamma}_i\}$ is the vector, that describe the possible deviation of the link i in space relative to the base point, $\vec{\alpha}_i = \{\alpha_1,...,\alpha_l\}$, $\vec{\beta}_i = \{\beta_1,...,\beta_j\}$, $\vec{\gamma}_i = \{\gamma_1,...,\gamma_k\}$ are possible variations relative to the base point of the link i in the plane $x, y, z,$ respectively. This model is corrected by the basis angular n-segment model of the object of the control, which completely describes the General behavior of similar objects $\vec{A} = \{\vec{zv}_1,...,\vec{zv}_i,...,\vec{zv}_n\}$. The base model is more complete than the individual model, however, it does not reflect the individual characteristics of the patient. If necessary the addition of the individual models $\vec{A}' = \vec{I} \cup \vec{A} \setminus \vec{I}$ occur in the tuning module by the basic angular model to the links. Recorded data $\vec{M}$ are compared with the individual model $\vec{A}'$ in the unit tracking where in the case of the output values of the angles of the vector $\vec{M}$ from the given vector $\vec{A}'$ of boundaries (the exceeding of specified values) the vector of deviations is formed:

$$\vec{D} = \{\vec{zv}_1,...,\vec{zv}_i,...,\vec{zv}_x\}, \tag{1}$$

where $\forall \vec{zv}_i \in \vec{M},\ \alpha_i \in \vec{M} > \alpha_i \in \vec{A} \cup \beta_i \in \vec{M} > \beta_i \in \vec{A} \cup \gamma_i \in \vec{M} > \gamma_i \in \vec{A}$.

The vector $\vec{D}$ get in the block of the expert estimate for acceptance of the resolve $\vec{K} = F_k(\vec{M}, \vec{A}', \vec{D}, \vec{G})$, (where F_k – is the operator of the estimate, $\vec{G}$ – is the vector of additionally attract data) about the correction of the individual model $\vec{I}$ at the measured data, if the vector of the deviation $\vec{D}$ reflects only the individual characteristics of the patient. Otherwise, the vector of deviation is corrected in accordance with additional data $\vec{D}' = F_D(\vec{D}, \vec{G})$, where F_D – is the operator of the correction. Vectors $\vec{K}'$ and $\vec{D}'$ are formed by the neural network algorithm or by using fuzzy logic with involvement of expert. The classifier of dynamic models determine movement $\vec{B}' = F_B(\vec{B}, \vec{M}, \vec{I}, \vec{G}_B)$ (where $\vec{F}_B$ is the function of the estimate, $\vec{G}_B$ – is the vector of additional parameters and factors) what the patient commits in the current time t by database of possible behaviors of the patient $\vec{B} = \{\vec{B}_1',...,\vec{B}_i',...\vec{B}_e'\}$ (where $\vec{B}_i' = \{\vec{zv}_1',...,\vec{zv}_i',...,\vec{zv}_n'\}$ is the vector, that describe the i-e motion, $\vec{zv}_i' = \{\vec{\alpha}_i', \vec{\beta}_i', \vec{\gamma}_i'\}$ is the vector of the moving of the *i*-th segment in time, $\vec{\alpha}_i' = \{\vec{\alpha}_{t1},...,\vec{\alpha}_{t+\Delta},...,\vec{\alpha}_{t+T}\}$, $\vec{\beta}_i' = \{\vec{\beta}_{t1},...,\vec{\beta}_{t+\Delta},...,\vec{\beta}_{t+T}\}$, $\vec{\gamma}_i' = \{\vec{\gamma}_{t1},...,\vec{\gamma}_{t+\Delta},...,\vec{\gamma}_{t+T}\}$ are vectors of variances of angles of the segment in the planes x, y, z in time, respectively, T – is the time of the execution of the movement). At time $t+\Delta$ the behavior is forecasted where Δ depends to the estimation accuracy of the movement and of the speed of the movement of the patient.

On based of the available data, including a database of violations in behavior of the patient $\vec{F}$, the statement of the possible diagnose $\vec{F}' = F_F(\vec{B}', \vec{I}, \vec{F})$ is generated, where F_F is a function of the detecting of failures. The $\vec{F} = \{\vec{F}_1',...,\vec{F}_i',...\vec{F}_h'\}$ describes of various failures $\vec{F}_i'$ with possible deviations and anomalies in the recorded and additional data. I. e. $\vec{F_i}' = \{\vec{Df}, \vec{Gf}, \vec{Gf_B}\}$, where $\vec{Df} = \{\vec{Df_1}, ..., \vec{Df_i}, ..., \vec{Df_x}\}$ is the vector of possible deviations and anomalies in the recorded data when the *i*-th violation (where $\vec{Df_i} = \{zvf_1, ..., \vec{zvf_i}, ..., \vec{zvf_q}\}$ is the vector of possible deviations in q segments in the *i*-th violation) $\vec{Gf} = \{\vec{Gf_1}, ..., \vec{Gf_i}, ..., \vec{Gf_y}\}$ and $\vec{Gf_B} = \{\vec{Gf_{B1}}, ..., \vec{Gf_{Bi}}, ..., \vec{Gf_{Bz}}\}$ are vectors of possible deviations and anomalies in additional data in the *i*-th violation. The general structure of the neural network is given in work [5] for making decisions in diagnosis. In addition to it, a neural network for the processing of recorded data was developed, the generalized structure of which is shown in Fig. 2a.

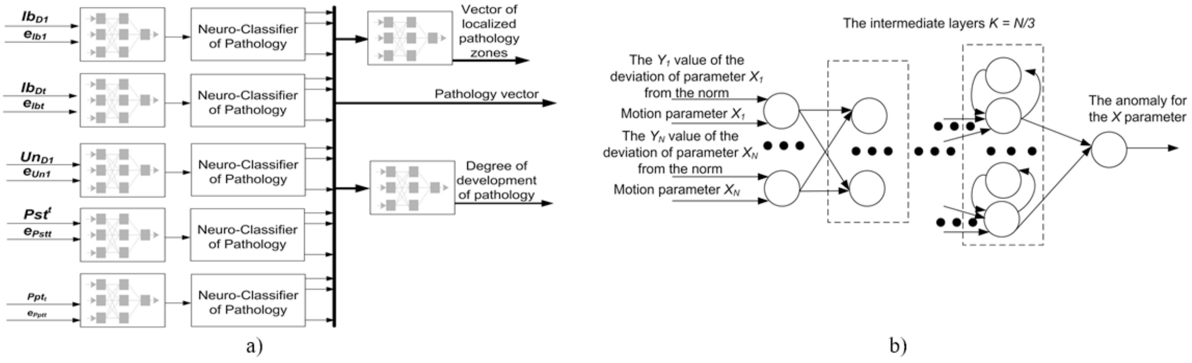

Fig. 2. (a) The generalized structure of the neural network for processing the recorded data; (b) Generalized structure of the basic neural network.

In the above structure of the neural network, each block is formed on the basis of the core network (Fig.2b), the adjustment of the weights of each block is individual and depends on the type of pathology, individual characteristics (parameters of the individual model), type and parameters of motion. The base network is recurrent, with the time of storage and processing equal to the value of the time window of the useful signals. The number of intermediate layers is three times less than the number of processed parameters.

The control subsystem is designed for assess the permissible degree of the bending of the spine and for the formation on the basis of assessments the valid and possible control actions and movements, and for the correcting of the movements, that are occurred in the current time t. The control subsystem as well as the evaluation system consists of two neural networks: one for the formation of a possible scenario $\vec{S}$ (the forecast of outcome of performing movement at this moment), second for the accepting of solutions $\vec{P}$ by the predicting scenario.

Based on the possible diagnosis and the projected movement of the patient the further scenario of variance of the state of the object control $\vec{S}$ is formed as in the vicinity of the control point, so and in General. At it the development of possible violations $\vec{R}$ take into the regard, as in the vicinity of observation points, so and in General in the object of the control, with the development of the detecting of the violation $\vec{F_i}'$. It should be noted that the scenario is formed on the time T_S, that is determined by the severity of the detecting of the violation $\vec{F_i}'$. The scenario describes the magnitude of the deviations $\vec{Vf}$ and their criticality $\vec{Cf}$ for health in dependent to the detection of the violation $\vec{F_i}'$ and the predicted movement $\vec{B}'$, i. e. $\vec{S} = \{\vec{Vf}, \vec{Cf}\}$.

The algorithm for generating control signals for actuators consists of the following steps:

- Detection of incorrect movement. Incorrectness in this case implies the possibility of damage to parts of the nervous system or bone-cartilaginous tissue, or a significant deviation from the prescribed technique of rehabilitation of the trajectory. Also the step of the correction of the methodology;
- Verification of the corrected technique in the prediction block based on the neuromechanical model;

- Correction of the methodology until all the movements in the techniques will correct;
- Generation of control signals based on the corrected procedure.

Formation of a set of exercises for each technique occurs in a similar way. Thus, the reversing link is formed with the help which the regulation occur as actions of controlled object so and the individual model, and most trainees of neural networks. With proper formation of the structure of neural networks, basic models and additional information the structure of the system of the diagnostics and of the rehabilitation will reflect the structure of the work of the human nervous system when the painful sensation are occurrence.

3. Neuro-mechanical model

However, existing diagnostics and rehabilitation systems of the spine have drawbacks associated with the lack of adequate models of the nervous system and its sites, taking into account pain sensations and not allow predicting the results of damage to parts of the nervous system. These models are important in the rehabilitation and diagnosis of spine violations [6]. The individual model of the patient includes the angular model of movements, the model of the osteoarticular system, and the model of the nervous system. Control and correction of the movements is carried out on the basis of decision making, which are formed by the neural network processing unit of the deviations from the established norm, the estimated friction values of the kinematic pairs, the load level and the degree of mechanical impact on the elements of the nervous system (Fig. 3).

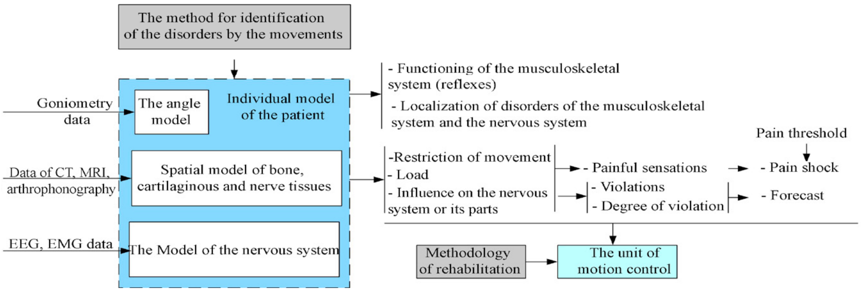

Fig. 3. The system of diagnosis and rehabilitation of the spine and musculoskeletal human system.

The basic idea of developing a neurobiomechanical model of the vertebral motor segment is the ability to take into account and localize the pain syndrome that arises from the deformation of the spinal canal of the spinal cord and its roots. This poses the task of modeling the stress-strain state of not only the bone-cartilaginous segment of the spine, but also the need to model the deformed state of the structures of nerve tissues, determine the site and the area of deformation. The spine segment (Fig. 4) is a composite construction of a variable section. The base model of the spine [7], was the basis of the neuromechanical model of the vertebral motor segment being developed.

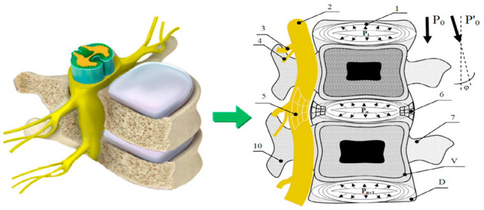

Fig. 4. (a) Neuro-mechanical model of the vertebral-motor segment in the section; (b) Scheme of distribution of the load of the vertebral segment, spinal cord and nerve roots. 1 – pulpous nucleus; 2 – solid membrane of the spinal cord; 3 – a forward spine of a spinal nerve; 4 – posterior spine of spinal nerve; 5 – the surface of deformation of the spinal nerve sheath; 6 – deformation surface of isotropic constituents of the orthotropic fibrous ring; 7 – spinal process of the vertebra; V – the body of the vertebra, consisting of a spongy bone of varying degrees of porosity; D –intervertebral disc; 10 – transverse process of the vertebra; $P_1, ..., P_{n+1}$ is the internal disk pressure; P_0 is the external normal distributed load; $P_0^{'}$ – external distributed load with a bending moment.

To study the deformation parameters of the biomaterial, which is inhomogeneous in volume, it is proposed to use a deformability matrix, the main components of which are determined on the basis of computational models of the theory of deformation of biomaterials. The main properties of biomaterials that are part of the neurobiomechanical model being developed are given in work [8].

During rehabilitation, the model of the nervous system is supplemented with parameters that characterize pain sensations in the performance of motor actions. Pain parameters are formed on the basis of the joint data obtained from the patient and his biomechanical model when assessing the zones and the amount of the pressure on nociceptor neurons. The model of the nervous system also includes parameters of damages or pathologies of the osteochondral, muscular and nervous system, which increases the reliability of the estimates obtained. Mechanical or chemical impact on the zones of the nervous system makes it possible to assess the occurrence of pain sensations and the change in parameters of signals passing through the affected parts of the nervous system (Fig. 5). It should be noted that the complete mathematical model of the nervous system and neuron is not currently built. There are many models of neurons and the nervous system: McCulloch-Pits, Hilton, Harmon, Descasai, etc. Models allow to take into account such parameters as: amplitude, processing lag, feedback, dynamic component, membrane electric capacity, time constant, internal action potential, the neuron response, the influence of magnetic fields, the absolute refractivity phase and the relative refractivity phase (not susceptibility, decrease in response and speed), the phase of increased excitability [9,10]. The functioning of the nervous system responsible for the movements can be represented on the basis of the frequencies f of the signals generated by the neuron, the contraction and relaxation of the muscles and the angular model that forms as a result of these contractions. It is obvious that the frequency of pulses from the efferent neurons to the effector is determined by the function of the sum of the frequencies $\vec{f}_R$ generated by the afferent neurons from the receptors, the sum of the frequencies $\vec{f}_B$ generated by the afferent feedback neurons, and the degree of damage to the k nerve center:

$$f = f\left(\vec{f}_R, \vec{f}_B, k\right). \tag{2}$$

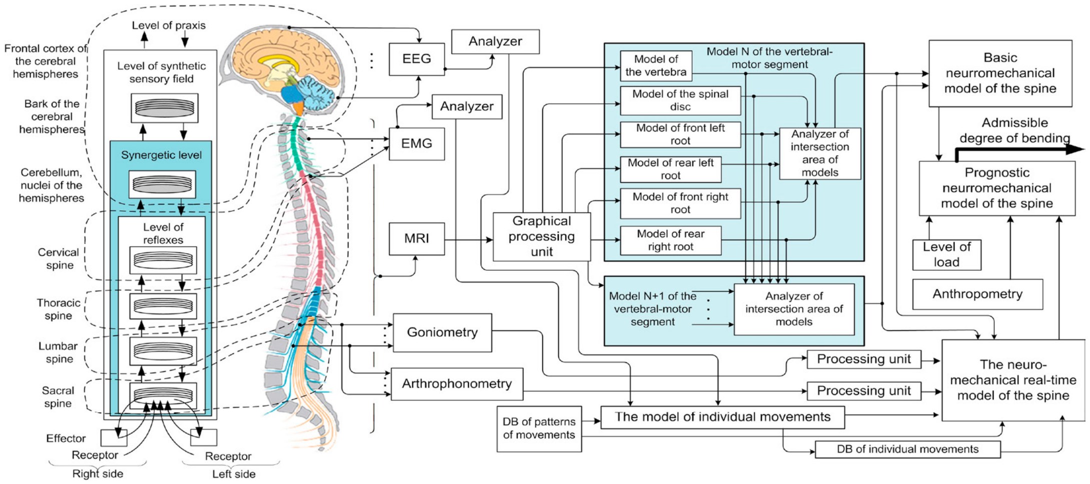

Fig. 5. Diagnostics of the nervous system based on the movements.

The angle α of the kinematic pair (describing the synergetic level) in space $\vec{X}_\alpha, \vec{Y}_\alpha, \vec{Z}_\alpha$ and at time t formed by the group of muscles $\vec{M}$ under the influence of the group of neurons $\vec{N}$ and controlled by the nerve center located in the vertebrae $\vec{S}$ is described by functions of signals with a frequency fm applied to the muscles for flexing, the signals with frequency f_S, applied to the muscles for extension, the parameters of the muscles $\vec{P}_\alpha$ and the forces $\vec{F}_\alpha$ acting on the kinematic pair:

$$\begin{gathered}\alpha\left(\vec{M},\vec{N},\vec{S},\vec{X}_\alpha,\vec{Y}_\alpha,\vec{Z}_\alpha,t\right)=f\left(\sum f_{\mathrm{m}}(t),\sum f_{\mathrm{s}}(t),\vec{P}_\alpha(t),\vec{F}_\alpha(t)\right),\\ \vec{X}_\alpha\left(\vec{A}_\alpha,\vec{O}_\alpha,\vec{B}_\alpha\right)=f\left(\vec{O}_{MX},\alpha\right),\ \vec{Y}_\alpha\left(\vec{A}_\alpha,\vec{O}_\alpha,\vec{B}_\alpha\right)=f\left(\vec{O}_{MY},\alpha\right),\vec{Z}_\alpha\left(\vec{A}_\alpha,\vec{O}_\alpha,\vec{B}_\alpha\right)=f\left(\vec{O}_{MZ},\alpha\right),\end{gathered} \tag{3}$$

where $\vec{A}_\alpha,\vec{O}_\alpha,\vec{B}_\alpha$ are the coordinates in the space of the boundary A, the center O and the boundary B of the kinematic pair forming the angle α, $\vec{O}_{MX}=\{\vec{X}_{\alpha\,min},...,\vec{X}_{\alpha-1}\}$, $\vec{O}_{MY}=\{\vec{Y}_{\alpha\,min},...,\vec{Y}_{\alpha-1}\}$, $\vec{O}_{MZ}=\{\vec{Z}_{\alpha\,min},...,\vec{Z}_{\alpha-1}\}$ are the vectors describing the coordinates of the kinematic pairs from the lowest to the nearest kinematic pair capable of changing the spatial position of the angle α. The level of the synthetic sensory field generates the control signals fm and f_S on the muscles $\vec{M}$ in segments of the spine $\vec{S}$ along the neurons $\vec{N}$ to change the position of the body in space from $\vec{\alpha}$ (described by the set of all angles) to the position $\vec{\alpha}'$ taking into account equilibrium of the body F and the reflections $\vec{R}_S$:

$$R_E\left(\vec{M},\vec{N},\vec{S},\vec{f}_m,\vec{f}_s\right)=f(\vec{\alpha},F,\vec{\alpha}',.\vec{R}_S). \tag{4}$$

4. Algorithm for constructing a neuromechanical model

The medical images processing posed within the framework of the developing neuromechanical model of the spine, it is proposed to apply the method described in [11]. This method takes into account the difference in the position of the cutting planes relative to the symmetry axes of the vertebra for different patients, the location of individual vertebrae of one patient due to the characteristic lumbar spine of the physiological lordosis, the features of the patient placement in the scanner apparatus (Fig. 6). After the procedure for determining the types of the elements present in the images, the block of processing graphic information is based on the use of the Delaunay triangulation algorithm (Fig. 2) to construct a set of surface points of identified types of objects:

- Surface point set bone tissue of the vertebra $V=\{V_1(x,y,z),...,V_i(x,y,z)\}$;
- Surface point set of the intervertebral disc $D=\{D_1(x,y,z),...,D_i(x,y,z)\}$;
- Surface point set of the spinal cord $B=\{B_1(x,y,z),...,B_i(x,y,z)\}$;
- Surface point set of the anterior spinal nervous root $R_A=\{R_{A1}(x,y,z),...,R_{Ai}(x,y,z)\}$;
- Surface point set of the posterior spinal nervous root $R_P=\{R_{P1}(x,y,z),...,R_{Pi}(x,y,z)\}$.

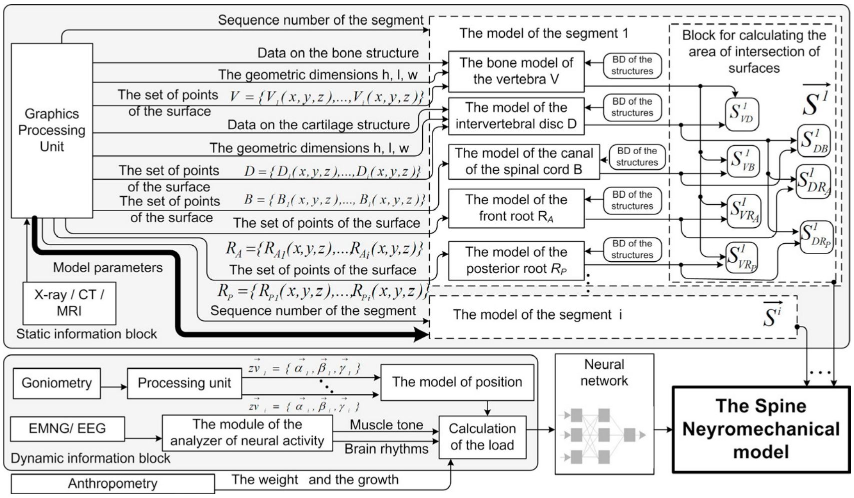

Fig. 6. The algorithm for constructing a neuromechanical model.

The intersection detection is based on the standard algorithm proposed in [8]. The total area of intersection of the elements of the segment of the spine can be represented as a vector:

$$S^1 = \{S^1_{VD}, S^1_{VB}, S^1_{VR_A}, S^1_{VR_P}, S^1_{DB}, S^1_{DR_A}, S^1_{DR_B}\}, \tag{5}$$

where S^1_{VD} is the area of intersection of the bone surface of the vertebra and the surface of the intervertebral disc, S^1_{VB} is the area of intersection of the bone surface of the vertebra and the surface of the canal of the spinal cord, $S^1_{VR_A}$ is the area of the intersection of the bone surface of the vertebra and the surface of the anterior nerve root of the spinal cord, $S^1_{VR_P}$ is the area of the intersection of the bone surface of the vertebra and the surface of the spinal cord , S^1_{DB} is the area of intersection of the surface of the intervertebral disc and the surface of the canal of the spinal cord, $S^1_{DR_A}$ is the area of intersection of the surface of the intervertebral disc and the surface of the anterior nerve root of the spinal cord; $S^1_{DR_P}$ is the area of intersection of the surface of the intervertebral disc and the surface of the spinal cord back. As a result, the adaptive biomechanical model of the *i*-segment of the spine, taking into account the load applied in time, can be represented as a vector:

$$M = \{\overline{V}(t,zv_i), \overline{D}(t,zv_i), \overline{B}(t,zv_i), \overline{R_A}(t,zv_i), \overline{R_P}(t,zv_i), P(t,\phi), \sigma(t)\}, \tag{6}$$

where $\overline{V}(t,zv_i)$ is the spatial dynamic bone model of the vertebra, $\overline{D}(t,zv_i)$ is the model of the intervertebral disc, $\overline{B}(t,zv_i)$ is the model of the location of the canal of the spinal cord, $\overline{R_A}(t,zv_i)$ is the model of the location of the anterior nerve root of the spinal cord, $\overline{R_P}(t,zv_i)$ is the model of the location of the posterior nerve root of the spinal cord, $P(t,\varphi)$ is the load applied to the vertebra is calculated on the basis of spatial positioning and body weight; $\sigma(t)$ is the parameter of the strength of biomaterials that make up the vertebral column.

5. Conclusion

Application of the developed principles for the construction of intelligent diagnostic systems and rehabilitation of the human spinal column will allow:

- Evaluate and control the permissible degree of displacement of the vertebrae and flexure of the spine as a whole,
- Assess the probability of damage to nerve fibers during the movement.
- Take into account the effect of deformation of the nerve roots of the spinal cord on the complex functional state, the development of pathologies and the onset of pain syndrome.
- To reveal potentially pathological zones of increased bone-joint friction of segments of the spine.
- Correlate structural disorders of the patient and their manifestation on the results of EEG and EMG examination.
- To predict the development of various diseases and pathologies (osteochondrosis, neuropathy, spondylosis, etc.)
- To carry out automatic control of the executive mechanisms of rehabilitation complexes.
- Carry out an accelerated procedure for the rehabilitation of patients who initially have spinal injuries.

The developed approach allows to systematize the information obtained by complex application of diagnostic tools of the spine and to form an optimal course of rehabilitation exercises with allowance for the permissible degree of flexion of the joints of the spine.

Acknowledgements

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