MODELING OF THE SPINE COMPENSATORY RESPONSE TO DEFORMITY

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Objective. To analyze mathematical model of the efficiency of the compensatory mechanism of the deformed spine.
Material and Methods. The developed basic kinematic model of the spine was used. The restoration of the position of the projection of the general center of mass (GCM) was mathematically modeled, and mechanogenesis of the spinal deformity and possibility of its compensation were evaluated. To assess the reliability of the mathematical model, spinal skiagrams taken from patients with clinically confirmed pathology and sagittal imbalance were used.
Results. On the basis of quantitative characteristics of the primary spine deformity of a certain clinical case and using the developed algorithm, it is possible to create a model of both a primary deformity and a compensatory response from intact segments of the spine taking into account the influencing factors. This makes it possible to use the proposed kinematic model in scientific research on predicting the course of various types of spinal deformities.
Conclusion. The proposed algorithms simulating the development of spinal deformities based on the restoration of the position of the GCM projection reflect their mechanogenesis and can be used to model various pathological conditions of the spine. A complete correction of the deformity does not mean a complete cure, since the required spinal fusion creates a new, prognostically less significant, but pathological situation.
Key Words: spine, modeling, compensatory response.

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The sagittal balance of the spine is a phenomenon of dynamic balance between the shape of the spinal column and the mechanisms that support it and compensate for abnormalities in the harmonious profile of the spine. The sagittal balance is a component of the postural balance. Today the assessment of the sagittal balance parameters is an integral part of the preoperative planning of surgical treatment in patients with degenerative diseases of the spine. The shape and spatial position of the spine are both comprehensive indicators of the forces acting on the spine and the final outcome of mechanogenesis of deformities in various pathologies of the spine, which has not been sufficiently studied to date.

Secondary changes in the shape and orientation of the spine occur in response to a local primary deformity and aim at maintaining the orthostatic position of the human body while minimizing energy expenditure [11, 12, 14].

These compensatory reactions can be divided into physiological (within the functional capabilities of the motion segments of the spine) and pathological in the form of hyperextension of the motion segments of the spine and the involvement of the lower limbs' joints [5, 6].

The compensatory mechanisms include cervical hyperlordosis, reduction in thoracic kyphosis, retrolisthesis, hyperextension in the lumbar spine, backward pelvic deflection, flexion of the knee joints, extension of the ankle joints. Barrey et al. [5] suggest evaluating the parameters of PI (vertical pelvis inclination), SVA (sagittal vertical axis, or the distance between the posterior upper corner of S1 and the plumb line), and compensatory mechanisms to assess the degree of the sagittal balance disturbance and to plan surgical treatment [16]. The state of the sagittal spino-pelvic balance and the impact of its parameters on degenerative changes in the anterior and posterior support complexes of the spinal motion segment, clinical outcomes of decompression and stabilization interventions and development of the pathology in the adjacent segments are of particular interest [12, 13]. Large number of studies has been devoted to postural balance under normal conditions and in case of various pathologies of the spine [5, 8, 10–14, 16].

The aim of the study was to analyze the mathematical model of the effectiveness of the compensatory reaction of the spine to the deformity.

Material and Methods

We have used the developed basic kinematic model of the spine [1, 2].

We have calculated the coordinates of the point of projection of the general center of mass (GCM) onto the supporting area for different combinations of the lengths of the superior and inferior parts of the trunk in accordance with the normal condition of the spinal segments (Fig. 1).

The following formula was used to calculate the X coordinate:

$$X = (L \cdot \sin\alpha + L_1 \cdot \sin\alpha_1)/2,$$

where L is the length of the chord of the arc located above the level of pathology; L_1 is the length of the chord of the arc located below the level of pathology; α is the angle of the chord of the arc located above the level of pathology; α_1 is the angle of the chord of the arc located below the level of pathology.

The arm of the superior segment creates a left-hand moment, whereas the arm of the inferior segment creates the right-hand moment, therefore their action is oppositely-directed, and their values are subtracted. Starting from the T12–L1 segment, both chords have the same orientation, therefore the values of their arms are summed up.

In this model, the position of the GCM projection onto the X axis is localized at the point 37.3 ± 2.7 mm. When modelling the left and right limits of the norm, this parameter had values of 18.0 and 58.0 mm, respectively. The average value was 38.0 mm.

Thus, we have established that the position of the GCM is relatively constant for different combinations of the length of the sections in the normal state.

Our model implies that several factors influence the feasibility of physiological compensatoty possibilities:

1) level and length of the primary deformity;

2) magnitude and type of the primary deformity;

3) functional capabilities of the motion segments, which are closely related to the patient's age;

4) direction and sequence of involvement of the motion segments into the mechanism of compensatory reactions.

The physiological compensatory response develops immediately after the onset of the primary deformity, and X-ray reveals the outcomes of this process aimed at maintaining the postural balance and orthostatic position of the body.

We have used mathematical models for evaluation of the restoration of the position of the projection of the GCM as well as mechanogenesis of the spinal deformity and feasibility of its compensation. To assess the reliability of the mathematical model, spinal skiagrams taken from patients with clinically confirmed pathology and sagittal imbalance were used.

Results and Discussion

Questions of the balance of the human body are closely related to the analysis of the acting forces. One of the components of these forces is the mass of the body, the other is efforts produced by the muscles. At present, these components cannot be reliably accounted for. In such a situation, one must assess the balance of the body by estimating the projection of the GCM onto the supporting area. One of the approaches to solve this problem is to use kinematics based on mathematical modeling.

We can assume that the balance maintenance stereotype is developed on case by case basis and subsequently maintained following the principle of minimizing energy expenditure. Nevertheless, there is a statistically determined norm for the GCM position, which is localized 20 mm anteriorly from the promontory, and its projection onto the supporting area is located 50 mm anteriorly from the inter-malleolar line [3].

It is fair to say that the position of the GCM of the body with a constant shape remains constant, regardless of the parts into which this body is divided.

According to the laws of statics, the equilibrium condition is as follows:

$$m_1 l_1 = m_2 l_2 \text{ or } \frac{m_2}{m_1} = \frac{l_1}{l_2},$$

where m_1 and m_2 are masses of the body parts; l_1 and l_2 are arm lengths for these masses.

If the left side of the expression is a constant, then maintaining the equilibrium must satisfy the following requirement:

$$\frac{l_1}{l_2} = const.$$

In this case, a change in a value of one arm should lead to an adequate change in a value of the other arm. Moreover, the result depends not only on the length of the arm, but also on the direction of its moment, therefore, it is necessary to analyze the difference in the values of the arms of the parts of the body.

The superior and inferior parts of the trunk can be represented by rectangles [4, 7, 9, 17] whose length and position are determined by the length and slope of its longitudinal axis (the chord of the corresponding arc of the spine). The center of mass of each figure is localized at the point of intersection of the diagonals, that is, in the middle of the chord under study, and its projection onto the horizontal surface is determined by the length and angle of inclination of this chord.

Thus, we were able to link the change in the projection of the GCM with the change in the shape and orientation of

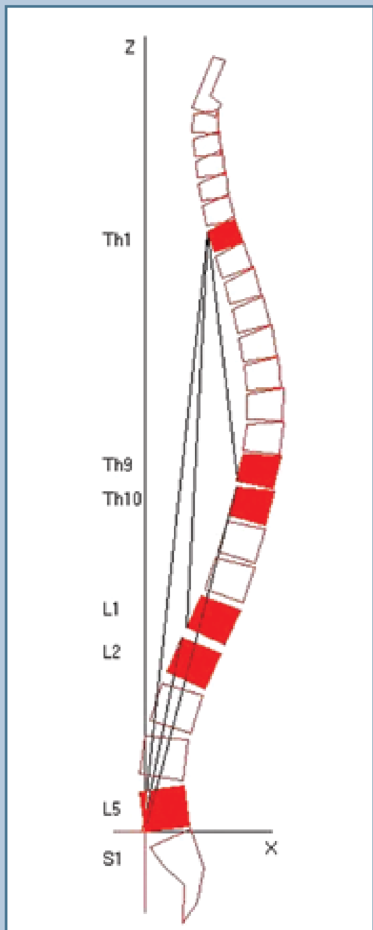

Fig. 1
Scheme of the ratio of the chords of the adjacent sections of the trunk over the length of T1 to L1 and L2 to L5, T1 to T9 and T10 to L5

the spine, revealed a deviation in the GCM while performing the function of the motion segments and onset of deformity at any level of the spine.

In case of deformity occurrence, the position of the GCM projection changes, and compensatory mechanisms must be engaged as much as necessary to restore its position.

Compensatory capabilities of the motion segments of the spine depend on the age of the patient. There is sufficient objective evidence that the amplitude of movements in the segments of the spine decreases with age. If the amplitude of movements in segments of the spine at the age of 2–13 years is taken as 100 %, then at 35–64 years it will be 50 %, and at 65–77 years it will be 30 % [15].

This dependence can be described by an exponential function:

$$y = a \cdot e^{b \cdot x},$$

where y is the amplitude in percentage or fractions of a unit (from 0 to 1); x is age. The a and b coefficients can be determined using the logarithm of the left and right sides of equation:

$$ln(y) = ln(a) + b \cdot x.$$

Let's use the following designations: $ln(y) = Y$, $ln(a) = A$, $b = B$, $x = X$.
We have a linear approximating function: $Y = A + BX$.
We can use a system of linear algebraic equations to find the coefficients A and B:

$$\begin{cases} nA + b\sum_i X_i = \sum_i Y_i \\ A\sum_i X_i + b\sum_i X_i^2 = \sum_i X_i Y_i \end{cases}$$

where n is a number of measurements, in this particular case $n = 3$.

By solving the equation, we get: $a = 1.175$, $b = -0.019$.
Therefore the function is as following: $y = 1.175 \cdot e^{-0.019 \cdot x}$.

Let's use this formula to determine the amplitude of motion at the age of 45 years assuming that its initial value was 20°:

$$1.175 \cdot e^{-0.019} \cdot 45 \cdot 20° = 10.14°.$$

We can use this approach to model the amplitude of movements in each segment of the spine during experiments.

The application of this approach to estimating the balance of the trunk under various pathological conditions of the spine in specific clinical observations [8, 10, 13] showed that in the absence of compensatory reactions from the motion segments of the spine, even a very small primary deformity significantly disturbs the balance of the acting forces (Fig. 2).

The lower the level of the primary kyphotic deformity, the more likely it is that the imbalance will appear (Fig. 3).

As the degree of listhesis increases, the imbalance increases (Fig. 4).

Ineffectiveness of compensatory reactions may be caused by their blockage due to underlying pathology or severe pain syndrome.

At the same time, in case of adequate compensatory reactions of the spinal segments even pronounced primary deformities of the spine do not cause an imbalance, even though a number of indicators characterizing the shape and orientation of the spine remain grossly impaired (Fig. 5).

The increase in the magnitude and extent of the primary deformity leads to postural imbalance and involvement of the lower limbs' joints (Fig. 6).

Our studies [1] show that compensatory reactions are manifested, first of all, in the inferior part of the spine; only when their physiological functional capabilities are exhausted, do the superior segments become involved.

The subsequent hyperextension in the superior and then inferior segments of the spine is largely associated with degenerative lesion of the intervertebral discs due to an increased bending load.

The involvement of these segments develops sequentially away from the center (the level of the primary deformity) towards the periphery and occurs on step by step basis. Therefore, if the primary deformity occurs at L5–S1 level, then, due to the absence of the inferior spinal segments, the physiological compensatory manifestations progress in the cranial direction (Fig. 7).

The change in the shape and orientation of the spine under the action of compensatory mechanisms is defined by two factors:

1) a change in the central angle of the inferior arc leads to a change in the position of the chord of this arc;

2) a change in the position of the arc may arise due to flexion or extension in the hip joints, but it is not necessarily accompanied by changes in the central angle of the arc.

The simulation of the situation makes it possible to define the role of each of the factors in the process of changing the shape and orientation of the spine. The calculations showed that there is a definite relationship between these values. For example, the central angle is = 36.1° + n3.8°, and the slope of the chord is = 13.5° + n2.8° (n is the number of degrees of increment in the angular ratio of adjacent lumbar vertebrae). The analysis of these values in a specific clinical case is shown in Fig. 8.

At a given magnitude of the lumbar lordosis (56.6°), the angle of its chord should be 22.0°. In reality, it is 4.5° and is due to the anterior pelvic tilt due to flexion in the hip joints, as evidenced by the angle of the sacrum (38.7°), which exceeds the norm (53–79°). There is an inexplicable inclination of the trunk forwards due to flexion in the hip joints.

In this observation, the absence of the effect of full compensation due to the physiological capabilities of the spinal segment leads to involvement of the hip joints, as can be seen from the discrepancy between the actual and calculated characteristics of the position of the chord of this arc.

This model makes it possible to reproduce both the primary deformity and the compensatory response of the intact segments of the spine, taking into account the acting factors of influence and quantitative characteristics of the primary deformity of the spine in a specific clinical observation.

Conclusions

1. The proposed algorithms simulating the development of spinal deformities based on the restoration of the position of the GCM projection reflect their mechanogenesis and can be used

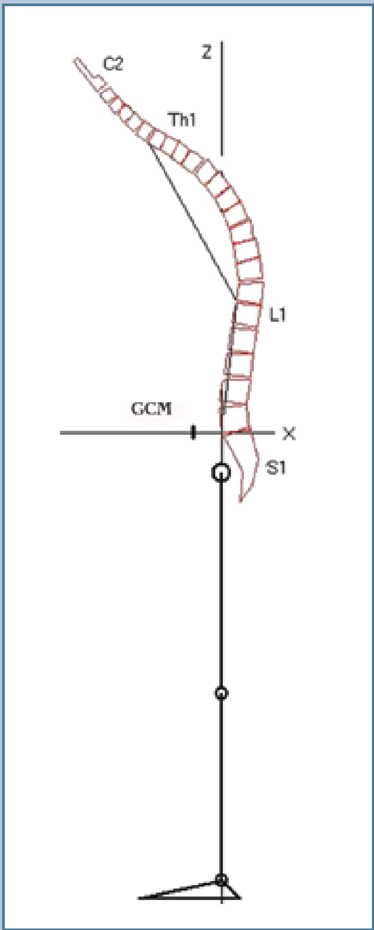

Fig. 2
The skiagram shows ankylosing spondylitis, flexion deformity of the lumbar spine: the position of the general center of mass (GCM) of the body is -56.2 mm, within the limits of the supporting area

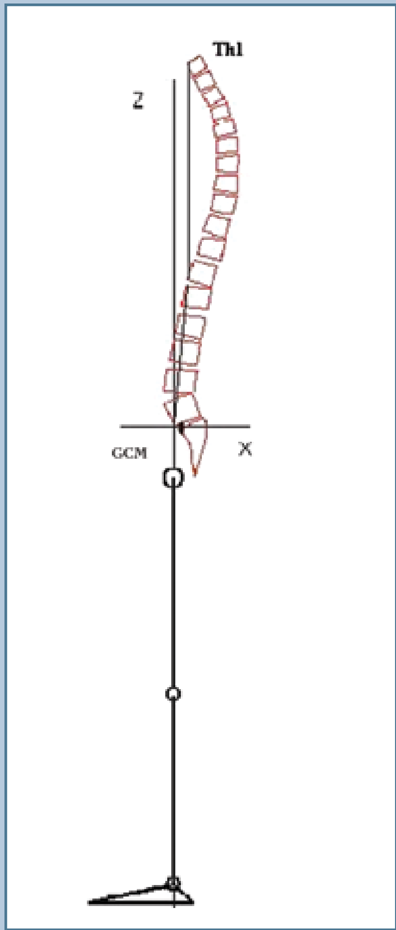

Fig. 3
The skiagram shows grade I isthmic spondylolisthesis of L5: the position of the general center of mass (GCM) of the body is 9.5 mm, within the limits of the supporting area

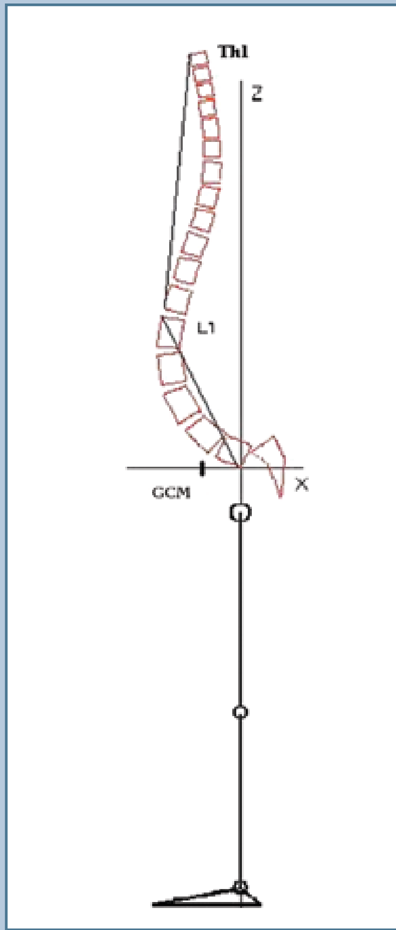

Fig. 4
The skiagram shows grade IV dysplastic spondylolisthesis of L5: the position of the general center of mass (GCM) of the body is -64.0 mm, within the limits of the supporting area

to model various pathological conditions of the spine.

2. The trunk balance is maintained through the physiological capabilities of the motion segments of the spine.

3. The involvement of the lower limbs' joints in the process of compensation of the deformity is aimed at maintaining the orthostatic position of the human body.

4. The preservation of the proper postural balance in a persistent deformity is not a reason to forego the correction of the deformity, since other biomechanical parameters are pathological.

5. Complete correction of the deformity does not mean complete cure, because spinal fusion creates a new, prognostically less significant, but pathological situation.

The study did not have sponsorship. The authors declare no conflict of interest.

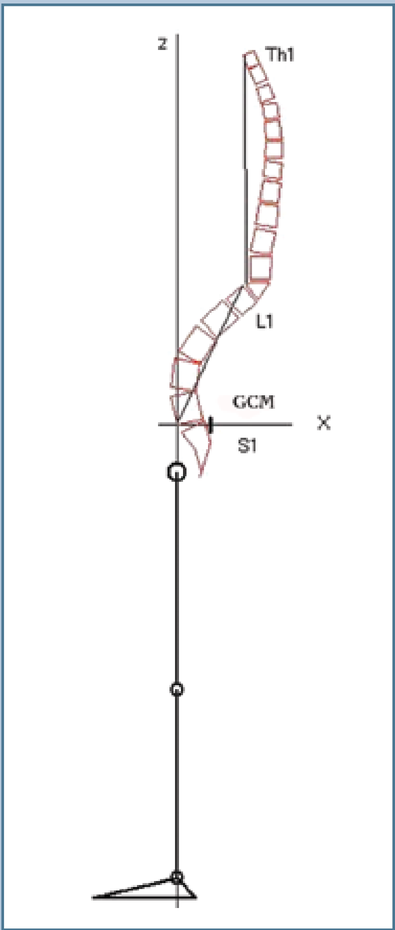

Fig. 5
The skiagram shows congenital complete wedge-shaped T12 vertebra, the magnitude of kyphosis at the T11–T12 level is 40°: the position of the general center of mass (GCM) of the body is 40.0 mm

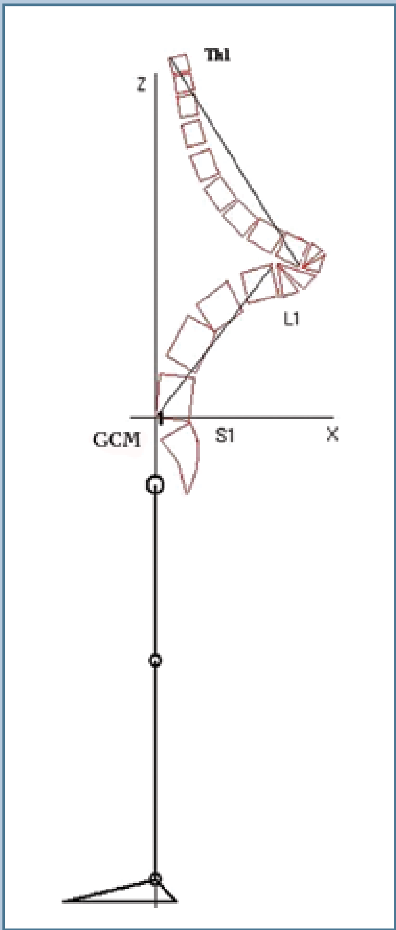

Fig. 6
The skiagram shows post-tuberculous kyphosis of the thoracolumbar spine, angle of kyphosis between T9 and L2 vertebrae is 144°: the position of the general center of mass (GCM) of the body is 4.0 mm

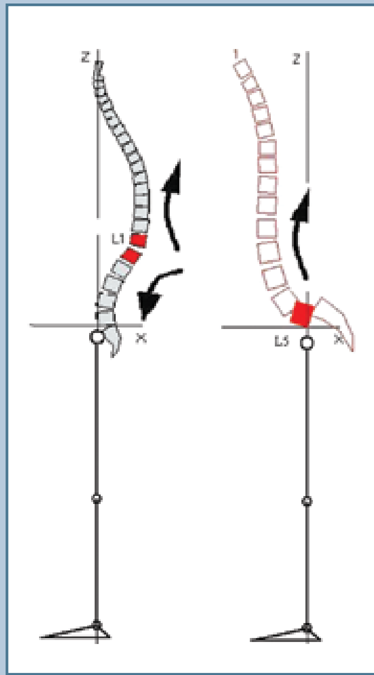

Fig. 7
The skiagram shows the direction of the progression of the compensatory reactions

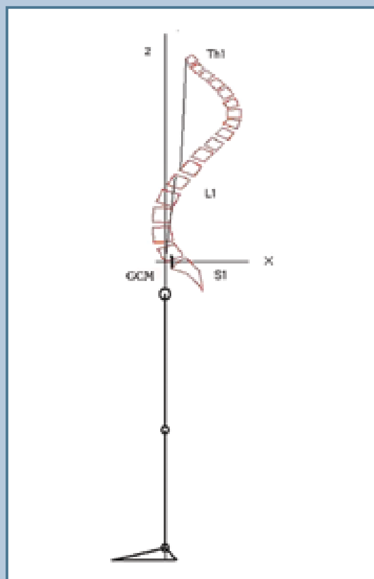

Fig. 8
The skiagram shows Scheuermann's disease, flexion deformity of the thoracic spine: the position of the general center of mass (GCM) of the body is 11.0 mm

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