Biomechanics of compensatory mechanisms in spinal-pelvic complex

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Abstract. 3D geometric solid computer model of spinal-pelvic complex was constructed on the basis of computed tomography and full body X-ray in standing position data. The constructed model was used for biomechanical analysis of compensatory mechanisms arising in the spine with anteversion and retroversion of the pelvis. The results of numerical biomechanical 3D modeling are in good agreement with the clinical data.

1. Materials and methods
With the help of biomechanics methods, the compensatory changes in the sagittal profile of the spine were simulated, resulting from a change in the normal position of the pelvis in the sagittal plane due to its rotation around the biococxoforal axis. The change in the position of the pelvis was modeled by increasing and then decreasing the initial value of pelvic tilt (PT, pelvic tilt is an orientation of the pelvis in respect to the thighbones and the rest of the body) in the range from 5° to 25° in steps of 5°. The presented biomechanical model allowed reproducing the changes in sagittal vertebral-pelvic interrelations, which are characteristic for patients with deforming arthrosis of the hip joint of the third stage, accompanied by the formation of its flexion-leading contracture, and also for patients with degenerative-dystrophic spinal disease. When simulating the compensatory changes in sagittal profile of the spinal column, the rotated pelvis was fixed, and the seventh cervical vertebra was returned to its original position, at which the plumb line, drawn from the center of the C7 (C7 plumb line), passed through the cape of the sacrum. This mechanism of maintaining the sagittal balance of the trunk, allowing to minimize muscular efforts aimed at maintaining the vertical position of the body, was accompanied by a change in the physiological curves of the spine – lumbar lordosis and thoracic kyphosis. The stresses appearing in the vertebrae, arched joints and intervertebral discs were examined with the help of finite-element method and their localization was also determined.

1.1. Initial data
Computed tomography (CT) scans of a pelvis-spine complex of a healthy person (volunteer), performed from the level of the seventh cervical vertebra to the proximal parts of the femur, as well as the full body X-ray of the same subject executed in a standing position [1].
1.2. 3D solid models of pelvis-spine complex creation

Surface models obtained by semi-automatic processing of CT in special software products are only surfaces in the form of triangles that limit the volume of the objects under study, and are not suitable for performing computer biomechanical modeling. In this connection, for the implementation of biomechanical computer finite element modeling on the basis of the initial data (CT and X-ray diffraction), a solid 3D geometrical model of the pelvis-spine complex was constructed, containing the volumes of the objects under study.

CT data were used at first stage. CT data was processed using Mimics software, in which the models of vertebrae, pelvis and upper thirds of femurs were constructed. Since the CT scan was performed in the position of the patient lying on the back, the lumbar lordosis and thoracic kyphosis on the constructed model were smoothed out, and the location of the vertebrae relative to each other did not correspond to that in the standing position. At the second stage in SolidWorks software the constructed vertebral models were moved in the sagittal plane in exact accordance with their location on the roentgenogram performed to the subject in standing position. As a result, a pelvis-spine model was obtained containing vertebrae, pelvic bones and upper thirds of the femurs, the spatial arrangement of which corresponded to the true sagittal spine-and-pelvic relationship of the subject in the standing position. Then solid 3D models of intervertebral discs, articular joints and ligaments of the spine have been completed with the help of the SolidWorks software product on the basis of known information about the anatomical structure of the lumbar-motor segments of the examined spine sections.

1.3. Finite-element modeling

Constructed 3D solid models of pelvis-spine complex were loaded into the ANSYS 18 finite element analysis system. It was used to model the rotation of pelvis around the bicoxo-femoral axis anteriorly (anteversion) and then backward (retroversion). In this case, the value of the PT parameter, equal $10^\circ$, was successively changed between $+25^\circ$ and $-25^\circ$ with a step of $5^\circ$ (figures 2 and 3). Then the position of pelvis was fixed and the seventh cervical vertebra was returned to its normal position, keeping the original plumb line drawn from the center of C7 body through the cape of the sacrum.

Mechanical parameters of the vertebrae bone tissue, pelvis and femurs, as well as the parameters of intervertebral discs, arched joints and ligaments, were modeled on the basis of literature data. All pelvis-spine complex elements were considered to be isotropic, homogeneous and linearly elastic. Large deformations of pelvis-spine complex elements were assumed during calculations. Bonded contact was used between the contacting elements of pelvis-spine complex. Static formulation was used in calculations.

Tetrahedral finite-element computational mesh was created, the characteristic size of elements was calculated on the basis of the mesh convergence analysis and was assumed to be 2.5 mm. Displacements and equivalent von Mises stresses of the pelvis-spine complex were analyzed.

2. Results

2.1. 3D solid models of pelvis-spine complex

Figure 1 a shows 3D solid model of pelvis-spine complex, constructed on the basis of CT and full body X-ray data. Blue color shows pelvic bones, brown – proximal femur bones, green – vertebrae, red – intervertebral disks, lilac – sacrum, yellow – ligaments. Figure 1 b shows the lumbosacral and thoracic vertebrae, while their relationships are modeled on the basis of the full body X-ray in standing position. Red marks show position of the vertebrae on roentgenogram. Figure 1 c shows sagittal and frontal projections of the spine. In sagittal projection, spine model is superimposed on the X-ray. The plumb line from the center of the C7 vertebra body is shown in orange, the vertebrae of the lumbosacral segment are green, the thoracic vertebrae are yellow, the seventh cervical vertebra is red and the sacrum vertebra is lilac.
2.2. Finite-element modeling

Finite-element modeling allowed calculating stress-strain state of the pelvis-spine complex in following ways of fixing and loading: 1) PT increased to 25° from the initial with a step of 5° and subsequent fixation of pelvis in this position, returning the seventh cervical vertebra to its normal position to restore the plumb line; 2) PT reduced to 25° from the original in 5° increments and subsequent fixation of pelvis in this position, returning the seventh cervical vertebra to its normal position to restore the plumb line.

Figure 2 shows 3D models of spine: normal and with the described changes. Vertical axis in each illustration is saved. Changes in physiological curves of spine are demonstrated. For each model of spine a plumb line is shown. Displacements are shown on scale from blue (zero displacement) to red (maximum displacement). Boundaries of undeformed spine are shown by thin black lines for each model.

Figure 2 demonstrates that with the increase in pelvic anteverision angle and subsequent return of seventh cervical vertebra to normal position, lumbar lordosis and thoracic kyphosis increase. In this case, plumb line practically does not change its position and passes slightly anterior to the cape of sacrum.

Figure 3 shows the results of modeling changes in the sagittal profile of the spine with increasing retroversion of the pelvis in steps of 5°.

Figure 3 illustrates the increase in retroversion of the pelvis and an increase in the distance from the plumb line drawn from the center of the body of C7 to the cape of the sacrum. There is also a significant increase in thoracic kyphosis and a flattening of the lumbar lordosis, leading to an inclination of the upper half of the trunk anteriorly and a sagittal imbalance.
Figure 2. Changes in the sagittal profile of the spine with an increase in the initial pelvic anteversion in steps of 5°.

Figure 3. Changes in the sagittal profile of the spine with a decrease in the initial pelvic anteversion in steps of 5°.

Figure 4 shows distribution of effective stresses in various parts of spine and in various parts of vertebrae. Such stress field is typical for sagittal vertebral-pelvic relationships with an increase in pelvic anteversion.

Figure 4 shows that highest stress values for this variant of the sagittal profile occur in the region of the articular joints of the lumbar vertebrae, as well as in the anterior parts of the bodies of the upper thoracic vertebrae. With further increase in pelvic anteversion, stress values also increase. Analysis of deformations of intervertebral discs indicated the greatest changes in the lumbosacral spine.

Effective von Mises stresses for the vertebrae for pelvis retroversion are shown in figure 5. With this variant of static deformation of pelvis-spine complex, the highest stresses occur in the posterior parts of the lumbar vertebrae, in the sacrum, and also in the anterior sections of
Figure 4. Effective stresses in the vertebrae with increasing pelvic anteversion (biomechanical model of a patient with coxarthrosis of III st., accompanied by a flexion-reducing contracture of hip joint.

Figure 5. Effective Mises stresses for vertebrae at tilting the pelvis back.

The data obtained as a result of biomechanical modeling of various variants of static deformations of pelvis-spine complex are fully confirmed by the results of clinical and radiological examination and assessment of the sagittal balance of patients suffering from both deforming arthrosis of the hip joint and degenerative-dystrophic disease of the spine.

3. Discussion
The data obtained as a result of biomechanical modeling of various variants of static deformations of pelvis-spine complex are fully confirmed by the results of clinical and radiological examination and assessment of the sagittal balance of patients suffering from both deforming arthrosis of the hip joint and degenerative-dystrophic disease of the spine.
Figure 6. Review X-ray of the patient’s pelvis D. Aseptic necrosis of the head of the femoral bones of the fourth degree, secondary bilateral coxarthrosis of the third degree.

3.1. Clinical example 1
Patient D. was 56 years old on examination and treatment in the clinic of military traumatology and orthopedics of the Military Medical Academy about aseptic necrosis of the femoral bones head of the IV degree, secondary bilateral coxarthrosis of the third degree, flexor-leading contractures of the hip joints (figure 6). In an objective clinical examination, lumbar lordosis and a positive symptom of Thomas were diagnosed.

Analysis of the sagittal profile of the patient D. testified to excessive pelvic anteversion, which arose as a result of the flexion element of the hip joint contracture, as well as the compensatory increase in lumbar lordosis (figure 7) with the formation of pain vertebrogenic and discogenic syndromes.

The presented variant of the sagittal profile is typical for patients with the phenomena of deforming arthrosis of the hip joint, which is accompanied by the formation of the flexion-leading contracture. It completely coincides with the results of 3D modeling of this variant of static deformation of pelvis-spine complex, presented in figure 2.

3.2. Clinical example 2
Patient Z. 53 years old was on treatment at the clinic of military traumatology and orthopedics of the Military Medical Academy in 2011 for degenerative-dystrophic disease of the lumbosacral spine, degenerative stable spondylolisthesis L4 of the vertebra of I st., degenerative subcompensated stenosis of the vertebral canal with neurogenic syndrome “Intermittent claudication.” As a result of the study of the sagittal profile, a decrease in pelvic anteversion and lumbar lordosis has been diagnosed (figure 8).

This type of sagittal profile is typical for patients with degenerative-dystrophic disease of the spine, accompanied by the formation ofantesponilolisthesis and stenosis of the spinal canal. It completely coincides with the results of 3D modeling of the considered variant of pelvis-spine complex static deformation, presented in figure 3.
Figure 8. Sagittal X-ray of the patient’s pelvis-spine complex. Reduced pelvic anteverision and lumbar lordosis, L4 antepspondilolisthesis on the I-st stage, degenerative-dystrophic disease of the spine.

Thus, the obtained results of biomechanical 3D modeling of the pelvis-spine complex, as well as the study of the behavior of the constructed model with a change in the spatial location of the pelvis, fully coincided with the data of additional examination of patients with diseases of the musculoskeletal system resulting in the formation of static deformations of the pelvis-spine complex, and also with the description of changes in the sagittal profile of the spine available in the scientific literature for various diseases [2–4].

Conclusions
Accurate 3D solid geometric model of the human spinal-pelvic complex was constructed. Full body x-ray in the standing position and a computer tomogram in the supine position were used as the initial data. The constructed 3D model was used in the biomechanical analysis of compensatory mechanisms arising in the spine with various pathologies.

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