ISSN 0030-5987. Orthopaedics, traumatology and prosthetics. 2023. № 3

УДК 616.711-089.881:004.942](045)

DOI: http://dx.doi.org/10.15674/0030-59872023313-18

Study of the L_{IV} vertebral body load during dynamic simulation of movements in the lumbar spine using musculoskeletal models after posterior bisegmental spine fusion performance

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One of the risk factors for complications in the spinal motion segments of the thoracic and lumbar regions, as well as in the adjacent segments with spinal fusion ones, is changes in the sagittal vertebral-pelvic balance. Purpose. To determine the effect of muscle changes that occur during the performance of two-segment L_{IV}–S_I spinal fusion on the load of adjacent motion segments. Material and methods. The spinal fusion of two spinal motion segments of the lumbar spine was simulated at the L_{IV}–L_V and L_V–S_I levels at different angles of segment fixation in the OpenSim programme. Five models were analysed: 1 (basic) — without changes; 2 — changes in the points of attachment and muscle strength; 3 — normo-lordotic fixation; 4 — hypolordotic; 5 —hyperlordotic. The load on the zone of interest was measured as the magnitude of the projection of the force vector depending on the angle of inclination of the torso as a percentage of the body weight. Results. Simulation of the above configurations of the instrumental spinal fusion (intact, normo-lordotic, hyperlordotic, hypolordotic positions due to a change in the angle of the L_{IV}–S_I spinal fusion) showed that the load force of the adjacent segments when bent forward depended on the angle of the instrumental spinal fusion performed. Conclusions. As a result of study of the kinematic model of the lumbar spine using bisegmental spinal fusion of L_{IV}–S_I, it was proved that the load force of the adjacent segments when bent forward depended on the angle of the instrumental spinal fusion performed. It was determined that the upper adjacent vertebra of the fixation zone had a relatively insignificant increase in load in the case of fixation in the hyperlordotic position; in the hypolordotic position, the load on the upper segment led to an increase in loads on the upper adjacent segment, and in the hypolordic position, it led to a slight decrease compared to the normo-lordotic fixation. According to the results of the study, minimal muscle damage is expected during the surgical intervention, so the reliability of the model is closer to minimally invasive surgery. The developed kinematic models can be useful in the planning of the transpedicular fixation surgery to prevent complications.

Одним із чинників ризику розвитку ускладнень у хребтово-рухових сегментах грудного та поперекового відділів, а також суміжних сегментах зі спондилодезованими, є зміна сагітального хребтово-тазового балансу. Мета. Визначити вплив змін м'язів, які відбуваються під час виконання заднього двосегментарного спондилодезу L_{IV}–S_I на навантаження суміжних рухових сегментів. Матеріал і методи. Моделювали спондилодез двох хребтово-рухових сегментів поперекового відділу хребта на рівнях L_{IV}–L_V та L_V–S_I під різними кутами фіксації сегментів у програмі OpenSim. Проаналізовано 5 моделей: 1 (базова) — без змін; 2 — зміни точок прикріплення та сили м'язів; 3 — нормолордотична фіксація; 4 — гіполордотична; 5 — гіперлордотична. Навантаження на зону інтересу вимірювали як величину проєкції вектора сили залежно від кута нахилу тулуба у відсотках до маси тіла. Результати. Моделювання наведених конфігурацій інструментального спондилодезу (інтактного, нормолордотичного, гіперлордитичного, гіполордотичного положень за рахунок зміни кута спондилодеза L_{IV}–S_I) показало, що сила навантаження суміжних сегментів за згинання вперед, залежить від виконаного кута інструментального спондилодезу. Висновки. У результаті дослідження кінематичної моделі поперекового відділу хребта з використанням бісегментарного спондилодезу L_{IV}–S_I доведено, що сила навантаження суміжних сегментів за згинання вперед залежить від виконаного кута інструментального спондилодезу. Визначено, що верхній суміжний хребець зони фіксації мав порівняно незначне збільшення навантаження в разі фіксації в гіперлордотичному положенні, за гіполордотичного — навантаження на верхній сегмент призводили до зростання навантажень на верхній суміжний сегмент, а гіполордотичного — незначного зменшення порівняно з варіантом нормолордотичної фіксації. За результатами дослідження передбачається мінімальне ушкодження м'язів під час хірургічного втручання, тому достовірність моделі більш наближена до малоінвазивної хірургії. Розроблені кінематичні моделі можуть бути корисними під час планування операції транспедикулярної фіксації для запобігання ускладнень. Ключові слова. Спондилодез, моделювання, динамічне навантаження.

Keywords. Spinal fusion, simulation, dynamic load

Introduction

Posterior spondylodesis of the lumbar spine is one of the most common methods of surgical treatment. The number of such operations is growing rapidly, but the share of complications is also increasing along with it. The total number of complications or side effects during spine surgery is unknown and highly variable, ranging from 1.8 to 56.4 % according to various sources [1].

One of the risk factors for the development of complications in the spinal motor segments (SMS) of the thoracic and lumbar regions, as well as adjacent segments with spondylodesis, are changes in the sagittal spine-pelvic balance [2]. Compensatory changes in the amount of sagittal curvatures of the spine (for example, an increase in thoracic kyphosis with a corresponding increase in the depth of the lumbar lordosis) normally have practically no effect on the position of the line of gravity. However, flattening of the sagittal curves with the formation of the flat back degenerative deformation is associated with activation of alternative compensation mechanisms [3–5], which worsen the deformations of the spinal segments. Aging of the spine is accompanied by atrophy of the extensor muscles and leads to progressive kyphosis and disruption of the sagittal balance [6–8]. It is necessary to mention that the development of degenerative diseases of the spine is often characterized by anterior sagittal imbalance, loss of lumbar lordosis, and increased pelvic tilt [9–12]. Anterior imbalance is directly related to loss of lumbar lordosis. In addition, there are other changes in vertebral-pelvic parameters that correspond to compensatory mechanisms. In order to optimize the treatment of degenerative diseases of the lumbar spine and avoid underestimation of the severity of the disease, it is very important to recognize them [13]. Compensatory mechanisms reduce the effects of lumbar kyphosis due to anterior sagittal imbalance and occur in the spine, pelvis and/or lower extremities.

Such anatomical features of the sagittal balance result in the development of changes in loads on adjacent segments of the spondylodesis zone, intervertebral disc sections and arcuate joints, which increases the risk of progression of degenerative processes with the development of retrolisthesis, spondyloarthrosis, interspinous hyperpressure with the formation of interspinous neoarthrosis, etc.

Purpose: to determine the impact of muscle changes occurring under the conditions of surgical access to perform posterior two-segment L_{IV}–S_{I} spondylodesis on the load of adjacent motor segments.

Material and methods

Modeling of dynamic simulation of movements was performed using OpenSim software [14] with the involvement of additional applications for calculating load forces.

The model of the human skeletal and muscular system was taken as the basis [15]. For simplicity, only the muscles that influence sagittal movements of the trunk are shown (Fig. 1).

We studied the time course of load force changes caused by the surfaces of the bodies of the lumbar vertebrae and the articular surface of the sacrum on the ilium in the sacroiliac joint during bending of the upper half of the human body. The load force is a vector quantity and is described using three parameters: the length of the force vector (a scalar quantity), its direction, and the point of application.

The direction of the load force of the body is determined by the directionality of its projection relative to the corresponding axis of the coordinate system (Fig. 2)

The projection of the force vector on the X axis describes the load in the sagittal plane, its positive value indicates the forward direction, and negative the backward one. The approximation of the action of the force vector on the Y axis shows a vertical direction, a positive value indicates an upward direction, and a negative value indicates a downward direction.

Spondylodesis of two spinal-motor segments of the lumbar spine at the L_{IV}–L_{V} and L_{V}–S_{I} levels under different segment fixation angles was simulated.

To compare the load force in segments of the lumbar spine adjacent to the fixed ones, 5 models were created:

– 1 (basic), all spinal-motor segments and muscles of the lumbar spine are fully functional (there are no

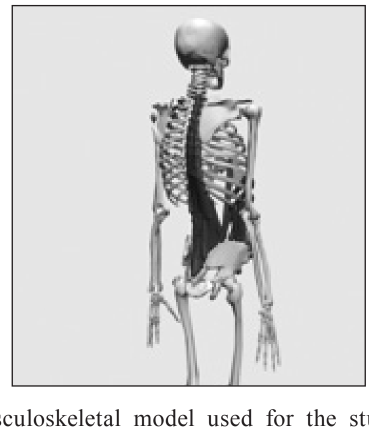

Fig. 1. Musculoskeletal model used for the study (muscles of the right half of the model responsible for sagittal movements of the trunk are shown)

effects of muscle damage and denervation, all attachment points are preserved);

– 2, all spinal-motor segments of the lumbar spine are fully functional, but the parameters of the muscles and their attachment points have changed;

– 3, fixation is unchanged relative to the «preoperative» state of the L_{IV}–L_V segment at an angle of 22°, the L_V–S_I segment at an angle of 24°;

– 4 fixation of the L_{IV}–L_V segment was performed with reproduction of the hypolordotic position at a sagittal angle of 8°, and of the L_V–S_I segment at an angle of 10°.

– fixation of the L_{IV}–L_V segment was performed with reproduction of the hyperlordotic position at a sagittal angle of 32°, and the L_V–S_I segment at an angle of 34°.

For models 2–4, changes are made in the muscles that correspond to those that occur during a surgical posterior approach to the lumbar spine for L_{IV}–S_I posterior instrumented spondylodesis. Muscle denervation was modeled by removing the corresponding muscle fiber from the calculation.

Dynamic simulation of bending in the lumbar spine was carried out in the range from 0° to 45°. Movements in the hip joints were not taken into account in this experiment.

The load forces below the spondylodesis zone, that is, at the level of the sacroiliac joint, were studied. The load on the desired zone was measured as the force vector projection depending on the angle of inclination of the trunk as a percentage of body weight.

Under the conditions of a bending cycle of up to 45° in the lumbar spine of a person, the load force on the body of the L_{IV} vertebra in this model, which is taken as the basic one, changed dynamically.

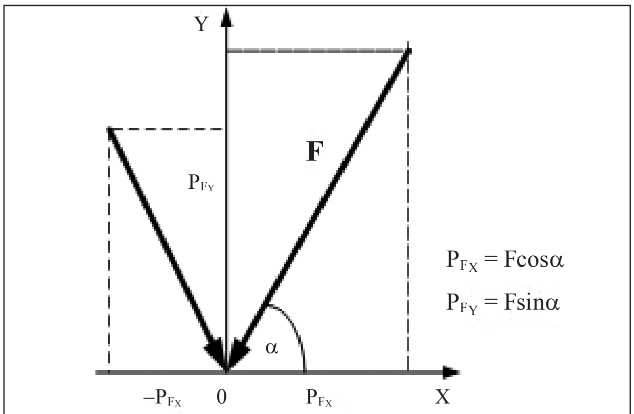

Fig. 2. An example of determining the force projection on the coordinate axis

Results and their discussion

Study of the load on the body of the L_{IV} vertebra under the conditions of bending movements in the lumbar spine in normal conditions (model 1)

In the first period of movement (bending from a vertical position to 45°), gradual changes in load forces were noted on the X axis from –6.94 % of body weight to –0.93 %, the force vector was directed backwards. The difference for this period was 6.01 %.

Along the Y axis, the specified parameter at the beginning of the movement (between 0° and 13° of flexion) slightly increased from 48.95 to 49.97 %. Then (from 14° to 44°) there was a gradual decrease in the load force from 49.89 to 42.65 %, reaching a minimum at an angle of 45°, the difference during this period was 7.40 %. During extension (return to the vertical position), load dynamics were mirrored (Fig. 3).

Study of the load on the body of the L_{IV} vertebra by simulating partial muscle damage and transfer of their attachment points (model 2)

The model was built to determine the change in load force on adjacent segments under the conditions of a full bending cycle under the simulation of damage to the muscles of the back of the lumbar spine during an instrumented spondylodesis approach at the L_{IV}–S_I level.

In the case of bending to an angle of 45° in the lumbar spine of a person, the load force on the body of the L_{IV} vertebra in model 2 on the X axis shows a gradual change in the value of the load force –7.11 % of the body weight to –0.85 % of the body weight with the direction of the force vector backwards. The difference for this period was 6.26 %.

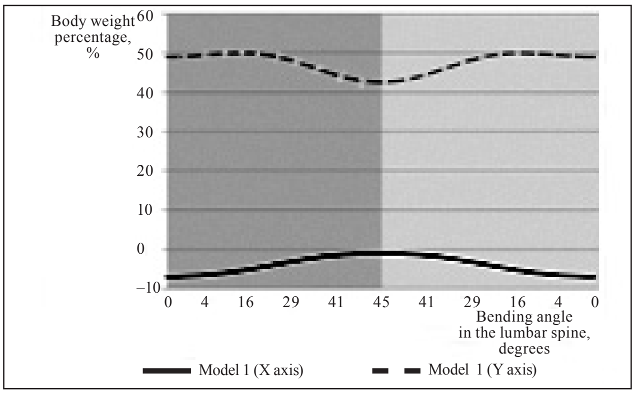

Fig. 3. Graphs of changes in the projection of the load force vector on the body of the L_{IV} vertebra on the X and Y axes during bending in the lumbar spine (model 1)

Along the Y axis, for bending up to 10°, the load force gradually increased from 48.62 to 49.31 %, then from 11° to 44° it decreased from 49.26 to 41.09 %, reaching a minimum at a bending angle of 45° –41,01% of body weight. The difference for this period was 8.30%. During extension, the mirror direction of load change was observed (Fig. 4).

Load on the body of the L_{IV} vertebra during L_{IV}–S_I spondylodesis in the normolordotic position of the lumbar lordosis (model 3)

For bending on the X axis, a change in force values was noted from –16.14 % to –1.31 % of body weight at 45°. The direction of the force vector is backward, the difference for this period was 14.83 %.

Along the Y axis, there was a gradual decrease in the load force from 63.49 to 46.98 % at 45°, a difference of 16.51 %. In the process of extension, reverse changes occurred (Fig. 5).

Load on the body of the L_{IV} vertebra during L_{IV}–S_I bisegmental spondylodesis in the hypolordotic position of the lumbar lordosis (model 4)

In the case of bending on the X-axis, a gradual change in the force value was recorded from –16.02 % of body weight to a maximum of –1.67 % of body weight at the end of the period at a bending angle of 45°, the difference during this period was 14.35 %. The direction of the load force vector has not changed compared to previous models.

Along the Y axis during bending, there was a gradual decrease in the load force from 60.80 to 43.70 %, the difference was 17.09 %. During extension, reverse changes occurred in a mirror image (Fig. 6).

Load on the body of the L_{IV} vertebra in L_{IV}–S_I bisegmental spondylodesis in the hyperlordotic position of the lumbar lordosis (model 5)

For bending up to 45° along the X axis, changes in load force from –15.95 to –1.04 % of body weight were noted. The difference for this period is 14.91 %.

Along the Y axis, there was a gradual decrease in the load force from 64.13 to 48.01 % at 45° (the difference during this period was 16.12 %). In the second period of movement (return to the vertical position

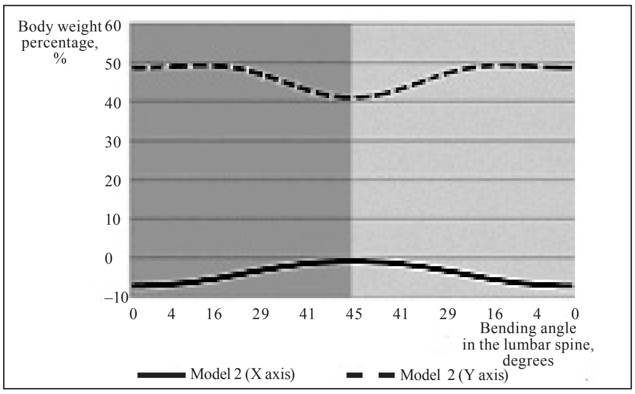

Fig. 4. Graphs of changes in the projection of the load force vector on the body of the L_{IV} vertebra on the X and Y axes during bending in the lumbar spine (model 2)

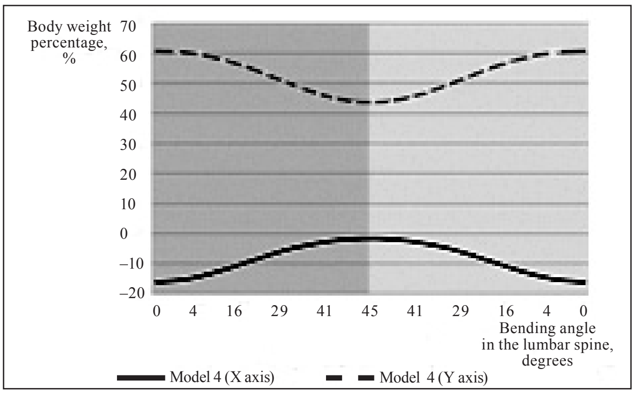

Fig. 6. Graphs of changes in the projection of the load force vector on the L_{IV} body of the vertebra on the X and Y axes due to bending in the lumbar region of the spine (model 4)

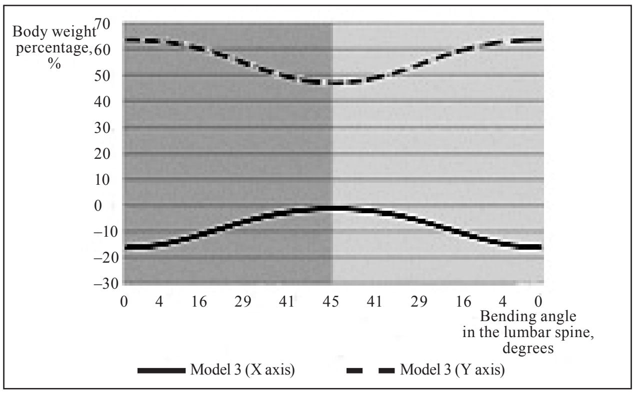

Fig. 5. Graphs of changes in the projection of the load force vector on the L_{IV} body of the vertebra on the X and Y axes due to bending in the lumbar spine (model 3)

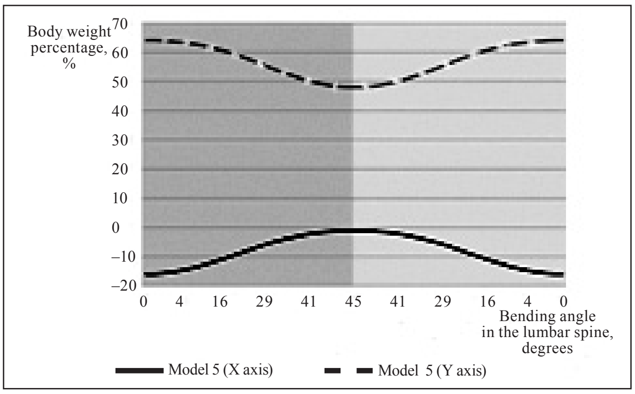

Fig. 7. Graphs of changes in the projection of the load force vector on the body of the L_{IV} vertebra on the X and Y axes due to bending in the lumbar spine (model 5)

Table

Load force on the iliac bone surface in the sacroiliac joint in all models

Angle (degrees)	Percentage of body weight (%)									
	model 1		model 2		model 3		model 4		model 5	
	X	Y	X	Y	X	Y	X	Y	X	Y
0	6.9	48.9	7.1	48.6	16.1	16.1	16.0	60.8	15.9	64.1
45	0.9	42.6	0.8	41.0	1.3	1.3	1.7	43.7	1.0	48.0
Change (% of body weight)	6.1	7.3	6.3	7.6	14.8	14.8	14.3	17.1	14.9	16.1

from a bending angle of 45°), reverse changes occurred in a mirror image (Fig. 7).

Discussion

Muscle strength and function were the same for all types of instrumented spondylodesis created, and did not take into account trauma during access. All of these factors and the results of our study predict minimal muscle damage during surgery.

To analyze the simulation results, the obtained indicators are tabulated.

In models with spondylodesis, load changes occur mainly in the vertical direction (along the Y axis), the maximum changes (17.1 %) were recorded in model 4 with hyperlordotic fixation. In the horizontal direction (X-axis), the changes are not significant, within 1% in models with spondylodesis, but compared to the basic model (1), an increase in the load force by 2.5 times was noted. It stands to mention that the direction of the load force is a vector quantity, so an increase in the load in the vertical direction correspondingly decreases it in the horizontal direction, and vice versa. That is, the method of lordotic fixation can change the ratio of the vertical and horizontal direction of the force, and accordingly, adjust the load on the body of the vertebra.

The mechanical effect of force loads on adjacent segments with the fixation zone can be determined from the results of the study. Modeling provides greater insight and characterization and explains the relationship between muscles, spondylodesis, kinematics of loads on the vertebral body above the level of instrumentation after a surgical intervention. Such changes in the load amplitude, firstly, can affect the development of diseases of the adjacent segment adjacent to the spondylodesis zone, and secondly, be one of the factors in the development of complications directly related to the transpedicular construction.

The experiment also provided evidence that changes in the sagittal position of the lumbar lordosis are essential among other possible mechanical factors that need to be taken into account during surgical treatment using instrumental spondylodesis. Fixation in the hyperlordotic position led to an increase in loads on the upper adjacent segment, however, the obtained indicators of increase in load force were insignificant in relation to fixing the lordosis in an intact position.

The study showed changes in the kinematics of load forces on the vertebra adjacent to the level of instrumental spondylodesis. The developed kinematic models in this study can potentially be offered as a guide during planning of surgical intervention as preventive measures of complications of transpedicular fixation. It is necessary to be careful in case of extrapolation of these results in clinical practice.

In general, the modeling of the presented configurations of instrumental spondylodesis (intact, normlordotic, hyperlordotic, hypolordotic positions due to changes in the L_{IV}–S_I spondylodesis angle) showed that the load force of adjacent segments during forward bending depends on the performed angle of instrumental spondylodesis.

Conclusions

The study of the kinematic model of the lumbar spine using L_{IV}–S_I bisegmental spondylodesis has shown that the load force of adjacent segments during forward bending depends on the performed angle of instrumental spondylodesis. The upper adjacent vertebra of the fixation zone has been found to have a relatively insignificant increase in the load when fixed in the hyperlordotic position, while in hypolordotic one the load on the upper segment led to an increase in the loads on the upper adjacent segment, and in the case of hypolordotic one to a slight decrease compared to the normolordotic fixation option.

According to the results of the study, minimal muscle damage is expected during surgery, so the reliability of the model is closer to minimally invasive intervention.

The developed kinematic models can be useful when planning a transpedicular fixation operation in order to prevent complications.

Conflict of interest. The authors declare no conflict of interest.

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The article has been sent to the editors 29.06.2023

STUDY OF THE L_{IV} VERTEBRAL BODY LOAD DURING DYNAMIC SIMULATION OF MOVEMENTS IN THE LUMBAR SPINE USING MUSCULOSKELETAL MODELS AFTER POSTERIOR BISEGMENTAL SPINE FUSION PERFORMANCE

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