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External Dynamic Apparatus Correction in Rigid Posttraumatic Spinal De-formations Engineering and Clinical Aspects

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Abstract

Study design: *The authors define most dangerous sections and calculate the stresses arising in the parts of the external fixation device. They configure external fixation devices taking into account the obtained results and use them in medical practice.*

Objective: the development of an apparatus correction technique for the treatment of spinal deformations.

Summary of background data: *standard methods of rigid deformation correction are technically complicated and high-costly; there are also possible formidable intraoperative complications. Authors consider a variant of apparatus external correction as an alternative to the known methods, which is devoid of the aforementioned disadvantages.*

Methods: *The authors use theoretical and experimental research methods. The theoretical deductions are confirmed experimentally during clinical trials. Clinical studies were evaluated using ray-based diagnostic procedures, computed tomography, and patient interviewing using the Oswestry Disability Index and visual analogue scale.*

Results: *The calculations showed that in case of one-sided point load, the stresses arising in the dangerous section of screws-rods from that load can reach 60 – 70% of the total stresses in the device nodes.*

During clinical testing it was established that external apparatus correction leads to normalization of anatomical relationships in the area of damaged segments, normalization of the spinal column axis, and reduction of pain; it does not preclude the use of dorsal internal puncture fixation.

Conclusions: *It is advisable to load the structural element of the external spinal fixation device in a skew-symmetric pattern, applying distraction and compression forces to the transverse plate on both sides along parallel straight lines in opposite directions.*

Apparatus external fixation makes it possible to perform a complete correction of rigid deformations without releasing the supporting structures, to control the level of neurological dis-orders, to simplify the technique of internal fixation operations, to use the minimally invasive procedure for the installation of the internal pedicle fixator.

Key-words: Rigid Deformation, Thoracic Spine, Lumbar Spine, Deformation Correction, Dynamic Correction, External Fixation, Pedicle Fixator, Calculation of Stresses, Stress Load, Elements of the Fixator.

Key points:

- The authors defined the rates of the stresses arising in the external fixation device, optimized the construction of the device for the correction of spinal deformations, and determined the clinical effect of apparatus correction of spinal deformation.
- In the case of a long-standing spinal injury, provided there is no bone blocking of the verte-bral segments, external pedicle fixation at the level of the thoracic and lumbar spine enables to discretely eliminate kyphotic deformity and traumatic spondylolisthesis, as well as to restore the normal height of the compressed vertebra and intervertebral discs.
- The technology of surgical intervention and perioperative period management comply with the rules and principles of external osteosynthesis.

1. Introduction

Correction of vertebral column deformations is a prerequisite for the relief of pathological symptoms in the aftermath of injuries, even after previous surgical interventions.[1, 2, 3]

There are methods to correct rigid and marked deformations of the thoracic and lumbar spine, they include multi-level vertebrotomies. Such surgeries are traumatic and technically diffi-cult.[4, 5, 6, 7]

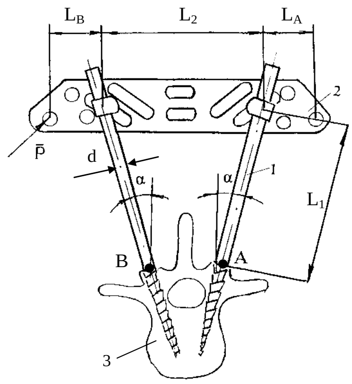
The method of controlled external pedicle fixation seems to be more attractive for accomplishing correction in case of these pathologies.[8, 9, 10, 11, 12, 13.]

2. Materials and Methods

In the process of spinal deformation correction, the screws-rods of the external spinal fixation device are exposed to the greatest stress at the point of their embedding in the vertebrae. An increase in the diameter of the screws-rods is limited by the strength characteristics of the vertebrae themselves.[10] The control forces in distraction rods,[12] which are necessary for correction, can cause a limiting state in the material of the screws-rods. In calculating and using an apparatus for external spinal fixation, the consideration of stresses in the embedding of rods-screws is of paramount importance.

Compressive or tensile forces *P* (Figure 1) are created in distraction rods to turn individual vertebrae in the required direction, which lead to stresses in the rods-screws. The greatest stress in the dangerous section causes an asymmetrical one-sided force *P* that acts on the transverse plate from the distraction rod (Figure 1).

Figure 1 - The Scheme of the Structural Element of the External Spinal Fixation Device: 1 – Screw-Rod; 2 – Transverse Plate; 3– Vertebra (L_1 = 0.06 m, L_2 = 0.10 m, L_A = 0.032 m, L_B = 0.032 m, d= 0.004 m)

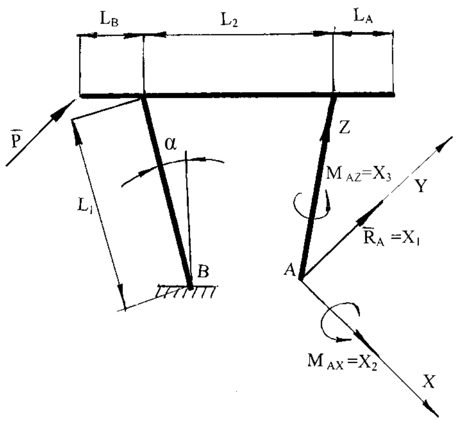


To determine the stresses in the embedding, let us consider internal force factors arising in the dangerous section of screws-rods screwed into the vertebra and interconnected by a plate (Figure 1). Force *P* is directed perpendicular to plate 2.

The structural element (Figure 1) of the external spinal fixation device is a statically indeterminate structure. To disclose the static indeterminacy and define the internal force factors arising in the cross sections of the structural element parts, let us use the method of forces.[14]

Let us take the scheme without any ties at point A (Figure 2) as a basic structure freed from additional ties.

Figure 2 - The Basic Structure Used in the Calculation by the Method of Forces



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The action of the rejected embedding on the screw-rod at point A is replaced with the force $R_A = X_1$ and the moments: $M_{AX} = X_2$, $M_{AZ} = X_3$. The canonical equations for the system under consideration take the following form:

$$\delta_{11} \cdot X_1 + \delta_{12} \cdot X_2 + \delta_{13} \cdot X_3 = -\Delta_{1p}$$

$$\delta_{21} \cdot X_1 + \delta_{22} \cdot X_2 + \delta_{23} \cdot X_3 = -\Delta_{2p}$$

$$\delta_{31} \cdot X_1 + \delta_{32} \cdot X_2 + \delta_{33} \cdot X_3 = -\Delta_{3p}. \quad (1)$$

The chosen basic structure of the force method and the calculation procedure for this method[1] allowed making epures of bending and torsional moments from the action of the external force *P*, unit force and unit moments. After multiplying the plotted epures and determining the canonical coefficients δ therefrom, the following values were obtained:

$\delta_{11} = 4.427 \cdot 10^{-5}$; $\delta_{12} = 1.879 \cdot 10^{-4}$; $\delta_{13} = 5.754 \cdot 10^{-4}$:

$\Delta_{1p} = -2.33 \cdot 10^{-3}$; $\delta_{22} = 0.02$; $\delta_{23} = -3.739 \cdot 10^{-3}$;

$\Delta_{2p} = 0.029$; $\delta_{33} = 6.981 \cdot 10^{-3}$; $\Delta_{3p} = -0.046$.

These calculations assumed that $\delta_{ij} = \delta_{ji}$. After substituting the obtained values into the equations of the system (1), we obtain the following system of linear equations:

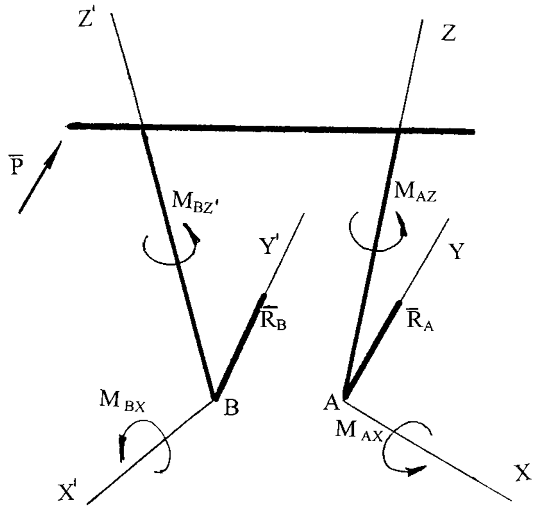
$$4.427 \cdot 10^{-5} \cdot X_1 + 1.879 \cdot 10^{-4} \cdot X_2 + 5.754 \cdot 10^{-4} \cdot X_3 = 2.330 \cdot 10^{-3}$$

$$1.879 \cdot 10^{-4} \cdot X_1 + 0.02 \cdot X_2 + 3.739 \cdot 10^{-3} \cdot X_3 = 2.90 \cdot 10^{-2}$$

$$5.754 \cdot 10^{-4} \cdot X_1 - 3.739 \cdot 10^{-3} \cdot X_2 + 6.981 \cdot 10^{-3} \cdot X_3 = -4.60 \cdot 10^{-2} \quad (2)$$

The solution of this system of equations provides the following values of the unknown parameters: $X_1 = 79.643$; $X_2 = -2.439$; $X_3 = -1.283$. This means that the internal force factors in the section passing through point *A* take the following values: $R_A = 79.643$ N; $M_{AX} = -2.439$ N·m; $M_{AZ} = -1.283$ N·m. To determine the supporting force at point *B*, we mentally discard the tie in the embedment and replace its action by the screw-rod reactions R_B, M_{BX}, M_{BZ} (Figure 3).

Figure 3 - The Scheme of Forces to Determine the Reaction at Point B



Then we make the equilibrium conditions in projections on the axis $X'YZ'$

$$\sum F_{ky} = 0;\ R_A + R_B + P = 0; \qquad (3)$$

$$\sum m_{Z'} \cdot (F_k) = 0;$$

$$-M_{AX} \cdot \sin 2\alpha + R_A \cdot (L_2 - 2 \cdot L_1 \cdot \sin\alpha) + M_{AZ} \cdot \cos 2\alpha - P \cdot L_B \cdot \cos\alpha + M_{BZ'} = 0; \quad (4)$$

$$\sum m_{X'} \cdot F_k = 0;$$

$$-M_{AX} \cdot \cos 2\alpha - R_A \cdot (L_2 - 2 \cdot L_1 \cdot \sin\alpha) \cdot \sin\alpha - M_{AZ} \cdot \sin 2\alpha + P \cdot (L_B \cdot \sin\alpha + L_1) + M_{BX'} = 0 \quad (5)$$

From the equation (3) we obtain the force R_B= -279.643 N; from the equation (4) – the moment value M_{BZ}= - 1.252 N·m, from the equation (5) – the moment value $M_{BX'}$= 3.987 N·m.

According to the fourth strength theory,[1] the stress at point *B* is

$$\sigma_B = \frac{\sqrt{M_{BX}^2 + M_{BZ}^2}}{W_{1X}} = 1.97 \cdot 10 N/m^2 \quad (6)$$

Where W_{1X} is the axial moment of resistance when bending the screw-rod. $W_{1X} \approx 0.1 \cdot d^3$.

The stress at point *A* is:

$$\sigma_A = \frac{\sqrt{M_{AX}^2 + M_{AZ}^2}}{W_{1X}} = 1.3 \cdot 10^8 N/m^2. (7)$$

The dependence of stressesσfrom loadPin dangerous sections (at $\alpha = 28^\circ$)is given in Table 1.

Table 1 - The Dependence of Stresses σ from Load P in Dangerous Sections (at α = 28°)

P, H	σ_B, Pa	σ_A, Pa	$\sigma_A/(\sigma_A + \sigma_B)$
60	$1.999 \cdot 10^8$	$1.083 \cdot 10^8$	0.351
100	$1.978 \cdot 10^8$	$1.101 \cdot 10^8$	0.358
140	$1.967 \cdot 10^8$	$1.157 \cdot 10^8$	0.370
190	$1.968 \cdot 10^8$	$1.272 \cdot 10^8$	0.393

One-sided loading of the structural element of the external spinal fixation device leads to uneven redistribution of stresses in the embedment of the screws-rods in the vertebra. The indicated calculations showed that for the considered scheme (Figure 1), the stresses arising in the dangerous section of the screws-rods from the applied load (point *B*) reach 60–70% of the total stresses in the embedding. In this connection, it is more expedient to load the structural element of the external spinal fixation device according to a skew-symmetric pattern – to apply forces *P* to the transverse plate (Figure 1) on both sides along parallel straight lines in opposite directions.

The study takes into consideration the treatment results of 7 patients aged from 20 to 45 years, with the consequences of a fracture (type A) in thoracic (Th 12, 2 patients) and lumbar (L1-2, 5 patients) spine. The majority of patients in the group were men (5 patients) with varying degrees of neurologic deficit. The patients were operated on using an external correction and fixation device in the period from 3 to 12 years after injuries or previously conducted decompression-stabilization surgeries. Their examinations showed that bone blocks of the anterior or posterior support structures at the level of the damages were absent.

Evaluation of the orthopedic result was carried out by X-ray spondilography (Cobb angle, determination of sagittal balance) and computed tomography (CT). The patients with symptoms of spinal cord injury were examined by magnetic resonance imaging (MRI) scanners in order to determine the patency of cerebrospinal fluid spaces. The Oswestry Disability Index (ODI) was used to determine the functional result. The level of pain syndrome was taken into account on a visual analogue scale (VAS).

3. Results and Discussion

The radiological results of the correction were investigated depending on the type of the damage preceding the onset of deformation. In the group of patients with consequences of type A damage (n = 7), the average degree of kyphotic deformity was 27.4° ± 8.2°. In the postoperative period, these values decreased to 5.0° ± 3.1° on an average, with a loss of correction in the long-term period up to 2° ± 1.5°.

In the study of global sagittal balance, it was noted that the plumb line deviation relatively the neutral point of the sacrum in the pre-operative period was +4 cm, in the postoperative period - ±2.5 cm.

The treatment gave good results in all patients: the functional disability index ODI changed, on an average, from c 50 ± 6.1 to 20.5 ± 4.3. The VAS measurements also improved (from the average 7.4 ± 1.1 before the operation to 2.3 ± 0.1 points after the operation).

There were no episodes related to fracture and dismantling of the external device.

Clinical Example

Patient K., a man, 20 years old, was admitted to the hospital with the diagnosis "Spinal cord injury, late phase", "Chronic lumbodynia syndrome", "Severe kyphotic spinal deformity at the L3 vertebra level against the background of the collapse of the L3 body and the presence of an interbody implant made of porous titanium nickelide".

His anamnesis included catatrauma 3 years prior the admittance, the diagnosis was "Comminuted (type A3) fracture of L3, compression of the spinal cord". The emergency procedures were: decompressive laminectomy at the level of L3, the elimination of spinal stenosis, pedicle fixation at the level of L2-4 vertebrae, monosegmental interbody spinal fusion of L2-3 with an implant of porous nickel titanium (lateral access). 18 months after the operation, the pedicle fixator was removed due to screw break and migration of the structure (Figure 4).

At the time of admission to the hospital, there was absence of an interbody bone-metal block and presence of instability syndrome at the level of the injury. During the first stage of treatment (5 days long), doctors used an external fixation device and restored the axis of the spinal column and the height of the compressed vertebra (Figure 5). The second stage of treatment included: a) installation of an interbody lift-cage in the area of the defect of the vertebral body and adjacent disks and b) conversion of the external fixation to an internal version of pedicle osteosynthesis using the trans-muscular screw installation technique (Figure 6a and 6b).

Figure 4 - Computed Tomography Scan Before the Surgery

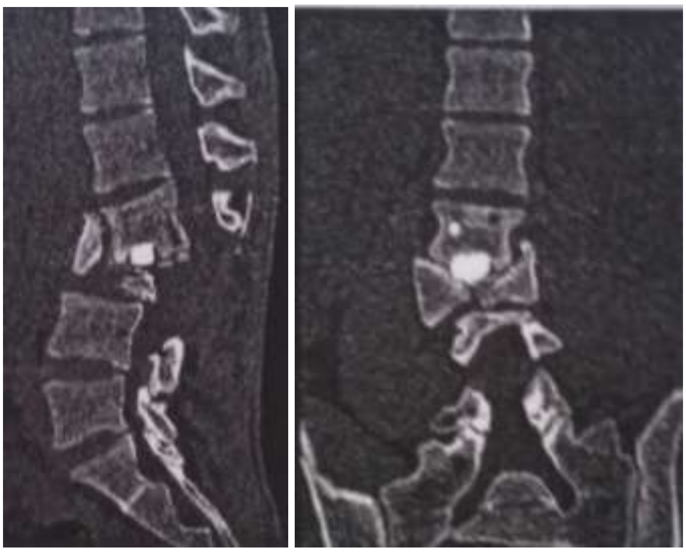


Figure 5 - The Result of the Apparatus Correction of the Deformation

Figure 6 - The Result of Internal Fixation after Correction by an External Device –
a) X-ray Spondylography, Lateral Projection, b) X-ray Spondlography, Direct Projection

4. Conclusions

An analysis of the calculation of stresses in the elements of the device for external correction of deformations and the results of treatment of inveterate post-traumatic spinal deformities allows drawing the following conclusions.

1. It is more expedient to load the structural element of the external spinal fixation device according to a skew-symmetric scheme, applying distraction and compression forces to the transverse plate on both sides along parallel straight lines in opposite directions.
2. Apparatus external correction is a promising and effective method for the treatment of posttraumatic deformations of the spinal column. In the absence of bone intervertebral blocking, the external mechanical action on the vertebrae with an external fixation device allows eliminating all components of the deformation without resorting to mobilizing operations.
3. It is possible to replace external fixation with internal fixation, also with the use of transcutaneous or transmuscular techniques.

Conflicts of Interest and Source of Funding

The authors report no conflict of interests concerning the materials or methods used in this study or the findings specified in this paper. No funds were received in support of this work. The manuscript submitted does not contain information about medical device(s)/drug(s).

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