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MATHEMATICAL JUSTIFICATION OF THE CHOICE OF RODS FOR EXTERNAL FIXATION DEVICES FOR POLYSTRUCTURAL PELVIC INJURIES

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Abstract.

**Aim:** In order to fulfill the purpose of biomechanical substantiation for extrafocal pelvic osteosynthesis in osteoporosis we studied the stress-strain state (SSS) of LEG under conditions of external fixation by apparatuses with cylindrical and conical rods.

**Material and methods:** Studies of the stress-strain state of the lower extremity belt by the finite element method were carried out under conditions of external fixation by devices with cylindrical and conical rods. In the finite element method, the approximate solution is constructed as a superposition of approximating functions. At the first stage of solving the problem, the object is divided into areas of a simpler form - finite elements whose geometric dimensions are significantly smaller than the dimensions of the entire biomechanical system. Modern software systems generate finite elements of the grid automatically using elements with triangular faces in most cases. At the junctions of the elements (nodal points), the real stress field is replaced by the action of forces and movements. The type of finite elements is characterized by the number of nodes and the degree of approximation of unknowns within the domain and largely determines the accuracy of the resulting solution in the finite element method. Various types of biological tissues were taken into account in the conducted studies: compact and spongy bone, cartilage tissue, intervertebral disc, ligaments. In this study, the material was considered homogeneous and isotropic. The main load is body weight. In the calculation, the body weight was taken to be equal to 700 N. The geometric model was built on the basis of tomographic sections of the pelvis carried out through 0.5 – 1 cm for irregular zones. A pelvis with rotationally unstable (type B1 according to AO classification) damage after osteosynthesis by an external fixation device was modeled in the variants of using cylindrical and conical rods. Mises stresses were used to assess the stress state. The resulting model consists of 75,845 finite elements and has 132253 nodes. The construction of the geometric model was carried out in the SolidWorks program. VAT calculations and analysis were carried out in the ANSYS program.

**Results and Discussion:** In the first variant of the study of the pelvic model with normal bone tissue and cylindrical rods, the calculation results showed that with a single support standing (support on the left limb), the supporting side with pronounced stress concentration zones in the sacroiliac joint, the place of entry of the rod into the bone and in the area of reducing the thickness of the iliac wing is more tense. Two stress concentration zones are observed along the passage of the rod. The most intense is the area of the screw entry into the bone (18.5 MPa). There is also an area of increased stress at the site of a decrease in the thickness of the iliac wing (8.1 MPa), where the rod passes closest to the cortical layers. The calculation of the model using conical shaped rods showed that the nature of the VAT distribution for the model as a whole has not changed, and the stress state level has decreased. So, at the point of entry of the screw into the bone, the value of the Mises stresses is 16.4 MPa, and at the point of reduction of the thickness of the iliac bone – 6.3 MPa. It is worth noting that the area with an increased stress state along the passage of a conical rod is smaller than for a cylindrical one. In the second variant of the study for a pelvic model with osteoporotic bone tissue, a comparative analysis of VAT when using cylindrical rods of an external fixation device showed that the general nature of the distribution of stresses and deformations for the model as a whole did not change, but the VAT level increased. At the point where the screws enter the bone, it is 28.4 MPa, at the point where the thickness of the iliac wing decreases – 9.1 MPa. The level of tension has also increased throughout the "rod-bone" contact. A comparative analysis of VAT for the variant of conical rods of the external fixation apparatus and osteoporotic bone tissue showed that the general nature of the VAT distribution for the model as a whole has not changed, and the level of stress state has increased as well as in the model with cylindrical screws. At the point where the screws enter the bone, it is 26.5 MPa. At the site of the reduction in the thickness of the iliac wing, the stress level is 7 MPa.

**Conclusions:** The use of conical shaped rods in the external fixation device of the pelvis makes it possible to reduce the level of stress-strain state both in the area of the entry of screws into the bone and in the area of the thinnest part of the iliac wing. For external osteosynthesis of the pelvis in polystructural injuries, lowering the stress state when using conical rods plays an important role, since the strength characteristics of osteoporotic bone tissue are significantly lower than those of normal. Thus, the use of conical rods in external pelvic fixation devices improves the strength characteristics of the "pelvis – rod" system, which makes it possible to recommend their testing in clinical practice.

**Key words.** Osteoporosis, pelvis, external fixation, mathematical justification, cylindrical or conical rod.

**Introduction.**

Immobilization of the lower extremity girdle (LEG) is an essential prerequisite for an effective treatment of polystructural pelvic injuries (PPI). The selection criteria for the method of stabilization of LEG should be reliability of fixation, speed, and ease of use, since the process of operation should not aggravate both the general condition of the injured person and the course of the traumatic disease. Immobilization of the lower extremity girdle in the acute phase of the injury these requirements to the greatest extent are met by the method of extrafocal osteosynthesis, which has become widespread with polystructural pelvic injuries PPI [1-3]. But the fixing
properties of the rod devices depend on the risk of violation of the structural and functional state of the bone tissue since the effect of fractures on its mineral density is known [4-10].

In addition, injuries of organs of the digestive, endocrine, and genitourinary systems, located in the pelvic cavity, cannot but affect the risk of developing osteopenia and osteoporosis. An early development of osteoporotic changes in the iliac ilae, characteristic of PPI, exerts a negative effect on the strength characteristics of the pelvis-rod system [8,11-13].

The aim of the study was the biomechanical substantiation of extra-focal pelvic osteosynthesis in osteoporosis.

Materials and Methods.

The stress-strain state (SSS) of the lower extremity belt was studied by the finite element method (FEM) under conditions of external fixation by devices with cylindrical and conical rods. In FEM, an approximate solution is constructed in the form of a superposition of approximating functions. For solving the above problem, at the first stage the object is divided into areas of a simpler form, finite elements (FE), whose geometric dimensions are much smaller than those of the entire biomechanical system [14].

Modern software systems generate FE cells automatically using in most cases elements with triangular faces. At junctions of the elements (nodal points) the real stress field is replaced by the action of forces and displacements.

The type of FE is characterized by the number of nodes and the degree of approximation of the unknowns within the region and largely determines the accuracy of the obtained FEM solution. The elements used in building the calculation model are presented in Figure 1.

The studies took into account different types of biological tissues: compact and cancellous bone, cartilage tissue, intervertebral disc, ligaments. In this study, the material was considered to be homogeneous and isotropic. The elastic modulus (Young’s modulus E) and Poisson’s ratio ν for different materials are summarized in Table 1.

The body weight is the main load. In the calculation, the body weight was taken equal to 700 N. The values of the resulting forces for the pelvis were taken in accordance with the data given in [15,16].

The geometric model was built on the basis of tomographic sections of the pelvis, drawn through 0.5-1 cm for irregular zones. The pelvis was modelled with a rotationally unstable injury (type B1 according to AO classification) after osteosynthesis with an external fixation device in versions of using cylindrical and conical rods (Figure 2).

In order to estimate SSS, von Mises stresses were used. The obtained FE model (Figure 3) consisted of 75845 FE and had 132253 nodes. The geometric model was built in the SolidWorks program. The calculations and analysis of SSS were carried out in the ANSYS program.

Results and Discussion.

In the first version of the study of the pelvic model with the normal bone tissue and cylindrical rods, the calculation results showed (Figure 4) that with a single-limb support (the left limb support) more stress was observed on the supporting side with pronounced zones of stress concentration in the region of the sacroiliac joint, at the site of entry of the rod into the bone and in the area of a reduced thickness of the iliac ala.

Table 1. Mechanical characteristics of biological tissues.

<table>
<thead>
<tr>
<th>Tissue</th>
<th>E (MPa)</th>
<th>ν</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compact bone</td>
<td>18350</td>
<td>0.3</td>
</tr>
<tr>
<td>Osteoporotic compact bone</td>
<td>1500</td>
<td>0.3</td>
</tr>
<tr>
<td>Cancellous bone</td>
<td>330</td>
<td>0.3</td>
</tr>
<tr>
<td>Osteoporotic cancellous bone</td>
<td>150</td>
<td>0.3</td>
</tr>
<tr>
<td>Cartilage</td>
<td>10.5</td>
<td>0.49</td>
</tr>
<tr>
<td>Intervertebral disc</td>
<td>4.2</td>
<td>0.45</td>
</tr>
<tr>
<td>Ligaments</td>
<td>50</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Along the passage of the rod (Figure 5), two stress concentration zones were observed. The most intense was the area where the screw enters the bone (18.5 MPa). An area of increased stress was also observed at the site of reduced thickness of the iliac ala (8.1 MPa), where the rod passed most closely to the cortical layers.

The calculation of the model using conical rods showed (Figure 6) that the nature of SSS distribution for the model
Figure 4. Von Mises stress in the calculation model: a) front view; b) left view.

Figure 5. Zones of stress concentration along the passage of a cylindrical rod.
Figure 6. Mises stress in the calculation model: a) front view; b) left view.

Figure 7. An area with an increased SSS of the ilium along the passage of a conical rod.
as a whole had not changed, and the level of stress state had decreased. Thus, in the area where the screw entered the bone, the von Mises stress was 16.4 MPa, it being 6.3 MPa in the area of reduced thickness of the ilium. It should be noted that the region with an increased stress state along the passage of a conical rod was smaller than for a cylindrical one (Figure 7).

In the second version of the study, for a model of the pelvis with the osteoporotic bone tissue, a comparative analysis of SSS using cylindrical rods of an external fixation device showed that the general distribution of stress and strain for the model as a whole did not change, but the level of SSS increased (Figure 8a-d).

It was 28.4 MPa in the area of entry of the screws into the bone and 9.1 MPa at the site of reduced thickness of the iliac wing. The level of the stress state also increased throughout the entire “rod-bone” contact (Figure 8e,f). A comparative analysis of SSS for the version with conical rods of an external fixation device and the osteoporotic bone tissue showed that the general character of SSS distribution for the model as a whole had not changed, but the level of stress state had increased as well as in the model with cylindrical screws (Figure 9). In the area where the screws entered the bone, it was 26.5 MPa. In the area of reduced thickness of the iliac ala the level of stress was 7 MPa.

Figure 10 shows a comparison of SSS in the iliac section for cylindrical and conical rods with the normal and osteoporotic bone tissue.

**Conclusion.**

The mathematical model, taking into account osteoporosis, differs from the model with normal bone tissue by changing the physical properties of materials (bone tissue), namely, by other values of the elastic modulus E (Young's modulus). This parameter, under unchanged other conditions (the geometry of the model and its loading), leads to a change in the stress state. For osteoporotic bone tissue, destruction occurs when lower stresses are reached (120 MPa - normal cortical bone tissue, 75 MPa - osteoporotic bone tissue, and for normal spongy tissue, the tensile strength is 6.6 MPa and 3.3 MPa for osteoporotic). Those, the study of models with altered bone properties
Figure 9. SSS models of the pelvis with the osteoporotic bone tissue using conical rods of an external fixation device.

Figure 10. Comparison of SSS in the iliac section for cylindrical and conical rods in the normal and osteoporotic bone tissue.
(osteoporosis) allows an assessment of whether bone tissue destruction will occur, especially in areas of stress concentration (such as the nail-bone contact area). The use of conical rods in a device for external fixation of the pelvis makes it possible to reduce the level of SSS both in the area of entry of screws into the bone and in the area of the thinnest part of the iliac ala. For extrafocal pelvic osteosynthesis during polystructure injuries a decrease in the stress state, when conical rods are used, plays an important role since strength characteristics of the osteoporotic bone tissue are significantly lower versus the normal one.

The study showed that stress concentration zones are located at the point where the rods enter the bone and at the place where the rods pass close to the surface of the ilium. The resulting stresses are far from the tensile strength of the metal (the rods will not break), however, destruction may occur in the bone tissue, especially osteoporotic (with a lower tensile strength). The conical shape of the rods forms a smaller channel in the bone tissue, which reduces the stress state in the bone tissue, especially in the area close to the surface of the ilium.

Thus, the use of conical rods in devices for external fixation of the pelvis improves strength characteristics of the “pelvis-rod” system, which makes it possible to recommend their approbation in clinical practice.

REFERENCES
методе конечных элементов. В проведенных исследованиях учитывались различные виды биологических тканей: компактная и губчатая кость, хрящевая ткань, межпозвоночный диск, связки. В данном исследовании материал считался однородным и изотропным. Основной нагрузкой является вес тела. В расчете вес тела брался равным 700 Н. Геометрическая модель строилась на основе томографических срезов таза, проведенных через 0,5 – 1 см для нерегулярных зон. Моделировался таз с ротационно-нестабильным (тип В1 по классификации АО) повреждением после остеосинтеза аппаратом внешней фиксации в вариантах использования стержней цилиндрической и конической формы. Для оценки напряженного состояния использовались напряжения Мизеса. Полученная модель состоит из 75845 конечных элементов и имеет 132253 узла. Построение геометрической модели проводились в программе SolidWorks. Расчеты и анализ НДС проводились в программе ANSYS.

Результаты и обсуждение. В первом варианте исследования модели таза с нормальной костной тканью и цилиндрическими стержнями результаты расчета показали, что при одноопорном стоянии (опора на левую конечность) более напряженной является опорная сторона с выраженными зонами концентрации напряжения в области крестцово-подвздошного сустава, места входа стержня в кость и в области уменьшения толщины крыла подвздошной кости. Вдоль прохождения стержня наблюдаются две зоны концентрации напряжений. Наиболее напряженной является область входа винта в кость (18,5 МПа). Также наблюдается область повышенного напряженного состояния в месте уменьшения толщины крыла подвздошной кости. Вдоль прохождения стержня наблюдаются две зоны концентрации напряжений. Наиболее напряженной является область входа винта в кость (18,5 МПа). Также наблюдается область повышенного напряженного состояния в месте уменьшения толщины крыла подвздошной кости (8,1 МПа), где стержень проходит наименее близко к костным слоям. Расчет модели с применением стержней конической формы показал, что характер распределения НДС для модели в целом не изменился, а уровень напряженного состояния понизился. Так в месте входа винта в кость величина напряжений Мизеса составляет 16,4 МПа, а в месте уменьшения толщины крыла подвздошной кости – 6,3 МПа.

Стоит отметить, что область с повышенным напряженным состоянием вдоль прохождения конического стержня меньше, чем для цилиндрического. Во втором варианте исследования для модели таза с остеопоротической костной тканью сравнительный анализ НДС при использовании цилиндрических стержней аппарата внешней фиксации показал, что общий характер распределения напряжений и деформаций для модели в целом не изменился, но уровень НДС повысился. В месте входа винтов в кость он составляет 28,4 МПа, в более уменьшенной толщине крыла подвздошной кости – 9,1 МПа. Уровень напряженного состояния повысился и на всем протяжении контакта «стержень-кость». Сравнительный анализ НДС для варианта конических стержней аппарата внешней фиксации и остеопоротической костной ткани показал, что общий характер распределения НДС для модели в целом не изменился, а уровень напряженного состояния также, как и в модели с цилиндрическими винтами повысился. В месте входа винтов в кость он составляет 26,5 МПа. В месте уменьшения толщины крыла подвздошной кости уровень напряженного состояния – 7 МПа.

Выводы. Использование стержней конической формы в аппарате внешней фиксации таза позволяет снизить уровень напряженно-деформированного состояния как в области входа винтов в кость, так и в зоне наиболее тонкой части крыла подвздошной кости. Для внешнего остеосинтеза таза при полиструктурных травмах понижение напряженного состояния при использовании стержней конической формы играет важную роль, так как прочностные характеристики остеопоротической костной ткани существенно ниже, чем у нормальной. Таким образом, применение конических стержней в аппаратах внешней фиксации таза улучшает прочностные характеристики системы «таз – стержень», что позволяет рекомендовать их апробацию в клинической практике.

Ключевые слова: остеопороз, таз, внешняя фиксация, математическое обоснование, цилиндрический или конический стержень.