Comparative analysis of the revision acetabular customized implant position by finite element modeling

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Abstract. The article contains a biomechanical assessment of the performance of a customized endoprosthesis of the hip joint. Finite-element models of the hip bone and the implant in the projected and actual positions are prepared. The article provides the results of the static structural analysis for a patient in the two-leg standing position in the post-operative period. The results are compared for various implant positions. As a recommendation, it is proposed to optimize the location and the number of screws for a more uniform stress distribution.

1. Introduction

The number of patients suffering from osteoarthritis constantly grows. From 10 to 40 people out of each 1,000 suffer from osteoarthritis of the large joints of the lower limbs [1]. During primary surgeries on hip joint osteoarthritis, a standard endoprosthesis of a specific type-size and form is typically implanted. However, 20% of patients require secondary revision surgeries [2]. It should be pointed out that every new surgery on the same patient is complicated by an increasing bone deficit.

When a revision implant surgery is carried out on a highly deficient bone, customized implants have to be used. One of the widely used designs is a hemispherical cup with multiple holes and additional screw fixation through the flanges adjacent to the intact bone surface. One study [3] assesses the efficiency of customized three-flange acetabular elements designed with computer modelling and manufactured by additive technologies.

2. Finite-element models

The geometric data was obtained from the surface models of the implant and screws, as well as a CT-based pelvic bones reconstruction for a patient treated at the Federal State State-Funded Institution “Russian Scientific Research Institute of Traumatology and Orthopaedics named after R R Vreden” of

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the Ministry of Health of the Russian Federation. The analysed implant is a customized endoprosthesis of the hip joint replacing a standard endoprosthesis.

The structure of the hip element of the endoprosthesis consists of a stem inserted in the pelvic bone, of a hemispherical cup and a support flange attached to the ilium. The external surface of the endoprosthesis in the bone contact area is a porous structure which improves osteointegration. The implant is fixed by regular surgical screws attaching the system to the hip bone.

In the original state, the reconstruction of the pelvic bones cannot be divided into finite elements because of the multiple mesh imperfections. Therefore, the geometric model should be simplified and its defects should be eliminated without compromising the geometrical data. When preparing the finite-element models of the pelvis, it has been taken into account that pelvic bones are composed of an outer layer of dense tissue of uniform thickness of 1 mm, filled with spongy tissue inside. The resulting finite-element models are presented in figure 1 and 2.

![Figure 1. Finite element model of the system in the projected position](image1.png)

![Figure 2. Finite element model of the system in the actual position](image2.png)

3. **Characteristics of the materials**
The physical and mechanical qualities provided in table 1 are those that are most frequently cited in studies concerning similar situations [4, 5]. The materials were analysed as solid materials with isotropic behaviour, ignoring the microstructure of the bone tissue and the porous structure of titanium.
Table 1. Physical and mechanical properties of the materials

| Material         | Elasticity module, MPa | Poisson’s ratio | Density, kg/mm$^3$ | Maximal stress, MPa |
|------------------|------------------------|-----------------|--------------------|---------------------|
| Titanium alloy   | 800                    |                 |                    |                     |
| Cortical tissue  | 160                    |                 |                    |                     |
| Spongy tissue    | 10                     |                 |                    |                     |
| Polyethylene     | 20                     |                 |                    |                     |

The experience of use of titanium alloy has proved that this material provides a sufficient biological reaction when used appropriately. Implant inserts are often made of polyethylene with an ultrahigh molecular mass.

4. Boundary conditions
The biomechanical structure is subjected to the static forces of the tightened screws and the weight of the patient. The gravity, which is equal to the patient’s weight, may be applied at the centre of gravity located in the plane of symmetry of the human body. The static balance equations prove that in the two-leg standing position the gravity is balanced by reaction of the support equal to half of the patient’s weight. The most convenient option is applying the load at the end zone of the simplified hip bone model, while the upper part of the sacrum is fixed. The free ends of the hips are fixed with a sliding hinge on the longitudinal axis (Figure 3).

Figure 3. Problem statement

The load is applied in two steps. First, the tightening of the screws is done; it produces the forces that pull the implant and the bone together. Second, the free ends of the leg models are subjected to forces of 440N, equivalent to 88 kg; this force is directed along the hips; the screw tightening is maintained as at the previous step.
5. **Analysis of the stress-strength state of the system in the projected position**

At both steps of the process, maximum stress in the model takes place in the screws at the points of contact with the bone. Increased stress in the screws may be caused by computational effects, as the contact between the bone and the implant surface was made bonded, without any sliding allowed. Higher stresses are located at the screw hole edges of the prosthesis and at the junction of the prosthesis cup and the support flange. However, these effects do not affect the structural integrity of the assembly.

In the upper damaged (right) part of the pelvic bone (Figure 5) the highest equivalent stress is observed at the hole edges. The stress reduces sharply when moving further from the holes. At the second step of calculation, the increase in the bone stress does not exceed 30%; the factor of safety is sufficiently high.

![Figure 4. Stress in the cortical layer of the upper part of the pelvic bone after the tightening of the screws for implant projected position](image)

![Figure 5. Stress in the cortical layer of the upper part of the pelvic bone in the two-leg standing condition for implant projected position](image)

In the cortical layer of the lower part of the pelvis bone (Figure 6) high stress takes place at the edges of the screw holes and at the border of the spongy layer near the resection area. Stress peaks take place locally in the narrow part of the bone.

The spongy tissue presents stress concentration in the same area. The maximum value of 22.82 MPa exceeds the allowable limit. The stress values may be overestimated due to the relatively coarse finite elements mesh in the area. However, even in this case, the values outside this region are still comparable with the allowed limits. This means that there is a high possibility of bone deterioration during the screw tightening.
6. Analysis of the stress-strength state of the system in the actual position

During the surgery operation, the endoprosthesis stem and two screws adopted a new position and got outside of the upper part of the pelvic bone (Figure 2). As a result, the stress distribution is observed on the edges of the screw holes and on the edge of the hole for the endoprosthesis stem. The maximum value of the stress (97.38 MPa) does not exceed the limit value for cortical layer. The spongy layer also has an acceptable safety factor.
In the cortical layer of the lower part of the pelvic bone, the overall stress state distribution is decreased in comparison with the stress state of the system in the projected position. The maximum stress (40 MPa and higher) are found in the finite elements of poor quality which have a heterogeneous thickness of the cortical layer.

![Figure 9. Stress in the cortical layer of the lower part of the pelvic bone in the two-leg standing condition for implant actual position](image)

7. Conclusions
The results of the analysis are presented in the tables 2 and 3 for a comparison of the values of maximum strength and safety factor in the two stages of calculation for different positions of the endoprosthesis.

When the implant position changes, the stress is redistributed. There is an increase in maximum stresses by 26% in the cortical layer of the upper part of the pelvic bone after tightening the screws. At the stage of two-leg standing position the maximum stress more than doubled. It is justified by a numerical error in single finite elements. The value of the stresses is increased on the edge of the hole of the endoprosthesis stem in the spongy layer.

The increase in maximum stresses by 30% was noted at the second stage of calculation in the cortical layer of the lower part of the bone. There is a sufficient safety factor.

There are no drastic changes in the overall stress state. A strength condition for the pelvic bones and implant components is achieved.

| Table 2. Maximum stress (σ) and factor of safety coefficients (n) of the assembly components in the projected position |
|---------------------------------------------------------------|
| Assembly components                      | Screw tightening step | Two-leg standing step |
|--------------------------------------------|------------------------|------------------------|
| Upper part of the pelvic bone              | σ = 30.71 MPa          | σ = 42.1 MPa           |
| (cortical layer)                           | n = 5.21               | n = 3.8                |
| Upper part of the pelvic bone              | σ = 3.79 MPa           | σ = 3.87 MPa           |
| (spongy layer)                             | n = 2.64               | n = 2.58               |
| Lower part of the pelvic bone              | σ = 37.27 MPa          | σ = 48.27 MPa          |
| (cortical layer)                           | n = 4.3                | n = 3.74               |
| Lower part of the pelvic bone              | σ = 22.26 MPa          | σ = 22.82 MPa          |
| (spongy layer)                             |                         |                        |
| Endoprosthesis                            | σ = 93.4 MPa           | σ = 388 MPa            |
|                                            | n = 8.57               | n = 2.06               |
The article examines the important problem of biomechanics of the reconstructed pelvic with the an individual implant.

During the study, the finite element models of the “skeleton – hip joint endoprosthesis” system were developed. A theoretical assessment of the strength of the pelvic bones and the individual endoprosthesis was carried out. It was shown that the cortical bone and the implant have sufficient factors of safety. The elevated stresses in the spongy tissue are not considered destructive because the ability of the bone to regenerate over time due to mechanical stimulation.

The results of the development of mathematical models and the assessment of the stress-strength states of the system in the projected and actual positions have been introduced in medical practice.

### References

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### Table 3. Maximum stress (σ) and factor of safety coefficients (n) of the assembly components in the actual position

| Assembly components | Screw tightening step | Two-leg standing step |
|---------------------|-----------------------|-----------------------|
| Upper part of the pelvic bone (cortical layer) | $\sigma = 38.33 \text{ MPa}$ | $\sigma = 97.38 \text{ MPa}$ |
| | $n = 4.17$ | $n = 1.64$ |
| Upper part of the pelvic bone (spongy layer) | $\sigma = 2.84 \text{ MPa}$ | $\sigma = 6.94 \text{ MPa}$ |
| | $n = 3.52$ | $n = 1.44$ |
| Lower part of the pelvic bone (cortical layer) | $\sigma = 45.57 \text{ MPa}$ | $\sigma = 63.73 \text{ MPa}$ |
| | $n = 3.51$ | $n = 2.51$ |
| Lower part of the pelvic bone (spongy layer) | $\sigma = 4.03 \text{ MPa}$ | $\sigma = 4.37 \text{ MPa}$ |
| | $n = 2.48$ | $n = 2.29$ |
| Endoprosthesis | $\sigma = 97.92 \text{ MPa}$ | $\sigma = 232.5 \text{ MPa}$ |
| | $n = 8.17$ | $n = 3.44$ |