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A BIOMETROLOGICAL PROCEDURE PRECEEDING THE RESURFACING

Anna M. Ryniewicz[1], **Tomasz Madej**[1], **Andrzej Ryniewicz**[2], **Łukasz Bojko**[1]

1) AGH University of Science and Technology, Faculty of Mechanical Engineering and Robotics, Al. Mickiewicz 30, 30-059 Kraków, Poland (✉ anna@ryniewicz.pl, +48 12 617 3065, tmadej@agh.edu.pl, lbojko@agh.edu.pl)

2) Cracow University of Technology, Faculty of Mechanical, Al. Jana Pawła II 37, 31-864 Kraków, Poland (andrzej@ryniewicz.pl)

Abstract

This paper presents a preoperative hip reconstruction method with diagnosed osteoarthritis using *Durom Hip Resurfacing System* (DHRS). The method is based on selection and application of the resurfacing to the pelvis reconstructed on the basis of computed tomography. Quality and geometrical parameters of distinguished tissues have a fundamental significance for locating and positioning the acetabular and femoral components. The application precedes the measurements of anatomical structures on a complex numerical model. The developed procedure enables functional selection of endo-prosthesis and its positioning in such a way that it secures geometric parameters within the bone bed and the depth , inclination angles and ante-version of the acetabular component, the neck-shaft angle and ante-torsion angle of the neck of the femoral bone, and reconstruction of the biomechanical axis of the limb and the physiological point of rotation in the implanted joint. Proper biomechanics of the bone-joint complex of the lower limb is determined by correlation of anatomical-geometrical parameters of the acetabular component and parameters of the femoral bone.

Keywords: cox-arthrosis, resurfacing, modelling, bio-metrology, computed tomography.

1. Introduction

Degenerative changes in the hip joint have differential etiology. The process starts with changes in the cartilage or subchondral layer of bone as a consequence of metabolism disturbance or improper biomechanical processes (instability of joint, excessive load, misalignment, injury). The changes deepen as the disease progresses. The total arthroplasty and hip resurfacing of hip joint are now the most frequently used methods of treatment of advanced degenerative changes [1–4]. It cannot be clearly said whether the hip resurfacing is better or worse than classic implants [1, 2, 5–7]. The resurfacing is limited by the necessity of placing the femoral component on a healthy, osteoporotically unchanged femur. The advantage of hip resurfacing consists in a smaller surgical intervention and increased range of motion, due to a large diameter of the femoral and acetabular components. The treatment procedure should ensure proper selection and fixing of the prosthesis components in a proper spatial arrangement, as well as recreating biomechanics of the joint. Minor errors of seating cause increased wear and decreased survival of the implant. These reasons have led the authors to develop a method which – before the resurfacing surgery – enables to use the diagnostic imaging procedures, as well as modelling and measurement of anatomical structures for functional selection of the prosthesis structure. Moreover, virtual reconstruction of the bone structures of hip belt may be the basis for their replication from polyamide on a 3D printer. On that basis one can establish step by step the medical procedure. In that way virtual information may be transferred to the operation room and in this stage in the conditions of complicated operations it is used to improve and shorten the time of surgical operation.

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The aim is to develop a method of bio-metrological analysis of the reconstructed hip complex and virtual application of resurfacing, selected and positioned on the basis of morphometric measurements of hip belt of an individual patient.

2. Material and methods of research

The material includes the clinical case of a patient (man, age 62 with diagnosed osteoarthritis of the left hip joint) with the recommendation for the resurfacing procedure. Preoperative procedure with the aim to exchange the articular surfaces is shown on the numerical model of the patient's hip belt which is spatially reconstructed, on the basis of *Computed Tomography* (CT).

Positioning of the acetabular and femoral components in the bone structures determines the conditions of using an artificial joint. Due to the existence of individual differences in the system of osteo-articular pelvic, before implantation of the hip joint, the fundamental issue is identification of the geometric-anatomical parameters which are present in the pelvis and femur.

The next step is choosing a construction of hip resurfacing arthroplasty from the base of implants approved for orthopedic applications taking into account the set parameters.

Selected constructions or a construction of the prosthesis are modelled in 3D. The final result of such procedures is selection and targeted bio-metrological application of positioning of the implant in the patient's pelvic bone and femur, in accordance with the defined anatomical and geometrical parameters and biomechanical conditions.

The stages of this method are shown in a scheme of procedures of selection and positioning of the hip resurfacing arthroplasty in the patient's anatomical structures (Fig. 1.).

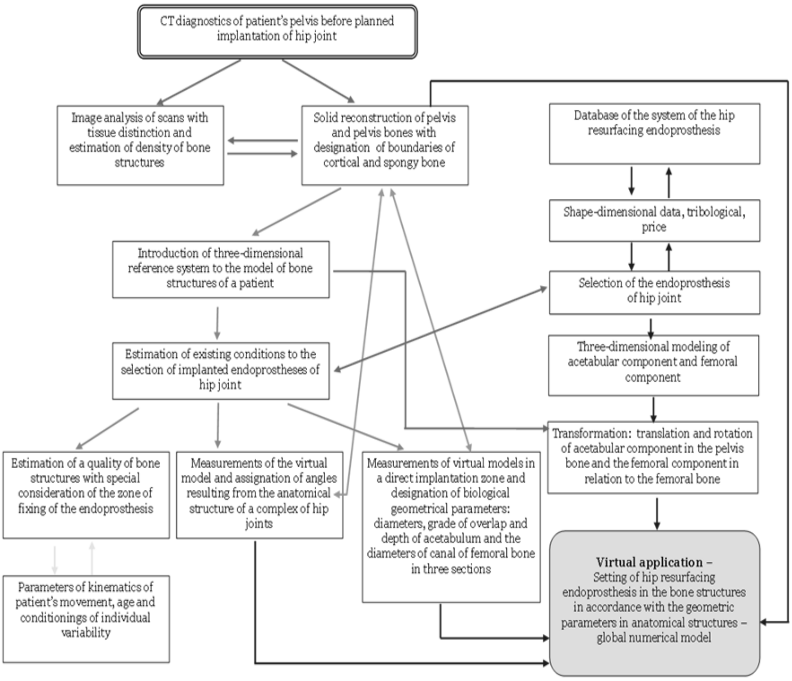

Fig. 1. A scheme of procedures of selection and positioning of the hip resurfacing prosthesis in the patient's anatomical structures.

2.1. Modelling and measurements of bone structures

The virtual representation of the osteo-articular system of hip belt was carried out on the basis of the spiral imaging technique performed on a 64-row Siemens Somatom Sensation camera in Cardiac Diagnostic Imaging Laboratories in John Paul II Hospital in Kraków for the smallest possible width of 0.4 mm scans and the greatest possible resolution in each scan (1 voxel – 0.4 mm x 0.21 mm x 0.21 mm). The scans were performed in the horizontal plane using the dicom standard. On the basis of imaging the accuracy of the mapping which assured proper quality of the numerical model was determined. The mapping made in Amira 3.1 software was exported to FEMAP NE/Nastran v.8.3 Modeler software introducing the basic reference system of planes: sagittal, frontal and horizontal ones. In the reconstruction the bone structures distinguishing between the cortical and cancellous bones were considered.

The developed method prefers using a relationship between the bone density and its strength properties. The patient's bone density is important for positioning and stabilization of the implant. In the diagnosed patient, after consultation with a radiologist and orthopaedist, the density of bone structures in the context of osteoporosis was estimated. Osteoporotic changes were excluded. The quality and geometrical parameters of patient's distinguished tissues had a fundamental significance for application and positioning of the acetabular and femoral components. The proper biomechanics of osteo-articular complex of the lower limb is determined by correlation of the anatomical and geometrical parameters of the acetabulum and the femoral bone. The geometrical parameters were determined in the established frame of reference on a complex numerical model using the methods of descriptive geometry: examples, rotations, sections and basic concepts: a straight perpendicular to the plane, perpendicular planes, determination of angles between straight lines and planes, and determination of the angle between the straight line and the plane.

The choice of the hip resurfacing prosthesis size, regardless of the type of system, begins from selection of the size of femoral components, which is dependent on the geometrical parameters of the femur. Therefore, in the presented method, first of all, the measurements of the femoral head were carried out. The head diameters were 49.9 mm and 47.6 mm, and the diameters of the neck were 34.8 mm and 36.5 mm, respectively. The axis of the hip bone stem was set as a straight line connecting the middle points of three sections done in the longer part of the hip bone (Fig. 2.).

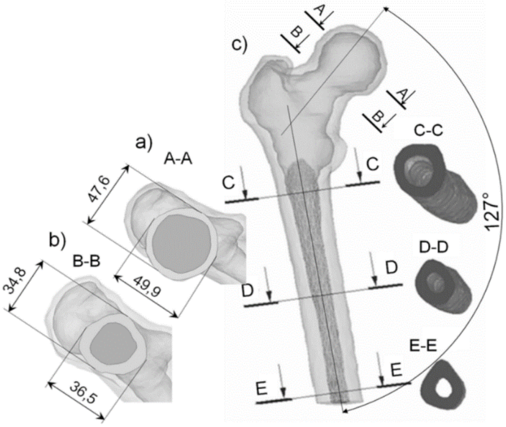

Fig. 2. The measurements of the femur: a) the diameters of the head; b) the diameters of the neck; c) the femoral neck-shaft angle.

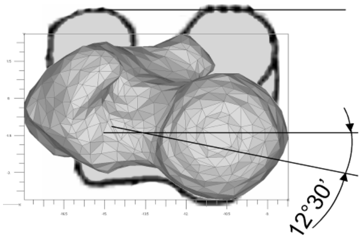

Fig. 3. Determination of the ante-torsion angle of the neck of femoral bone.

The neck-shaft angle was measured between the designated axis of the neck and the axis of the femoral shaft. In the diagnosed case, the neck-shaft angle was 127°.

The optimal conditions for the resurfacing procedure should ensure the femoral head-neck index to be within the range of 1.2–1.4 [8]. In the discussed case, the femoral head-neck index was 1.36.

The ante-torsion angle of the femoral neck is determined in such a way that the proximal and distal ends of the femur are projected onto one another. This angle is determined by the axis of the neck and the axis of the knee joint in the projection on the horizontal plane (Fig. 3.). The measured ante-torsion angle was 12°30'.

The measurements of the diameter of the acetabulum were made in the procedure of its section on the inclination plane made by the acetabular lip. The local reference system was assumed in such a way that the plane yz is the plane set by the acetabular lip, whereas the plane xz composes the cutting plane of acetabulum going through its centre (Fig. 4.).

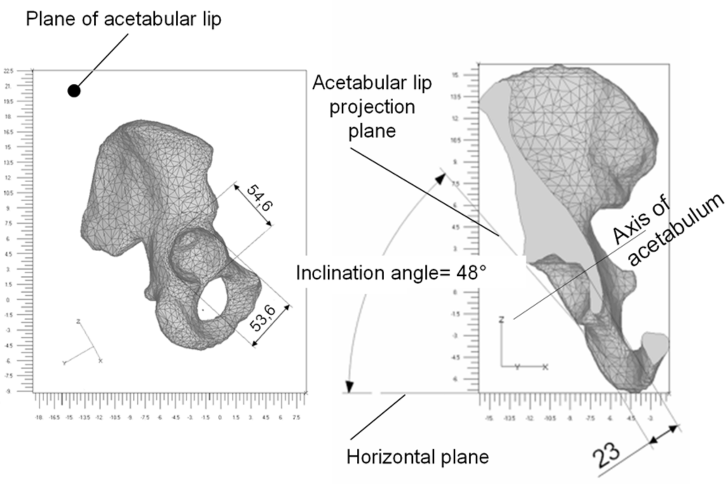

Fig. 4. The measurement of the acetabulum and determination of the inclination angle.

The acetabulum was oval and its symmetry axes were 54.6 mm and 53.6 mm, respectively. To determine the depth of the acetabulum, the angle of inclination and the angle of ante-version, the axis of acetabulum was defined. The axis is a straight line going through its centre and perpendicular to the plane of acetabular lip.

The depth of the acetabulum was determined in the cutting plane of pelvis bone with the plane going through the axis of acetabulum and its projection onto the horizontal plane (Fig. 4b.). The depth of the acetabulum was 23 mm.

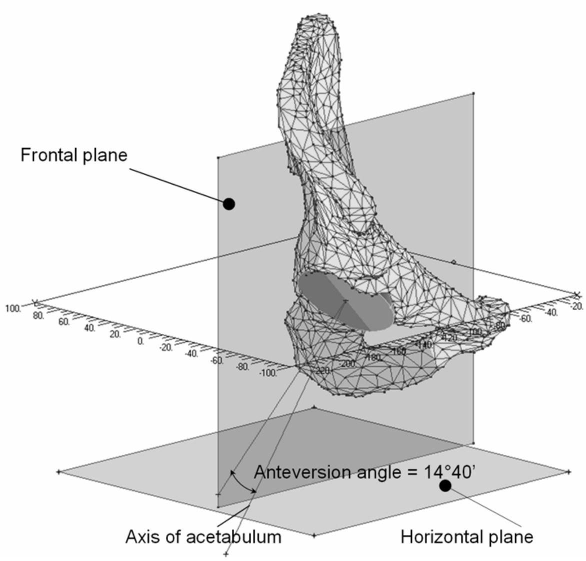

Fig. 5. Determination of the ante-version angle of acetabulum.

The inclination angle is the angle between the acetabular lip and the horizontal plane. This angle was determined in the plane perpendicular to both these planes as the angle between its traces (Fig. 4b.). The inclination angle was 48º20’. The ante-version angle is the angle between the axis of acetabulum and its projection onto the frontal plane (Fig. 5.). It was measured on the plane determined by these two straights. The ante-version angle was 14º40’.

The uncertainty of linear measurement was $u = 0.06$ mm, whereas the uncertainty of the measured angles $u = 8’$.

2.2. Modelling of hip resurfacing prosthesis

The hip resurfacing prostheses allowed for the clinical use are produced in various material and dimensional configurations, enabling to select individual geometric and biomechanical parameters.

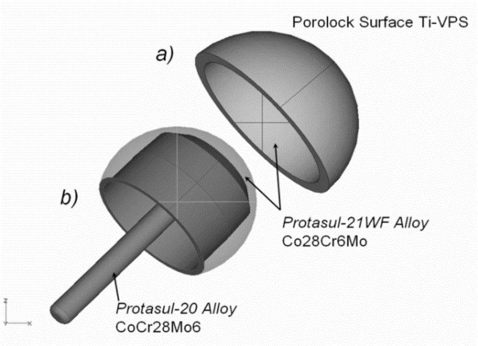

Fig. 6. The elements of endo-prosthesis DHRS modelled in FEMAP/NE Nastran v.8.3 Modeler software: a) the acetabular component; b) the femoral component.

A review of the constructional solutions of these prostheses was conducted. [3, 9, 10]. In the presented clinical case the Duron Hip Resurfacing System by Zimmer firm was used.

To create the geometry of the femoral and acetabular components the modelling based on Boolean algebra was used [11, 12] (Fig. 6.). Due to the geometric parameters of the head and the acetabulum the Duron Femoral Component 50P 01.00211.150 and Duron Acetabular component 56P 01.00214.056 were chosen.

3. Positioning of hip resurfacing endo-prosthesis

Modelling in the FEMAP/Nastran v.8.3 NE Modeler enables to separate structures, their intersections, sections, and turnovers in the accepted reference system. These procedures constitute an original solution for assessment of the position, with respect to known solutions in the literature [13, 14].

On the basis of the patient's hip belt bio-measurements the choice of the hip resurfacing endo-prosthesis and the virtual location of the following solid components: the acetabular one in the pelvis bone and the femoral one on the head of femoral bone was modelled (Fig. 7.). The DAC 56P acetabular component had an outer diameter of 56 mm, internal diameter of 50 mm, wall thickness of 3 mm, space depth for femoral component of 24.5 mm, and the pivot point was in the center of the sphere limited by 165° angle. The inclination angle of 48°20' (Fig. 4.) and the ante-torsion angle of 14°40' (Fig. 5.) were maintained in its location. The acetabular component on the outer surface of spherical cup had a porous titanium layer and was fixed in the pelvis bone on the basis of osteo-integration. In this case, the angles of inclination and ante-version of the acetabular component were in the safety zones of 40° ± 10° for the angle of inclination and 15° ± 10° for the angle of ante-version [2, 15], as recommended in the literature. The proposed procedure protects the anatomical positioning of the acetabular component in a properly shaped bone bed, after removing only the tissue debris of articular cartilage and subchondral bone layer. In the distant prognosis it secures proper osteo-integration, a suitable degree of covering, and minimisation of wear of the edge of acetabular component.

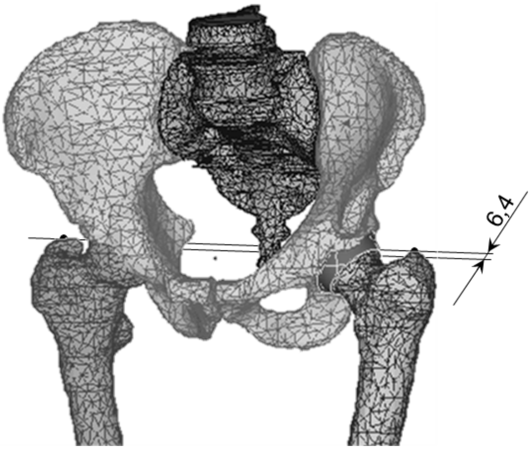

Fig. 7. The numerical model of pelvis with DHRS endo-prosthesis (DFC 50P 01.00211.150 and DAC 56P 01.00214.056).

The 50P DFC femoral component had an outer diameter of 50 mm, height of 37 mm, stem diameter of 8 mm and length of 72.4 mm. The neck-shaft angle of 127° (Fig. 2.) and the ante-torsion angle of neck of 12°30' (Fig. 3.) were maintained in its location. The femoral component is fixed on the head of femur processed in the shape of a 40 mm cylinder tipped with a cone according to the operative procedure, and its stem is cemented in the processed neck canal. The femoral component does not penetrate the medullary canal, the femoral neck is not removed, the anatomical ante-torsion is maintained. The tribological contact of femoral and acetabular components takes place between the sliding layers from the Co28Cr6Mo alloy. The optimal orientation of the prosthesis elements enables maintenance of the physiological point around which rotation of the lower limb occurs in the sagittal plane – the flexion and extension movements. In the proper biomechanical system, the axis joining the centres of the hip and the straight line joining tops of greater trochanters should be on the same height. At the same time the axis joining the centres of the joints should be parallel to the straight line joining the tops of greater trochanters and should lie in the frontal plane and be moved forward about 10 mm along this straight line. In the tested case the straight line connecting the tops of greater trochanters was determined and compared with the location of the axis connecting the centres of joints: the anatomical and implanted ones. The straight line and the axis of rotation were parallel to each other with a 3 mm deviation of parallelism and a 6.4 mm forward displacement of the axis of rotation of joints. The location of rotation points in the horizontal plane and the displacement and parallelism of the axis of rotation and the straight line secure functional cooperation of the anatomical and implanted joints.

4. Biomechanical analysis of conducted implantation

During the discussions it was decided to numerically verify the conditions of the transfer of loads in the analyzed joint stocked resurfacing.

Creation of three-dimensional system of fixes and loads. This system constitutes the own model and was determined on the basis of identifications of locomotive loads and movements in the Bergman hip joint and Będziński model. It was used in strength analysis of the hip joint after total alloplastic surgery [16].

In the elements of the loaded prosthesis, that is in the acetabular shell stabilized in the pelvic bone and in the femoral component, a characteristic feature was the circumferential asymmetry of stresses: from the maximal value of 13.70 MPa to the minimal one: 0.80 MPa (Fig. 8.). The maximal stresses of 13.70 MPa concentrated in the upper part of the acetabular shell, whereas in its bottom part they equalled to 4.50 MPa. A similar asymmetry occurred also in the femoral component. In the part contacting with the roof of the acetabular shell the maximal values of stresses amounted to 13.70 MPa, whereas in its lower part – only to 3.40 MPa. In the construction of the femoral component, accumulations on the small stem for its stabilization were characteristic (Figs. 8 and 9.) and had values of 18.50 MPa. It is noticeable that the accumulations occurred in the medium upper part of the stem (Fig. 8.). The stress analysis of this element illustrates the effect of bending of the stem which supports transfer of bending loads by the neck of femoral bone.

The distribution of stresses in the bone tissues surrounding the implantation zone may indicate the areas in which the accumulations happen and affect the prognosis of the operation. In the femoral head, in the area contacting with the component – in the layer of cement and in the bone tissue – circumferential accumulations occurred with maximal values of 15.65 MPa, which can cause crushing the bone cement used for stabilization and become a possible centre of aseptic loosening of the head component.

The stress analysis points to an asymmetrical distribution of stresses in the neck of femoral bone (Fig. 9.). The maximal stresses are equal to 8.30 MPa, whereas the minimal ones – to 2.10 MPa. There are two zones of maximal stresses located in the upper and lower parts of the neck. Such a distribution increases the risk of fracture of the neck of femoral bone.

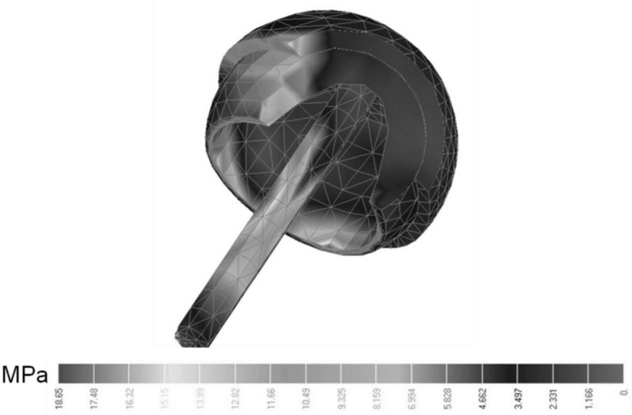

Fig. 8. The maps of stress distributions reduced to the contacting elements of head overlay and cup (the construction of endo-prosthesis separated from the tested model).

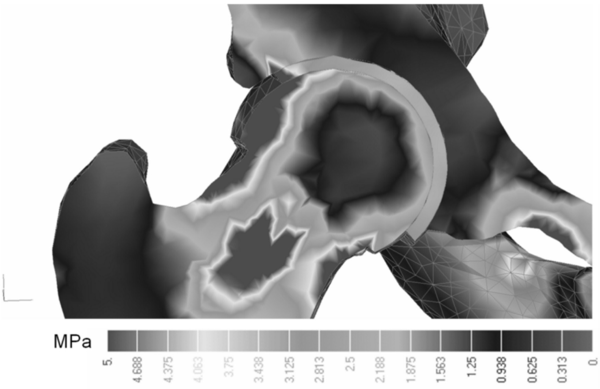

Fig. 9. The maps of stress distributions reduced to the construction of endo-prosthesis and to the fixing zone.

The observed circumferential asymmetry of stresses, like in the model by Cilinger [17], is disadvantageous both for the construction of endo-prosthesis and for its fixing zones. The construction of endo-prosthesis may be exposed to increased tribological wear in zones of the maximal stresses and - because they are asymmetrical – in the movement contact zone irregular wear may take place. In the conditions of exploitation, it may cause a change of the spherical shape of femoral component head and a change of shape of the spherical acetabular shell, so that the acetabular shell and femoral component may tend to be oval. The products of wear from the Co28Cr6Mo alloy may pass to the contact zone. The locomotive loads in the contact of the femoral component and the acetabular shell are transferred by the metal elements and such a character of their transfer due to the strength parameters causes concentration of stresses in these elements. It differs from the elastic transfer of contact loads which is characteristic for the natural head and the acetabulum covered in the articular cartilage and lubricated with the synovial fluid [12]. In that joint, the zones of concentrations of stresses occur in the bone structures of head and acetabulum remote from the movement contact. In Fig. 9 it is possible to observe the unloading of the head of femoral bone directly under the metal component, where the stresses achieve values of tenths of MPa and increase only in the stabilizing stem and in the internal structure of femoral neck. The distributions of stresses in the distal part of femoral bone increase to 4.10 MPa. It may result from the presence of a medullary canal and a related

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decrease of the cross-section area of femoral bone. In the upper contact zone of acetabular shell with pelvic structures, the stresses maintain within 2.20 MPa. It is an advantageous effect which may support the osteo-integration process of an artificial acetabular shell with the bone.

5. Conclusion

The support of implantation using CT, solid modelling, bio-metrology and fixing an endo-prosthesis in the virtual bone structure enables to optimize selection of the prosthesis. Such selection enables securing the geometrical parameters in the range of bone bed: the depth of acetabular component, the inclination and ante-version angles, the femoral neck-shaft angle, the ante-torsion angle of neck, creating the biomechanical axis of limb and the physiological point of rotation in the implanted joint as well as locating the axis of rotation of both joints in the horizontal plane.

The conducted numerical analysis shows that in the hip resurfacing arthroplasty the connection of a hard metal acetabular shell with a femoral component increases strength and resistance to wear, but it can also cause an excessive stiffening of the system. Asymmetric areas of concentration of maximal stresses in the zone of tribological contact may cause unbalanced wear of constructional elements. The unfavorable effect on the stabilization of endo-prosthesis results from the circumferential asymmetry of distribution of stresses in the zones of fixing the femoral component and the acetabular shell.

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