# STRAIN-STRESS ANALYSIS OF PATHOLOGICAL HIP JOINT AFTER OSTEOTOMY

Tomáš Návrat*, Martin Vrbka**, Zdeněk Florian***, Zbyněk Rozkydal+

*This work presents the procedure of a computational model of pathological hip joint allowing a simple modification of individual parts of the model according to the planned course of femoral and pelvic osteotomy. Both presented models were subjected to strain-stress analysis by a finite element method using the ANSYS program system. The obtained results are compared with physiological hip joint results and the feasibility of planned osteotomy is evaluated based on selected mechanical parameters. The conclusions are consulted with surgeons and possible correlations with clinical results are searched for.*

Key words: *biomechanics, healthy hip joint, pathological hip joint, osteotomy, contact pressure, FEM*

## 1. Introduction

The load of a hip joint is given by the pressure exerted by body weight and a dynamic tension around articular muscles. Concentric surfaces of acetabulum and femoral head, appropriate congruence of joint surfaces, physiological collodiaphyseal angle and anteversion angle jointly allow physiological distribution of load forces.

Hip joint biomechanics was elaborated by F. Pauwels [9] who published his theory in 1935. He based his investigations on mathematical two-dimensional models and anteroposterior radiographs. Pauwels observed that hip joint of a patient standing on one leg holds full body weight, while muscles compensate descending pelvis on the other side. The resultant force acting on the hip is a four times higher than patient's body weight. Modification of collodiaphyseal angle after valgus or varus osteotomy of proximal femur entails a change of hip joint load, distribution of forces and enlargement of contact surface. This reduces pathologically increased surface pressure on articular cartilage, which allows preservation of biological hip joint. For decades, orthopaedists have adhered to Pauwels' rules when planning and realizing osteotomy of proximal femur. The problem was that Pauwels did not calculate load forces after pelvic osteotomies that have become increasingly popular among orthopaedists all over the world especially to treat post-dysplastic hip alterations.

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Modelling of physiological pathological hip joint by a finite element method is a new qualitative step towards improved osteotomy planning process. This method makes it possible to model and compute future load and distribution of contact pressure in the hip joint. An optimum correction of angles of proximal femur and the best position of femoral head against acetabulum can be planned, which will improve the support of the head by its own acetabulum and provide distribution of load forces to a larger contact surface. In so doing, irreversible wear and destruction of articular cartilage is avoided and a functional biological joint can be preserved for many years.

Osteotomy (osteo = bone, tome = to cut) cuts the bones adjacent to the joint, while the bones are directed to a better geometrical position in order to maximize the coverage of femoral head by acetabulum, concentricity of head and acetabulum, and maximum mobility and stability of the hip joint. Individual bone fragments are then fixed against each other. The advantage of osteotomy is that individual parts of the joint are preserved. These parts can further develop and, after some time, be remodelled. Moreover, there is no foreign body in the organism. Various types of osteotomy are used in clinical practice. The aim of osteotomy is to improve anatomic and biomechanical states in pathological joint so that they approximate those of a healthy hip joint. This improves also distribution of a contact pressure between the head and acetabulum. Other goals of osteotomy include ensuring appropriate tonus in gluteal muscles etc. Osteotomy often helps avoid a total replacement of the joint or, at least, delay it. Therefore osteotomy is used mainly in young adult patients. Depending on the site of section, pelvic osteotomy and femoral osteotomy, or a combination of both, are known. Some types of osteotomy are more appropriate for children and adolescents, other types for adults. The surgery itself is very demanding, with long-term therapy and convalescence. References [1], [2], [3], [4], [5], [6], [7], [8] were used for the purposes of this work.

## 2. Problem and objectives statement

The aim of hip joint surgery is to improve adverse morphological and force states in pathological hip joint so that they approximate those of a healthy hip joint. The surgery modifies the shape and corrects relative position of individual parts of hip joint, or leads to the replacement of damaged joint with artificial hip joint. Strain-stress analysis of pathological and healthy joints is necessary to evaluate mechanical feasibility of a proposed surgical intervention. Today, the majority of studies focus on mechanical analysis of a total replacement hip joints. Therefore our attention was paid to computational modelling of reconstructions on pathological joints. The results of these analyses should significantly help surgeons select an appropriate type of hip joint surgery. These problems are investigated in cooperation with the 1st Department of Orthopaedic Surgery of the St. Anne's University Hospital in Brno.

The aim of this work is to realize strain-stress analysis of pathologic hip joint and correct this joint by means of osteotomy. The scope and type of osteotomy was designed by surgeon according to the therapy being used. The model of pathological hip joint geometry was modelled based on computer tomography of the actual damaged hip joint. For the purposes of a comparative analysis, a healthy hip joint was modelled as well.

## 3. Methods

The problem outlined above was solved by a finite element method using the ANSYS program system. Three-dimensional computational models of healthy and pathological hip joints were created for the purposes of this work. Both models were subjected to a comparative strain-stress analysis in order to compare strain and stress states in the joint area. As soon as the conclusions resulting from analyses were formulated, the pathological joint was modified by femoral osteotomy. Input geometric data were obtained from computer tomography of the particular patient who underwent surgical osteotomy.

### 3.1. Geometric model and a mesh of finite elements

**A. Healthy hip joint**

Geometric model was created using data obtained from independent computer tomography scans of pelvis, sacrum and femur. The complete input data in IGES format were provided by the Department of Imaging Methods of the St. Anne's University Hospital (for our purposes, they were processed by Ing. Přemysl Kršek, Ph.D.). In fact, the data were individual CT sections that included numerous limiting points and line segments. The distance between sections was 5 mm in pelvis and 2.5 mm in femur (Figure 1). Considering a complicated shape of individual bones and the suitability of using a mapped mesh, the bones were subdivided to a larger number of small volumes. These volumes were obtained after a sophisticated modification of CT sections. Their shape reflects the conditions that must be met so that the mesh could consist of hexahedral elements. Both pelvis and femur model allowed for two types of bone tissue. Spongy bone is modelled using volume elements, and cortical bone is modelled by means of shell elements (Figure 2). The model includes sacrum, pelvis, femur, cartilages and ten muscles (adductor brevis, adductor longus, adductor magnus, gluteus medius, gluteus minimus, gluteus maximus, pectineus, piriformis, quadratus femoris, rectus). Each muscle is modelled using cable elements that carry tension load only. The elements are defined by two nodes (the beginning and the attachment of the

*Fig.1: Sections of pelvis and femur*

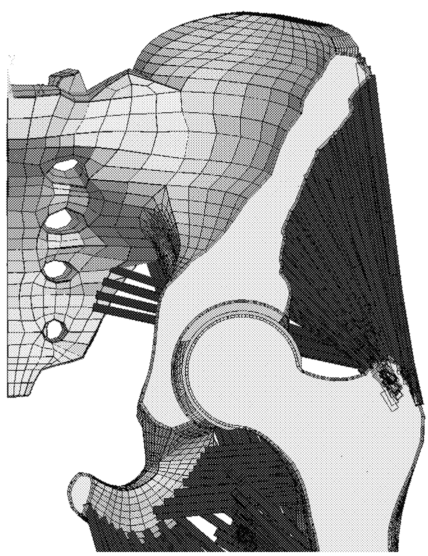

*Fig.2: Finite elements mesh in healthy hip joint*

muscle). In real muscles, the beginning and the attachment represent specific area of a given bone. Therefore individual muscles are replaced with a larger number of elements.

**B. Pathological hip joint**

Geometric model of pathological hip joint can be effectively created by using data obtained during CT examination when the area of patient's body sufficient to make a diagnosis and select appropriate type of surgery is scanned. However, these data are not fully sufficient to create a hip joint geometric model. Missing parts must be therefore modelled based on general view of the joint and appropriate practical experience.

Procedure of generation of geometric model and element mesh :

1. Based on CT sections, external contour in the form of curves was created by segmentation method (Figure 3). RHINOCEROS software was used for this purpose.
2. External surfaces of femur and pelvis were modelled by modifying the curves. This was partly done in RHINOCEROS software and CATIA CAD system.
3. Volume objects were created from external surfaces. Contact joint was modified by modelling of cartilages in acetabulum and on the femoral head. Modelling was done in CATIA system.
4. Geometric model was loaded in the ANSYS computational system; tools for generation of mapped and free mesh were used. A finite element mesh is shown in Figure 4.

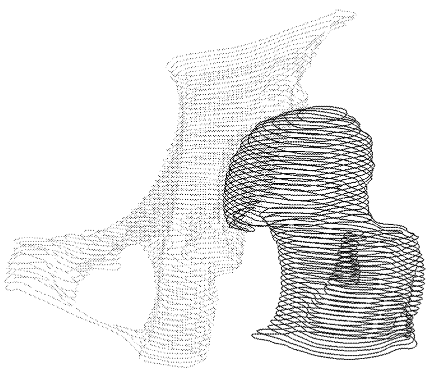

*Fig.3: Pelvic and femoral sections*

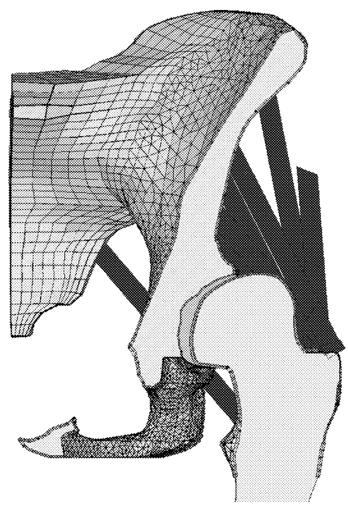

*Fig.4: Finite element mesh in pathological hip joint*

Pelvis and femur models allow for two types of tissue. Muscle model is detailed above.

Doc. MUDr. Zbyněk Rozkydal, Ph.D. selected the patient of the $1^{st}$ Department of Orthopaedics who was suitable for computational modelling and whose necessary entrance examinations were available. Data in DICOM format were provided by the Department of Imaging Methods of the St. Anne's University Hospital in Brno headed by doc. MUDr. Petr Krupa, CSc. The patient (52 years old woman) suffered from dysplasia of right hip joint with degenerative changes (cysts, osteophytes, subchondral sclerosis). The joint had the following geometric parameters : CCD angle = 141°, Wiberg's angle = 0° and Sharp's angle = 75°.

**C. Osteotomy of pathological hip joint**

Geometric model was based on the pathological hip joint model. It was suggested that the joint would be modified via varus osteotomy of femur (Figure 5) and extending the coverage of femoral head by adding a bone graft. Geometric model after osteotomy is shown in Figure 6. Modelling of such surgical intervention requires using extremely complicated Boolean operations and three-dimensional transformations concerning the parts being cut. It emerged that this task could be without major problems done in CATIA CAD system. Afterwards, the model was imported to the ANSYS Workbench program system where a mesh of finite elements was generated (Figure 7), appropriate boundary conditions defined and the computation launched. The computational model did not allow for connecting elements that fixed individual separated parts of bones. The contact of separated parts was connected at the level of a fine element mesh.

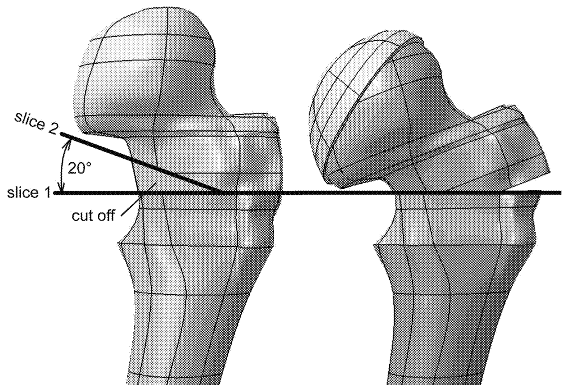


*Fig.5: Scheme of varus femoral osteotomy*

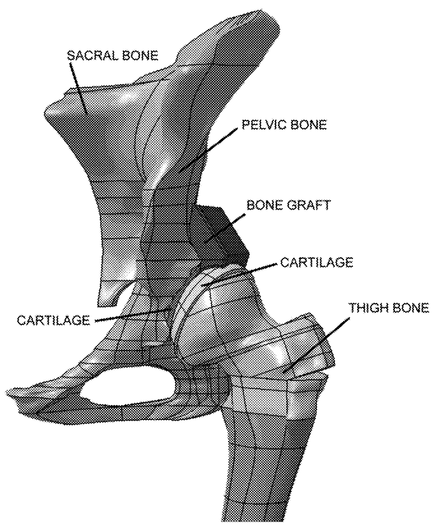


*Fig.6: Model of geometry of pathological hip joint after osteotomy*

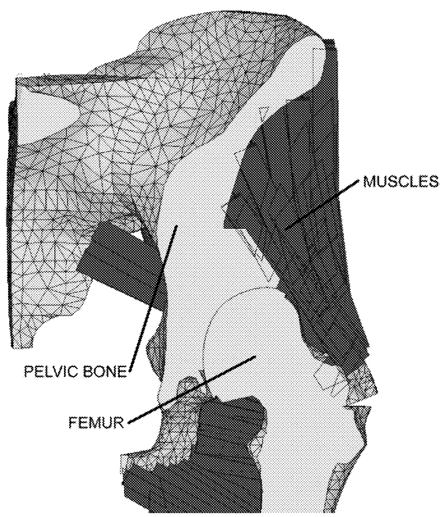


*Fig.7: FEM model of pathological hip joint after osteotomy*

### 3.2. Model of the contact between objects

For the purposes of evaluation of contact pressures between individual hip joint components, connections between objects were modelled using surface-to-surface contact elements with Coloumb friction model. In all the three models, contact elements were employed in the contact between acetabular cartilage and femoral cartilage.

### 3.3. Model of material

The material model of the bones is based on the isotropic, linearly elastic continuum. All material properties have been taken from references [10], [11], [12] and are summarized in Table 1.

| Material | Modulus of elasticity | Poisson's ratio |
|---|---|---|
| Spongy bone | 490 MPa | 0.3 |
| Cortical bone | 14100 MPa | 0.3 |
| Cartilage | 60 MPa | 0.4 |

*Tab.1: Material properties*

### 3.4. Boundary conditions

The load corresponds to the weight of a man of 80 kg, standing on one limb. Since the model contains only a portion of the femur, the load acting on the leg from the base has to be counted over to the distal end of the femur. The deforming boundary conditions are given in the plane of symmetry of the sacrum where all displacement is built in and in the symphysis pubic where displacement perpendicular to the medial plane is built in.

### 3.5. Summary information about computational models

Finite element mesh consisted of about 160 000 elements and 200 000 nodes. A total number of DOF (degrees of freedom) was approximately 600 000 (accurate number of element for each variant is shown in Table 2). Due to its extensive scope and non-linear nature, the solution of the assignment is extremely time-consuming and makes heavy demands on hardware resources.

| | Healthy hip joint | Pathological hip joint | Hip joint after osteotomy |
|---|---|---|---|
| Number of elements | 66 811 | 164 093 | 158 823 |
| Number of nodes | 93 688 | 207 207 | 205 162 |
| Number of active DOF | 310 081 | 644 835 | 613 371 |

*Tab.2: Summary information*

| Value / Model | Healthy joint | Pathological joint | After osteotomy |
|---|---|---|---|
| Maximum contact pressure value [MPa] | 3.1 | 28.3 | 14.7 |
| Contact pressure value for comparison of variants* [MPa] | 2.2 | 28.3 | 8 |
| Total contact area** [$mm^2$] | 2805 | 2095 | 2154 |
| Area in contact*** [$mm^2$] | 2460 | 600 | 1929 |
| Resultant contact force in the joint [N] | 2240 | 3281 | 3308 |

* representative contact presure value measured in the upper part of acetabulum except for points of concentrations
** area of all contact elements
*** area of contact elements with non-zero contact pressure

*Tab.3: Summary of results*

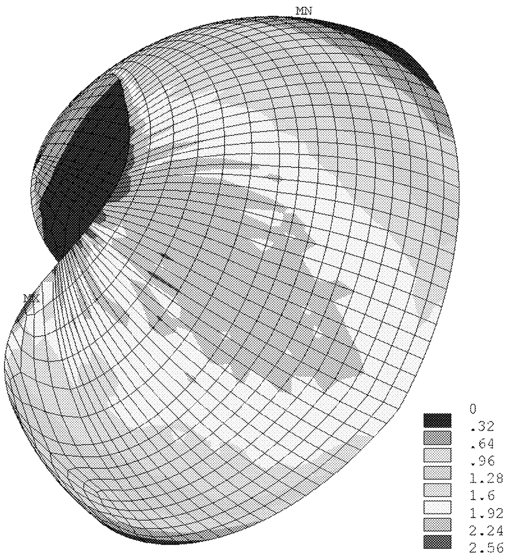


*Fig.8: Distribution of contact pressure between femoral head and acetabulum in healthy hip joint; plan view; values in [MPa]*

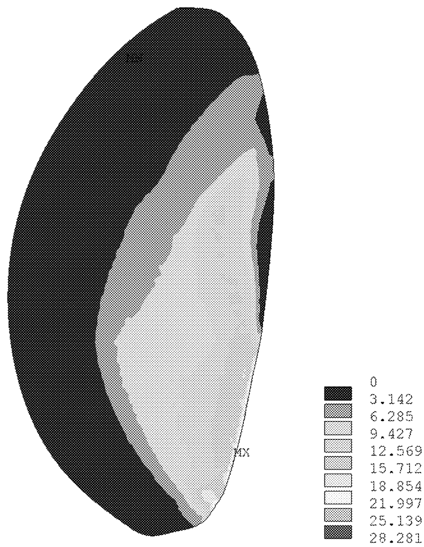


*Fig.9: Distribution of contact pressure between femoral head and acetabulum in pathological hip joint; values in [MPa]*

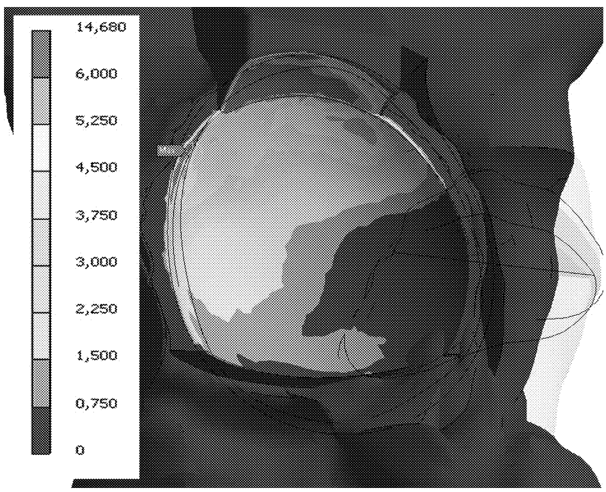


*Fig.10: Distribution of contact pressure between femoral head and acetabulum in hip joint after osteotomy; values in [MPa]*

## 4. Results

Interaction between femoral head and acetabulum is best understood from the distribution of contact pressure. Contact pressures exerted on acetabulum cartilage in individual variants are shown in Figure 8, Figure 9 and Figure 10. The results are summarized in Table 3.

## 5. Discussion

There are several criteria of evaluation of the degree of hip joint damage. Based on these criteria, it is possible to identify to what extent the shape and relative position of femoral head and acetabulum of pathological joint differs from those of physiological joint. For instance, ventrodorsal radiographs are evaluated for Wiberg's angle and collodiaphyseal angle (CCD angle). If Wiberg's angle is $> +25°$, the joint is considered as physiological one. Values under $+20°$ indicate pathological joints. Sharp's angle is measured between the reference line connecting the lower contour of teardrop figure that defines the bottom of acetabulum, and the line connecting the centre of the lower edge of teardrop figure and lateral edge of acetabulum. Physiological values range between 33–38°, the upper limit ranges between 39–42°, angle exceeding 42° indicates pathology. Collodiaphyseal angle is measured between the femoral diaphysis axis and the line connecting the centre of femoral head and the centre of femoral neck. CCD angle around 125° is considered to be physiological in adults. If CCD substantially exceeds physiological values, it is called coxa valga; on the contrary, CCD being significantly below physiological values indicates coxa vara. Table 4 compares the values of respective angles measured for the purposes of this work. The values in Table 4 prove that correction of the femur by osteotomy resulted in adjustment of angles to their physiological ranges.

| | Healthy joint | Pathological joint | After osteotomy |
|---|---|---|---|
| CCD angle | 115° | 141° | 113° |
| Wiberg's angle | +37° | 0° | +30° |

*Tab.4: The measured angle values*

In the healthy hip joint, maximum contact pressure of 3.1 MPa was measured at the internal edge of cartilage due to a change of stiffness of contact surfaces (cartilage – pulvinar acetabuli). Contact pressure in the upper part of the cartilage reaches approximately 2 MPa.

In the pathological hip joint, it is obvious that due to insufficient coverage of femoral head, contact pressure peaks are localized around the upper edge of acetabular cartilage, with maximum contact pressure being measured in anterosuperior part of the cartilage. Maximum contact pressure of the pathological joint is 28.3 MPa, which exceeds by 25 MPa maximum contact pressure measured in the healthy hip joint (i.e. contact pressure is approximately ten times higher).

In segments with high contact pressure and high radial stress (up to 30 MPa), destruction of cartilage and bone tissue is expected. This is supported also by the radiograph of damaged hip joint shown in Figure 11.

Analysis of the hip joint after osteotomy shows increased coverage of femoral head resulting in distribution of contact pressure to a larger area. Thus the pressure decreases approximately by 18 MPa as compared to previous pathological state. Maximum pressure is localized in the front part of the cartilage and is caused by discretization of a given area (sharp edge of the cartilage). Comparison of all the three models shows that maximum contact pressure in the upper part of acetabular cartilage increases in the pathological joint from 2 to 28 MPa as compared with the healthy joint. In the joint after osteotomy, the pressure increases from 2 to 8 MPa. Obviously, the load of cartilage is substantially lower in the joint after osteotomy. At the same time, improvement of stress state in overloaded bone matter is expected due to remodelling processes.

Among patients who underwent valgus or varus osteotomy of proximal femur due to developmental dysplasia of hip joint between 1980 and 1990, 30 patients (33 hips) aged 13 to 51 years (who were monitored for 15 to 25 years) showed average duration of beneficial

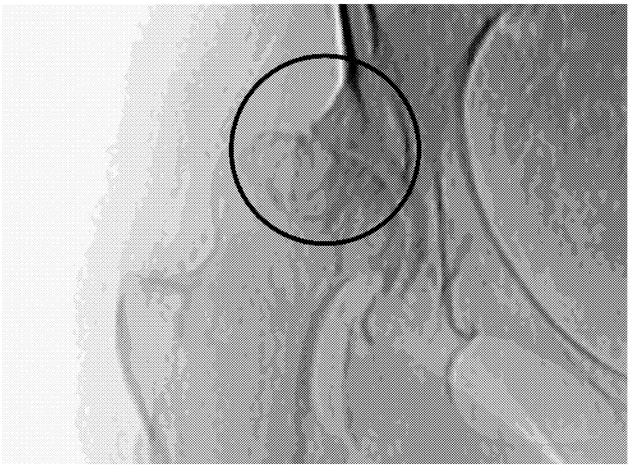

*Fig.11: Destruction of cartilage and bone tissue of the pathological hip joint*

effect of 16 years with average Harris hip score of 74 points. Fifteen (15) patients were full-time workers and 6 were awarded a partial disability pension. Nineteen (19) patients were satisfied with the surgery, 8 were partially satisfied (they would agree to have the operation again) and 3 were dissatisfied. Eight (8) patients underwent a conversion to a total replacement after a longer period of time.

## 6. Conclusions

This work focused on computational modelling of healthy, pathologically developed and pathological hip joint after osteotomy. Computational modelling was done by a finite element method using the ANSYS program system. A comparative analysis shows that osteotomy of pathologically developed hip joint results in increased coverage of femoral head, which decreases contact pressure between femoral head and acetabulum. Thus it has been proved that osteotomy ensure better mechanical and anatomical conditions and improve the patient's state. The results from computational modelling were compared with the results and findings from clinical practice. This will serve as a basis for further research in this particular area and specifically for clinical practice.

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