A NUMERICAL STUDY OF EFFECTS OF THE MANUFACTURE PERTURBATIONS TO CONTACTS OF THE TOTAL HIP REPLACEMENT

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In endoprosthesis surgery there are typically a high percentage of implant defects, these can lead to failure of the whole prosthesis. One type of total hip replacement function loss is acetabular cup loosening from the pelvic bone. This article examines manufacture perturbations as one of the possible reasons for this kind of failure. Both dimension and geometry manufacturing perturbations of ceramic head and polyethylen cup were analyzed. We find that perturbations in the variables analysed here affect considered values of contact pressure and frictional moment. Furthermore, contact pressure and frictional moment are quantities affecting replacement success and durability. From obtained results we can recommend to fit head and cup with a clearance of between 0 mm and 0.05 mm. We do not recommend using interference type of fit. Roundness perturbation of ceramic head should not exceed 0.025 mm.

Keywords: *total hip replacement, FEM, roundness, contact pressure, frictional moment, biomechanics*

1. Introduction

This article examines a number of the biomechanical problems associated with total hip replacements (THR). The manufacture perturbations (fabrication tolerances) and impacts of femoral head and acetabular cup upon the failure of function of THR. THR failure is typically accompanied with severe pain and necessitates reoperation and prolonged convalescence.

THR function loss is associated with a combination of several risk factors – use of inappropriate prosthesis materials, geometry, surface finish treatment, ... A recent clinical study of 600 THR's with ceramic-ceramic contact between femoral head and acetabular cups showed there was 20 % failure in period 1977–1989 [4]. One type of THR functionality loss is loosening of the acetabular cup from pelvic bone (Fig. 1).

2. Aims and objectives

The Faculty Hospital Brno (FHB) has an ongoing project examining the clinical impact of manufacture perturbations in hip prostheses [1]. During a five year period (1990–1995), a significant failure rate in THR due to loosening was at the FHB (Tab. 1). The Institute of Solid Mechanics, Mechatronics and Biomechanics at Brno University of Technology was invited to help with solving this problem situation.

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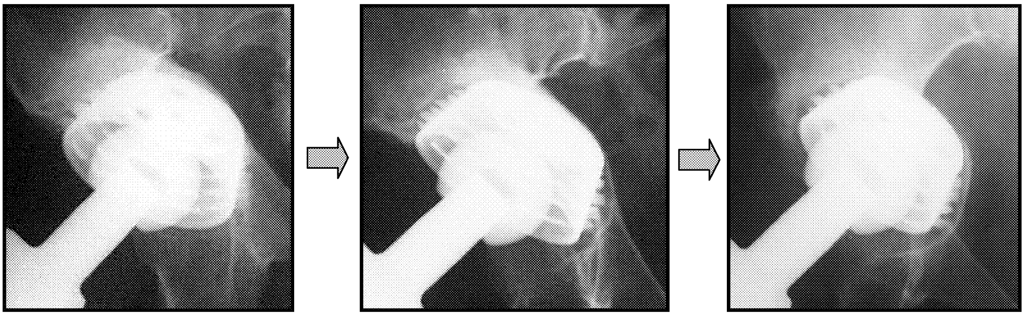

Fig.1: Continuity of acetabular cup loosening from pelvic bone [1]

Producer / Type of the cup	Failed THR due to loosening of the cup
Johnson&Johnson / Mercing	58 %
Balgrist / AlloPro	2 %
Walter-Motorlet (Fig. 2)	26 %

Tab.1: % of failed THR [1]

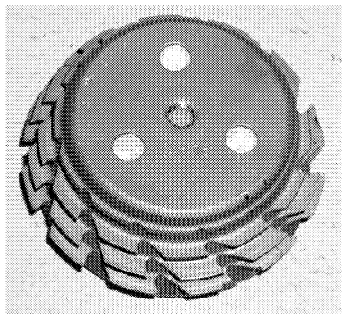

Fig.2: Acetabular cup made by Walter-Motorlet Co. [1]

Loosening of the cups is thought to be caused by the deterioration of the polyethylene, worn particles dislodged from the prosthesis then damage the tissue around the cup [2]. Amount of polyethylene wear is influenced by contact pressure and frictional moment between head and cup [18], [21]. Contact pressure and frictional moment are thought to be influenced by contact surfaces inaccuracies created during the fabrication process.

The objective of this study was therefore to computationally model the influence of fabrication tolerances on contact conditions between the acetabular cup and the femoral head in THR. The considered variables were firstly the contact pressure between acetabular cup and femoral head and secondly the frictional moment needed to be overcome to turn the femoral head in the acetabular cup.

This work evolved from the system approach first described by Dunham et al. [12]. Using this technique the problem is studied from both internal and external views and threads between them. We therefore established eight categories which needed to be determined for our model to be accurate.

a) topography, geometry – geometry of hip joint with applied total replacement
b) links – attachment of pelvic, contact surfaces between components
c) active elements – femoral head loading by force
d) affecting element – type of fit between femoral head and acetabular cup (interference, fine, clearance)
e) structure – model of materials
f) processes – pushing and rotation the ball head into the cup
g) expressions – deformation of the components, increase of tension/pressure, frictional moment
h) consequences – abrasion (defect) of the components, loss of functionality

Considering these parameters means that a typical problem approach could be utilized. In this way we defined a), b), c), d) and e) as inputs and f), g) and h) as outputs of our computational algorithm.

3. Computational modelling inputs

A model of the hip joint (Fig. 3) was created using FEM system ANSYS in conjunction with standard Newton-Raphson's iterative scheme, which is implemented in ANSYS. The contact conditions between the femoral ball head and the acetabular cup were achieved by applying contact elements and using the Augmented Lagrange Multiplier technique.

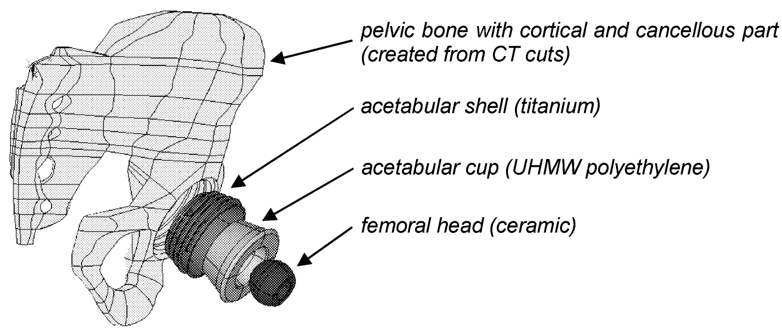

Fig.3: Hip joint parametric model

This model was created as parametric in order to study influences of perturbations of fabrication tolerances on the contact conditions. The investigated parameters included inner cup diameter, femoral head roundness and position of the roundness perturbations. The diameter of the inner cup was examined in the interval of 31.7 mm (the interference fit of 0.3 mm) to 32.4 mm (clearance fit of 0.4 mm). The roundness of the femoral head was tested in the range of 0−0.2 mm. The shape of the roundness perturbations is depicted in Fig. 4. The position of the roundness perturbarations was investigated in relation to the constant position of the loading force F. Three angles of 0°, 45° and 90° (β in Fig. 4) were considered.

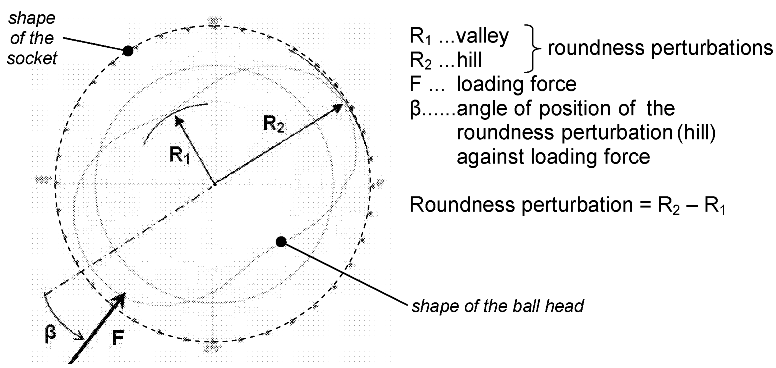

Fig.4: The roundness perturbations shape of the ball head

Linear isotropic material models were used for all components with characteristics summarized at the Tab. 2. Values of ceramic and titanium were taken from material lists, other characteristic from literature survey.

Model part	**material**	**modulus of elasticity** E [MPa]	**Poisson's ratio** μ [–]
Femoral head	ceramic Al_2O_3	3.9×10^5	0.23
Acetabular cup [7, 11]	UHMW polyethylene	1.0×10^3	0.40
Acetabular shell	titanium	1.0×10^5	0.30
Pelvis [12, 13, 14, 15, 16, 17]	cancellous bone	2.0×10^3	0.25
	cortical bone	1.4×10^4	0.30

Tab.2: Material characteristics

Values of modulus of elasticity of UHMWPE polyethylene varies in published literature (Tab. 2). It ranges from 600 MPa to 1200 MPa. Therefore sensitivity analysis was done for this parameter with results listed in 4.4.

The first contact pair was modelled by creating contact elements between the femoral head and the acetabular cup, with with friction coefficient of 0.1 (Coulomb model used). The second contact pair was created between the acetabular cup and the shell. This pair was not further evaluated in this study. Titanium shell was bonded into the pelvic bone.

In the finite element model two boundary conditions were considered, loading applied to the centre of the femoral ball head and bonding of the model at the plane of symmetry (Fig. 5). The loading of the model was performed in two steps. In the first step a constant loading force of 2500 N was applied in a direction as shown on (Fig. 5, Step 1). In the second step loading force of the same magnitude was applied while the femoral head was being rotated by 30 degrees as shown on (Fig. 5, Step 2).

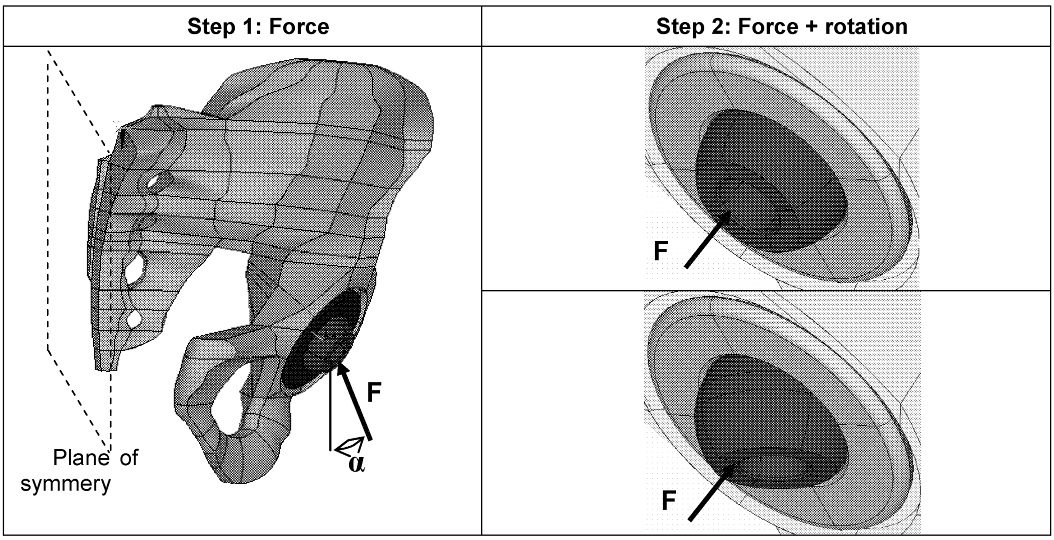

Fig.5: Load steps of the system and boundary conditions

Magnitude and direction of the loading force F were established from equilibrium of forces of a man standing on one foot. Input for the calculation was an average weight 80 kg of a human body.

Resulted value of the loading force F was 2500 N and the direction of the loading force α was 13.5°.

4. Results

4.1. Measuring of the perturbations

In this study one used and four unused acetabular cups and two unused femoral heads (all made by Walter-Motorlet) were studied and measured (Tab. 3). We found, that the inner spheric surface of the used cups showed non-uniform abrasion caused by wear. This was due to the non-uniform contact pressure caused by geometry and perturbations. Two types of head and cup contact surface perturbations were observed. First dimension type (different diameters of femoral head and acetabular cup) and second geometry type (roundness perturbations of spherical surfaces (Fig. 4)). Founded dimension type of perturbation evoke interference type of fit between head and cup (Fig. 6).

Cup / head	Diameter [mm]	Roundness perturbation [mm]	Used / unused
Cup 1	31.97	0.117	Unused
Cup 2	31.88	0.090	
Cup 3	31.83	0.064	
Cup 4	31.79	0.087	
Cup 5	**32.11**	**0.357**	**Used**
Head 1	32.02	0.011	Unused
Head 2	32.04	0.009	

Tab.3: Perturbations measured [1]

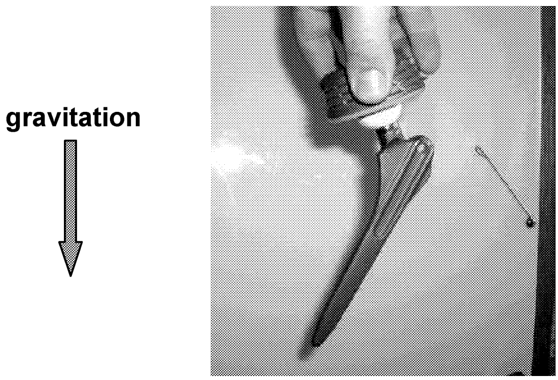

Fig.6: Due to interference fit, the femoral stem holds in acetabular cup in spite of direction of gravitation [1] (fixing unused cup and head together)

4.2. Modeling of the dimension perturbations

In order to model the dimension perturbations the inner diameter of the acetabular cup was varied. This resulted in change of the fit between the femoral head and the acetabular cup (from interference fit to clearance fit). Values for the contact pressure (Fig. 7) and the frictional moment (Fig. 8) were considered.

We found that by increasing the clearance starting from 0.0 mm (fine fit) the value of contact pressure raised linearly within the investigated interval (Fig. 7). Increasing the clearance between the head and the cup by 0.1 mm the contact pressure raised by $\sim$10 %. On the contrary the value of the frictional moment slightly decreased (Fig. 8) when increasing the clearance. This was due to a smaller size of the contact surface.

Reducing the clearance below 0.0 mm (fine fit), we found that the value of contact pressure raised with approximately double speed than for the positive clearance values (Fig. 7). However the value of the frictional moment steeply increased (circa 10 %) when reducing the clearance by 0.1 mm (Fig. 8). This was caused by the increase of circumferential tension due to negative clearance (interference).

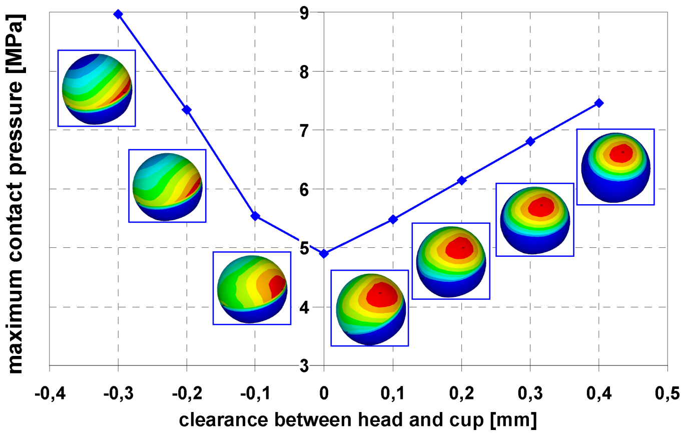

Fig. 7: The clearance between head and cup functionality on the contact pressure

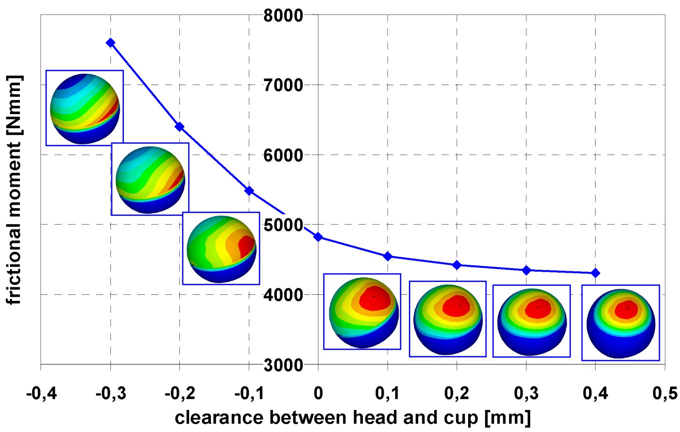

Fig. 8 The clearance between head and cup functionality on the frictional moment

4.3. Modeling of the geometric perturbations

To study influence of geometric fabrication tolerances the roundness of femoral head was varied, ranging between 0.05 mm to 0.2 mm. Position of the roundness perturbation (hill) was changed against the direction of the loading force (Fig. 9). The assumed angle values were 0°, 45° and 90°. Clearance between femoral head and cup was changed, with values −0.1 mm (interference fit), 0.0 mm (fine fit) and 0.1 mm (clearance fit). Values of contact pressure and frictional moment were considered (Fig. 9).

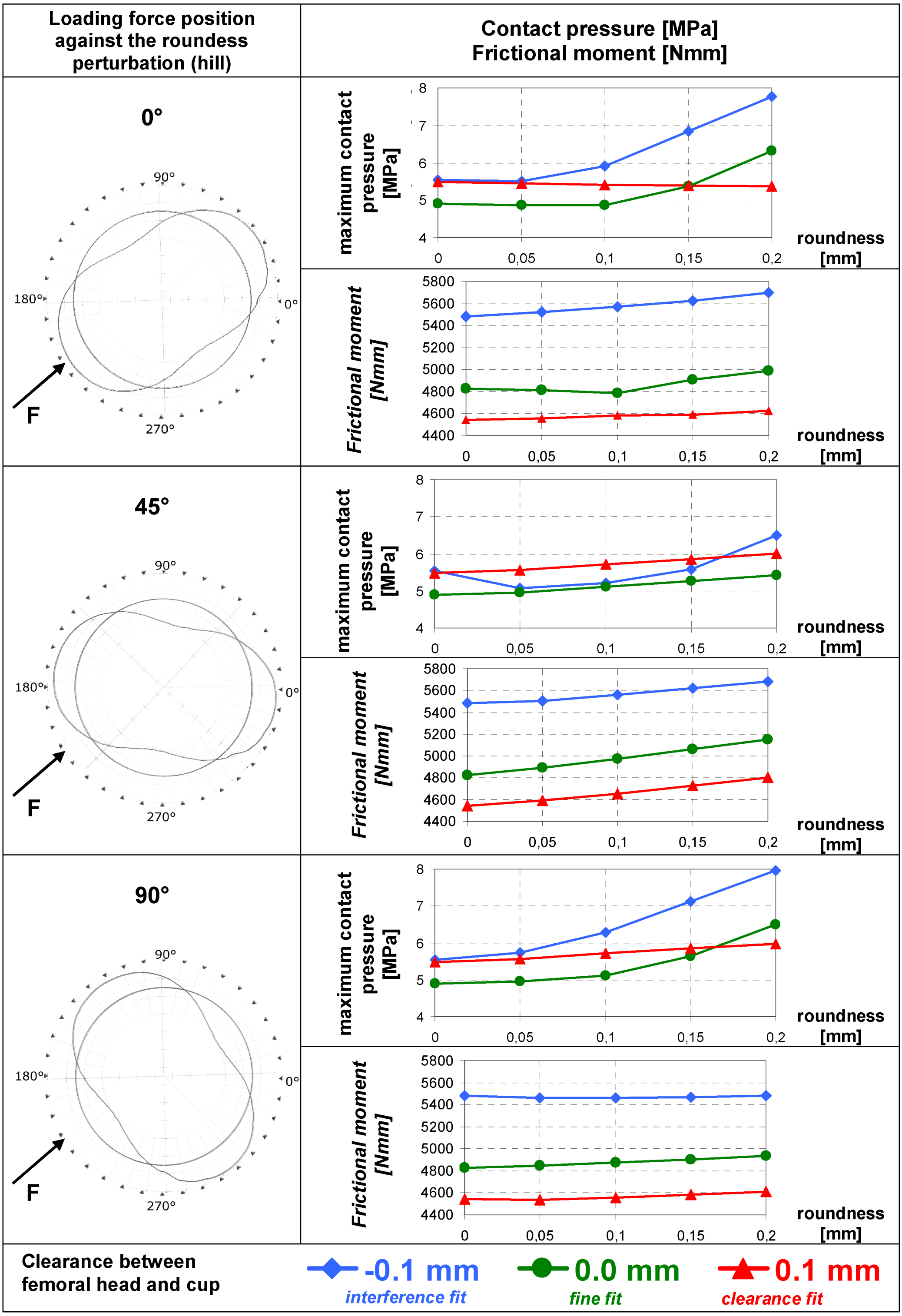

Fig.9: Contact pressure and frictional moment functionality of roundness of femoral head

We found, that increasing the roundness perturbation the contact pressure and the frictional moment raised, regardless the clearance value or the position of roundness perturbation against the loading force (Fig. 9). Bellow the value of roundness perturbation of 0.05 mm the values of contact pressure and frictional moment changed slightly. Above the value of roundness perturbation of 0.05 mm results changed steeply.

Changing the roundness perturbation to 0.2 mm, the value of contact pressure increased by 45 % in the case of interference fit, 30 % in the case of fine fit and 10 % in the case of clearance fit. Value of frictional moment increased by 5 % maximum in all types of fits.

Position of the roundness perturbation affected contact pressure values, especially in case of the interference or fine fit. Highest values of contact pressure were found at extreme positions (0°, 90°) of the perturbation (hill). We did not found any significant influence of changes of the perturbation position on the frictional moment.

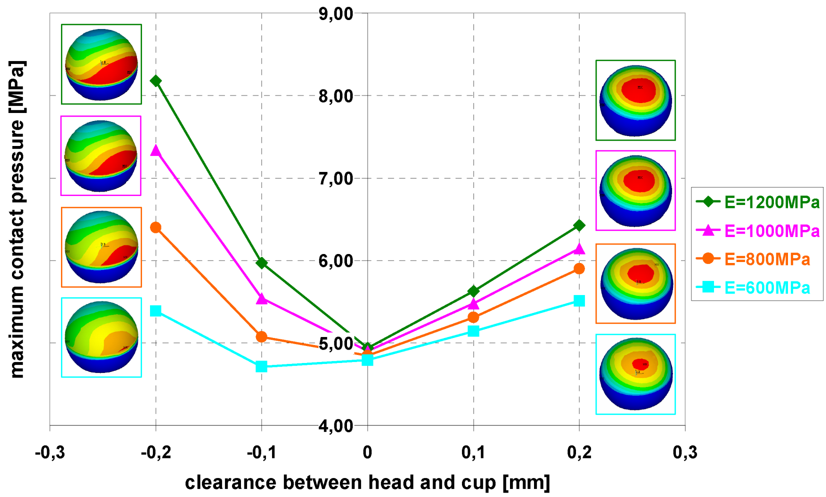

Fig.10: Acetabular cup modulus of elasticity functionality on the contact pressure

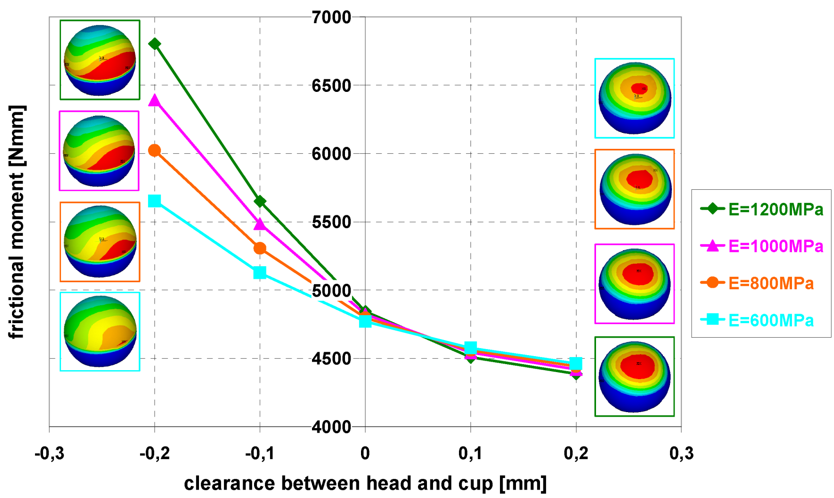

Fig.11: Acetabular cup modulus of elasticity functionality on the frictional moment

4.4. Polyethylen cup modulus of elasticity sensisivity analysis

To study the influence of the elasticity modulus of the polyethylene cup the modulus of elasticity value varied from 600 MPa to 1200 MPa. Values of contact pressure (Fig. 10) and frictional moment (Fig. 11) were considered.

Results shows that if the value of elasticity modulus of cup decrease, than the values of contact pressure decrease due to increase of contact area for all types of fit. From the same reason, the frictional moment decrease in the case of clearance fit. With decrease of modulus E value in the interference type of fit, the effect of equatorial tension decrease, and the frictional moment decrease too. In the case of clearance fit, value of frictional moment is almost the same for all values of elasticity modulus.

5. Conclusion

In this study parametric model of the hip joint with total hip replacement was created. The influence of fabrication tolerances on contact conditions between the acetabular cup and the femoral head was studied. Values of contact pressure and frictional moment were considered.

We discovered, that if the value of perturbations increase, the contact conditions deteriorate. We also found, that the best type of fit was fine fit, it means without clearence and interference. As this type of fit is hard to fabricate we recommend to fit head and cup together with clearance value ranging 0 mm to 0.05 mm. In this clearance interval the values of considered quantities varied in less than ten percents. We do not recommend using interference type of fit because of strong deterioration of the contact conditions.

Roundness perturbation of head was considered as geometric type of perturbation. We found, that increasing the roundness perturbation the contact pressure and the frictional moment raised, regardless the clearance or interference value. We recommend to fabricate the ball head with value of roundness perturbation bellow 0.05 mm because in this range the values of contact pressure and frictional moment change only slightly.

Both contact pressure and frictional moment values affect the success and durability of the replacement, therefore it is recommended to minimize their values. The relationship between contact pressure and wear is analyzed at [8], [18], [19] and [20].

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