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Interaction Between Pelvic Bone and Acetabular Component with Non-Uniform Cement Layer

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Summary: *The article deals with contact stress analysis of pelvic bone after implantation of cemented acetabular component with imperfections of cemented layer. 3D high resolution FE model of pelvic bone was created from the sequence of CT–slices. Boolean operations were used for inserting the spherical cemented component. Cemented component was eccentrically inserted into the pelvic bone and that created imperfection as non-uniform cement layer. Two contacts were defined in the FE model. The first contact is defined between the cement layer and the pelvic bone and the second one is between the cement layer and the polyethylene cup. The model was loaded by quasi–static joint forces, representing the maximum value of stance phase of gait [Bergmann et al., 2001]. The FE model was used to ascertain the contact stress conditions in the underlying subchondral bone.*

1. Introduction

Research in the field of human joints has advanced most in the area of the hip joint, which is for the function of the lower limb the most important one [Middleton et al., 2001]. In spite of the successful use of the total endoprostheses there are still a number of problems connected with the artificially created co-existence and interaction between the bone tissue and the technical material of the endoprostheses [Huiskes, 1986]. The fact, that there is still no optimal replacement is demonstrated by the every-year development of new or modified femoral components and acetabular cups. Micromotions and consecutive loosening of the acetabular implant is one of the most serious therapeutic complications, which is often approved several years after the implantation. Worldwide experiences demonstrate that 80% of all revised endoprostheses are damaged by the aseptic loosening [Maher and Predergast, 2002]. At the Orthopaedic Clinic of the 1st Faculty of Medicine of the Charles University in Prague, where endoprostheses are applied for more almost 40 years, 25-30% reimplantations have been carried out in the last years. It means that one reimplantation comes to every three primoimplantations [Sosna and Pokorny, 2000]. The important role in the process of the acetabular cup loosening is remodelling of bone tissue as a result of the change of stress field after implantation. Living bone tissue is continuously in the process of growing, strengthening and resorption, a process called "bone remodelling". Initial cancellous bone adapts its internal structure by trabecular surface remodelling to accomplish its mechanical function as a load

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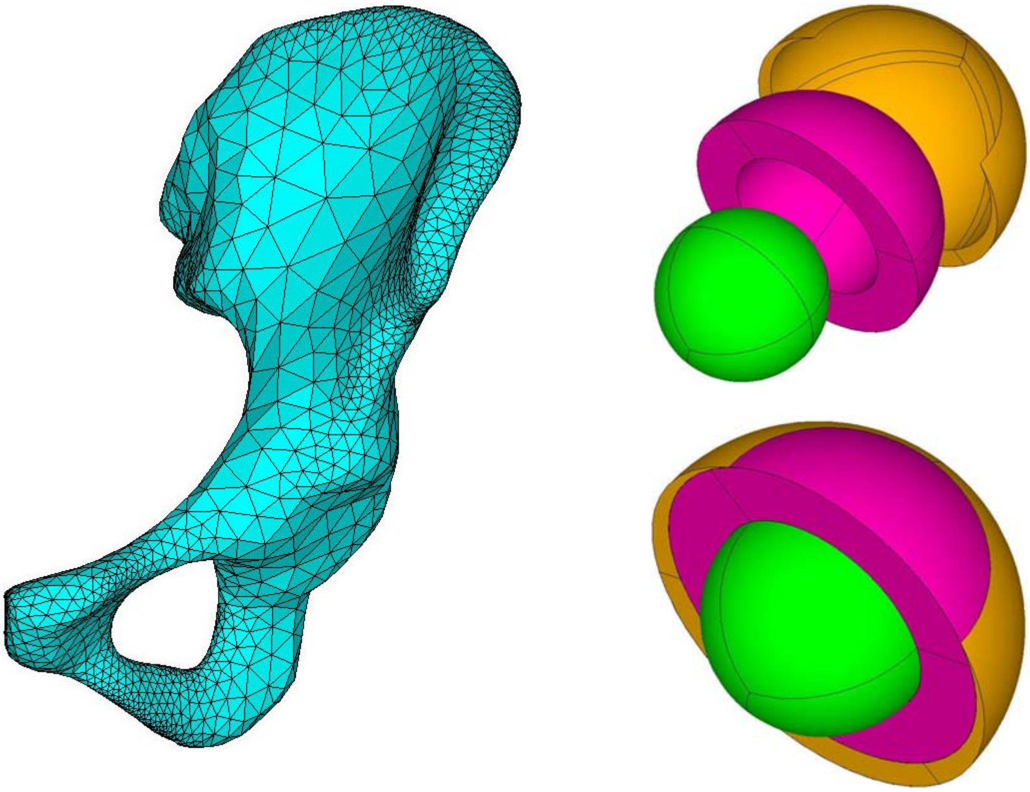
Figure 1: Irregulate shape of cement layer

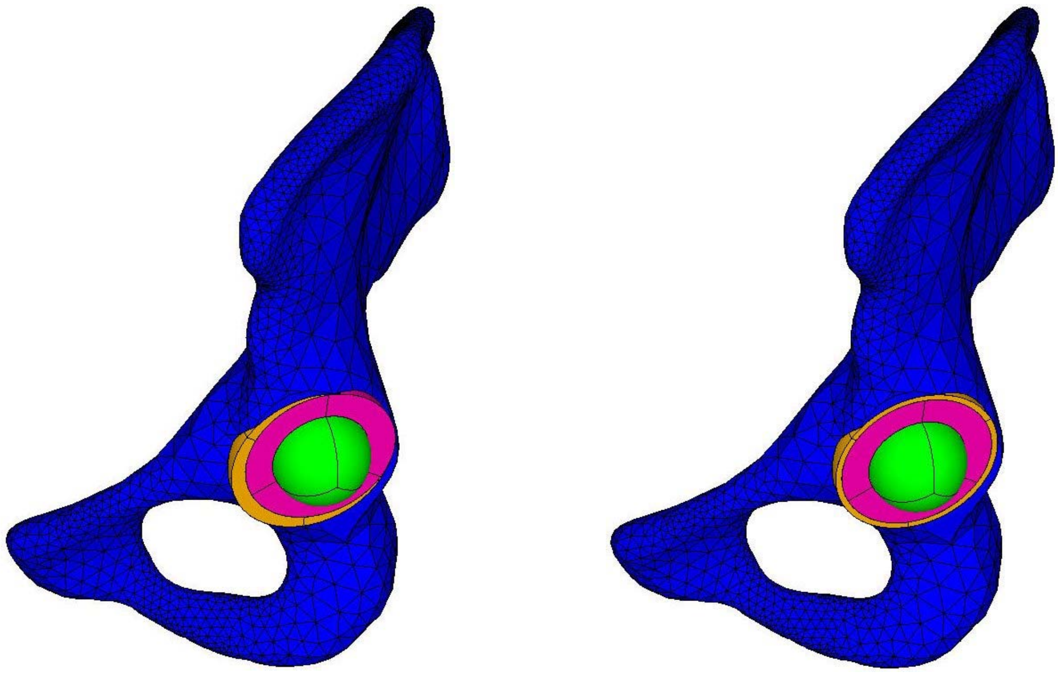


(a) Geometric model of pelvic bone

(b) Geometric model of the accetabular component with imperfection in the cement layer

Figure 2: Geometric models

bearing structure. In the case of cemented acetabular implants the remaining cartilage is removed from the acetabulum and the shape is adapted to the original one by means of a spherical milling machine. By this procedure a roughly spherical bed is obtained. The size and character of the contact stress distribution in subchondral bone depends on the type of imperfections in cement layer. One of the imperfections is non-uniform cement layer.



(a) FE model with imperfection in cement layer (b) FE model without imperfection in cement layer

Figure 3: FE models

This imperfection is created during the implantation process, when polyethylen cup is not placed in the centre of the acetabulum so that the cup forces out the bone cement and creates direct contact between polyethylene cup and pelvic bone (Fig. 1).

2. Materials and Method

The three-dimensional geometrical model of the left pelvic bone (Fig. 2a) is generated from the sequence of 240 CT slices using segmentation procedures [Jirousek, 2004] followed by surface reconstruction. Geometric model of the acetabular component polymethylmethacrylate bone cement and polyethylene cup with ceramic head (Fig. 2b) is inserted into the pelvic bone by means of Boolean operations. The endoprosthesis is inserted with 47.5° inclination and 19.7° anteversion with the ceramic head being positioned out of centre of the acetabular cavity for first model (Fig. 3a) and at the centre of the acetabular cavity for second model (Fig. 3b).

Table 1: Material propertiesassigned to the FE model

Material	E (Mpa)	μ	References
Pelvis - Trabecular bone	100	0.3	[Dalstra et al., 1993]
Pelvis - Subchondral bone	500	0.3	[Dalstra et al., 1993]
Pelvis - Cortical bone	5,600	0.3	[Choi and Goldstein, 1992]
Bone cement (PMMA)	25,000	0.35	[Helsen and Breme, 1998]
Polyethylene (UHMWPE)	1,200	0.39	[Helsen and Breme, 1998]
Ceramics (Al2O3)	380,000	0.22	[Helsen and Breme, 1998]

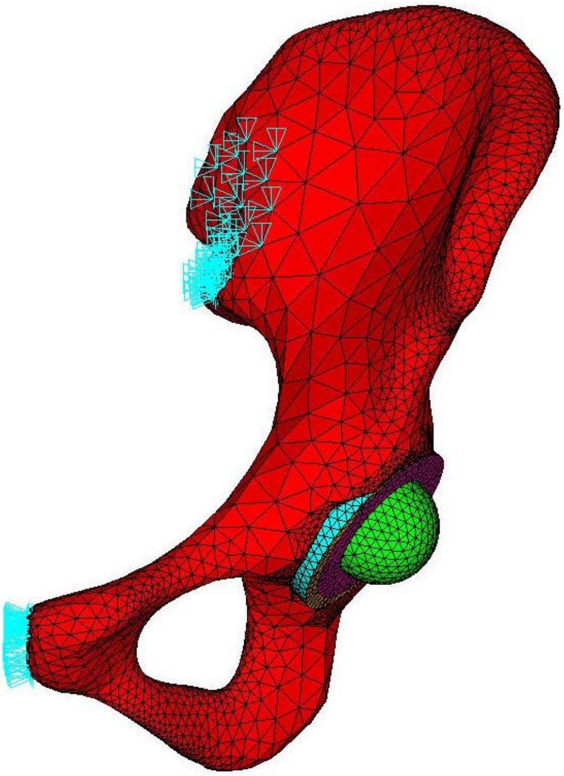


Figure 4: FE model and specified boundary conditions

The whole high resolution finite element models (Fig. 3) is composed of the above mentioned geometrical models. Modelling and all simulations are carried out using ANSYS [ANSYS, 1983] FE package. Elements representing trabecular bone are created using quadratic tetrahedral elements SOLID187. The same element type was used for meshing all the other parts of the cemented acetabular component model. The surface of the pelvic bone is covered by the layer of cortical bone modelled with quadratic shell elements SHELL93 of 0.9 mm constant thickness and the surface of acetabulum is covered by the layer of subchondral bone modelled with quadratic shell elements SHELL93 of 0.7 mm constant thickness. Material properties assigned to the FE model are shown in Tab. 1.

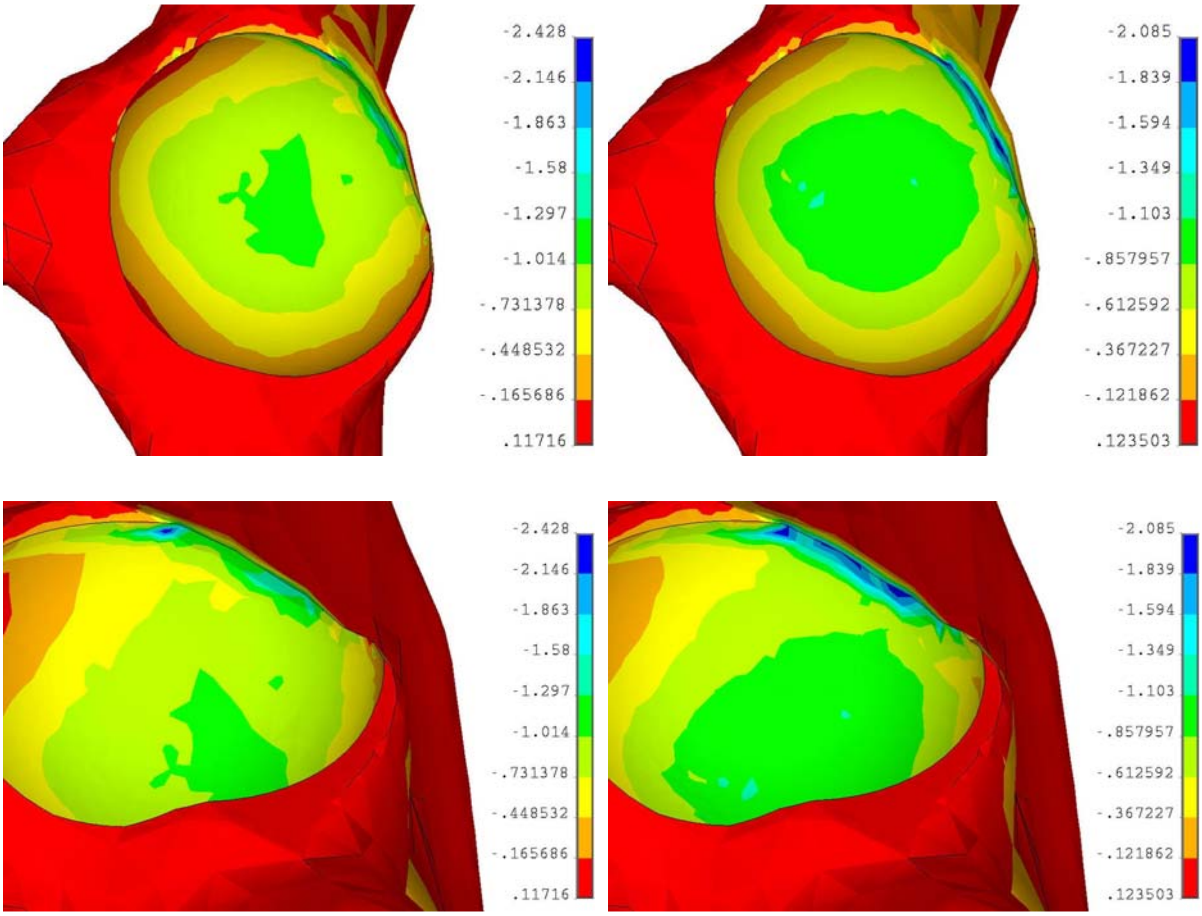
3. Numerical Contact Analysis

Boundary conditions are specified at the sacro-illiac joint, where the nodes are fixed in all directions and at the contralateral side of the pubic symphysis, where the nodes are fixed in x and y directions (Fig. 4). Three contacts are defined in the first FE model and two contacts in the second FE model. The first contact is defined between the pelvic bone and the external surface of the cemented layer. Surface elements TARGE170 cover the surface of subchondral bone and elements CONTA174 cover the opposite surface of the cement layer. The second contact is defined on the internal surface between the cemented layer (TARGE170) and the polyethylene cup (CONTA174). The third contact is defined between the pelvic bone (TARGE170) and the polyethylene cup (CONTA174). The friction value used f=0.5 represents an intermediate value determined for the wet femoral bone and the titanium implant [Shirazi-Adl et al., 1993], but could vary according to surface roughness of the cement layer and the bone tissue or even the presence of an affective lubricant (e.g. blood). The friction value f=0.6 is used for the first contact. The friction value f=0.8 is used for the second contact and f=0.3 is used for the third contact. FE model without imperfection in the cement layer haven't the third contact between the pelvic bone and the polyethylene cup.

Bergman et al. [Bergmann et al., 2001] conducted unique data based of hip contact forces with instrumented endoprostheses. Synchronous analyses of gait patterns and ground reaction forces were performed at four patients during the most frequent daily activities. In our computational model quasistatic joint contact forces, representative of the stance phase of gait, were applied to the model (body weight BW=84 kg) during normal walking 4 km/per hour. The loading was applied to the centre of the ceramic head. Interaction of the cemented acetabular component with the underlying subchondral bone is studied as a contact analysis.

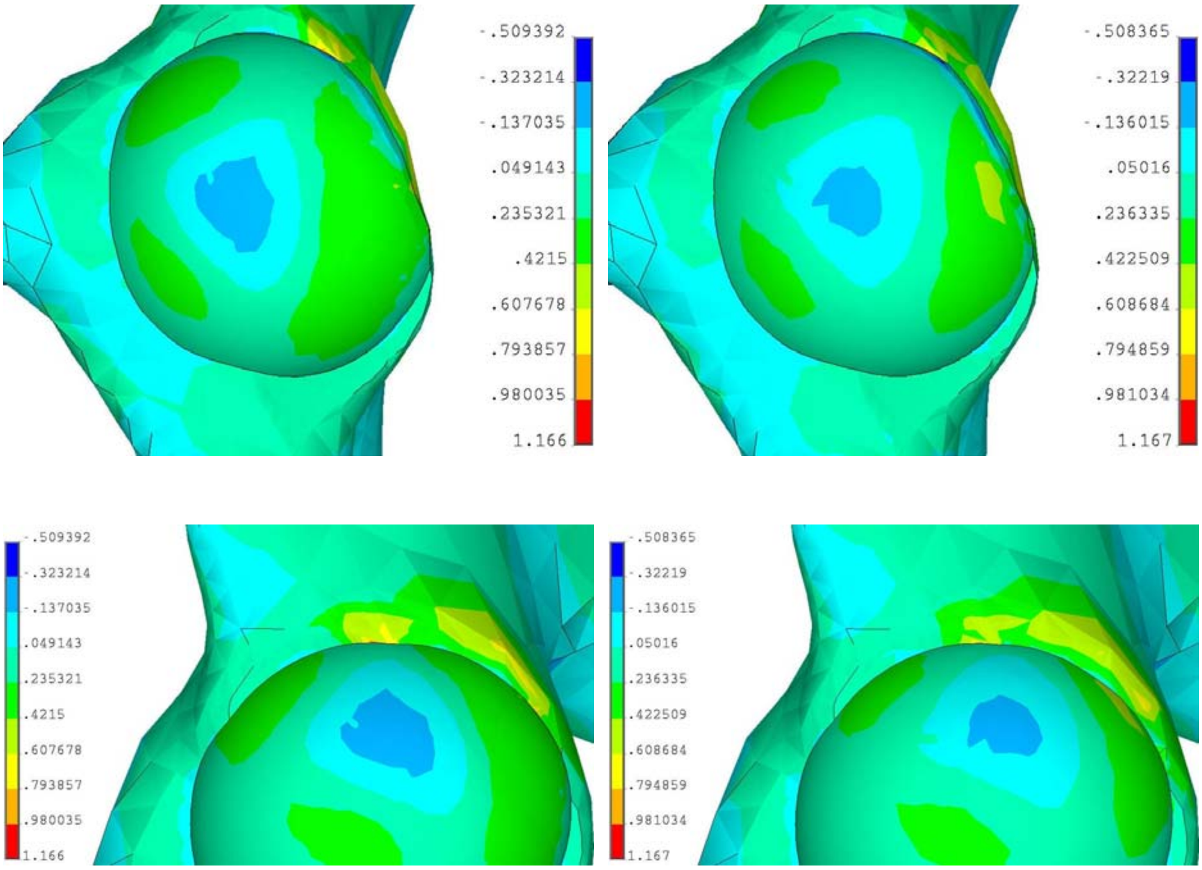
4. Results and Conclusions

Stress distribution in subchondral bone tissue depends on the imperfection in the cement layer. If the imperfection is in the cement layer then the local stress concentration is in the pelvic bone on the border of the imperfection. On the other hand if the cement layer have no imperfection then the stresses are distributed on the border of the cement layer. Maximal values of contact stresses in the subchondral bone occurring during one step (normal walk) are given in Fig. 4. Computational modelling has showed that the subchondral bone at the contact with the cement layer is even unphysiologically loaded by tension stresses (Fig. 5) during the routine activities of the man. The FE model is appropriate for the solving contact stress analysis of the interaction between the pelvic bone and the cemented acetabular component and will be used in the next analysis.



(a) Model with imperfection in cement layer (b) Model without imperfection in cement layer

Figure 4: Principal stress distribution σ_3



(a) Model with imperfection in cement layer (b) Model without imperfection in cement layer

Figure 5: Principal stress distribution σ_1

Table 2: Results of contact stress analysis

Model	Stress s3 max [MPa]	Stress s1 max [MPa]
With imperfection in cement layer	-2.4	0.9
Without imperfection in cement layer	-2.0	0.7

5. Acknowledgement

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