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ANALYSIS OF THE MANUFACTURE PERTURBATIONS OF THE TOTAL HIP REPLACEMENT

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Abstract: *One type of total hip replacement function loss is acetabular cup loosening from the pelvic bone. This article examines manufacture deviations as one of the possible reasons for this kind of failure. Both dimensions and geometry manufacturing deviations of ceramic head and polyethylene cup were analyzed. We find that deviations 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.*

Keywords: Total hip replacement, FEM, Roundness, Contact pressure, Frictional moment.

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 (Fuis et al., 2001 – 2010).

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 (Gualtieri et al., 2001). One type of THR functionality loss is loosening of the acetabular cup from pelvic bone (Fig. 1).

Fig. 1: Continuity of acetabular cup loosening from pelvic bone (Krbec et al., 2001).

The Faculty Hospital Brno (FHB) has an ongoing project examining the clinical impact of manufacture perturbations in hip prostheses (Krbec et al., 2001). During a five year period, a failure rate of 26 % (Walter Motorlet Co. – Fig. 2) in THR due to loosening was at the FBH.

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 (Charnley et al., 1969). Amount of polyethylene wear is influenced by contact pressure and frictional moment between head and cup (Mak et al., 2002) and (Saiko and Calonius, 2003). Maximal value of the contact pressure is thought to be influenced by contact surfaces inaccuracies created during the fabrication process.

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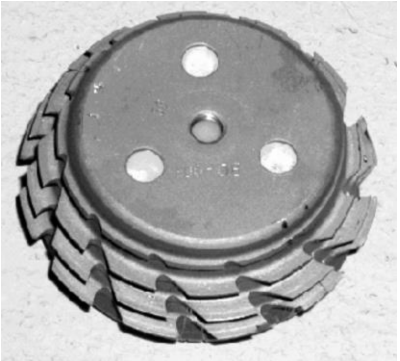

Fig. 2: Acetabular cup made by Walter-Motorlet Co. (Krbec, et al., 2001).

2. Computational modelling

The parametric geometry model of the system was created due to the possibility to study influences of perturbations of the shape deviations. Model consists of the following parts: 1 – pelvis bone with cortical and cancellous part, 2 – acetabular shell (titanium), 3 – acetabular cup (UHMW polyethylene) and 4 – femoral head (ceramic) (Fig. 3).

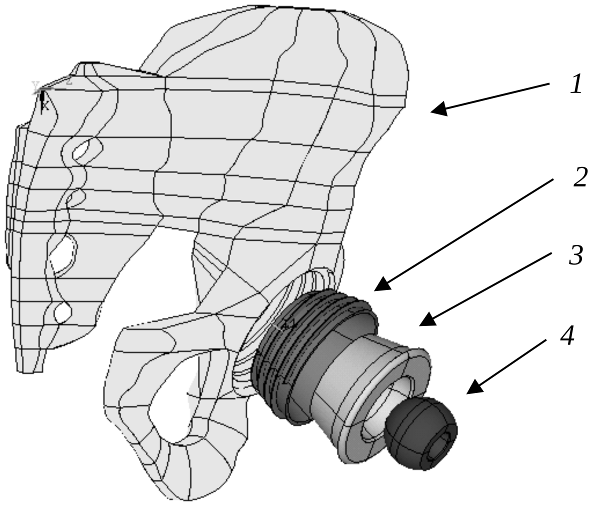

Fig. 3: Components of the analysed system.

The variable geometry parameter was inner cup's diameter – from 31.7 mm to 32.4 mm (from interference fit (overlap) 0.3 mm to clearance fit (gap) 0.4 mm - nominal diameter is 32 mm). The variable material parameter was modulus of elesticicty of the acetabular cup – Tab. 1. Linear isotropic material models were used for all components with characteristics summarized in Tab. 1.

Tab. 1: Material characteristics.

Model part - material	**Modulus of elasticity E [MPa]**	**Poisson`s ratio μ [-]**
Femoral head - ceramics Al_2O_3 (Fuis et al., 2009, 2011)	3.9×10^5	0.23
Acetabular cup - UHMWPE	600 – 1200 (analysed interval)	0.40
Acetabular shell - titanium	1.0×10^5	0.30
Pelvis - cancellous / cortical bone (Dunham et al., 2005; Boyce et al. 1996; Jiahau, 2006; Rho et al., 1998)	$2.0 \times 10^3 – 1.4 \times 10^4$	0.25 – 0.30

The first contact pair was modelled by creating contact elements between femoral head and acetabular cup, with coefficient of friction f = 0.1. The second contact pair was created between acetabular cup and shell. The loading and boundary condition of the analysed system is shown in Fig. 5 and is realized by the force F = 2500 N which is applied in the centre of femoral ball head (α = 13.5°). This loading corresponds to the physiological loading of the pelvic (weight of a human is 80 kg).

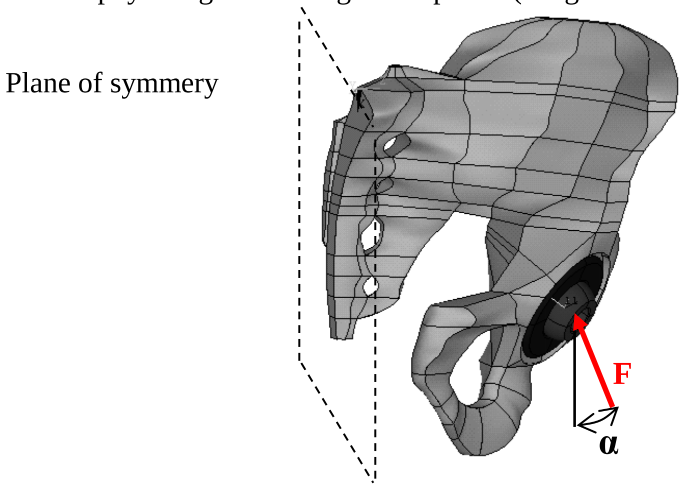

Fig. 5: Loading of the head.

3. Results

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). 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. 6 for E = 1000 MPa). Increasing the clearance between the head and the cup by 0.1 mm the contact pressure raised by ~10 %. 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.

To study the influence of the elasticity modulus of the polyethylene cup the modulus of elasticity value varied from 600 MPa to 1200 MPa. 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.

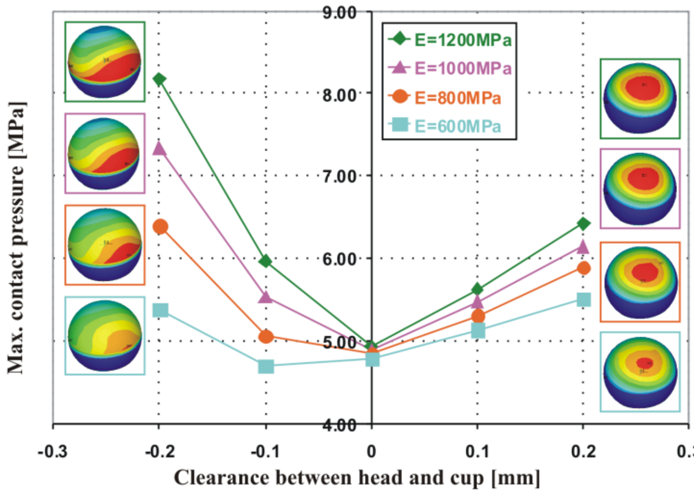

Fig. 6: Acetabular cup modulus of elasticity vs. contact pressure and different clearance.

4. Conclusion

We discovered, that if the value of deviations 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.

Value of the contact pressure affects 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 (Teoh et al., 2001; Ipavec et al., 1999 and Genda et al., 2001).

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References

Boyce T.M., Fyhrie D.P., Brodie F.R. and Schaffler M.B. (1996) Rezidual Mechanical Properties of Human Cortical Bone Following Fatigue Loading, in: 20th Annual Meeting of the American Society of Biomechanics, Atlanta, Georgia.

Charnley, J., Kamangar, A. and Longfield, M. (1969) The Optimum Size of Prosthetic Heads in Relation to the Wear of Plastic Socket in Total Replacement of the Hip, Medical & Biological Engineering, Vol. 7, pp. 31-39.

Dunham, Ch. E., Takaki, S.E., Johnson, J.A. and Dunning, C.E. (2005) Mechanical Properties of Cancellous bone of the Distal Humerus; in: ISB XXth Congress - ASB 29th Annual Meeting, 564, Cleveland, Ohio.

Fuis, V. and Janicek, P. (2001) Stress and reliability analyses of ceramic femoral heads with axisymmetric production inaccuracies. in: Proc. 9th Mediterranean Conference on Medical and Biological Engineering and Computing, Pula, Croatia, IFMBE Proceedings Pts. 1 and 2, pp. 632-635.

Fuis, V. (2004) Stress and reliability analyses of ceramic femoral heads with 3D manufacturing inaccuracies, in: Proc. 11th World Congress in Mechanism and Machine Science, Tianjin, China pp. 2197-2201.

Fuis, V. et al. (2006) Reliability of the Ceramic Head of the Total Hip Joint Endoprosthesis Using Weibull's Weakest-link Theory. in: World Congress on Medical Physics and Biomedical Engineering, IFMBE Proc. Vol. 14, pp. 2941-2944.

Fuis, V, Janicek, P. and Houfek, L. (2008) Stress and Reliability Analyses of the Hip Joint Endoprosthesis Ceramic Head with Macro and Micro Shape Deviations, in: 13th Conf. ICBME, IFMBE Proc. Vol. 23, Iss. 1-3, pp: 1580-1583.

Fuis, V. and Varga, J. (2009) Stress Analyses of the Hip Joint Endoprosthesis Ceramic Head with Different Shapes of the Cone Opening. in: Proc. 13th International Conference on Biomedical Engineering, IFMBE Proceedings Vol. 23, Iss. 1-3, pp. 2012-2015.

Fuis, V., Navrat, T. and Vosynek, P. (2010) Analyses of the Shape Deviations of the Contact Cones of the Total Hip Joint Endoprostheses. in. Proc. 6th World Congress of Biomechanics (WCB 2010) Singapore, Series: IFMBE Proc. Vol. 31, pp. 1451-1454.

Fuis, V., Malek, M. and Janicek, P. (2011) Probability of destruction of Ceramics using Weibull's Theory, in: Proc. 17th International Conference on Engineering Mechanics, Svratka, Czech Republic, pp. 155-158.

Genda, E., Iwasaki, N., Li, G., MacWilliams, B.A., Barrance, P.J. and Chao, E.Y.S. (2001) Normal Hip Joint Contact Pressure Distribution in Single-Leg Standing – Effect of Gender and Anatomic Parameters; J. of Biomechanics 34, pp. 895-905.

Gualtieri, G., Calderoni, P., Ferruzzi, A., Frontali, P., Calista, F. and Gualtieri, I. (2001) Twenty Years Follow-up in Ceramic-Ceramic THR at Rizzoli Orthopaedic Institute, in: 6th Int. BIOLOX Symposium, pp. 13-17.

Jiahau, B.Y. (2006) Mechanical Properties and Testing of Bone, Postdoctoral Research Associate, Dental Biomaterials, Indiana.

Krbec, M. et al., (2001) Loosening of the uncemented cups of total hip replacement from pelvic bone, V. National congress ČSOT, p. 108, Prague.

Mak, M.M. and Jin, Z.M. (2002) Analysis of Contact Mechanics in Ceramic-on-Ceramic Hip Joint Replacement; Journal of Engineering in Medicine, Vol. 216. No. 4.

Ipavec, M., Brand, R.A., Pedersen, D.R., Mavcic, B., Kralj-Iglic, V. and Iglic, A. (1999) Mathematical Modelling of Stress in the Hip During Gait; Journal of Biomechanics 32, pp. 1229-1233.

Rho, J.Y, Kuhn-Spearing, L. and Zioupos, P. (1998) Mechanical properties and the hierarchical structure of bone, Medical engineering & physics, Vol. 20, No. 2, pp. 92-102.

Saikko, V. and Calonius, O. (2003) An Improved Method of Computing the Wear Factor for Total Hip Prostheses Involving the Variation of Relative Motion and Contact Pressure with Location on the Beraing Surface; Journal of Biomechanics, Vol. 36, pp. 1819-1827.

Teoh, S.H., Chan, W.H. and Thampuran, R. (2001) An Elasto-plastic Finite Element Model for Polyethylene Wear in Total Hip Arthroplasty, J. Biomech 2002, 35: 323-330.