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EARLY DEFECT DETECTION OF ACETABULAR IMPLANTS

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Abstract: *The paper is focused on possibilities of modern X-ray detectors and micro-focus X-ray source for investigation of early degradation processes of acetabular implants. To simulate the most adverse activity (downstairs walking) a hip joint simulator was developed. The experimental setup was designed for cyclic loading of polyethylene acetabular cup implanted into the human pelvic bone and fixed by commercial polymethyl methacrylate bone cement. To predict the bone degradation numerical analysis of detailed three-dimensional model of the acetabular cup and the cement mantle implanted in a bone block was performed. Using large area flat panel detector and microfocus X-ray source it is possible to investigate micro-damage propagation and detect early defect in the bone-implant interface.*

Keywords: ***bone–cement interface, computed tomography, crack detection, hip simulator***

1. Introduction

Total hip arthroplasty has emerged as one of the most successful interventions in orthopaedics. In spite of the successful use of the total endoprosthesis there is still a number of problems connected with the artificially created co-existence and interaction between the bone tissue and the technical substances of the endoprosthesis. From an engineering perspective these must be designed with the sufficient mechanical strength and be able to endure the biological environment in which they are placed. In order to reduce the incidence of an implant failure, it is important that the entire system is fully characterized; from the anatomy of the joint and the biological response, through to the micro-structure of the material and the design geometry.

2. Materials and methods

To determine the degradation caused by cyclic mechanical loading radiological investigation have been used. Cement layer degradation were investigated using hip simulator. To predict the bone degradation numerical analysis of detailed three-dimensional model of the acetabular cup and the cement mantle implanted in a bone block was performed. Image data from microtomography (μCT) were used to reconstruct the complex geometry of the inner structure of the trabecular bone and the interface between the pelvic bone and the implant. Visualization of trabecular bone structure and cement layer changes (damage accumulation) provided information about implant instability progress.

To obtain mechanical properties of the trabecular bone for numerical model time-resolved μCT described in Jirousek & Zlamal (2011) and Digital Volume Correlation (DVC) was employed. Regard to the cancellous bone microstructure composed of trabeculae the sample $12\,\mathrm{mm}$ high and $10\,\mathrm{mm}$ in diameter was drill out from proximal femur. Special loading device was designed for this purpose. The frame of the device was made from plastic material with very low absorption of X-rays. The sample was fixed in an cylindrical chamber and loaded. The incremental loading with $100\,\mu\mathrm{m}$ increments up to $10\,\%$ deformation was applied in the experiment. The loading device was mounted on a rotational table and placed between the X-ray source and detector. Microfocus X-ray source was used together with X-ray detector Medipix-2 for the imaging.

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To obtain a better information about stress distribution during the gait cycle (one step) and location of early defect regions the numerical simulation was performed. Finite element model of acetabular socket with cement layer and acetabular component was developed. 10-node tetrahedral elements was chosen for meshing of all components because of the thin geometry and small radius of the cement mantle model. The simulation was assumed to be quasistatic, divided in 20 loadsteps. The loading force value and the direction of downstair walking in each load step was measured by Bergmann (2001). The contact was used for more accurate force transmission to the pelvis. The model was constrained by fixation of all degrees of freedom at the bottom part. At $20\,\%$ of the gait cycle the maximum stress $12.48\,\mathrm{MPa}$ was reached in area of the acetabular labrum. In this region the risk of potential damage is expected.

New hip joint simulator was designed to allow fatigue testing of the sample of pelvic bone with implanted cemented acetabular component. The simulator was designed as an accessory for Instron 1343 (Illinois Tool Works, Inc.). Fatigue tests were carried out using servo-hydraulic loading device. The force-driven loading had a sinusoidal run. The hip contact force of required direction and magnitude was applied to the implant using spherical femoral component head. According to hip contact forces measurement presented by Bergmann (2001) mean value $1300\,\mathrm{N}$ and amplitude $1000\,\mathrm{N}$ were chosen to simulate the most unfavorable activity (downstairs walking).

High resolution μCT was used in the investigation of changes in the cement layer cement-bone interface and the actual trabecular bone at the microscopic level. The process of damage accumulation was monitored by repeated scanning. Imaging was performed four times a sample. First the pelvis resected by the dimensions of the corresponding size of the detector with intact acetabulum was scanned. After that the joint replacement was implanted and re-imaged. A quarter of a million load cycles were applied to the pelvis at the hip simulator. After this time some initialization damage of cement could be expected, therefore another scanning has been done. After 300,000 load cycles the pelvis damage was seen with the naked eye, therefore the loading test was completed and final imaging was done. To acquire the radiograph of acetabular region microtomography device in detail described in Jakubek (2006) was used. Sequence of 360 projections with $1\,^\circ$ step was acquire using microfocus X-ray source and flat panel detector. High resolution models based on a sequence of 1100 slices with resolution $2368 \times 2240\,\mathrm{px}$ and $16\,\mathrm{bit}$ color depth were developed to investigate implant degradation during the loading.

3. Results and conclusions

The failure of total hip joint replacement was described in this work by the method combining of material testing, numerical simulation, ex vivo experiments and radiological imaging. Mechanical tests were carried out to obtain mechanical properties of trabecular bone. Assessed material properties were used in numerical simulations. Presented hybrid experimental–numerical approach allow successful monitoring of cemented hip joint replacement degradation. Finite element model of the acetabular cup and the cement mantle in a small bone block was developed. Numerical analysis was carried out and from stress distribution during gait cycle number of cycles with $25\,\%$ damage probability was estimated. The implanted cup was then loaded in a custom hip simulator to initiate fatigue crack propagation in the bone cement. The crack propagation and debonding was observed using μCT. The replacement degradation was observed at the place predicted by numerical model.

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