EFFECT OF IMPLANT MATERIAL PROPERTIES ON REMODELLING OF A COMPOSITE HIP STEM

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INTRODUCTION

Stress-shielding following uncemented hip replacement causes bone remodelling due to alteration of the load transfer pathways. The degree of bone resorption is related to the geometry and bending stiffness of the stem. Large diameter, cobalt chrome stems are attributed with producing the most pronounced bone loss.

The Epoch hip prosthesis (Zimmer Inc., Warsaw, IN) is a low bending stiffness, noncemented stem. It consists of a CoCr core with a polymer (Ultrapek) outer surrounded by a porous coated layer. The design couples the concepts of the low modulus cemented hip with the noncemented stem. It consists of a CoCr core with a polymer (Ultrapek) outer surrounded by a porous coated layer. The bending stiffness of the prosthesis is similar to that of a normal femur [1]. Traditional clinical appraisal of femoral stem performance requires clinical follow-up for many years to fully assess the efficacy of the device. Numerical bone remodelling simulations allow for theoretical preclinical prediction of implant success.

Periprosthetic bone remodelling after reconstruction with the Epoch hip prosthesis was investigated by finite element modelling. To demonstrate the influence of the implant material properties, the results were compared with the same stem made entirely of cobalt chrome, and a stem with the same stiffness as cortical bone (isoelastic).

METHODS

A representative cadaveric femur was selected by a surgeon for CT-scanning using a Toshiba Whole-Body X-Ray CT Scanner. Slices were taken at 3 mm intervals proximally and 5 mm intervals distally. A slice thickness of 2 mm was used in all cases. Custom software was used to extract the contour of the periosteal surface of the femur at each slice. The contours were imported into MSC.Patran 2001 (MSC.Software Corporation, Santa Ana, CA) and used to reconstruct the geometry of the femur. A solid finite element model of the intact femur was subsequently created with 10-noded tetrahedral elements.

A finite element model of the implant was constructed from a CAD file obtained from the manufacturer. This was positioned appropriately within the femur model. The implant material properties were as follows: composite stem (CoCr core E = 210 GPa, polymer outer E = 4 GPa), CoCr stem (E = 210 GPa), and isoelastic stem (E = 20 GPa).

The initial bone material properties were assigned at each element integration point according to a relationship between the elastic modulus and the apparent density [2]. Apparent density was determined from the Hounsfield units in the CT data. A complete muscle set was used, representing 45% of the gait cycle [3].

An adaptive elasticity method, incorporating a forward Euler integration scheme, was used to simulate internal bone remodelling (change in density). This method assumes that bone reacts to a local difference between the strain in the implanted femur (actual strain) and the strain at the same position in the intact femur (attractor-state strain). The strain difference causes a gradual change in bone density as the actual strain endeavours to approach the attractor-state strain. Numerical analysis was performed with Abaqus v6.2 (Hibbitt, Karlsson & Sorensen Inc., Pawtucket, RI).

The minimum principal strains were used as the remodelling signal. Thus for an element in compression, resorption would occur if the strain (ε) was greater (ie. less negative) than the attractor-state strain (εAS), and apposition would occur if the strain was less (ie. more negative) than the attractor-state strain. A dead-zone width equal to 50% (ε = 0.5) of the attractor-state strain was implemented. The change in bone density per iteration time (Δt) was expressed by a change in Hounsfield units (ΔHU):

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\Delta HU = \Delta t \left( K_{\text{res}}(\epsilon - (1 - s)\epsilon_{\text{AS}}) + K_{\text{app}}(\epsilon - (1 + s)\epsilon_{\text{AS}}) \right)
\]

where Kres and Kapp determine the rates of resorption and apposition respectively. These values were kept relatively low to ensure a stable solution. The change in Hounsfield unit at each integration point determined the corresponding new elastic modulus which was input to the subsequent iteration. Integration continued until the change in bone density was minimal.

The Hounsfield unit distribution was output to file at regular intervals during the analysis. These was viewed using lab software and simulated DEXA images were produced. The simulated DEXA images were analysed by calculating the average greyscale value in a region of interest corresponding to Gruen Zone 7 using Global Lab Image/2 (Data Translation Inc., Malboro, MA). The percent change in bone density from the initial state was quantified in this manner and compared for each model.

RESULTS

The amount of bone loss in Gruen Zone 7 for the standard composite Epoch, the CoCr stem, and the isoelastic stem is presented in Figure 2.

DISCUSSION

Numerical bone remodelling simulation with physiological loading predicted a distinct difference in the degree of bone loss associated with the material properties of the femoral component.

In a dual-energy x-ray absorptiometry study on 24 patients with the Epoch, average bone loss in Gruen Zone 7 was 15.8% [4]. Our model underestimates this value somewhat; however, no standard deviation was specified in this publication [4]. Therefore it is not known whether the current patient specific numerical prediction lies within the range of clinical data. Nevertheless, this study demonstrates a relationship between bone loss and the bending stiffness of the hip implant and may be a useful preclinical screening technique for new implant designs and materials.

REFERENCES


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