Analysis of femoral hip prosthetic geometry and material interdependence

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Introduction

Since the early 1970’s attempts have been made to reduce the stress shielding effects of stiff stems used in total hip replacement (THR). To this end, endeavours have been made to design stems of traditional geometry from materials with an elastic modulus similar to bone, such as carbon fibre reinforced polymers. These attempts have met with unsatisfactory results due to the increased levels of proximal bone-prosthesis interface stress (Huiskes et al., 1992) and the lower fatigue resistance of polymeric materials (Srinivasan et al., 2000).

To reduce stress shielding and stem-bone interface micro motion while simultaneously satisfying fatigue resistance requirements, a fundamental relationship to be addressed is the interdependence of the stem's material and geometry. Dramatically changing the material properties of stems used in THR necessitates a reconsideration of the stem geometry. Changing the stem geometry necessitates a reconsideration of the material properties. To investigate the appropriate geometry for a low elastic modulus material, a finite element model of an implanted, non-cemented stem was analysed with various stem material properties.

Methods

A three-dimensional finite element model of the proximal femur was constructed from CT scan cross sections, Figure 1, and assigned inhomogeneous cortical and cancellous bone material properties from QCT data that were validated in a previous study (Taylor et al., 2001). A commonly used non-cemented stem (Alloclassic™ Zweymüller™, Sulzer Orthopaedics, Winterthur, Switzerland) was selected for modelling and together with the femur contained 42,978 quadratic tetrahedral elements. The stem was assigned an isotropic Young’s modulus between 4 and 120 GPa representative of the variable material properties between neat PEEK, fibre reinforced PEEK, and titanium alloy. The maximum load during staircase climbing (Bergmann et al., 2001) was selected as the boundary condition. The interface between the stem and femur was modelled using Coulomb friction with values representative of low (high) bone on growth; μ = 0.2 (μ = 0.8).

Results & Discussion

Reduction of the elastic modulus of the stem resulted in less stress shielding and greater interface stress (implying a greater potential for interface micro motion) proximally. These results agree with those observed in previous studies (Huiskes et al., 1992).
Stress at the junction of the medial stem neck and intramedullary shaft exceeded the fatigue stress limit for carbon fibre reinforced PEEK but not for titanium; 84 MPa (Victrex Europa, 1997) and 550 MPa (Gere and Timoshenko, 1991) respectively, Figure 2. Previous experimental fatigue results of carbon fibre reinforced PEEK stems under similar load conditions verify this as a region of failure (Liao and Reifsnider, 1994). This is indicative that, for a stem constructed from a polymeric (implying a low elastic modulus) material, the neck diameter of the intramedullary stem may need to be increased. Careful consideration however must be given to the resulting decrease in the range of motion due to such an increase in neck diameter.

It was observed that as the elastic modulus of the stem decreased the significance of the load transmitting capacity of the distal stem was reduced, Figure 3. An indication that a stem constructed from a low elastic modulus material may not need to extend as deep into the intramedullary canal as stems designed from traditional orthopaedic metallic materials.

It can be concluded from these results that, as generally accepted, stress shielding of the proximal femur can be reduced by lowering the elastic modulus of the intramedullary stem at the expense of increased proximal interface stress. However a polymeric material, with, in general, an inherently lower fatigue resistance should not be expected to be as fatigue resistant as a metallic material. Therefore an alternate geometry may need to be pursued for a stem designed from a polymeric material. From this study it has been observed that a larger diameter neck and shorter stem may need to be considered for a stem designed from a low elastic modulus material.

References


