Influence of an Interference-fit on the strain distribution in the implanted proximal femur

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Introduction

Performance of non-cemented porous-coated femoral hip prosthesis is greatly influenced by the initial stability in the immediate post-operative period. Bone ingrowth is hindered by excessive micromotion at the bone-implant interface (Cameron et al., 1973). In order for non-cemented implant to achieve greater long-term stability through bone ingrowth, minimal micromotion immediately post-operatively is vital. Excessive micromotion prevents calcification of the tissue within the pores, and as a result, only fibrous tissue fixation occurs. Removal of fibrous tissue-fixed implants has been shown to be easier than osseous tissue-fixed implants.

The majority of the cementless hip stems are designed with an initial interference-fit with the bone. The cavity in which the hip prosthesis will be placed is under-reamed so that an interference-fit is created between the femur and the stem. The femur will be left with a residual compressive stress, which is anticipated to reduce micromotion through greater friction force at the bone-implant interface and hence encourage bone ingrowth.

Most of the finite element analyses of the implanted proximal femur do not take into account the residual stress induced by an interference-fit. The objective of this study is to simulate an interference fit in a finite element model of an implanted proximal femur.

Method

A finite element (FE) model was constructed based on computer-tomography (CT) scans of a male human femur obtained from the Visible Human website. The stem used was a proximally porous coated DePuy IPS stem made of titanium alloy. The IPS stem is designed to be implanted into an under-reamed cavity to produce an interference-fit. The implanted femur model was meshed with linear tetrahedral element.

CT scan gray scale values were converted to apparent density values (Hvid et al., 1989) using a linear relationship between CT number and apparent density. The elastic modulus of the bone was assumed to have a relationship with apparent density (Carter and Hayes, 1977) in the form

\[ E = 2875 \rho^{3} \]  

where \( E \) is the elastic modulus and \( \rho \) is the apparent density, assuming the bone was loaded at a physiological strain rate of 0.01s\(^{-1}\). The assignment of material properties was performed using a modified version of the software Bonemat (Zannoni et al., 1998). The distribution of the elastic modulus of bone followed a logarithmic curve, which gave smaller differences between two elastic modulus at the cancellous bone end and greater differences towards the cortical bone end. The elastic modulus of the titanium stem was assigned as 116 GPa.

The bone-stem interface was assumed to be frictionless. Figure 1 showed the forces applied to the models. The joint reaction force was 2870 N, at an angle of 6 degrees to the vertical in the sagittal plane and 20 degrees to the vertical in the frontal plane. An abductor muscle force of 1270 N was applied to the
greater trochanter and was assumed to be vertical in the sagittal plane and at 20 degrees to the vertical in the frontal plane. The femur was constrained in all directions at the distal end. Three different analyses were performed. Models 1 and 2 assumed perfectly elastic material behaviour, and model 3 assumed elastic-perfectly plastic material behaviour. In this case, bone was assumed to yield at a constant yield strain of 1.5 % strain. Models 2 and 3 were modeled with interference-fit of 0.1 mm. Equivalent strain (comprising of elastic and plastic strain components) is reported at the bone-prosthesis interface at the mid section of the porous coating. The severity of loading in bone, which exhibits heterogeneous behaviour, is better described by strain than stress.

Results and Discussion

Figure 2 showed the equivalent strain at the proximal femur, approximately equal to the mid section of the porous coating of the stem (figure 1). The values were from the bone nodes at the prosthesis-bone interface. This represented the typical strain distribution of the bone at the prosthesis-bone interface.

In the elastic, press-fit analysis, the low strain value corresponds to high stiffness region of the femur. The peak strain of 0.01 occurs at the anterior-medial location and high strain is observed at the posterior-lateral side.

Both the elastic and elastic-plastic analyses with interference-fit showed a significantly higher strain than the elastic, press-fit analysis. The elastic analysis showed peak strain of 0.0235 and the elastic-plastic analysis showed peak strain of 0.0373. In both cases, the peak strain occurs at the posterior-lateral side instead of the anterior-medial side as in the elastic press-fit analysis. High strain is also observed in the anterior-medial side. Larger strain deformation occurred at the posterior-lateral side where the bone is softer. Stronger bone on the anterior and medial side of the femur may have pushed the stem toward the lateral side, thus giving a non-uniform interference fit.

Both the elastic and elastic-plastic analyses with interference-fit showed a similar strain distribution. However, in regions where plastic deformation occurs, there is a redistribution of load, and this can be seen from the higher strain at the posterior lateral side.

In practice, it is not clear if interference-fit is ever achieved as designed. It is difficult to ream a cavity with the exact geometry to accommodate the hip stem. Insertion of the stem also could have caused shearing of cancellous bone by the rough porous coating. The extent of the damage to the cancellous bone structure in the immediate post-operative period is therefore unknown. However, assuming that a small interference-fit is achievable, the result of our analysis showed that its effect is very significant. Even a small interference-fit of 0.1 mm can caused difference in strain by more than 50 percent in the softer cancellous bone. Changes in strain in the denser cancellous bone and cortical bone remained small.

The present study did not find extensive plastic deformation. However, if greater interference-fit is achieved, there could be extensive plastic deformation and this may have implications for future implant

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Position: - Anterior = 25, medial = 45, posterior = 65, lateral = 0, 85. Values shown at the position axis represent the hoop forming the hip stem-bone interface at the mid section of the porous coating of the stem.

E = elastic, P = plastic, non-inter = interference fit not modeled, inter = interference fit modeled.
subsidence. This study assumed bone to yield plastically at a strain value of 1.5 percent strain. This value must be viewed as a guide to the risk of plastic deformation, as studies have shown cancellous bone to yield at much lower strains (Keaveny et al., 1994). A study by Kopperdahl and Keaveny (1998) suggested that in tension, yielding of cancellous bone occurred at 0.78% strain regardless of the bone apparent density, and in compression, yielding of bone had a linear dependency on the apparent density.

The question of whether bone will relax considerably in a short time is not clear. Zilch et al. (1980) reported that stress relaxation of a bone specimen under compressive strain reach a constant value in just a few minutes, and the stress relaxed by about 17 percent. This supports the need to take residue stress into account. Ramamurti et al. (1997) in an in-vitro experiment fitted an oversized porous-coated pin into a canine cancellous bone. They applied a torque to turn the pin 20 microns at regular intervals. At least for the first 11 days, they found that the torque needed to turn the pin remained almost the same. They suggested that bone-prosthesis interface was not affected by stress relaxation. However, whether the torque needed to turn the pin is caused by ploughing of bone by the porous-coating beads or by the need to overcome the frictional force remained unclear.

If interference-fit is indeed achieved in the surgery, and stress relaxation of the bone is not great, interference-fit may play an important role in the bone remodeling process of the bone in the immediate post-operative period and therefore should be included in future finite element simulations.

References