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Finite element modelling – predictor of implant survival?

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The cancellous bone stresses surrounding proximal femoral prostheses were investigated using the finite element method and the results correlated with clinical subsidence data for similar implant configurations. The finite element study has shown that press-fit prostheses generate significantly higher cancellous bone stresses than bonded (cemented and HA coated) prostheses. The cancellous bone stresses surrounding press-fit implants are sensitive to the coefficient of friction, with up to a 60% decrease observed when the coefficient of friction was increased from 0 to 0.4. Resecting the femoral neck generally increased the cancellous bone stresses however varying the thickness of the cement mantle had little or no effect. Good correlation was found between the finite element results and the clinically measured subsidence data. Implant configurations generating higher cancellous bone stresses were those which subsided the most. This observation suggests that it may be possible to use the initial cancellous bone stresses to predict the likelihood of migration and hence late aseptic loosening.

1. Introduction

The incidence of late aseptic loosening of proximal femoral prostheses, accounting for 80% of all revision surgery [1], may be predicted from early subsidence rates measured two years post-operatively [2, 3]. The rate of subsidence appears to be dependent on the implant design and, more importantly, the method of fixation. It has been suggested that the rate of subsidence and hence the incidence of late aseptic loosening, is dependent on the initial fixation conditions [2]. This suggests that it may be possible to identify a factor which, at implantation, affects the long term stability of the prosthesis, enabling the development of a pre-clinical screening procedure.

The femoral component of total hip replacement is supported proximally by a layer of cancellous bone [4] and the failure or remodelling of this layer has been speculated as being the mechanism of subsidence [5]. The finite element method has been used to analyse the cancellous bone stress distribution surrounding various implant configurations. In particular, the cancellous bone stresses were examined in relation to the ultimate compressive strength (UCS) and reported *in vitro* fatigue [6] and creep [7] thresholds. The possibility of using the cancellous bone stresses as a predictor of implant subsidence was assessed, based on the hypothesis that increasing cancellous bone stresses lead to increased subsidence rates, by comparing results directly with the *in vivo* measured subsidence rates of similar implant configurations.

2. Methods

A finite element model of an intact femur was generated from transverse CT scans of a cadaveric specimen and then was 'reamed' and 'implanted' with a 14 mm femoral component of the Freeman hip (Corin Ltd, UK). A layer of surface-to-surface contact elements were generated at the bone–prosthesis interface to allow the various methods of fixation to be simulated. Four primary methods of fixation were examined, cemented, fully ingrown HA coated, smooth and ridged press-fit, as described by Taylor *et al.* [8]. Each model consisted of approximately 2300 eight noded brick elements, 300 contact elements (600 in the cemented model) and 3000 nodes.

The material properties of the intact and implanted femur used in this study are shown in Table I. All of the materials were assumed to be homogeneous, isotropic and perfectly elastic except for cancellous bone which was assumed to be elastic-perfectly plastic. The elastic limit of the cancellous bone was calculated from the equations of compressive strength generated from experimental data [9]. The assumption of

TABLE I Mechanical properties of the intact and implanted femur

Material	Young's modulus (GPa)	Poisson's ratio	Ultimate compressive strength (MPa)
Prosthesis (Cobalt-chrome)	200	0.33	—
Bone cement	2	0.33	—
Cortical bone	17	0.33	—
Cancellous bone	0.4	0.33	6

elastic-perfectly plastic continuum behaviour is reasonable for modelling the global deformation of the cancellous bone, when compared to experimental data [10].

The time dependent behaviour of cancellous bone is virtually unknown [11]. Kempson *et al.* [12] speculated, with no experimental evidence, that human cancellous bone will fatigue at stress levels approximately one third of its UCS. This 'rule of thumb' has been subsequently used, with some success, to assess the *in vivo* fatigue susceptibility of implanted ankle [13] and knee [14] joints. Recently relationships for the compressive fatigue [6] and creep [7] behaviour of bovine cancellous bone have been reported, as shown in Equations (1) and (2) respectively.

$$\varepsilon_{max} = 0.00241(N_f)^{-0.072} \quad (1)$$

$$t_f = 8.67 \times 10^{-31}(\sigma/E)^{-15.12} \quad (2)$$

where ε is the global strain (microstrain), σ is the global stress (MPa), E is the global compressive modulus (MPa), N_f is the number of cycles to failure and t_f is the time to failure. For an assumed modulus of 400 MPa Michel *et al.* [6] reported fatigue failure would occur at an apparent stress of 4 MPa after 1 million cycles and Bowman *et al.* [7] reported creep failure would occur at an apparent stress of 2.2 MPa after 8 h.

All models were loaded with a 3 kN joint reaction force applied to the femoral head at an angle of 6° from the vertical in the coronal plane, whilst the distal end of the femur was rigidly constrained [8]. The cancellous bone stresses were examined for a number of implant configurations:

i) Comparison of the methods of fixation — Four methods of fixation were compared, proximally HA coated, fully cemented, smooth and ridged press-fit. For the press-fit implants, the coefficient of friction at the bone–prosthesis interface was varied from 0 to 0.40, representing the extremes of friction that the prosthesis was likely to experience *in vivo* [15].

ii) Neck retention versus neck resection — The effect of the high level of neck resection of the Freeman was compared with more conventional resection levels for the cemented and smooth press-fit prostheses. Resection of the femoral neck was achieved by removing bone elements, and thus material, from the medial aspect of the neck.

iii) Effect of varying the cement mantle thickness — The cement mantle thickness was varied, by implanting prostheses 1, 2 and 3 mm smaller in diameter than the reamed cavity and filling the space with bone cement.

In all of these analyses the principal cancellous bone stresses were examined at two levels, 20 and 35 mm below the medial resection level and the results were compared with those of the intact femur. It should be noted that the apparent stress levels have been reported, at the continuum level, for the cancellous bone, rather than the trabecular tissue stresses. The stresses were analysed with respect to the UCS and the reported *in vitro* fatigue and creep thresholds. The results were also compared directly with the measured mean subsidence, two years post-operatively, for similar implant configurations.

3. Results

3.1. Effect of the method of fixation

For all methods of fixation the peak minimum principal stresses occur around the medial aspect of the prosthesis wedge. The peak maximum principal stresses are significantly smaller and therefore not reported [8]. The cemented and HA coated prostheses produce peak cancellous bone stresses of approximately 4 MPa, an increase of 2 MPa compared to the intact femur (Fig. 1). These stresses correspond to approximately 60% of the ultimate compressive strength of cancellous bone. The smooth and ridged press-fit designs of the prosthesis generated significantly higher cancellous bone stresses, of up to 16 MPa, corresponding to a factor of 8 increase compared to the intact femur. These high stress levels grossly exceed the ultimate compressive strength, by up to 265%, allowing extensive yielding of the cancellous bone to occur in our model.

Increasing the coefficient of friction, from 0 to 0.4, at the bone–prosthesis interface for the press-fit implants produced up to a 60% reduction in the peak cancellous bone stresses (Fig. 2), due to the rougher prosthesis being capable of transferring a portion of the load as shear at the interface. The cancellous bone stresses appear to converge asymptotically at approximately $\mu = 0.3$. The subsequent results are reported for coefficients of friction at the bone–prosthesis interface of 0.0 and 0.2 [15].

3.2. Neck retention versus resection

The resection of the femoral neck had little effect on the cancellous bone stresses surrounding the cemented prosthesis (Fig. 3), causing a slight increase, of approximately 1 MPa, in the peak minimum principal stresses 20 mm below the original resection level, but with no detectable difference 35 mm below the resection level. However for the press-fit prosthesis ($\mu = 0$),

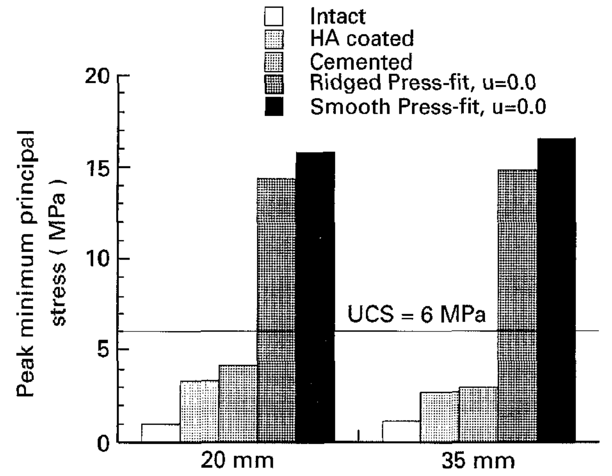

Figure 1- Comparison of the peak principal stresses for the various methods of fixation.

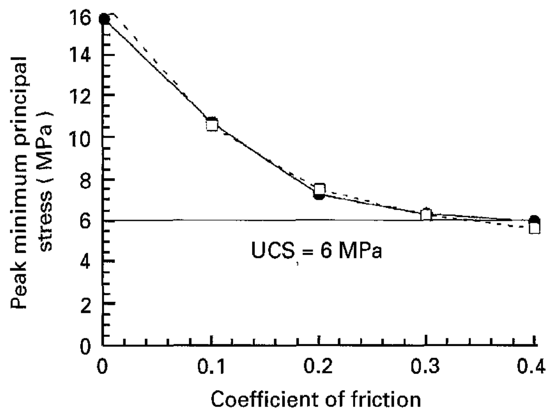

Figure 2 The effect of friction on the cancellous bone stresses produced by the press-fit prostheses. (●), 20 mm; (□), 35 mm.

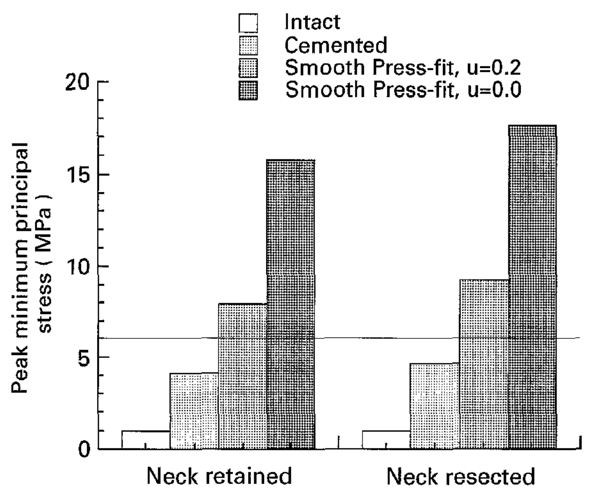

Figure 3 Effect of neck resection on the peak minimum principal stresses 20 mm below the original resection level.

resection of the femoral neck had a significant effect on the cancellous stress distribution. The peak minimum principal stresses increase by approximately 4 and 1 MPa, 20 and 35 mm below the original resection level respectively. A similar trend was observed when the coefficient of friction at the bone–prosthesis interface was increased to 0.2.

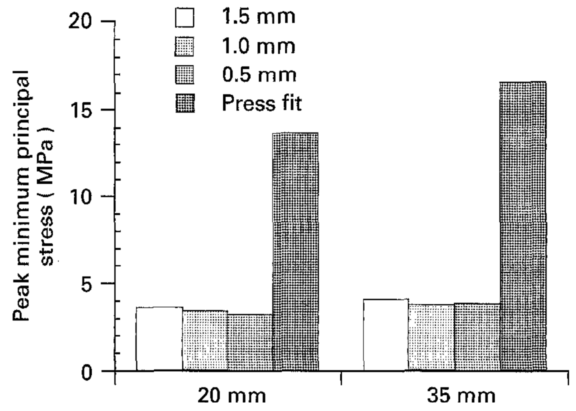

Figure 4 Effect of cement mantle thickness on the peak cancellous bone stresses.

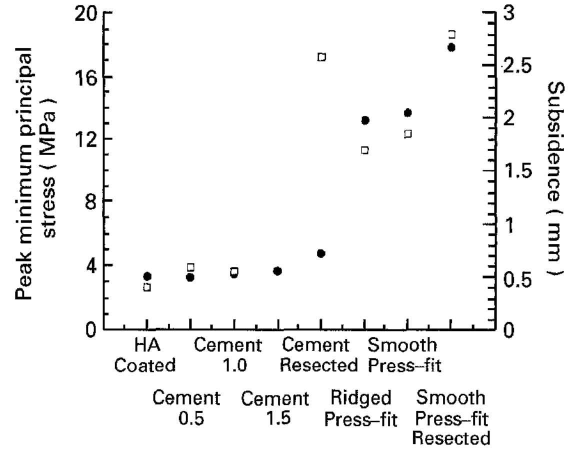

Figure 5 Comparison of the predicted cancellous bone stresses and the migration measured 2 years post-operatively. (●), calculated cancellous bone stresses; (□), subsidence measured at two years.

3.3. Effect of cement mantle thickness

Reducing the thickness of the cement mantle had little effect on the peak cancellous bone stresses (Fig. 4), especially when compared with those produced by a smooth press-fit implant.

3.4. Comparison of finite element results and measured clinical subsidence data

The peak minimum principal cancellous bone stresses for the reported implant configurations were compared directly with the measured subsidence 2 years post-operatively [2, 16]. The rank order of the predicted cancellous bone stresses follows a similar pattern to the measured clinical subsidence (Fig. 5). The only exception to this is the cemented implant with the neck resected. The finite element model predicts only a slight increase in the peak cancellous bone stresses, suggesting there would only be a slight increase in the measured subsidence. However, Braud and Freeman [16] reported a substantial increase in the mean annual subsidence rate, from 0.4 to 1.3 mm, when compared with the femoral neck intact. It should be noted that there were only 10 hips in this group, and therefore may not be a representative sample. The rank order is maintained when the press-fit prostheses are modelled with a coefficient of friction of $\mu = 0.2$.

4. Discussion and conclusions

The press-fit designs of proximal femoral prostheses generate substantially higher stresses within the cancellous bone than the cemented and (fully ingrown) proximally HA coated designs, and these stresses were sufficient to cause permanent deformation. For the press-fit models, increasing the coefficient of friction to 0.2 produced a 50% decrease in the peak cancellous bone stresses. However, even with $\mu = 0.2$, the press-fit prostheses still generate cancellous bone stresses approximately 1.75 times greater than the cemented and HA coated designs and approximately 3.5 times greater than the intact femur and these are still sufficient to cause permanent deformation.

The resection of the femoral neck had a significant effect on the cancellous bone stresses surrounding the press-fit prosthesis, but little or none on those surrounding the cemented implant. For the smooth press-fit implant, resection of the femoral neck resulted in a substantial decrease in the medial load bearing surface area, thus increasing the cancellous bone stresses [17]. Resection of the femoral neck results in only a relatively small reduction in the load bearing surface area for the fully cemented prosthesis, producing only a small increase in the peak cancellous bone stresses. Varying the cement mantle thickness did not alter the load transfer mechanism and therefore the cancellous bone stresses remained virtually unchanged.

The cancellous bone has been modelled as having a single modulus of 400 MPa, however there is likely to be large variation in the modulus *in vivo*, both within a single bone and within the patient population. Taylor *et al.* [8] noted that changes in the cancellous bone stiffness, within a physiological range, did not alter the observed cancellous bone stress distribution but merely shifted the threshold at which potential permanent deformation occurred, due to associated changes in the UCS.

The predicted cancellous bone stresses have only been discussed in relation to the UCS of the cancellous bone under monotonic loading. The press-fit prostheses have been shown to produce stresses sufficient to produce permanent deformation. However, the cemented and HA coated prostheses generated stress levels that were approximately 60% of the UCS, which are not sufficient to produce permanent deformation of the cancellous bone and hence subsidence. The clinical subsidence studies have shown that prostheses with all forms of fixation do subside, albeit at different rates, suggesting, from a mechanical point of view, that subsidence is due to a time (creep) or frequency (fatigue) dependent failure mechanism of the supporting cancellous bone.

Examining Fig. 6 reveals that all methods of fixation approach or exceed a fatigue failure threshold of 4 MPa [6] suggesting that subsidence of all of these implants would be likely. The press-fit implants grossly exceed the fatigue threshold suggesting that they are likely to subside more than the bonded (ingrown HA coated and cemented) designs, as is indeed the case. All the implant configurations would exceed a fatigue threshold of 2 MPa, as proposed by Kempson *et al.* [12]. However, it is interesting to note that the cancellous bone stresses of the intact femur are below both of these reported fatigue thresholds.

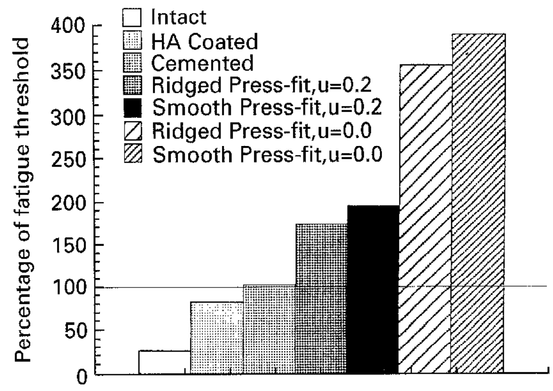

Figure 6 The cancellous bone stresses plotted as a percentage of the fatigue failure stress, of 4 MPa, at 1 million loading cycles [6].

The cancellous bone stresses produced by the press-fit prostheses grossly exceed a fatigue threshold of 4 MPa. When modelled with a frictionless bone–prosthesis interface these prostheses produce peak permanent strains of up to 2.75% after a single load cycle. This corresponds to a permanent deformation of 0.14 mm for a 5 mm thick layer of cancellous bone. When compared against the mean measured clinical subsidence of approximately 2 mm over a two year period, it seems unlikely that such prolific yielding occurs *in vivo* in a single load step. Based on this observation, it seems more sensible to assume that the *in vivo* coefficient of friction approaches or exceeds 0.2.

Bowman *et al.* [7] reported that creep failure occurs at low apparent stress levels of approximately 2.2 MPa (8 h); all methods of fixation exceed this creep threshold value. However, consideration of the type of loading suggests that the hip is more likely to be subjected to fatigue rather than creep processes. Although creep failure may occur at lower apparent stresses, prolonged periods of standing would be required to produce such failure (8 h) and this is unlikely to occur in the elderly. Also, any deformation which may occur may well recover during periods of unloading, due to the visco-elastic nature of cancellous bone. The authors therefore feel that subsidence is more likely to be due to fatigue, rather than creep, of the supporting cancellous bone.

The *in vitro* measured fatigue thresholds take no account for the body's ability to repair any accumulated damage, and thus *in vivo* the fatigue thresholds may be higher than those used here. However, the remodelling and repair response of the elderly may be severely impaired so these results represent the worst case scenario of the *in vivo* situation [18].

The rank order of the predicted cancellous bone stresses correlated well with the clinical subsidence data, supporting the hypothesis that higher cancellous bone stresses produce increased clinical subsidence. This simplified analysis has shown that the cancellous bone supporting a proximal femoral prosthesis is at risk, to a greater or lesser extent depending on the method of fixation, of fatigue failure. Fatigue of cancellous bone will inevitably lead to implant migration.

This may explain the good correlation between the predicted cancellous bone stresses and the measured clinical subsidence, as the rate and magnitude of the subsidence would be dependent on the initial cancellous bone stresses.

These results suggest that it may be possible to use the initial cancellous bone stresses to predict the likelihood of subsidence and hence the incidence of late aseptic loosening. They also cast light on the potential failure mechanism which results in subsidence.

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