THE EFFECT OF CREEP AND LOAD LEVEL ON THE DAMAGE ACCUMULATION WITHIN THE CEMENT MANTLE OF THE CEMENTED IMPLANTED FEMUR

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INTRODUCTION

Failure, or loosening, of the femoral component in cemented total hip replacement (THR) is usually caused by fatigue failure of the cement mantle under cyclic loading. It has been shown that the likely mode of fatigue failure is damage accumulation, where small internal flaws and microcracks propagate under dynamic loading conditions to eventually form critical defects [1].

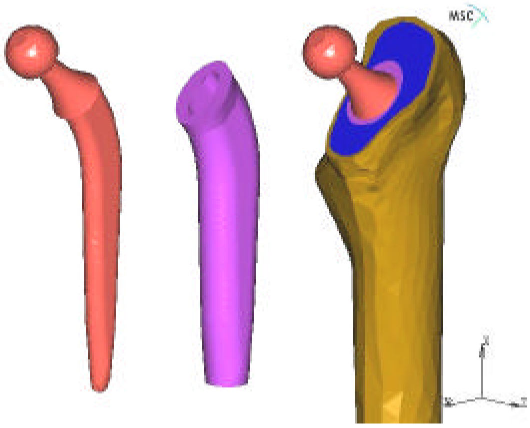

Figure 1. The finite element model

The finite element (FE) technique is a suitable tool to examine the cement mantle, being able to compute stresses and strains at every (finite) point within a complicated three-dimensional geometry. The addition of adaptive simulation algorithms makes it possible to study the cement mantle over time, simulating time dependant properties like creep and damage accumulation.

The aim of this study is to investigate the damage accumulation in the cement mantle for different load levels and to establish the effect creep has on the damage accumulation in a fatigue analysis. Although creep and damage accumulation have been simulated in separate FE studies before [2,3], this study models both time dependant properties simultaneously and aims to provide a direct relationship between creep and damage accumulation.

METHODS

The implanted femur was generated and meshed using I-DEAS™ (figure 1). The femur was based upon a composite Sawbones femur model. The stem used was a Charnley type with collar, based on the DePuy version. A 4mm cement mantle was used to fix the implant in the femur. The mesh used was a tetrahedral mesh, with three elements through the thickness of the cement mantle as this was the area of interest. The implant was assigned a Young's modulus of 200GPa, the cement 2.8GPa, the proximal and distal cancellous bone 0.75 and 5GPa respectively and the cortical bone 17GPa. The Poisson's ratio for the implant and cement was 0.3; the cancellous and cortical bone was given a Poisson's ratio of 0.28. A joint reaction force of 2450N acting on the prosthetic head was applied, with angles of 23° in the frontal plane and 6°in the sagittal plane. The muscle forces included were the abductor muscles, assumed acting on the greater trochanter with a total force of 1650N, with angles of 24° in the frontal plane and 15° in the sagittal plane [2]. This loadcase is hereafter referred to as the standard loadcase, being based upon a patient weighing 100kg (220lb). We introduce two more loadcases, for a lighter patient and an obese patient and scale the forces accordingly [4]. These loadcases are summarised in table 1.

Analysis Name	Patient weight (kg) - [lbs]	Time dependant properties simulated
Standard	100 - [220]	Creep & Damage
Light	70 - [154]	Creep & Damage
Heavy	150 - [330]	Creep & Damage

Table 1. Summary of analyses performed

One further analysis was performed to investigate the effect of creep on damage accumulation. This involved the standard loadcase analysis, but simulated damage accumulation without creep.

The loads described above were applied cyclically to simulate normal gait. Calculation of the time dependant properties of the cement at every loading cycle would be computationally expensive and unnecessary, so to make the analysis more efficient an iteration procedure was developed, based on a similar technique created by Verdonschot [2]. The iteration procedure consists of a number of iterations, each being capable of simulating a number of loading cycles. At the beginning of each iteration, the FE model is loaded, and the stresses calculated. The number of cycles to failure ($\mathbf{N_f}$) for the highest stressed element is calculated using data from S-N curves. The number of cycles to be simulated in the iteration is essentially a set percentage of $\mathbf{N_f}$. Once the number of cycles to be simulated within the iteration is determined, creep and damage for all elements can be calculated. If damage reaches a predetermined value the element is deactivated and the load transferred to the surrounding elements. The equivalent Von Mises stress must be used to calculate creep and $\mathbf{N_f}$ as the creep data and S-N curves come from uniaxial tests.

The damage (**D**) of an element is calculated using the following linear Palmgren-Miner law:

$$D = \frac{n}{N_f} \qquad (1)$$

where n is the number of cycles completed.

When **D** gt. 1 for any element, the element is deactivated. Damage is calculated as a scalar quantity, meaning that a failed element cannot transfer load in any direction, even though failure only occurs in one direction. The iteration process is repeated until bulk failure of the cement mantle takes place.

RESULTS

Figures 2 & 3 illustrate the effect creep has on the damage accumulation in the cement mantle for the standard loadcase. The dark elements in figure 3 represent the failed elements. The inclusion of creep within the analysis significantly reduced the damage within the cement mantle.

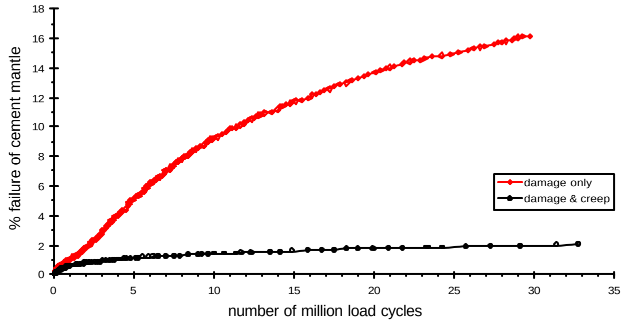

Figure 2. Element failure in cement, standard loadcase

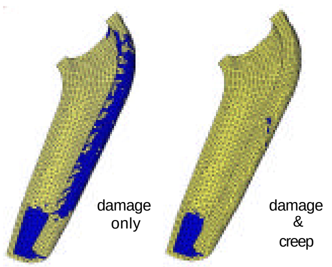

Figure 3. Element failure after 30 x 10^6 cycles

The effect different load levels have on the damage accumulation in the cement is shown in figure 4. The same percentage of damage at 30 million cycles in the light loadcase occurs at about 11 million cycles and 3 million cycles for the standard and heavy loadcases respectively.

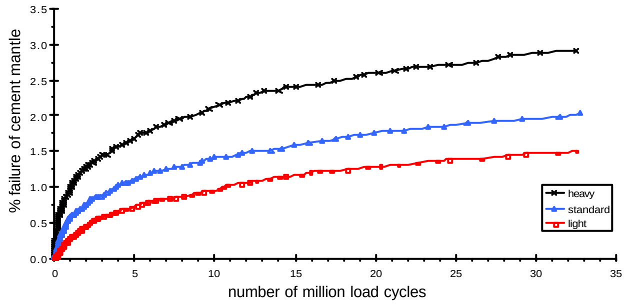

Figure 4. Element failure for different applied loads

DISCUSSION

This is a comparative study and does not claim to predict the life of a cemented hip replacement. The inclusion of creep was shown to significantly reduce the damage accumulation in the cement mantle. The reason for the reduced failure is that creep reduces the average stress within the cement mantle [3].

Considering figure 4, the level of damage reached by the light loadcase was reached by the heavy loadcase in about a tenth of the time. Cemented THRs enjoy a low failure rate at 10 years post operatively and are implanted into a wide spectrum of patients. It is likely that heavier patients account for a larger percentage of failed THRs. Further work should account for this elevated load level as well as the standard loadcase. Another variable that may affect the life of the cement mantle is the orientation of the implant. Not every implanted femur is orientated perfectly and a further study could assess how a misaligned implant affects the damage accumulation in the cement mantle.

The results presented here account for creep and damage accumulation only. Other time dependant properties such as stem-cement interface debonding and bone remodelling have not yet been included in the analysis.

CONCLUSION

Creep notably reduces the rate of damage accumulation in the cement mantle and should therefore be included in further FE analyses.

In order to adequately assess the performance of an implant design or type of bone cement, their sensitivities to variants in loading magnitude (body mass) should be assessed. Only by performing studies of this type will it be possible to identify potentially weak designs.

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