A PRELIMINARY INVESTIGATION ON THE INFLUENCE OF CROSS SECTION GEOMETRY ON CEMENTED INTERFACE STRESSES IN FEMORAL HIP REPLACEMENTS

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ABSTRACT

This paper describes the preliminary investigation done to assess the effect of stem cross-sectional geometries on stresses generated at the bone-cement and cement-stem interfaces. Simplified finite element numerical models of cemented hip replacements were used and materials were assumed isotropic and linearly elastic. The cross-sections were symmetric about the medial-lateral axis. A layer of 2 mm thickness of cement was interposed between the stem and the femoral cortex and a complex system of forces and moments generated by the hip joint contact force was applied. Maximum and minimum principal stresses were determined for twelve different cross-sectional geometries at the medial, lateral, anterior and posterior aspects of the interfaces. The results obtained evidenced that organic type geometries provoke lower tensile and compression stresses; rigid (sharp) geometries and cross-sections of low second moment of area provoke higher interface stresses.

INTRODUCTION

Cemented prosthesis fixation relies on a stable interface between prosthesis and cement mantle and on the mechanical bond between cement and bone. Mechanical and biological factors can influence and contribute to prosthesis loosening, which accordingly to Malchau et al. [1] is the main mode of failure of cemented femoral hip replacements.

Surgeons and engineers have been involved in the design of total hip replacements for many years and new designs have been launched into market claiming the solution of problems inherent in pre-existing ones. Within the cemented stem, the femoral component transmits the joint reaction force through the cement to the proximal femur. Several design factors can influence the stress-strain distribution and thus the longevity of the hip replacement: stem size, stem cross-section shape, stem frontal plane shape, stem length, cement thickness and cement material properties and the nature of the stem-cement and cement-bone bonds [2].

This paper describes the beginning of a research whose objective is to development a novel cemented hip femoral component. The effect of cemented stem geometries on the stresses at the bone-cement and cement-stem interfaces was critically assessed using a simplified three-dimensional femur-cement-prosthesis construction [3]. Other investigators have used this type of simplified model because it allows a much easier understanding of the load transfer mechanism.

MATERIALS AND METHODS

A simplified three-dimensional numerical model of the cemented implanted femur was used. All material structures were assumed isotropic and linearly elastic (elastic modulus of the femur and stem equal to 20 GPa and 210 GPa respectively; Poisson's ratio equal to 0.3). A cement mantle (elastic modulus equal to 3 GPa and Poisson´s ratio equal to 0.28) of 2mm thickness was interposed between the femur and the stem. All cross-sections were assumed symmetric about the medial-lateral axis. A perfect bond between the implant and the cement mantle and the surrounding bone structure was assumed, therefore no friction was considered. Twelve different geometric sections were considered and assessed in this study. The geometric sections were taken from proximal transverse sections of cemented commercial prostheses (e.g. Charnley, Freeman, Stanmore…) and from those presented in ref. [2]. Other geometries were idealized based on what we designated by "organic" (smooth) and "rigid" (sharp) geometries. The stem-cement mantle contact area of all geometries was very similar.

RESULTS AND DISCUSSION

The study is based on the premise that the proximal interfaces are critical regions of the cemented hip replacement. The mean and peak of the maximum (tension) and minimum (compression) principal stresses were obtained at the bone-cement and cement-stem interfaces. A typical and common mode of femoral component loosening is related to the loss of proximal stem support [4] and has been associated with the failure of the bone-cement or cement-stem interfaces laterally due to excessive tensile stresses and fracture of the proximal cement medially due to excessive compression [2]. Figure 1 illustrates the mean and peak maximum principal stresses observed at the medial aspect. Typically, the stresses developed at the bone-cement interface are much smaller then the ones developed at the cement-stem interface. In fact, for all aspects of the femur, considering either tensile or compressive stresses, these were much higher at the cement-stem interface, which means that the bonding at this interface is more prone to failure.

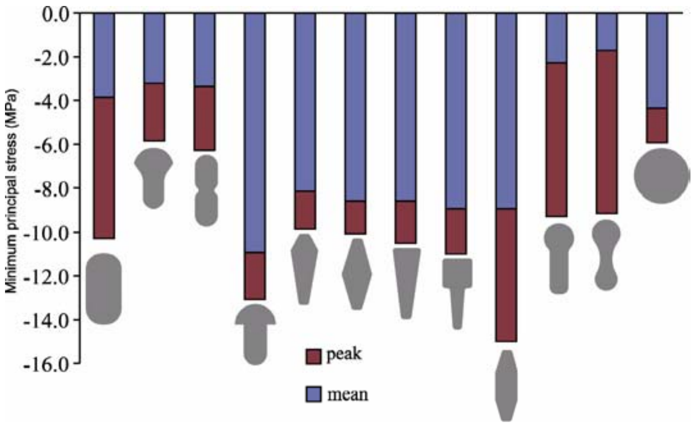

Figure 1. Mean and peak minimum principal stresses (medial aspect)

The mean and peak minimum compressive stresses are generally higher than the maximum tensile stresses. At the lateral and posterior aspects of the femur, significant stress differences were observed at the cement-stem interface. At the lateral aspect, sharp rigid geometries (e.g. #5, #6, #7, #8 and #9) provoke comparatively much higher mean and peak cement-stem stresses, of the order of 7-8 MPa and 9-10 MPa respectively. Organic geometries provoke stress values of the order of 1 to 3 MPa. For example, section #2 (Charnley type) induces a 4 times less stress value when compared with the ones obtained with sharp sections. The peak stresses are slightly higher than the mean ones, around 2 MPa for most of the geometries. The maximum principal stresses for sharp geometries are of the order 15 MPa. Section #9 provoked the highest stress value (25 MPa). Interesting to note that sections #1, #2 and #3 provoked the lowest stresses at the lateral and posterior aspects. Overall, section #2 provoked a relatively low peak stress, 3-4 MPa. Sections #1, #2, #3, #10 and #11 apparently seem to be the best suited for the biomechanical problem simulated.

Similar conclusions can be observed at the medial and anterior aspects. The organic geometries induced much lower medial interface stresses, in a very similar way to the lateral interface. Again, sections #1, #2 and #3 provoked lower stresses, of the order of -4 MPa, while sections #4, #5, #6, #7, #8 and #9 provoked stresses of the order of -10 MPa. Sections #10 and # 11 evidenced to be the best at the medial aspect of the implanted femur, since the stress levels are of the order of –2 MPa. The peak stresses induced by sharp geometries are of the order of 10 MPa. The difference between the mean and peak stresses is small. At the anterior aspect of the cement-stem interface, we noted more homogeneous stress levels for all geometries, but no correlation could be drawn between the geometry and these. The stress values were of the order of -4 to -6 MPa. A 14 MPa peak stress was observed for most of the cases simulated. Interesting to note that section #2 induced the lowest stress levels at all interfaces. Figure 2 illustrates the regions of compression and tension at the proximal region of the interfaces.

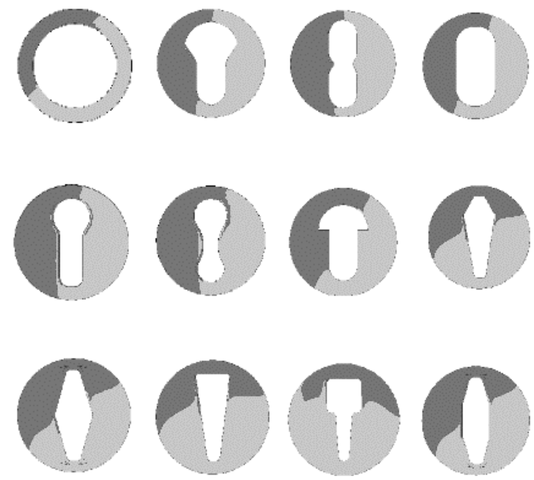

Figure 2. Tension-compression areas at the proximal region of the interfaces (dark – tension)

CONCLUSIONS

The studied evidenced the importance that stem cross-sectional geometry plays within the stresses developed at the cement-stem interface. For the simplified model used, the results show that the mean principal stresses are relevant at the lateral and medial aspects of the implanted femur; the peak stresses are important at the anterior and posterior aspects. However, these conclusions must be faced with necessary criticism, since they strongly depend on the numerical model used. Even though, they show a tendency. Organic cross section geometries provoke much lower stresses. Other design factors, such as the medial curvature radius, can also play a decisive role in the implanted femur performance. A detailed study on the influence that these design parameters exert within the stem-bone load transfer mechanism will allow the development of a new design that can possibly perform better than many commercial cemented ones. The doubt is to know how much is it possible to innovate within the design of a novel cemented hip femoral prosthesis.

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