The Influence of Implant Stiffness on Acetabular Stresses

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INTRODUCTION:

Common considerations associated with a total hip arthroplasty (THA) procedure include initial stability and potential of periacetabular stress-shielding [1]. Most modular cementless acetabular cup designs used in THA surgery employ some form of a porous coating bonded to a metal cup. Depending on the design, various types of liners can be assembled in the modular cup. The cup may be significantly stiffer than the pelvic host bone. It has been proposed that this stiffness differential may lead to a non-physiological stress state at the implant-bone interface resulting in potential stress shielding [2, 3]. Cups designed using materials with stiffness similar to the acetabular host bone may increase stress distribution in the acetabulum [2, 4].

The purpose of this study is to use finite element analysis (FEA) to evaluate stresses in acetabular bone after a THA procedure, subjected to physiological loading conditions. Three different components were virtually implanted in a pelvis model to compare stresses in the acetabulum. Comparison of stress results was used to study the influence of material stiffness of the cup on acetabular bone stress.

MATERIALS AND METHODS:

A previously developed partially validated patient specific FEA model of a left half of a pelvis was used [5, 6], to virtually implant three THR components – Trilogy®, Trabecular Metal® Modular Cup (TMMC) and Trabecular Metal Monoblock Natural Cup (TMNC). Figure 1 presents the three cup designs. Trilogy cup consists of a Titanium® Ti-6Al-4V shell coated with titanium fiber metal to enhance fixation through bone ingrowth [7] (Figure 1A). TMMC cup is built on the Trilogy design but replaces the fiber metal coating with Trabecular Metal (TM) which possesses a substantially higher friction coefficient than other implant materials and increases initial stability at implantation [8] (Figure 1B). Both of these cup designs have significantly higher stiffness than the contacting bone. TMNC design uses a flexible monoblock construct where ultra-high molecular weight polyethylene (UHMWPE) is compression molded directly into the TM material (Figure 1C and 1D). Since the elastic modulus of TM falls between that of cortical bone and subchondral bone [1], it results in a flexible construct which may reduce the potential for stress shielding [2]. 50 mm φ cups were used for all the models. For each model, the acetabulum was reamed by performing virtual surgery to implant the respective components. All the implants used in this study are commercially marketed by Zimmer, Inc. (Warsaw, IN).

The pelvic cancellous bone (E=0.07 GPa) was meshed using 10-node tetrahedron elements. Matching 6-node triangular shell elements were used to model a 1mm thick cortical shell (E=17 GPa) around the unloaded areas of the pelvis. Trilogy and TMMC cups were implanted with a UHMWPE liner. Linear elastic material properties of Titanium (E=110 GPa), TM (E=3 GPa), and UHMWPE (E=857 MPa) were used for respective components. For the TMNC cup, the layer where UHMWPE infiltrates the TM (TM+UHMWPE‘ in Fig. 1D) was modeled using an elastic modulus value of 4 GPa.

Sliding interfaces between head-liner and cup rim-pelvis were modeled using a friction coefficient of 0.05 and 0.3, respectively. To isolate the possible effects of friction coefficient (between the cup and the pelvic bone) on predicted stresses, identical sliding interfaces were defined between cup and pelvis using a high friction coefficient of 0.75 for all models. This assumption mimics the situation where some bone has already grown into the implant material. All other interfaces (liner-cup, cup-fiber metal, cup-TM porous coating and metal ring-TM) were defined as bonded contact. Muscle load and joint contact force (2322 N) data for stair climbing case were obtained from the laboratory of Prof. Bergmann [9, 10]. Fixed support conditions were assumed at the sacroiliac joint and the pubic symphysis. Figure 3 presents the details of a finite element pelvis model implanted with TM Natural Cup. Nonlinear static FEA were performed using ABAQUS ver. 6.7 (Simulia, Providence, RI) software.

RESULTS:

For all three models peak von Mises stresses were predicted at the superior rim and at the rim facing the body of ischium. High stresses were also predicted at the acetabular notch. The overall stress distribution for all three models has similarities in the one half of the acetabulum towards the iliopubic eminence, anterior iliac spine and inferior gluteal line. However some differences in stress prediction were noticed in the other half of the acetabulum facing the greater sciatic notch and ischial spine. Figure 3 presents the stress distribution in the acetabulum for all three models.

DISCUSSION:

The stress distribution predicted in the acetabulum was similar for the Trilogy and TMMC models. Both of these models use a Titanium cup and the only major difference between them is in the porous coating material, which does not seem to substantially contribute towards the overall stiffness of the cup. Compared to these two models, about 45% higher stresses were predicted in the TMNC model on some parts of the acetabulum, which may reduce the potential for stress shielding. The stress differential predicted in this study using a complex physiological model is consistent with similar data reported earlier [2] using a simpler model. However, the model developed in this study can provide stress predictions at exact locations within the acetabulum. It should be noted that the results of this study are limited to stair climbing load case and further research is necessary to study the stress response when the acetabulum is loaded based on other types of daily activities.

REFERENCES: