FINITE ELEMENT ANALYSIS OF A POROUS TANTALUM MONOBLOCK TIBIA COMPARED WITH A METAL-BACKED TIBIAL COMPONENT

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Introduction

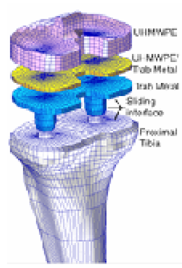
Porous tantalum metal with direct compression molded polyethylene has been utilized in monoblock acetabular cups for total hip arthroplasty to improve both bone ingrowth and eliminate backside polyethylene wear[1]. The same technology has been applied to tibial components for total knee replacements to produce a construct of similar stiffness to the underlying cancellous bone in the proximal tibia. The monoblock tibia consists of direct compression molded, ultra-high molecular weight polyethylene (PE) that penetrates 1-2 mm into the porous tantalum backing. Two hexagonal pegs are positioned in the proximal condylar regions of stiffest cancellous bone; the resultant high friction interface[2] can improve initial implant stability.

Porous tantalum, or trabecular metal™, has an elastic modulus of 3 GPa similar to stiff cancellous bone. The design rationale for these devices is that they produce a more normal physiologic stress in the underlying bone. Traditional metal-backed tibial components with moduli of 100-200 GPa are much stiffer than the cancellous bone, potentially leading to stress shielding[3].

The goal of this study was to compare the stress state of a trabecular metal tibial component with compression molded polyethylene to that of a titanium tibial tray with a modular polyethylene tibial insert. Finite element analysis was utilized to determine the stress history under a standardized gait load and more severe loads for these two types of design implanted in the same proximal tibia.

Methods

Previously developed and validated finite element (FE) models[4] of Insall-Burstein PS II total knee replacements implanted in proximal tibiae were utilized for this study. These models had a cemented titanium tibial tray with a central short post and a modular polyethylene insert. From a sample set of 10 tibiae, one specimen from a donor of relatively younger age (55 yrs) and good bone quality was chosen as a representative candidate for a monoblock tibia.



The FE model of this proximal tibia, created from 1 mm-spaced CT scans with 0.6 mm in-plane resolution to capture bony inhomogeneity, was modeled with a NexGen LPS monoblock component (Zimmer, Inc., Warsaw, IN). The material properties and thickness dimensions are summarized in Table 1; all properties were based on solid continuum behavior. The cemented IB implants were modeled with a bonded interface underneath the tray and around the central post. The trabecular metal (TM) tibial components had an interface with a coefficient of 1.0 (cancellous-porous tantalum interface: μ=0.98±0.17 [2]) underneath the monoblock and around the pegs. A 0.5 mm gap was included between the bottom of the pegs and the cancellous bone representing overdrilling according to surgical protocol; however, an interference fit at the corners of the hexagonal pegs was not modeled. The IB models consisted of approximately 25,000 linear elements, while the TM models contained 35,000 elements, based on refinement and convergence studies, to accurately capture the stress state around each post and its distal facets.

Table 1: Material properties used for the finite element analyses

	Modulus (MPa)	Yield Value	Poisson Ratio	Thickness (mm)
Bone (CT-derived)	50-18,000	ε=0.73%[5] cancellous	0.30	-
Titanium	110,000	-	0.30	3.0
TM[1]	3000	σ=25 MPa	0.31	5.0
TM/PE [1]	3300	-	0.35	2.0
PE	1000	σ=12 MPa	0.46	5.5

Both the IB and monoblock NexGen components were subjected to a severe load of 3000 N on the medial compartment, a bicondylar load of 3000 N, and a standardized gait load for stance phase based on the proposed ISO standard for knee simulators (#14243-1). The gait load consisted of an axial compressive load (max 2300 N), an anterior-posterior force (max 250 N), and an internal-external torque (max 6 N-m). These loads were applied with a rigid surface representing the femoral condyle and were applied equally on the medial and lateral condyles in the bicondylar and gait analyses. The distal tibia was fixed against all translations 170 mm distal to the components.

The analyses were performed with ABAQUS 6.3 (HKS, RI) and post-processed to obtain the von Mises stresses (σ_{VM}) and minimum principal strains (ε_3) in the cancellous bone as well as the stresses in the porous tantalum itself. The bone stresses and strains were compared between the IB and tantalum models as well as with experimentally determined yield values for proximal cancellous bone in the human tibia (Morgan & Keaveny, 2001).

Results

The peak field values of the von Mises stress and the minimum principal strain occurred in the plateau regions of the bone underneath the metal tibial tray for the IB component and around the pegs for the trabecular metal component. In all cases, the peak response due to the TM monoblock tibia was 2-3 times larger than the response for the metal-backed IB component. In particular, for the minimum principal strain under a severe medial load, the analyses predicted the bone would yield in localized regions (Fig. 2). Von Mises stresses in the tantalum itself were largest for the medial load at 12.2 MPa.

Table 2: Peak field values for the cancellous bone for 3 loadings

	Insall-Burstein PS II			NexGen TM Monoblock		
	Medial	Bi-condylar	Stance Gait	Medial	Bi-condylar	Stance Gait
ε_3 (%)	0.40	0.26	0.19	0.96	0.47	0.52
σ_{VM} (MPa)	5.5	2.3	2.7	11.3	6.7	4.7

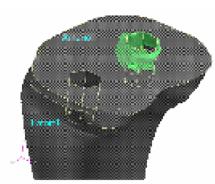


Figure 2: Isosurface showing the 0.73% yield strain localized around the medial condylar peg of the TM component for a 3000 N medial load.

Discussion

Metal-backed tibial components were developed to protect the underlying cancellous bone in older TKR patients by distributing the load across the entire plateau while varus-valgus moments were resisted by central posts or keels. In the case of younger patients with good bone quality, long-term problems can arise due to potential stress-shielding of these regions. With a TM monoblock tibial component, the strong, flexible material and placement of bicondylar pegs with a high interfacial friction produced local load transfer at these sites of stiffer cancellous bone in the proximal tibia. This loading may produce an additional benefit; the design rationale for these devices is to encourage bone ingrowth into the highly porous tantalum. Localized regions of peak strains could stimulate the necessary response to encourage bone remodeling; this could be an appropriate advantage for the younger patient when the bone is of sufficient quality.

References

[1] Poggie et al, Trans ORS, 1999; [2] Zhang et al, J Musc Res, 1999; [3] Lonner et al, J Arthroplasty, 2001; [4] Rawlinson et al, Trans ORS, 2003; [5] Morgan & Keaveny, J Biomech, 2001;

This work was supported by Zimmer, Inc.