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Finite Element Analysis - a comparison of an all-polyethylene tibial implant and its metal backed equivalent

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Abstract:	<p>Abstract</p> <p>Purpose: The hypothesis of this study is that all-polyethylene (APE) tibial implants offer a biomechanical profile similar to metal backed tray (MBT). There are significant financial cost saving implications, in selected patient groups, if APE performs as well as MBT.</p> <p>Methods: Using a finite element analysis (FEA) of CAD models provided by DePuy (Leeds), stress distributions were investigated for both an APE and MBT tibial implant. The performance was assessed for cancellous bone at 700MPa (normal) and at 350MPa (less stiff). Plots were recorded along the length of the tibia, showing the loads carried by the bone (cortical and cancellous), the implant interface, cement interface and the stem. Von Mises stress distributions and percentage volumes were used to assess bone resorption and hence potential for failure (fracture).</p> <p>Results: Higher stress shielding (resorption) occurred around the keel of the tray in the MBT. The stiffer MBT tray carried a higher proportion of the load down the stem. MBT stress in cancellous bone is lower than APE, as load is distributed to the cortical rim. APE had no areas of bone resorption (being more flexible resulting in less stress shielding).</p> <p>Conclusions: Higher stresses are produced and more load is transferred to cancellous bone in APE than MBT. MBT reveals greater potential for bone loss around the stem and keel. APE has a marginally favourable strain state in cancellous bone and spreads loads more at the cement interface than MBT. Both exhibit peak cement stresses around the cortical rim, but not to the point that cement failure occurs.</p>
Response to Reviewers:	

Finite Element Analysis – a comparison of an all-polyethylene tibial implant and its metal backed equivalent

Abstract

Purpose: The hypothesis of this study is that all-polyethylene (APE) tibial implants offer a biomechanical profile similar to metal backed tray (MBT). There are significant financial implications, selected patient groups, if APE can be deemed to perform as well MBT.

Methods: Using a finite element analysis (FEA) of CAD models provided by DePuy (Leeds), stress distributions were investigated for both an APE and MBT tibial implant. The performance was assessed for cancellous bone at 700MPa (normal) and at 350MPa (less stiff). Plots were recorded along the length of the tibia, showing the loads carried by the bone (cortical and cancellous), the implant interface, cement interface and the stem. Von Mises stress distributions and percentage volumes were used to assess bone resorption and hence potential for failure (fracture).

Results: Higher stress shielding (resorption) occurred around the keel and stem of the MBT revealing greater potential for bone loss in these areas. APE had no areas of bone resorption (being more flexible resulting in less stress shielding). The stiffer MBT carries a higher proportion of the load down the stem. MBT stress in cancellous bone is lower than APE, as load is distributed to the cortical rim. APE has a marginally favourable strain state in cancellous bone and spreads loads more at the cement interface than MBT.

Conclusions: Modern day APE bearings may be superior to previously designed implants due to improvements in manufacturing. In the correct patient group this could offer substantial cost savings.

Introduction

First generation TKA tibial trays were uniformly APE but experienced poor results due to aseptic loosening, mostly due to implantation technique [2,10,12,16,26]. The APE TKA tibial implant was then succeeded by MBT implants to address the loosening issues, with excellent results, offering modularity and intraoperative flexibility [13,19,24,25,28,33]. There were, however, issues with MBT locking mechanisms, back side wear and subsequent osteolysis [6,7,11,20,22].

Significant stress and strain distributions at the implant-bone interface, which vary with quality of the bone and the biomechanical properties of the implant, may lead to loosening, pain, subsidence and subsequent failure of the TKA. Finite element analysis (FEA) studies have assessed the impact of APE and MBT on cancellous bone [9,17,21,31], with higher cancellous bone stresses correlated with increased migration and subsequent poorest survival rates at 5 years [3,4,5,31].

Clinical results of APE and MBT have been described in the literature, and studies have shown that MBT can reduce the compressive stress in tibial cancellous bone, and dissipate load more uniformly across the proximal tibia protecting against loosening [3,17,31]. However, the manufacturing process of polyethylene has improved considerably. Implant survival has increased, and as such we wish to study the effect on a currently available modern arthroplasty system [1,8,18,19,23,27,32]. The hypothesis of this study is that APE can offer a biomechanical profile similar to MBT and therefore APE can be used in certain patients groups, offering substantial cost savings.

Materials and Methods

A 3D-cortical shell was created from a single CT scan in multiple planes spaced 0.7 mm apart using Simpleware™, facilitating model creation by using various techniques to retain the

pixels covering the relevant part of a left tibia from a healthy 48 year old male, weighing 105 Kg. The cortical shell was then imported as an IGES file into the Finite Element (FE) package ABAQUS (Dassault Systems, Paris, France) for further processing. ABAQUS is a commercial finite element analysis code than can solve complex 3D problems. The model was meshed with a total of 452,761 tetrahedral elements. A mesh convergence study was undertaken to ensure a sufficient number of elements were used.

The proximal tibial condylar surface of the knee joint was then sectioned in ABAQUS leaving an open space in the tibia. The cancellous bone volume was then defined using the inner surface of the imported cortical shell and enclosing the space, forming the cancellous bone volume.

A cement mantle of about 2 mm was then created using the outer surface of the implant stem. This cement part was then used to create the cavity in the cancellous bone for the insertion of the tibial tray. This was done by a Boolean subtraction of the volume of the cement from the cancellous bone-stock.

The CAD models of the implant parts, PFC Sigma Posterior Stabilised implant DePuy (Warsaw, Indiana), were provided in IGES formats. The cement-mantle, tibial tray and tibial bearing were assembled in their correct positions. The final assemblies of the implanted tibiae (APE and MBT) are shown in Figure 1.

Two different properties were assessed for the cancellous bone, 700 MPa representing stiff normal bone, whilst 350MPa represented less stiff bone (such as seen in metabolic bone disorders). A complete summary of the material properties of the bone and implant components is shown in Table I.

The material properties of the APE (Homogenous Linear Elastic Isotropic) were assigned by changing the material properties of the tibial tray part of the model from metal to polyethylene. The two parts (tray and bearing) were tied together in ABAQUS, creating a single polyethylene part. Interfaces between the bone and the cement and between the cement and the implant were also tied in the models.

The tibia was evenly resected, with a tibio-femoral angle of 90 degrees to the long axis of the tibia. The load was applied to the bearing with 50:50 load distributions medially and laterally. The total load applied on the model was chosen to replicate the maximum joint loads experienced during the gait cycle, at contra-lateral toe-off. The gastrocnemius muscle is the only active muscle at this late stance phase of gait. As the gastrocnemius muscle does not attach to any region of the proximal tibia, it was not necessary to include any ligaments or muscles in the models. The effect of the gastrocnemius however is represented in the applied joint reaction force. The total load was 2.1kN which has been used in previous studies in the literature, aiming to represent 2-3 times normal body weight [17,31].

Load plots were generated through the proximal and distal sections of the cancellous bone, cortical bone and tibial tray stem for all models. Von Mises stress distributions for each model (both APE and MBT in both 350MPa and 700MPa scenarios), were used to determine areas of bone that may undergo resorption, or failure (fracture). A value of $200\mu\epsilon$ was taken to represent the minimum strain required to maintain bone with $< 200\mu\epsilon$ resulting in bone resorption; $10,000\mu\epsilon$ will lead to bone failure (fracture) and $4000\mu\epsilon$ was taken to represent an acceptably high strain. Table II shows the corresponding stress thresholds set for cancellous bone.

Results

92 **Load transfer**

93 At the implant interface the underlying cancellous bone in the APE model carried a higher
94 proportion of the load 48% (700MPa) and 32% (350MPa) than the MBT 26% (700MPa) and
95 17% (350MPa).

96 Implanting the APE and MBT in the less stiff cancellous bone, caused the load transfer in the
97 cancellous bone region to be reduced, re-distributing load to the cortical rim, Figure 2.

98 The gradient of the load transfer plots seen in figure 3, reveals a rapid load transfer with the
99 APE, in contrast with the slower load transfer with the MBT. The APE stem carries a
100 significantly lower proportion of the load, as Figure 4 shows early, rapid load transfer.

101 The stem of the MBT carries a higher percentage of load than the APE. Load transfers in the
102 MBT stem are as high as 28% (700MPa) and 25% (350MPa) cancellous bone; compared to
103 the APE stem, 8% (350MPa) and 7% (700 MPa) respectively.

104 **Von Mises stress**

105 Cancellous bone stress contour plots exhibit differences between MBT and APE in both the
106 700MPa and 350MPa model, Fig 5 and 6. MBT exhibit reduced stresses in the underlying
107 proximal region of cancellous bone resulting in stress shielding, manifested as black areas of
108 resorption ($<200\mu\epsilon$). APE demonstrates increased stress peripherally (grey areas), the
109 percentage volume bone above $4000\mu\epsilon$ was 0.02% (700MPa) and 0.21% (350MPa). The
110 MBT did not demonstrate values above $4000\mu\epsilon$.

111 As cancellous bone stiffness increases, the stresses in APE encountered was 3.3MPa
112 (700MPa) compared to 2.4MPa (350MPa). The MBT the equivalent values were, 2.8MPa

(700MPa) and 2.0MPa (350MPa). Figure 2 shows higher loads carried by the cancellous bone by the APE than by the MBT.

The overall percentage bone loss volume (shown black in Figures 5 and 6) was 1.4% (700MPa) and 0.4% (350MPa) for the MBT. The APE percentage volume bone loss was 0.24% (700MPa) and 0% (350MPa). Resorption occurred around the MBT keel region, stiffer cancellous bone revealing greater potential for bone loss.

Shear stresses were concentrated in the periphery of the proximal cement layer (facing the tray), in the MBT, Figure 7, load transferred from the (stiff) metal tray to the cortical bone. APE exhibits a more uniform distribution of shear stresses due to the more flexible tray spreading the load over the resected surface. Two inward shear stress peaks (of opposing signs) can be seen on both the lateral and medial sides on the APE upper cement layer, due to axial compressive stress (not seen on the MBT). Shear stresses on the distal side of the cement layer (facing the resected bone surface) show that the shear stress peaks are found peripherally, adjacent to the cortical bone.

The maximum shear stresses in the cement are marginally higher on the distal side and are marginally higher for the MBT (2.6 MPa and 3.2 MPa) than the APE (2.3 MPa and 3.0 MPa) for 700 MPa and 350 MPa cancellous respectively. The stresses in all components are considerably lower than the cement shear fatigue endurance limit of 5 MPa.

Maximum compressive cement stresses were located peripherally on the distal cement face (facing the resected bone), unlike the shear stresses the maximum compressive stresses were marginally higher for the APE (7.5 and 8.5 MPa) than for the MBT (6.5 and 5.5 MPa) for 700 and 350 MPa cancellous bone respectively. The maximum compressive stresses in both

the APE and MBT cement were lower than the compressive fatigue endurance limits of 17MPa.

Discussion

The most important findings of this study was increase for potential bone loss due to resorption around the MBT stem and keel, when compared to APE in the cancellous region of the proximal tibia.

It has been the hypothesis of previous studies that APE suffers with excessive stresses in the proximal tibia and that this may cause prosthesis migration and subsequent cancellous bone failure. Historically early failures were also due to mal-alignment. Previous studies using FEA, unsurprisingly, showed that the location and magnitude of loading is significantly altered by component alignment - combined effects of greater than 3 degrees varus of the tibial component and higher body mass indexes are associated with increased medial component loading and failure [30]. Implant failures could also be linked to component design and geometry, with better coronal conformity being an issue addressed [14,15].

It has been shown here that implanting an all polyethylene implant into the proximal tibia caused increased load transfer and increased stresses on the underlying cancellous bone, evidenced by the generated load plots. Load transfers of 48% (700MPa) and 32% (350MPa) were encountered in APE whilst only 26% (700MPa) and 17% (350MPa) in MBT. Increased APE cancellous stresses were not so high as to overload the bone but would have the effect of reducing the stress shielding that might occur in the MBT.

APE causes the load to be transferred to the stiffer cancellous regions surrounding the polyethylene stem, the stem not carrying much of the load, with less stiff bone directing more load through the stem. The stiffer MBT will not allow the load to be dissipated

through the surrounding cancellous bone, and it will carry a higher proportion of the load in the stem. The stiffer cancellous bone also causes less load to be transferred into the cortical bone, Figure 4, the additional load being carried by the stem.

Von Mises stresses of 2.46MPa were present in the cancellous bone for the all-polyethylene implant whilst stresses of up to 2.0MPa were present for the metal tray for the cancellous bone. This has been reflected in other similar studies, reporting peak cancellous bone stresses of 7.95MPa for APE compared to 2.59MPa for the MBT [9,14, 15,17,18,21,29-31]. These stresses are insufficient to overload the bone.

Cement stresses in other studies also reported increased compressive stresses at the cement-cancellous bone interface for the all-polyethylene implant. Compressive stresses of 3.5MPa were found for the all-polyethylene implant and 1.3MPa for the metal-backed implant [17]. We found that the stresses were significantly below the fatigue endurance limit for the cement.

The main limitation of a study such as this is the material model used for the cancellous bone. It is known that the properties of cancellous bone vary spatially, and this is a level of complexity that has not yet been included in this study. We analyse results using a uniform material, investigating values based on what would be considered a high cancellous modulus and a low cancellous modulus. Further work should explore the use of spatially varying cancellous material properties. Another limitation is bone resorption thresholds used. There are a range of bone resorption models and a range of thresholds within these models. The approach adopted has been to use representative thresholds of the common strain based resorption model. Changing the model or the threshold might change the predicted quantity of bone resorbed but the relative effects of MBT and APE are likely to

remain the same. A final limitation is the degree of load alignment. In this preliminary study the load has been assumed to be perfectly aligned. Further studies could be undertaken to assess the degree of loading mal-alignment.

APE and MBT have advantages and disadvantages. Most surgeons will cite a lack of intra-operative flexibility with APE, but when adequate pre-operative planning is carried out identifying cases unsuitable for APE, there may be a significant financial saving to the healthcare economy.

Conclusion

FEA modelling reveals APE transfers more load to the cancellous bone than the MBT, and produces higher stresses in the cancellous bone.

MBT exhibits more potential bone loss due to resorption than APE in the cancellous region of the proximal tibia, particularly around the implant stem and keel.

APE produces marginally more favourable strain state in cancellous bone than the MBT, and spreads the stresses at the cement interface more than MBT.

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Figure 1: FEA implant APE (left) and the separate components of the MBT (right)

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Figure 2: Variation of the load carried by the cancellous bone with distance from the tray for all models

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Figure 3: Variation of the load carried by the cortical bone with distance from the tray for all models

Figure 4: Variation of the load carried by the stem with distance from the tray for all models

Figure 5: Contour plots of von Mises stress distribution for all models at the tibial surface

Figure 6: Cut view of cancellous bone in the ZY plane showing the critical stresses

Figure 7: Shear stresses at the cement interface for all implants

	Young's Modulus	Poisson's Ratio
Cancellous Bone	700MPa/350MPa	0.30
Cortical Bone	17,000MPa	0.30
MBT Implant	117,000MPa	0.30
MBT Tibial bearing	2,300MPa	0.25

APE implant	2,300MPa	0.25
Bone Cement	2,150MPa	0.30

Table I: Material properties of MBT and APE implants

	350MPa cancellous bone	700MPa cancellous bone
200 $\mu\epsilon$	0.07MPa	0.14MPa
4000 $\mu\epsilon$	1.40MPa	2.80MPa

Table II: Critical stresses for cancellous bone