Adaptive Bone Remodelling Following Unicompartmental Knee Arthroplasty

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Introduction: Bone remodelling following knee arthroplasty occurs in response to alterations in the mechanical loading environment. Unicompartmental knee arthroplasty (UKA) is suggested to clinically perform superiorly when compared to its total knee arthroplasty (TKA) counterparts [1]. However, both are prone to bone mineral density (BMD) loss [2]. Dual-energy x-ray absorptiometry (DEXA) has proved to be an accurate and reproducible tool for assessing BMD in TKA clinical studies. There is, however, limited information in the literature, in general, regarding BMD behaviour following UKA. Computational bone remodelling techniques have been used to predict bone remodelling behaviour following knee arthroplasty. This study used a strain adaptive bone remodelling algorithm coupled with the finite element (FE) method to simulate the bone remodelling behaviour of both the femur and the tibia post-operatively over a 60 month time period following a UKA.

Materials and Methods: A 3D femur and tibia model were constructed from human cadaveric computed tomography (CT) images. Correctly sized implant geometries (GRU) were supplied by Global Orthopaedic Technology in parasolid format. These geometries were positioned relative to the intact bone models and positions confirmed by an orthopaedic surgeon. Post-operative bone geometries were generated using a pre-processor (MSC.Patran, MSC.Software Corp., Santa Ana, CA). All geometries were meshed using 3D 10-noded modified second-order tetrahedral elements and mesh size ranged between 1-5mm. Only distal and proximal regions of femur and tibia were modelled to minimise computation time. Both the femur and the tibia models were loaded at 45% gait cycle for normal walking gait using loads based on Taylor et al. [2]. Loads were distributed using 60:40 ratio across the medial and lateral condyles, respectively. A cement mantle was defined by selecting an even layer of elements on the underside of the tibial uni component across the medial and lateral condyles, respectively. A cement mantle was defined by selecting an even layer of elements on the underside of the tibial uni component. Both the cement-bone and cement-implant interfaces were tied. The proximal end of the femur and the distal end of the tibia were constrained in all directions for both the intact and post-operative models (total of four) for all steps. Material properties for the bone were assigned as follows: PE (E=1GPa, \(\nu=0.3\)) and cement (E=2GPa, \(\nu=0.4\)). A strain-adaptive remodelling theory was used to predict the remodelling behaviour of the femur and tibia following UKA. Using the analysis software ABAQUS/Standard (Abaqus Inc., Providence, RI, USA) coupled with an in-house developed remodelling algorithm, the bone remodelling analysis was carried out on the post-operative model in a number of static steps. The difference in the equivalent strain between the intact and reconstructed model was used as the mechanical signal (or stimulus) [4] for the remodelling algorithm. Virtual DEXA images were generated from the FE models for each time-point by projecting them in the sagittal (femur) and coronal (tibia) planes. BMD gain and loss were also assessed both quantitatively and qualitatively.

Results: Most BMD changes occurred in the first few months after implantation, after which bone remodelling stabilised. The femur model experienced marked bone loss in ROI-7 (distal region), losing almost 7% of original bone stock. ROI-5 (at anterior flange) and ROI-4 (at posterior flange) increased in BMD by 8% and 2%, respectively. All other regions experienced minimal change. The tibia model showed a small increase in BMD (up to 2%) for all ROIs (in the region below the tibial implant).

Discussion: There is limited literature available regarding BMD changes following UKA, especially more so with regards to computational modelling. This study is unique in its ability to provide predictive results for both the femur and the tibia following UKA. The method has been previously validated and similar results have been noted with the tibia (no-keeled) model [5]. The FE predictions for the femur model were comparative to TKA results [6]. The most distal region of the femur, surrounding the peg, displayed most BMD loss. This occurs due to the stress-shielding effect of the pegs. However, as suggested clinically, these small changes in BMD may not even affect the long-term implant survival.

References:

Figure 1: Virtual DEXA images of the femur and tibia models with selected ROIs.

Figure 2: BMD change in the femur model over 60 months.

Figure 3: BMD change in the tibia model over 60 months.

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