Adaptive Bone Remodelling Following Total Knee Arthroplasty- A Finite Element Study

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Introduction: Periprosthetic bone resorption following total knee arthroplasty (TKA) is a clinical concern. Decrease in bone quality jeopardises implant fixation, consequently leading to revision surgery. It has been suggested that a reduction in the local stress distribution may cause a decrease in bone mineral density (BMD). Computational bone remodelling has been used previously to predict bone adaptation [1]. However, not much emphasis has been placed on TKA simulation. The aim of this study was to simulate the bone remodelling response of the femur and tibia, over a time period, following TKA, using an adaptive bone remodelling algorithm combined with the finite element (FE) method. Virtual dual energy x-ray absorptiometry (DEXA) images were generated and assessed.

Materials and Methods: A 3D femur and tibia model were constructed from human cadaveric computed tomography (CT) images. Correctly sized implant geometries (RBK) were supplied by Global Orthopaedic Technology in parapsolid 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 tray and the inner side of the femoral component. Both the cement-bone and cement-implant interfaces were tied. The proximal end of the femur and the distal end of the tibia models 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 obtained from the Hounsfield Unit (HU) values which were extracted from the CT files and converted into apparent bone density (\(\rho_{app}\)). These values were then converted to Elastic Modulus (E) according to Carter and Hayes [3]. Other material properties were assigned as follows: PE (E=1GPa, \(\nu=0.4\)) cobalt-chrome (E=220GPa, \(\nu=0.3\)) and cement (E=2GPa, \(\nu=0.3\)). A strain-adaptive remodelling theory was used to predict the remodelling behaviour of the femur and tibia following TKA. 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 assessed both quantitatively and qualitatively.

Discussion: The FE bone remodelling method has shown to provide good correlation with clinical findings. Clinical and FE studies have shown that for cemented knees, most bone loss occurs at the distal femoral region, especially at the anterior aspect [5, 6]. In the tibia there is generally an overall decrease in BMD in the proximal tibia and increase below the keel [7, 8]. This is in accordance with our predictions. BMD gain was found to be more predominant on the medial aspect (tibia). This may be due to the more medially inclined loading ratio, which affects the stress distribution within the bone. BMD gain in the tibia is shown to follow a path, which starts at the bottom of the keel and tends medially towards the tibial cortex. This illustrates the inherent tendency of load transfer to follow along the path of highest resistance. Bone remodelling occurs as a response to an altered mechanical environment. Changes brought about by different implant design or implant positioning or alignment may impose varying load transfer paths and magnitudes. The adaptive bone remodelling FE method is a good predictor of these post-operative bone remodelling behaviours.