Abstract

Total Hip Arthroplasty (THA) is a surgical procedure that restores normal movements of the hip joint, which may be impaired due to osteoarthritis, avascular necrosis, congenital deformities or post-traumatic disorders. Major biomechanical failure mechanisms of cementless implants are implant-induced adverse bone remodelling and progressive interface debonding owing to lack of biological fixation. Improvement in implant designs and surgical outcomes demand understanding of these failure mechanisms through rigorous preclinical investigations. The primary goal of the study was to gain an insight into biomechanical failure mechanisms in an uncemented femoral component using finite element (FE) analysis. Since the bone ingrowth and remodelling process is influenced by applied loading condition, the initial part of the study was directed towards the estimation of muscle and joint forces during physiological activities. The efficacies of four eminent open-source musculoskeletal models was evaluated in order to predict the most accurate values of hip joint reaction (HRF) and muscle forces. The estimated values of HRF were found to corroborate well with *in-vivo* measurements of different daily activities. Although the estimated values of HRF was within a satisfactory range, over-estimation of HRF (75%BW of measured value) was observed during the late stance phase of walking cycles for all the models. The similarity of predicted results with *in-vivo* measured values confirmed the suitability of musculoskeletal forces for FE analysis. The extent to which loading configurations influence the failure criteria such as, maximum principal strains, interface debonding, implant-bone relative displacement and adaptive bone remodelling of an uncemented femoral implant was investigated in the following study. The influence of three different loading configurations was investigated using patient-specific FE models of intact and implanted femurs. Lack of consideration of differences in activities overestimated (30-50%) bone resorption around the lateral part of the implant, producing clinically less relevant bone remodelling outcomes. In the next phase of the study, the spatial distribution of evolutionary bone ingrowth around a hip stem was predicted using a mechanoregulatory tissue differentiation algorithm. The local variation in host bone material properties and implant-bone relative displacement at the interface were accounted for the simulation using multiscale numerical framework. Higher bone ingrowth (mostly greater than 60%) was predicted in the antero-lateral regions of the implant, as compared to the postero-medial side (20-50%) which corroborated well with prior studies of a wedge-shaped implant. The effect of changes in applied loading conditions, bone orthotropy, mechanical stimuli and trabecular morphology on bone remodelling pattern was subsequently evaluated. A novel orthotropic bone remodelling algorithm, considering strain along principal stress directions as the mechanical stimulus was proposed for bone adaptation. The orthotropic remodelling formulations predicted 4-8% bone resorption in the proximal femur. A linear regression analysis revealed a significant correlation ($R = 0.71$) in bone density distribution between the isotropic and orthotropic formulations. The changes in bone morphology and its effect on periprosthetic bone adaptation was investigated using multiscale simulations, involving topology optimization and parametric cellular models. Despite higher bone apposition of 10-20% around the distal tip of the implant, the bone density distributions were well comparable to clinical observations towards the proximal femur. The proposed computational scheme appears to be a viable method for including bone anisotropy in the remodelling formulation.

Keywords: Preclinical analysis, uncemented femoral prosthesis, bone ingrowth, tissue differentiation, mechanobiology, orthotropic bone remodelling, topology optimization, multiscale framework.