Abstract

Numerical evaluations of periprosthetic bone ingrowth and remodelling are necessary to assess the failure mechanisms of an uncemented acetabular component. However, there is a scarcity of studies investigating bone ingrowth and remodelling associated with Functionally Graded Porous (FGP) acetabular component. Quantitative prediction of bone adaptation calls for Finite Element (FE) based numerical analysis, considering implant-induced changes in the mechanical and biochemical environment. The FE models of intact and implanted hemipelvises were based on patient-specific CT-scan dataset to account for geometry and heterogeneous material properties of bone. These models were used to investigate the influences of various musculoskeletal loading and implant-bone interface conditions on the preclinical evaluations of uncemented acetabular component. A new musculoskeletal model of forces, corresponding to common daily activities of sitting up/down, stairs up/down and normal walking of a pelvic bone, was estimated using a previously validated Gait2392 model in OpenSim freeware. Results indicated the need to consider loading conditions corresponding to common daily activities for a comprehensive evaluation of the failure mechanisms of the acetabular component. The porosity within the FGP acetabular component in the FE model was incorporated using effective properties of porous unit cells based on a numerical homogenization technique. The effect of the polar gradation exponent of the FGP design on failure mechanisms was also investigated. It was observed that a reduction in polar gradation exponent led to an increase in volumetric wear of polyethylene (PE) liner and implant-bone micromotions, along with a reduced effect of bone resorption. However, the design parameters, such as porosity values at the rim, the dome, and the radial gradation exponent, were assumed to be fixed. A multi-objective optimization scheme using genetic algorithm (GA) was employed to minimize periprosthetic bone resorption and PE wear associated with the FGP acetabular component. The optimal functionally graded porous designs (OFGPs) exhibited less strain-shielding in the cancellous bone as compared to the solid metal-backing (MB). However, the OFGPs exhibited increased volumetric wear (3–10%) compared to the solid MB. The OFGP−1, having a highly porous acetabular rim and a less porous dome, appeared to be a better alternative to the solid MB. Moreover, OFGPs resulted in higher micromotions than the solid MB. A novel bone remodelling framework was proposed to investigate the combined effect of bone anisotropy and mechanobiochemical (MBC) stimulus on periprosthetic bone remodelling. The predictions of the orthotropic MBC model were found to be qualitatively similar to those of the orthotropic strain-based model. However, the orthotropic MBC model predicted bone resorption in more bone elements. Two separate FE analyses involving bonded and debonded interfacial conditions were required to account for the interfacial micromotions, periprosthetic bone resorption and volumetric wear of PE liner. A multi-objective optimization of the FGP acetabular component was employed to minimize the interfacial micromotions, periprosthetic bone resorption and volumetric wear, using a kriging model coupled with GA. The resulting optimal design exhibited lesser strain-shielding and slightly higher PE wear than the solid MB. Moreover, the micromotion corresponding to the optimal design was found to be lesser than the solid MB and OFGP-1. Subsequently, the spatial distribution of the evolutionary tissue ingrowth around the optimally designed FGP acetabular component was investigated using a novel mechanobioregulatory framework, considering mechanical and biological factors, such as implant-bone micromotions, angiogenesis, oxygen tension, and growth factors. Higher bone ingrowth around the acetabular dome was observed as compared to other periacetabular regions. The proposed numerical frameworks highlighted the influence of biological and mechanical factors on bone ingrowth and remodelling around functionally graded porous acetabular component.

Keywords: Pelvic bone, Preclinical analysis, Cementless acetabular component, Mechanobiochemical, Bone orthotropy, Mechanobioregulatory, Mechanobiology.