A Mechanically Biocompatible Implant for Hip Replacement via Multiobjective Optimization of Material Properties

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Abstract

Bone resorption is ubiquitous in reconstructive orthopaedics. The process is often triggered by a mechanical biocompatibility between the implant and the surrounding bone that hosts it. This means that the former has mechanical properties that do not match those of the latter. In total hip arthroplasty (THA), the loss of normal bone stock is crucial for both primary and revision surgery. For primary THA, bone loss is caused by stress shielding, which can result in serious clinical consequences, such as periprosthetic fractures, and increased intracortical porosity, which in turn favours the ingress of particulate wear debris leading to implant loosening. For revision THA, the loss of normal bone stock compromises the bone's ability to adequately fix to the cementless revision implant. Among the large palette of cementless or porous-coated prostheses currently available in the market of total hip arthroplasty, there is not a single implant that can avoid bone resorption while concurrently providing implant stability.

In this work, we introduce a method to design a hip replacement implant with variable material properties that can concurrently minimize bone resorption and implant interface failure. While the implant is shaped for minimally invasive surgery, the material is designed with a microarchitectured cellular solid, obtained with a functionally graded periodic lattice. The method integrates concepts of multiscale mechanics theory, to handle the homogenized properties of the implant under multiaxial load, with multi-objective optimization, to obtain mechanical biocompatibility at minimum micromotion. In particular, Asymptotic Homogenization is applied to capture the stress distribution at both macro and microscale, and the Non-dominated Sorting Genetic Algorithm II is employed to obtain Pareto Front solutions of optimal relative density distribution.

CT scan data of a male patient are used to reconstruct an accurate 3D model of the femur geometry with a realistic graded distribution of bone properties. Walking and stair climbing loadings applied to the hip (Bergmann et al. 2010) are also used for the design of the implant against fatigue failure. For the material microarchitecture, a lattice cell topology optimized for maximum bone ingrowth is selected as the building block of the lattice implant (Hollister 2009); its relative density is set as the design variable to optimize for prescribed sample points of the domain.

Compared with conventional titanium implants, preliminary results show that a reduction of 70% of bone resorption and 50% of interface stress failure can be obtained with a functionally graded porous implant. The manufacturability of a proof-of-concept implant fabricated out of Titanium alloy by Electron Beam Melting (EBM) is investigated. The morphology of the cellular microstructure, including average pore size and cell wall thickness, are compared with nominal design values to determine the manufacturing constraints.

Reference:

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