Mechanical target for bone implant optimization based on numerical homogenization

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Abstract

Microstructurally architected materials have recently received a significant boost due to advent of new manufacturing techniques. Despite these functionally graded materials, such as graded lattice, are now widely employed in many fields of engineering: in bioengineering they play the role of artificial substitutes mimicking the real architecture of some biological tissues; their effectiveness for prosthetic implants, especially orthopedic and dental ones, is crucially affected from the accuracy level of their biological functions understanding, as much as from the choice of the optimization target. In recent studies the mechanical response of several kinds of Triply Periodic Minimal Surfaces (TPMS) is investigated in the limit of their manufacturability, due to their structural efficiency (1), or density-based topology optimization of homogenized lattice structures in a patient-specific hip endoprothesis is performed (2).

The goal of the present study is to provide a more reliable mechanical optimization target to mitigate the stress shielding experienced by the prosthesis-bone system due to the mismatch in the compliance properties between the bone and implant materials. The stress jump at the prothesis- bone system interface progressively impairs the stress resistance of the implant, since the surrounding extant bone tends to decrease in thickness, adversely affecting implant longevity and effectiveness.

The applied methodology is driven by a set of data acquired through micro Computed Tomography images (μCT) over a serie of human hip bone samples. We performed a statistical analysis, extrapolating the probability density functions (PDF) of a set of fundamental geometrical features: beyond the sole volume fraction of the bone tissue, we get information on the trabecular thickness distribution, and on the anisotropy of the trabecular architecture as well. In particular, from the binary images of μCT dataset the volume fraction is estimated as the ratio between the dimension of the bone tissue islands and the overall sample; the trabecular thickness is estimated by a direct interpolation through the superposition of ellipsoidal domains over the tissue islands; while the anisotropy is evaluated by using the Mean Intercepts Length (MIL) method (3,4). The statistical behavior of the aforementioned geometrical features are integrated in a computational study getting a continuum equivalent of the resected bone before the implantation. Due to high computational costs associated with stochastic computational homogenization, it is shown that the highly complex bone material with random microstructure can be replaced by a simplified ergodic model. The

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numerical homogenization techniques used to describe composites with random structures are several: from the stochastic collocation method to polynomial chaos, up to Monte Carlo methods and Stochastic Finite Elements (SFEM). The latter ones are the most widely used for this kind of composites (5,6).

The homogenized continuum equivalent allows to compute the minimal stress jump achievable, with the accuracy level provided by the geometrical features accounted in the model, at the prothesis-bone system interface. The stress jump is computed performing FEM analysis over the implant for different load conditions. The future perspective of this work opens up to an inverse problem formulation where the continuum equivalent material would be the mechanical target of a density-based topological optimization study on a regular periodic graded lattice, such as TPMs.

References:

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