Bone remodeling: multiscale mechanical models and multiphysical aspects

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Structural hierarchical multiscale optimization using a parameterized mimetic cancellous microstructure

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ABSTRACT

Bone tissue mechanical properties and trabecular microarchitecture are the main factors that determine the biomechanical properties of cancellous bone. Artificial cancellous microstructures, typically described by a reduced number of geometrical parameters, can be designed to obtain a mechanical behavior mimicking that of natural bone. In this work, we assess the ability of the parameterized microstructure introduced by Kowalczyk (*Comput Meth Biomech Biomed Eng*, 9:135–147, 2006) to mimic the elastic response of cancellous bone, and we devise an optimization method to size the geometrical parameters to obtain the microstructure that better mimics the elastic response of target a natural trabecular bone sample. The optimization is done using a Pattern Search optimization algorithm that minimizes the difference between the symmetry class decompositions of the elastic tensors. The performance of the method is demonstrated for 146 bone samples.

The parameterized microstructure is then used in a hierarchical multiscale optimization method for the design of elastic solids with biomimetic microstructures. The cost function is the structural compliance in the macroscale, while the design variables in the subscale are the geometrical parameters and the microstructure orientation; the goal is to obtain the microstructure distribution over the macrostructure domain that results in the minimum cost. The implementation consists of a finite element solver for the evaluation of the structural compliance under varying microstructure distribution, coupled to a gradient-based nonlinear constrained optimization solver (IPOPT, see A. Wächter & T. Biegler, *Mathematical Programming*, 106(1), 25–57, 2006) We use an offline strategy based on the response surface methodology (RSM) to fit polynomial functions for the evaluation of the microstructure elastic tensor in terms of the microparameters (V. Fachinotti et al., *International Journal of Solids and Structures*, 69–70, 45–59, 2015). This strategy drastically reduces the computing time with respect to the online design of the microstructures via SIMP methods. The proposed method is verified for a number of structural benchmark examples and the results are compared to solutions computed using topological optimization analysis. Finally, a three-dimensional example of the proximal femur subjected to physiological loading conditions is solved to obtain the spatial distribution of the bone density, elastic anisotropy and trabecular architecture. Effects of the porosity constraints are considered; results are validated via comparison with computed tomography data.