Multiscale poroelastic model of bone

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Abstract

Total Hip Arthroplasty is nowadays one of the most performed orthopedic surgery and is representing a major health and economic issue. Therefore, it is essential to provide a better understanding of bone mechanical behavior and its reaction to the implantation of a device such as a hip prosthesis. Numerical simulation can play a key role on this challenge, allowing for the reproduction, interpretation and analysis of the bone response to the external stimuli.

Bone is a complex material showing a hierarchical and porous structure, but also a natural ability to remodel itself thanks to specific cells, which are sensitive to fluid flows. Based on these characteristics, a multiscale numerical model has been developed within this thesis in order to simulate the bone response under external mechanical solicitations. The developed model relies on the homogenization technique for periodic structures based on an asymptotic expansion. It simulates cortical bone as a homogeneous structure. It is constituted of a porous microstructure with a 5% saturated with bone fluid, which, in the considered conditions, follows the Darcy’s law.

The first application of the developed model is a case study, consisting in the loading of a finite volume of bone, allowing for the determination of an equivalent poroelastic stiffness. Focusing on two extreme fluid boundary conditions (impermeable walls and atmospheric pressure), the analysis of the corresponding structural response provides an overview of the fluid contribution to the poroelastic behavior, impacting the equivalent stiffness of the considered material. This parameter is either reduced (when the fluid can flow out of the structure) or increased (when the fluid is kept inside the structure) and quantified through the developed model.

To validate the developed model, both numerical and experimental validation are proposed. The numerical validation consists in the estimation of the model accuracy when varying parameters such as material properties or boundary conditions. Then, an experimental validation is set up in order to attest the reliability of the numerical model. As a reference case, a previous work on a cubic trabecular bone sample, extracted from a human hip and put under a compressive load, has been used. Increasing the load applied on the top of the bone specimen, the displacement is extracted, allowing the computation of the equivalent strain-stress curve. The equivalent stiffness of the bone specimen, calculated numerically by the developed numerical tool, is then compared with the one from the experiments. A good agreement between the curves attests the validity of the developed numerical model, accounting for both the solid matrix and fluid contributions.

The presented poroelastic numerical model, accounting for the bone fluid contribution, is here developed in the perspective of providing a bio-reliable model of bones, to determine the critical parameters that might impact bone remodeling. Towards the design and manufacturing of new generation of prosthesis, this bone model shows both accuracy and ease of computation, which will be required for its application as a preoperative or design tool.