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Research paper

Efficient numerical analysis of bone remodelling

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ABSTRACT

This paper presents a formulation for the three-dimensional numerical simulation of mechanically regulated bone adaptation. Attention is focussed on a phenomenologically-based approach to bone remodelling that can be used as a computationally efficient tool to provide insight into the overall response of bone to mechanical loading. A discretisation approach is developed based on a hybrid finite element formulation where displacement, stress and density fields are approximated independently. The paper also discusses a solution algorithm tailored for shared memory multi-core computers. The performance of the model is demonstrated by two numerical examples.

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1. Introduction

Bone undergoes a continuous process of resorption and formation throughout its lifespan called bone remodelling. This process occurs in response to mechanical stimuli and the microstructure evolves to provide an internal architecture that is optimised with respect to strength, stiffness and weight. The finite element based numerical simulation of bone remodelling has been the subject of several studies (Beaupré et al., 1990; Huiskes et al., 2000; Mullender and Huiskes, 1995; Harrigan and Hamilton, 1993; Kuhl et al., 2003; Mullender et al., 1994; Jacobs et al., 1995, 1997) and this paper represents an alternative modelling approach where the focus is on computational efficiency that is vital for large scale problems. It should be noted that this paper does not attempt to explore the complex underlying biological processes that leads to remodelling. The simulation of bone remodelling involves the solution to the coupled conservation laws of mass balance and linear momentum balance. Although the numerical solutions to each of these governing equations are, in themselves, relatively straightforward, the solution of the resulting coupled system is more involved.

Numerical simulation can provide important insights into the macroscopic morphology of bone and morphological changes to bone as a result of mechanical loading (Jacobs et al., 1995). For example, numerical simulation can provide a predictive capability for the response of bone to surgical intervention. Stress shielding is a well known example of local bone remodelling and can occur with prosthetics when an implant carries a larger proportion of the mechanical load than the natural material it is replacing (for example, due to greater stiffness of the implant). This results in shielding of the surrounding bone which consequently undergoes bone remodelling and can become osteoporotic. Numerical simulations can potentially predict bone remodelling in such situations, thereby aiding the optimal design of such implants. Another example emanates from the degeneration of the intervertebral disc, leading to alternative load paths through the spine, partially shielding the vertebral bodies and thereby contributing to possible osteoporotic vertebral fracture (Pollintine et al., 2004). Once again, numerical simulation can enhance our understanding of processes such as these and, for example, contribute to improved calculation of fracture risk.

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