Journal of Biomechanics 44 (2011) 1852–1858

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Nanoindentation testing and finite element simulations of cortical bone allowing for anisotropic elastic and inelastic mechanical response

Davide Carnelli [a,b], Riccardo Lucchini [a], Matteo Ponzoni [a], Roberto Contro [a], Pasquale Vena [a,c,*]

[a] LaBS-Laboratory of Biological Structure Mechanics, Department of Structural Engineering, Politecnico di Milano, Milan, Italy
[b] Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA
[c] IRCCS, Istituto Ortopedico Galeazzi, Milan, Italy

ARTICLE INFO

Article history:
Accepted 14 April 2011

Keywords:
Cortical bone
Nanoindentation
Finite elements
Anisotropy
Post-elastic behaviour

ABSTRACT

Anisotropy is one of the most peculiar aspects of cortical bone mechanical behaviour, and the numerical approach can be successfully used to investigate aspects of bone tissue mechanics that analytical methods solve in approximate way or do not cover. In this work, nanoindentation experimental tests and finite element simulations were employed to investigate the elastic–inelastic anisotropic mechanical properties of cortical bone. The model allows for anisotropic elastic and post-yield behaviour of the tissue. A tension-compression mismatch and direction-dependent yield stresses are allowed for. Indentation experiments along the axial and transverse directions were simulated with the purpose to predict the indentation moduli and hardnesses along multiple orientations. Results showed that the experimental transverse-to-axial ratio of indentation moduli, equal to 0.74, is predicted with a ~3% discrepancy regardless the post-yield material behaviour; whereas, the transverse-to-axial hardness ratio, equal to 0.86, can be correctly simulated (discrepancy ~6% w.r.t. the experimental results) only employing an anisotropic post-elastic constitutive model. Further, direct comparison between the experimental and simulated indentation tests evidenced a good agreement in the loading branch of the indentation curves and in the peak loads for a transverse-to-axial yield stress ratio comparable to the experimentally obtained transverse-to-axial hardness ratio. In perspective, the present work results strongly support the coupling between indentation experiments and FEM simulations to get a deeper knowledge of bone tissue mechanical behaviour at the microstructural level. The present model could be used to assess the effect of variations of constitutive parameters due to age, injury, and/or disease on bone mechanical performance in the context of indentation testing.

1. Introduction

Instrumented indentation is a valid tool to measure mechanical properties of bone tissue at various structural levels (Ebenstein and Pruitt, 2006; Lewis and Nyman, 2008; Rho et al., 1997, 2002; Zysset et al., 1999). The determination of the elastic and inelastic properties of bone through micro or nanoindentation experimental tests should be performed by carefully considering at least two main factors; namely: the hierarchical arrangement of constituents and the anisotropy of the material response (Cowin, 2001; Currey, 2002; Weiner and Wagner, 1998).

Nanoindentation tests are localized measurements that enable one to consider separately the different microstructures as well as the typologies of tissue (osteonal bone, interstitial bone, fibrolamellar bone, etc.). Several studies identified anisotropic elasticity of cortical bone by performing nanoindentation tests along multiple orientations. At the nano and microscales, as an example, Fan et al. (2002), Franzoso and Zysset (2009) and Rho et al. (1999) found the axial direction to be stiffer than the transverse one with an average axial-to-transverse anisotropic ratio of ~1.5. This anisotropic ratio is of the same order of the values known for macroscopic cortical bone (Currey, 2002; Cowin, 2001). Further, direction-dependent hardness was evidenced in other studies (Rho et al., 1999; Wang et al., 2006).

In addition to the experimental testing, several models have been introduced to model the hierarchical structure of Haversian bone. Katz (2000) was able to reproduce the ultrasound testing results on bovine cortical bone along different directions through a two-level composite model, predicting an axial-to-transverse Young's modulus ratio of about 1.6. Other recent and more sophisticated models have been developed to predict the transverse-to-axial Young's modulus ratio in hierarchical models at lower hierarchical level: among these, Predoi-Racila et al. (2008) predicted an axial-to-transverse Young's modulus ratio of 1.7 for

* Corresponding author at: LaBS-Laboratory of Biological Structure Mechanics, Department of Structural Engineering, Politecnico di Milano, Piazza Leonardo da Vinci, 32, 20133 Milano, Italy. Tel.: +39 02 2399 4236; fax: +29 02 2399 4220.
E-mail address: vena@stru.polimi.it (P. Vena).

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doi:10.1016/j.jbiomech.2011.04.020