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Journal of Biomechanics 40 (2007) 3381–3388

JOURNAL OF BIOMECHANICS

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Side-artifact errors in yield strength and elastic modulus for human trabecular bone and their dependence on bone volume fraction and anatomic site

Grant Bevill[a], Sarah K. Easley[a], Tony M. Keaveny[a,b,*]

[a]*Orthopaedic Biomechanics Laboratory, Department of Mechanical Engineering, University of California, Berkeley, CA, USA*
[b]*Department of Bioengineering, University of California, Berkeley, CA, USA*

Accepted 5 May 2007

Abstract

In the context of reconciling the mechanical properties of trabecular bone measured from *in vitro* mechanical testing with the true *in situ* behavior, recent attention has focused on the "side-artifact" which results from interruption of the trabecular network along the sides of machined specimens. The objective of this study was to compare the magnitude of the side-artifact error for measurements of elastic modulus vs. yield stress and to determine the dependence of these errors on anatomic site and trabecular micro-architecture. Using a series of parametric variations on micro-CT-based finite element models of trabecular bone from the human vertebral body ($n = 24$) and femoral neck ($n = 10$), side-artifact correction factors were quantified as the ratio of the side-artifact-free apparent mechanical property to the corresponding property measured in a typical experiment. The mean ($\pm$SD) correction factors for yield stress were 1.32 ± 0.17 vs. 1.20 ± 0.11 for the vertebral body and femoral neck ($p < 0.05$), respectively, and the corresponding factors for modulus were 1.24 ± 0.09 vs. 1.10 ± 0.04 ($p < 0.0001$). Correction factors were greater for yield stress than modulus ($p < 0.003$), but no anatomic site effect was detected ($p > 0.29$) after accounting for variations in bone volume fraction (BV/TV). Approximately 30–55% of the variation in the correction factors for modulus and yield stress could be accounted for by BV/TV or micro-architecture, representing an appreciable systematic component of the error. Although some scatter in the correction factor–BV/TV relationships may confound accurate correction of modulus and yield stress for individual specimens, side-artifact correction is nonetheless essential for obtaining accurate mean estimates of modulus and yield stress for a cohort of specimens. We conclude that appreciation and correction for the differential effects of the side-artifact in modulus vs. yield stress and their dependence on BV/TV may improve the interpretation of measured elastic and failure properties for trabecular bone.

Keywords: Cancellous bone; Finite element modeling; Bone quality; Bone biomechanics; Bone strength

1. Introduction

The elastic and strength properties of trabecular bone are widely studied due to their relevance in understanding structure–function relations, as well as their role in the pathophysiology of aging, disease, and treatment. These properties are typically obtained from experimental testing (Carter and Hayes, 1977) or finite element modeling (Homminga et al., 2003; Van Rietbergen et al., 1995) of excised specimens of trabecular bone. However, all these measures contain an unavoidable artifact due to the loss of connectivity at the periphery of the excised specimen, termed the "side-artifact" (Ün et al., 2006). Since the side-artifact is a connectivity-mediated mechanism (Andrews et al., 2001; Onck et al., 2001; Ün et al., 2006; Zhu et al., 1994), it may affect measures of strength differently than elastic modulus due to failure mechanisms such as large deformation bending and buckling (Bevill et al., 2006; Gibson, 1985), and may also depend on volume fraction or anatomic site for the same reasons. Understanding how the side-artifact affects measures of elastic modulus vs.

*Corresponding author. Orthopaedic Biomechanics Laboratory, Department of Mechanical Engineering, University of California, Berkeley, CA, USA. Tel.: +1 510 643 8017; fax: +1 510 642 6163.
E-mail address: tmk@me.berkeley.edu (T.M. Keaveny).

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doi:10.1016/j.jbiomech.2007.05.008

strength and devising methods to correct for this artifact should therefore improve interpretation of biomechanical tests and may improve the fidelity of finite element models used to study whole-bone (Cody et al., 1999; Crawford et al., 2003; Homminga et al., 2001; Keyak et al., 2001) and bone-implant behavior (Huiskes and Chao, 1983; Keaveny and Bartel, 1995; Skinner et al., 1994).

The side-artifact mechanistically depends on trabecular spacing (or cell size in cellular foams) (Onck et al., 2001; Ün et al., 2006), and can result in underestimation of elastic modulus by as much as 50% in human vertebral bone (Ün et al., 2006). However, several fundamental questions remain unanswered. First, for human trabecular bone, errors due to the side-artifact have only been quantified for low-density anatomic sites. Theoretical analysis suggests that side-artifact errors should be less significant in high-density bone (Ün et al., 2006), but such predictions are confounded by the associated changes in micro-architecture with changing bone volume fraction (BV/TV) (Hildebrand et al., 1999) as well as potential differences between anatomic site (Morgan et al., 2003). Second, side-artifact errors have only been quantified for elastic modulus in trabecular bone. However, interruption of connectivity and loss of lateral support at the sides of excised specimens (Fig. 1) could augment errors in measurements of failure properties (relative to elastic behavior) by facilitating local buckling or large bending deformations. The differences between elastic and failure behavior have previously been examined using cellular solid analysis (Onck et al., 2001) and experiment on metallic foams (Andrews et al., 2001), where it was found that errors in elastic modulus were greater than those for ultimate strength in cellular materials that fail by plastic hinging. While the differing failure mechanisms between trabecular bone and metallic foams make it difficult to extrapolate these results to human trabecular bone, they nonetheless highlight the importance of distinguishing between elastic and failure behavior in the context of side-artifact errors.

The overall goal of this study was to address the role of anatomic site and BV/TV on the side-artifact error and also the issue of differential errors for elastic modulus vs. yield stress and strain. Since quantification of side-artifact errors would be difficult in an experimental setting, we used experimentally validated high-resolution finite element models. Focusing on human trabecular bone from the femoral neck and vertebral body, given the relevance of these sites to osteoporotic fracture and their combined wide range of BV/TV and architecture, our specific objectives were to (1) compare the magnitude of the side-artifact errors for modulus vs. yield stress; (2) determine the dependence of these errors on BV/TV, micro-architecture, and anatomic site; and (3) establish a technique to correct for side-artifact errors in trabecular bone of any volume fraction. This study is unique in that it is the first to compare side-artifact errors for measurements of elastic modulus vs. yield stress for trabecular bone from multiple human anatomic sites.

Fig. 1. Longitudinal cross-section (0.22 mm thick) of a core of vertebral trabecular bone with BV/TV = 0.16. The circled region at the right of the image illustrates a structure with complete loss of vertical connectivity due to the side-artifact. The circled region at the left of the image highlights a trabecula that has lost lateral support, but retained vertical load-bearing capacity. Such a structure may result in greater side-artifact errors in post-elastic measurements (e.g., yield and ultimate) than in elastic measurements due to large-deformation bending or buckling.

2. Methods

Thirty-four "on-axis" (Morgan and Keaveny, 2001) cylindrical cores of human trabecular bone (14.4–17.3 mm long, ~8.2 mm diameter) were taken from L4 vertebral bodies ($n = 24$ cadavers, BV/TV = 0.11 ± 0.04, age = 75 ± 13) and femoral necks ($n = 10$ cadavers, BV/TV = 0.20 ± 0.04, age = 73 ± 11). A three-dimensional high-resolution image was obtained for each specimen using micro-CT scanning (Scanco μCT 20; Scanco Medical AG, Basserdorf, Switzerland) with an in-plane voxel dimension of 21 μm and out-of-plane dimension of 22 μm. Standard micro-architectural metrics were then measured from these images, including mean trabecular separation (Tb.Sp*, where * denotes a three-dimensional measure made using a distance-transformation method), mean trabecular thickness (Tb.Th*), mean trabecular number (Tb.N*), degree of anisotropy (DA), connectivity density (CD) (Odgaard and Gundersen, 1993), and structure model index (SMI) (Hildebrand and Ruegsegger, 1997).

The effect of the side-artifact on apparent mechanical properties was assessed using a previously reported "inner-core" technique (Ün et al., 2006). Briefly, two concentric images were created directly from the micro-CT scan of each specimen—an 8 mm diameter core and an "inner" 6 mm diameter core—which were converted into voxel-based finite element meshes. Fully nonlinear (material and geometric) finite element analysis