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Shear strength and toughness of trabecular bone are more sensitive to density than damage

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ABSTRACT

Microdamage occurs in trabecular bone under normal loading, which impairs the mechanical properties. Architectural degradation associated with osteoporosis increases damage susceptibility, resulting in a cumulative negative effect on the mechanical properties. Treatments for osteoporosis could be targeted toward increased bone mineral density, improved architecture, or repair and prevention of microdamage. Delineating the relative roles of damage and architectural degradation on trabecular bone strength will provide insight into the most beneficial targets. In this study, damage was induced in bovine trabecular bone samples by axial compression, and the effects on the mechanical properties in shear were assessed. The damaged shear modulus, shear yield stress, ultimate shear stress, and energy to failure all depended on induced damage and decreased as the architecture became more rod-like. The changes in ultimate shear strength and toughness were proportional to the decrease in shear modulus, consistent with an effective decrease in the cross-section of trabeculae based on cellular solid analysis. For typical ranges of bone volume fraction in human bone, the strength and toughness were much more sensitive to decreased volume fraction than to induced mechanical damage. While ultimately repairing or avoiding damage to the bone structure and increasing bone density both improve mechanical properties, increasing bone density is the more important contributor to bone strength.

1. Introduction

Damage accumulation is detrimental to the mechanical competence of bone (Keaveny et al., 1999; Arthur Moore and Gibson, 2002; Moore and Gibson, 2003). In combination with the effects of damage in cortical bone (Fondrk et al., 1999; Reilly and Currey, 2000; Jepsen et al., 2001), it may be an important factor in fracture susceptibility in whole bones (Hoshaw et al., 1997). Osteoporosis and aging decrease bone mineral density (BMD) and trabecular thickness, and increase structure model index. These factors are associated not only with lower strength and energy to failure (Garrison et al., 2009), but with greater microdamage burden in trabecular bone as well (Wang and Niebur, 2006; Arlot et al., 2008). As treatments for osteoporosis might have differing effects on bone mineral density, architecture, and damage repair, it is important to assess the relative effects of each of these in order to guide the development and evaluation of new treatments and diagnostic methods.

Bone strength, toughness, and modulus are modulated by bone mineral density, trabecular architecture, and damage level (Keaveny et al., 1994; Yeh and Keaveny, 2001; Arthur Moore and Gibson, 2002; Badiei et al., 2007). Many of the architectural quantities are highly correlated to volume fraction, especially for bone from a single anatomic site (Arlot et al., 2008). As such, subtle effects of architectural changes can be obscured when BMD or volume fraction is included as explanatory variables. Under compressive loading, the effects of architecture were more highly correlated to the toughness and strength of trabecular bone than volume fraction, even within a small range of physiological variation (Garrison et al., 2009). However, bone is also loaded multi-axially *in vivo*, particularly during falls, and compressive material properties may not be sufficient for assessing fracture risk.

Damage induced under a single loading condition has anisotropic effects on the residual mechanical properties in trabecular bone. If microdamage occurs predominantly in structures along one fabric direction (Shi et al., 2009), the effects of damage on the compressive and shear moduli may differ (Liu et al., 2003b). Experimentally, damage induced by on-axis compression of vertebral trabecular bone caused smaller reductions in modulus and strength in transverse than in on-axis loading (Badiei et al., 2007). However, shear loading may be a more sensitive loading mode to accumulated on-axis damage than transverse loading (Ford and Keaveny, 1996; Liu et al., 2003a; Wang and Niebur, 2006). In fabric tensor models of trabecular bone mechanics,

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