Introduction: Bone mineral density is the standard clinical measure of fracture susceptibility, but it does not adequately predict fracture risk [1]. Bone quality, including factors such as microdamage, may also have a role in bone fragility. The likelihood of fracture is increased by a history of nonfracturing falls that may induce microdamage [2]. Microdamage is also known to decrease the modulus and strength of trabecular bone [3], which is a major load-bearing component at sites where osteoporotic fractures occur [4]. However, the role of microdamage in fracture etiology remains controversial. For example, in cortical bone, microdamage was associated with an increased fatigue life [5]. Bone density and microdamage both affect trabecular bone failure behavior, but their relative roles are not known.

The goal of this study was to determine the effects of pre-existing damage on the toughness of trabecular bone. Specifically, trabecular bone samples were damaged by overloading, then loaded to failure to measure the effects on modulus, strength, and toughness.

Materials and Methods: Fifteen on-axis cylindrical specimens were prepared from the proximal metaphyses of twelve bovine proximal tibiae. The principal axes of the cylinders were aligned with the principal material axes using μ-CT imaging, with an average error of 7.29 ± 3.6° (mean ± SD).

Specimens were assigned to low damage (n=6), high damage (n=5), or control groups (n=4) and embedded in brass endcaps for mechanical testing [6]. The undamaged modulus of each sample was determined using three non-destructive load cycles to measure the damaged modulus. Finally, all specimens were destructively loaded to 7.5% strain.

The initial and damaged moduli were found from the derivative of a quadratic curve fit from 0% to 0.4% strain at zero load. The original and damaged ultimate strengths were taken as the maximum of the stress-strain curve during overloading and failure, respectively. Ultimate strength reductions were measured only on specimens that reached an ultimate point during the damaging load. The toughness was measured as the area under the stress-strain curve to 5% strain.

Results: Both the high and low overload strains resulted in modulus reductions. The modulus decreased by 15.15 ± 9.98% in the low damage group and 30.04 ± 14.81% in the high damage group (p<0.01), with no dependence on volume fraction. The strength decreased 11.17 ± 11.34% in the low damage group compared to 29.80 ± 16.65% in the high damage group (p=0.45), independent of volume fraction (p=0.31). In contrast, the toughness increased with volume fraction (p=0.015) irrespective of damage level (p=0.103) (Fig. 1). However, there was a trend toward decreasing toughness with increasing damage (Fig. 2).

Discussion: The goal of this study was to quantify the relative roles of microdamage and density in trabecular bone fracture risk. Since toughness represents a material’s ability to absorb energy, it was chosen as a relevant measure of resistance to fractures during falls. The toughness increased with increasing density. However, in contrast to modulus and strength, the dependence had an exponent less than one, resulting in a saturation at high densities and a rapid decrease at low densities. Higher levels of microdamage did not affect the toughness. This may be due to the self-limiting nature of microcracks in trabecular bone [7, 8]. However, power analysis indicated a sample size of 20 would be needed to detect differences between damage levels.

The modulus and strength decreased with overloading, consistent with previous studies [3]. In this study, we demonstrated that the toughness is affected less by damage. As such, it may be a better measure of the role of microdamage in fractures.

The results also provide insight into the mechanisms of fracture risk reduction by bisphosphonates. Bisphosphonates inhibit bone remodeling to maintain bone mass [9], but also prevent the repair of microdamage [10]. The data suggest that the toughness increase associated with higher bone density may compensate for the increase in microdamage burden, resulting in an overall reduction in fracture risk.


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