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Fracture Toughness is More Sensitive to Bone Remodeling Parameters than Strength and Toughness

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Introduction: Common mechanical measures of bone quality include bone strength, fracture toughness and material toughness. Fracture toughness calculated from linear elastic fracture mechanics refers to the fairly localized energy required to cause macrocrack initiation or propagation [1]. Material toughness (work to fracture) is an extrinsic property, calculated from the area of the load-displacement curve and represents the energy absorbed prior to the generation of microcracks plus the energy required to start and drive the final macrocracks in order to break the material [2]. Both fracture and material toughness are frequently used in describing material quality however their sensitivity to bone remodeling parameters has not been compared. It was hypothesized that intrinsic material properties, i.e. strength and fracture toughness, are more reflective of bone remodeling parameters than are extrinsic material properties, e.g. work to fracture. The objective of this research was to investigate and compare the relationships between the common bone mechanical measures and the microstructural and compositional variables associated with bone remodeling and micro- and diffuse damage.

Materials and Methods: Twenty-two femoral midshafts from 12 female and 10 males ranging in age from 26 years to 92 years (average age = 62.5 ± 20.0 years) were used in this study. Mode I and Mode II compact tension and shear fracture toughness specimens were machined from the femurs and tested [3]. Mode I (G_I) and mode II (G_{II}) fracture toughness (strain energy release rates) were determined using linear elastic fracture mechanics. In addition, two longitudinally oriented three-point-bend specimens (30mm X 4mm X 2mm) were also removed from each femoral midshaft by a diamond wire saw [4]. Bending properties (ultimate load at failure, P_{ult}, and work to fracture or area under the load-displacement curve, W_{AUC}) were determined by loading each specimen until failure on a three-point-bend loading configuration with unsupported span of 15 mm on roller edges. The loading rate was 5mm/min on a MTS machine model 812.21 (MTS Systems Corporations, MN). The ultimate load at failure was the maximum load achieved during the loading cycle and the work to fracture was found from the area under the load-displacement curve (Fig. 1). After testing, thin sections were obtained from each specimen, polished and stained with hemotoxylin-eosin for morphological evaluation [5]. Compositional variables were also obtained from remaining bone [3]. Diffuse and microscopic damage were also measured from stained bulk sections obtained from the midshafts [6]. Microstructural and compositional variables were correlated to the mechanical measurements using simple regression analysis. The statistical package JMP^{TM} (SAS institute, Cary, NC) was used in the statistical analysis. Significance was set at $p<0.05$.

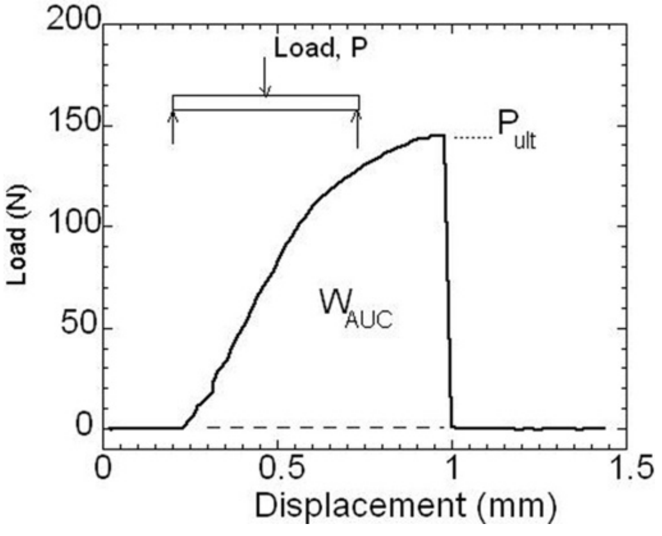

Fig. 1 Load-displacement test for calculating toughness (W_{AUC}) and failure load (P_{ult}) under three-pt-bend.

Results: G_I and G_{II} fracture toughness significantly correlated with six variables and ultimate load at failure significantly correlated with three variables and marginally ($p<0.096$) correlated with a fourth variable (Table 1). The work to fracture, W_{AUC}, was not significantly related to remodeling associated parameters but did significantly correlate with diffuse damage density.

Micro/Comp Variable	G_I	G_{II}	P_{ult}	W_{AUC}
Age	0.201 (-0.28)	**0.050 (-.42)**	**0.034 (-0.45)**	0.637 (-0.106)
Density	**0.020 (0.50)**	**0.003 (0.60)**	**0.040 (0.45)**	0.134 (0.33)
% Organic	**0.017 (0.51)**	0.60 (-0.12)	0.554 (-0.13)	0.685 (-0.09)
% Ash	**0.040 (0.44)**	**0.001 (0.65)**	**0.050 (0.42)**	0.172 (0.30)
% H20	**0.004 (-0.58)**	0.331 (-0.22)	0.572 (0.13)	0.700 (0.087)
% Porosity	0.425 (-0.18)	**0.005 (-0.58)**	**0.096 (-0.36)**	0.157 (-0.31)
Ost. Density	0.658 (0.10)	0.731 (-0.08)	0.370 (-0.19)	0.72 (-0.07)
Hav. size	0.438 (-0.17)	**0.057 (-0.41)**	0.206 (-0.28)	0.189 (-0.29)
Microdamage	**0.009 (-0.35)**	**0.081 (-0.23)**	0.173 (-0.31)	0.559 (0.135)
Diffuse Damage	**0.050 (-0.27)**	**0.02 (-0.31)**	0.387 (0.20)	**0.057(0.422)**

Table 1. Correlations between microstructural and compositional remodeling variables, damage and mechanical measurements (p (R)).

Discussion: Strength and fracture toughness are calculated to include maximum loads that are defined by the onset of failure or macroscopic cracking. According to these results, these intrinsic properties are more directly influenced by microstructural and compositional changes that occur with Haversian remodeling and bone damage than are the extrinsic property work-to-fracture. Therefore, strength and fracture toughness may be indicators that are more sensitive to bone adaptation than work to fracture. Based on the number of significant correlations, it may be concluded that fracture toughness is more sensitive to remodeling parameters compared to strength measures. It is also interesting to note that of all the variables investigated, work to fracture significantly correlated to ultrastructural damage only. Previous reports have found that the collagen network plays an important role in the toughness of bone [7], however collagen was not measured in this study. Based on the findings of this study, it is also concluded that bone toughness is independent of remodeling parameters but is significantly altered by ultrastructural damage.

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