A Quasi-Brittle Fracture Mechanics Model for Assessing Treatment Effects in Human Cortical Bone

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Abstract

Fragility fractures are increasingly common, yet efficacy of treatments often remains low. Most treatments address bone quantity, yet changes to bone quantity do not necessarily result in a corresponding change to fracture risk. To better understand fragility fractures, there is a need to improve fundamental understanding of bone fracture mechanics.
Ex-vivo treatment of bone with the FDA-approved compound Raloxifene provides a testbed to study fracture in the context of bone quality treatments. Bone fracture mechanics commonly employ linear elastic fracture mechanics (LEFM) stress-intensity factors or J-integral calculation. Large fracture process zones (FPZs) have been observed in bone, violating LEFM and restricting the J-integral. We hypothesize that quasi-brittle fracture mechanics (QBFM) can be used to assess changes in the fracture properties of bone with treatment.

Cadaveric human femur tissue is obtained and sectioned into 12 prismatic bars (4 mm x 4 mm x 24 mm) with a nominal 2 mm notch. Osteon diameters (On.Dm) were determined. Beams are randomly assigned to 2 treatment groups; 6 beams are treated with a Raloxifene solution (RAL), and 6 beams are treated with a control solution (VEH). Four-point bend fracture experiments are conducted in-situ a 3D X-ray microscope (Zeiss XRADIA) with a physiological bath. FPZ size is measured directly from 3D images. Quasi-brittle fracture mechanics methods with a size-scaling law are used to obtain intrinsic material properties: a true tissue fracture toughness and an associated material characteristic length scale.

RAL treatment is found to significantly increase the FPZ size compared to VEH. Such an increase in FPZ size is found to be associated with differences in micro-crack deflection processes during the formation of the FPZ. LEFM fracture toughness with the initial crack length does not distinguish RAL and VEH. QBFM fracture toughness with the effective crack length differs between RAL and VEH, with RAL possessing higher fracture toughness. Tissue intrinsic fracture toughness for RAL is found to be 36% higher than that for VEH, while in intrinsic length scale for fracture for RAL is 86% higher than for VEH. Intrinsic length scales are found to relate to bone microstructure lengths as expressed by the osteon diameter: 14.0 On.Dm (RAL) and 6.3 On.Dm (VEH).
Quasi-brittle fracture analysis of bone is necessary to understand treatment effects across length scales. Treatments to reduce bone fracture risk should consider and evaluate effects of fracture, microdamage, and microstructure properties.

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