MULTIAXIAL FAILURE BEHAVIOR OF HUMAN FEMORAL TRABECULAR BONE

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Introduction: The multiaxial failure behavior of trabecular bone has clinical importance since it determines the fracture strength of the proximal femur in vivo during a fall [1, 2]. Knowledge of the multiaxial failure behavior of trabecular bone should therefore enable finite element models of whole bones [3] to better predict failure loads in both research and clinical settings. Multiaxial strength of trabecular bone is also associated with implant loosening [4] due to the interface stresses. Theories such as the Tsai-Wu criterion [5, 6] and cellular solid [7] have been applied to trabecular bone with mixed success. Recently, by making use of the high-resolution finite element method that had been validated against experimental data [8], a biaxial yield envelope for bovine trabecular bone was obtained [9]. However, while these studies have provided insight into the multiaxial failure of trabecular bone, a complete failure criterion for any sort of human bone remains unknown. Thus, the overall goal of this study was to develop a complete multiaxial failure criterion for human femoral neck trabecular bone. Specifically, our objectives were to: 1) determine the multiaxial failure envelope for two human trabecular bone specimens in the 3D strain space, and 2) define a simplified failure envelope based on the failure points and evaluate its performance.

Methods: Two human femoral neck specimens with volume fractions 0.29 (63 y.o. male) and 0.29 (62 y.o. female) were scanned at 22-mm resolution with a micro-CT scanner (Scanco 20, Bassersdorf, Switzerland). High-resolution finite element models with 66-mm elements were obtained from the images by regional averaging to save computational time. The trabecular tissue material was modeled as bilinearly elastic with tensile-compressive yield strain asymmetry. Previously calibrated tissue level modulus and yield strains [10] were used in the materially nonlinear model. To determine the multiaxial failure envelope, 114 nonlinear analyses were completed for one model and 266 for the other such that they spanned the entire 3D strain space in 22.5° and 15° increments, respectively. All these analyses were performed in the principal material coordinate system.

For analyses a custom finite element code employing an implicit incremental method and an element-by-element conjugate gradient solver was used [8]. All analyses were performed on eight processors of an IBM SP2 parallel supercomputer, taking in total about 26,000 hrs. of CPU time. Normal yield strains along three axes were separately calculated, and for the 3D surface the first chronological yield point was found. A simplified triangulated yield surface was constructed using 7 points.

Figure 1. Biaxial plane-strain failure envelope of trabecular bone for two specimens in axial-transverse strain space. Triangles and circles indicate data for two different specimens. Filled symbols indicate failure in the axial direction while open symbols indicate failure in the transverse direction. Curves shown are a quadratic fit to the pooled data.

Figure 2. The all compressive octant is shown for one of the trabecular bone specimens with embedded simplified failure surface. The 3D strain-space failure envelope in this octant consisted of 43 points while the triangulated yield surface was constructed using 7 points.

Results: The biaxial failure points for the two specimens were very similar indicating that once the criterion is formulated in strain space, inter-specimen heterogeneity is minor (Fig. 1). The uncoupled nature of the curves in the axial-transverse loading plane was similar in the other two biaxial planes. The normal yield strains under uniform compressive loading (analogous to hydrostatic loading) were 33% lower than the yield strain for uniaxial strain (Fig. 2), emphasizing the reduction in strength under multiaxial loads. Compared to the full criterion, the simplified failure envelope (Fig. 2) had a mean percentage error of 3.91% for the first specimen and 3.35% for the second, indicating that the overall complex behavior can be well captured with relatively few parameters.

Discussion: These results indicate that trabecular bone has almost uncoupled failure behaviors along its three main axes, leading to a failure envelope that is nearly cuboid in shape. This uncoupling of yield behavior is indicative of bone adaptation in order to isolate the effects of damage from non-habitual loading, such as a fall. Such behavior will allow healing while preserving near intact material properties along habitual loading directions.

A complete multiaxial failure criterion for trabecular bone should incorporate the normal strain envelopes presented here, as well as the axial-shear behavior. Our previous work on bovine bone [7] established an approximately triangular failure envelope for that mode of loading. It is not clear if the bone is more susceptible to failure from normal vs. shear behavior although the latter is important since trabecular bone is particularly weak in shear [11].

Thus, we recommend that failure of trabecular bone can be best predicted by comparing the strain tensor in principal material coordinates with our 3D failure criterion together with an axial-shear failure envelope [7]. Use of this combined criterion in whole bone finite element models should improve their fidelity for fracture risk prediction, which in turn may provide new insight into etiology of hip fractures.

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