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**Nanomechanics of Bone: Nanogranular Friction and Heterogeneity**[1]

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Bone is a complex nanostructured biocomposite material composed of approximately 60 wt percent carbonated apatite mineralites (10s of nanometers in length and width, 3-5 nm in thickness) that permeate in and around type I collagen fibrils. Here, we present results from studies investigating the ultrastructural origins of the strength and toughness of bone, which is critical for its proper physiological function. A combination of dual instrumented nanoindentation, three-dimensional elastic-plastic finite element analysis (FEA) using a Mohr-Coulomb cohesive-frictional strength criterion, and angle of repose measurements was employed. Our results suggest that nanogranular friction between mineral particles is responsible for increased yield resistance in compression relative to tension and that cohesion originates from within the organic matrix itself, rather than organic-mineral bonding. Nanomechanical heterogeneity is also expected to influence elasticity, damage, fracture and remodeling of bone. Here, we quantify the spatial distribution of nanomechanical properties at the length scale of individual collagen fibrils using atomic force microscope-based nanoindentation. Our results show elaborate patterns of stiffness which do not correlate with topography, and hence are attributed to organic-inorganic compositional variations and nanoscale porosity. We propose a new energy dissipation mechanism arising from nanomechanical heterogeneity which offers a graceful means for ductility enhancement, damage evolution, and toughening. This hypothesis is supported by FEA which incorporate the nanoscale experimental data and predict markedly different biomechanical properties compared to a uniform material, through nonuniform inelastic deformation over larger areas and increased energy dissipation. The fundamental concepts discovered here are applicable to a broad class of biological materials and may serve as a design consideration for biologically-inspired materials technologies.

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