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Synchrotron-based X-Ray Computed Tomography (SRμCT) imaging of Crack propagation in Human Cortical Bone

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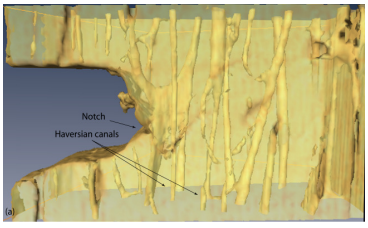
Abstract - This study characterizes the crack path and structure of human cortical bone using Synchrotron-based X-Ray Computed Tomography (SRμCT). The x-ray microtomography beamline at the Advanced Light Source at Lawrence Berkeley National Laboratory allows for materials to be non-destructively visualized in 3-dimensions with spatial resolution of a few micrometers. The process takes 2D projections and through a filtered back projection algorithm reconstructs the projections into a series of 2D slices through the sample. The crack path is segmented and visualized in 3D to examine how the crack interacts with the material's microstructure [Fig. 1(a)], and then the images are used to identify how changes in the microstructure of bone alter the fracture properties.

Many past studies use bone quantity (bone mineral density) as the only predictor to why certain bones are prone to fracture. However, there has been evidence that bone quantity is not a sufficient measure of bone strength and other factors relating to "bone quality" must be measured. Bone quality is defined as the characteristics of the tissue that influence the mechanical properties of the bone. For analysis of the bone quality the microstructure can be fully understood in 3 dimensions using the technique of Synchrotron-based X-Ray Computed Tomography (SRμCT).

Bone is a complex hierarchical structure of mineral phase (hydroxyapatite) and an organic matrix (mostly collagen). These constituents combined in a composite matrix to allow for bone to be both light and tough. The hierarchical structure of bone can be observed at several dimensional scales. At the nano scale, it is made up of fibrous polymer collagen and hard mineral nanoparticals of hydroxyapatite that reinforce it. At the micron scale bone is made up of osteons which are bone cylinders of ~ 100μm in diameter containing a central longitudinal tubular cavity (Haversian canal) containing blood vessels and nerves.

In this experiment we implement stable crack growth by conducting three point bend tests on human cortical bone samples. These samples vary in age and orientation so that a comparison between the reconstructed images as well as the segmented crack path can be observed. Also these images are used to verify changes in fracture toughness and relate them to the 3 dimensional nature of the structure. The toughness of bone is the ability of its structure to dissipate deformation energy with propagation of the crack and thus resist further crack growth. Indeed, the toughness of bone is a result of a multi-scale suite of potent extrinsic (shielding) mechanisms, coupled with an additional role of intrinsic toughening due to the significant "plasticity" in the material. Bone exhibits various features to achieve this and they are different for transverse and longitudinal cracks. Transverse cracks [Fig. 1 (b)] are harder to propagate due to twisting and deflection of the crack, while longitudinal cracks are easier to propagate as they follow the cement lines and Haversian canals. μXCT allows for the study of the crack propagation route within the bone itself giving insight into these toughening mechanisms.



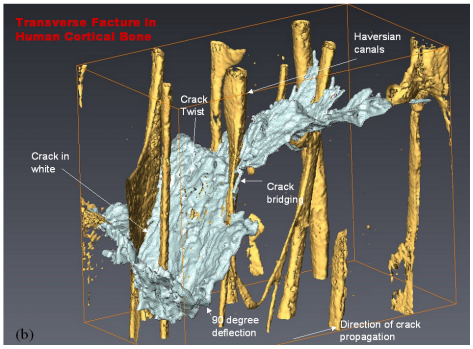


Figure 1: Synchrotron X-ray computed tomography images showing the dominant mechanisms of crack deflection and twisting in the transverse orientation. (a) A three-dimensional image of the sample in which the haversian canals are partially transparent. (b) Three dimensional representation of the crack path (in white) and haversian canals (in tan).

Reference:

1. Kurt J. Koester, Ager, J. W., and Ritchie, R. O., "The true toughness of human cortical bone measured with realistically short cracks," *Nature Materials* 7 (2008): 672-677.
2. E. A. Zimmermann, M. E. Launey, H. D. Barth, and R. O. Ritchie, "Mixed-Mode Fracture of Human Cortical Bone," *Biomaterials*, doi: 10.1016/j.biomaterials.2009.06.017 (2009).
3. R. K. Nalla, J. J. Kruzic, J. H. Kinney, M. Balooch, J. W. Ager III, R. O. Ritchie, "Role of microstructure in the aging-related deterioration of the toughness of human cortical bone," *Materials Science & Engineering C* 26, 1251-1260 (2006).