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Characterization of Fracture Resistance and Robustness in Network-Based Models of Heterogeneous Biological Materials

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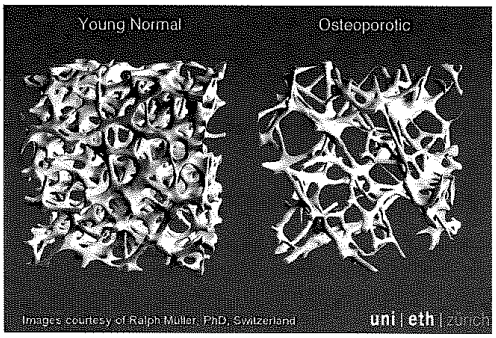
The human body is made up of complex, heterogeneous materials, which display mechanisms of strength and dynamics that are intrinsically linked across a wide range of spatial and temporal scales. This project focuses on bone, a biological material containing many mechanisms of fracture resistance within and between multiple scales. A comprehensive characterization of the composition and mechanics of bone is essential for predicting strength, dynamics, and vulnerabilities within the body, but methods for modeling bone which captures complex dependencies between multiple scales have not been fully developed.

Human bone consists of two types: cortical bone, which is hard, dense, and shell-like, and trabecular bone, which is a sparse interconnected network-like structure of struts and rods called trabeculae. In this project, we focus on trabecular bone, which is mostly found in the interior of the vertebrae and the ends of long bones such as the femur. With age, trabeculae thin and erode, causing the gaps and spaces between them to widen; this process becomes pronounced in the case of diseases such as osteoporosis and can lead to fracture (see figure). Osteoporosis, a metabolic disease leading to increased bone brittleness, is estimated to affect 10.2 million adults in the United States aged fifty years or older [1], and each year an estimated 1.5 million Americans experience a fracture due to bone disease [2]. Despite extensive efforts in characterizing complex bone structure to understand the fracture risks, factors affecting bone fragility remain poorly understood. It has only been recently shown that bone density, a quantity traditionally used to diagnose osteoporosis, is not the sole indicator of fracture risk [3]. Bone strength depends on multiscale and dynamic toughening mechanisms, and a mechanistic understanding of bone strength is critical for the diagnosis and monitoring of diseases such as osteoporosis [4]. Histomorphometry, the quantitative characterization of the morphology of trabecular structure, plays an important role in determining bone strength, and can provide salient diagnostic markers for disease [5,6].



There exists a wealth of micro-computed tomography (micro-CT) images of human bone samples from males and females of various ages that capture the trabecular structure at high resolution. The student will use micro-CT images of cadaveric vertebral bone to generate computational models from which strength and fragility can be characterized quantitatively. The web-like trabecular structure can be mathematically treated as a network graph; a complex network-based analysis of bone architecture is informative in characterizing mechanical function and stress response [7]. The student will process and threshold bone images to isolate the trabecular structure, which will then be converted into a network model using MATLAB. Starting with a percolation theory approach to analyzing the network and characterizing its fracture resistance, the student will determine mathematical rules for fracture and identify tradeoffs between robustness and fragility to various stresses, loads, and perturbations.

This project will employ and further develop the student's skills and knowledge in statistical physics, computation, and mathematical modeling, and will expose the student to an application of physics that has exciting implications for materials science and medicine. The student will have access to existing data, but will be working on a unique, independent project that addresses interesting and important physical questions. The student will also gain valuable experience working with interdisciplinary collaborators at UCSB and other universities, as well as in industry.

Our collaborators, the Elbanna Group at the University of Illinois, Urbana-Champaign, have developed synthetic 3D trabecular bone models using multi-objective topology optimization, which reverse-engineers biological structure by optimizing its performance under specified constraints. The student will use their models, generated from micro-CT data, to validate these synthetics, and compare histomorphometric analyses performed on the different models using micro-CT image analysis software.

Future work on this project can include the application of other complex network science methods to characterize the distribution and propagation of forces across trabecular bone. Complex network analysis techniques have been successfully used to quantify properties of granular and heterogeneous media and describe their behavior under compression [8,9]. For instance, the method of community detection, which is used to identify clusters in networks, has been used to describe forces within granular materials such as sand [8]. Furthermore, our approach to analyzing fracture resistance is to initially consider a quasi-static system, but a comprehensive quantification of bone strength necessitates the inclusion of the system's response to dynamic loading. We will incorporate dynamic perturbations into our computational models and integrate this large-scale characterization with models at smaller scales. The modeling approaches, tools, and software that will be developed in this project to characterize bone can also be generalized to a wide range of other heterogeneous materials found in biological, geological, and engineering systems which display similar interdependence of mechanisms across scales.

Undergraduate responsibilities: Under the supervision of the graduate student and faculty advisor, the undergraduate researcher will be in charge of all aspects of this project and accomplish the following tasks:

1. Learn fundamentals of bone architecture and histomorphometry, micro-CT image analysis, percolation theory, complex network science, and computational modeling.
2. Process and threshold high-resolution micro-CT bone images and perform histomorphometry analysis using micro-CT image analysis software.
3. Convert thresholded images into network models using MATLAB.
4. Assess strength of network structures using percolation theory, determine robustness/fragility tradeoffs and threshold rules for fracture.
5. Compare histomorphometric analyses of network models and topology-optimized synthetics.
6. Work together with the graduate student and advisor to determine the course of the project.
7. Prepare the results for publication, in collaboration with the graduate student, the faculty advisor, and other involved collaborators.

References

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