HIERARCHICAL HOMOGENIZATION METHODS FOR TISSUE MECHANICS AND BIOMATERIAL DESIGN

S.J. Hollister[a], M.L. Palmer[b], C.Y. Lin[c]

[a]Departments of Biomedical Engineering, Surgery, and Mechanical Engineering
The University of Michigan
Ann Arbor, Michigan 48109-2125
scottho@umich.edu

[b]Department of Mechanical Engineering and Medical Scientist Training Program
The University of Michigan
Ann Arbor, Michigan 48109-2125
mlpalmer@umich.edu

[c]Department of Mechanical Engineering
The University of Michigan
Ann Arbor, Michigan 48109-2125
cylin@engin.umich.edu

Biological tissues have hierarchical structures that determine two important aspects of their function. First, structural integration local to global from the cell level to the organ level determines the tissue's mechanical stiffness and strength. Second, localization from the global to local level determines how organ level mechanical loads are translated into cell level mechanical signals that are believed to regulate tissue structure. Hierarchical computational methods play an important role in better understanding tissue mechanical behavior. Our research group has adapted homogenization techniques to analyze both linear and non-linear elastic tissue mechanics. Linear homogenization methods have been integrated with large scale iterative conjugate gradient techniques to directly analyze 3D trabecular bone micro-computed tomography (micro-CT) images and compute effective linear stiffness. These techniques can be used to directly predict bone properties for any imaged bone structure. Non-linear homogenization methods using an Updated Lagrangian approach that incorporates an active stiffness component has been developed to analyze soft tissue hierarchical mechanics, including skeletal muscle tissue. Application of these techniques by Palmer et al. (2001) has demonstrated that muscle fibers are most likely damaged by heterogeneous fiber activation, rather than by enzymatic degradation of passive structures as has been hypothesized.

Another important research area for hierarchical computational methods is tissue engineering. Biomaterial scaffolds are porous structures that are used to regenerate tissue structure by delivery biofactors like cells and genes. These degradable ceramic and polymer scaffolds are often directly implanted into a tissue defect, necessitating immediate load bearing. The requirements for load bearing (a more dense structural need) and biofactor delivery (a more porous structural need) conflict. Resolving this conflict requires optimization techniques that can predict microstructural influences on scaffold effective properties. Our research group has also developed homogenization based 3D topology optimization techniques based on earlier work (Sigmund et al., 1995) that can design scaffold microstructures that match desired effective elastic properties for load bearing while maintaining a desired porosity for biofactor delivery. We demonstrate that these optimization methods can be used to design biomaterial scaffolds that match human trabecular bone properties.

References

[1] M L Palmer, J A Faulkner, R G Dennis, S J Hollister,"A Computational Model for Stretch-Induced Injury in Skeletal Muscle", 18th Congress International Society of Biomechanics (2001), p. 24.
[2] O. Sigmund, "Tailoring materials with prescribed elastic properties", Mech. Materials, 20:351-358, (1995).
Acknowledgments: This work was supported by the NIH DE 13608.