

Intra-voxel micro-elasto-plasticity for CT-based patient-specific fracture risk assessment of vertebrae

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Following previous studies employing X-ray physics and continuum micromechanics in order to retrieve voxel-specific elastic properties from Computed Tomographs (CT) [1], we here present an updated and improved approach applied to *in-vivo* images of vertebrae of a young patient. This approach concerns both elasticity as well as strength, and therefore promises considerable impact on patient-individual, image-based fracture risk assessment.

As a first step, we translate the attenuation information contained in terms of grey values in each of the 0.324 mm-sized voxels building up the computed tomograph, into voxel-specific vascular porosity values. Therefore, we consider the linear relation between grey values and X-ray energy-dependent attenuation coefficients, involving three unknowns (two linearity constants and the X-ray energy). The latter are obtained from three known attenuation-energy relationships related to three characteristic points found in the grey value histogram: (i) the left-most peak in this histogram relates to fatty physiological fluid, (ii) the central peak relates to soft tissues as found in the inner organs around the spine, and (iii) the densest voxel in the image relates to compact bone with quasi-zero vascular porosity. The energy-dependent attenuation coefficient of fat is documented in the NIST-database [2]. The latter also gives access to the energy-dependent attenuation coefficients of collagen and water, and their volume ratio in soft tissue (which can be gained from their mass densities and that of soft tissue [3]). The volume ratio, in turn, in conjunction with the average rule for attenuation coefficients [1,4], gives access to the attenuation coefficient of soft tissue. Also the attenuation coefficient of compact bone is retrieved from averaging the attenuation coefficients of collagen, water, and hydroxyapatite, according to their volume fractions in vertebral extracellular bone matrix. The latter follows from the mass density of extracellular bone matrix in vertebrae [5], and the averaging of collagen, water, and hydroxyapatite mass densities according to the composition rules evidenced in [6]. The resulting vascular porosity values enter a continuum micromechanics model for bone [7], which thereupon delivers voxel-specific elastic properties. The latter are mapped onto a 3D Finite Element mesh developed from the same patient data [8]. We illustrate a novel fracture risk assessment scheme by example of a very simple load case: We apply a distributed unit load of 1 MPa onto the upper surface of the third lumbar vertebral body, corresponding anatomically to the upper endplate, and compute the corresponding stress and strain distributions throughout the organ. These states are fed into a six-scale strength upscaling model for bone, namely an algorithmically stabilized and physically improved version of [9], as to compute element-specific proportionality factors by which the actual stress states needed to be multiplied as to reach material yield or material failure, see Figure 1. This is done for the described voxel-

specific heterogeneous case, as well as for vascular porosities averaged over the trabecular core. Homogeneous simulations obviously underestimate the fracture risk in the presently studies case of scoliosis, as seen in Figure 1.

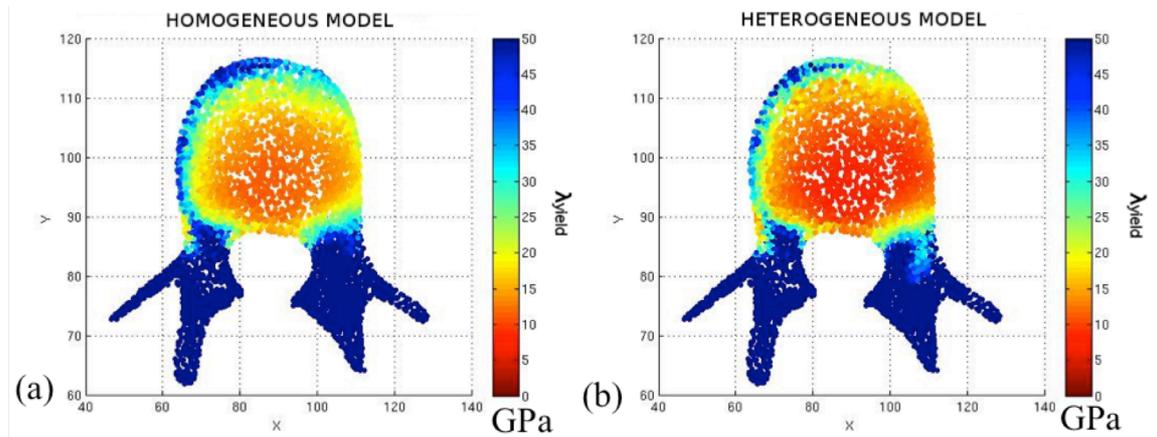


Figure 1: Maps of the dimensionless yield factor related to 1 Mpa pressure loading, across cross-section orthogonal to z through the vertebral body, for (a) homogeneous, and (b) heterogeneous Finite Element model, cross-sectional dimensions are in millimeter.

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