

Effect of Cartilage Mapping on Subchondral and Trabecular Bone Stresses

Timothy Ruckh, BS and Christian M. Puttlitz, Ph.D

Orthopaedic Bioengineering Research Laboratory

Colorado State University

Department of Mechanical Engineering

Background: One of the primary functions of articular cartilage is to absorb and distribute contact forces. The thickness and bulk moduli of tibial plateau cartilage varies significantly with respect to the location across the articulating surface (1, 2). It has been shown that varying the average thickness of articular cartilage by 10% causes an associated 10% change in the surface contact pressures (3). Osteoarthritis is characterized by a degradation of articular cartilage, and Wei *et al* (2005) found a correlation between subchondral plate thickness and shear stress in acetabular articular cartilage. They suggest a synergistic cascade of cartilage degradation in which an initial insult leads to adaptive stiffening of subchondral bone, which, in turn, contributes to increased cartilage damage and degradation (4). An investigation into the effect of articular cartilage thickness on the resulting local bone stresses may further elucidate the causal relationship between cartilage erosion and the progression of the disease..

Methods: A 3-D finite element model of an ovine tibia was constructed from QCT data and cartilage was extruded normal to the subchondral surface to 2 constant depths and 3 distributed depths which varied by 20%. Both cortical and trabecular bone were modeled as orthotropic, with trabecular bone divided into 10 distinct material property groups based upon Hounsfield attenuation coefficients. Given the applied static loading condition, the articular cartilage was modeled as linear elastic and isotropic with a bulk modulus of 15 MPa and a Poisson's ratio of 0.475 (4, 5). Each model was evaluated twice, lowering the long-term modulus of cartilage by 20% on the second trial. A set of models with the thickest distributed cartilage had varying Poisson's ratios from 0.15-0.475. All models were evaluated using ABAQUS/Standard. Von Mises and Tresca stresses were examined for each case in order to determine the if excessive shearing at the cartilage-subchondral bone interface exists due to the nearly incompressible constraint (Poisson's ratio ~ 0.5).

Results and Discussion: The data indicate that cartilage thickness heavily influences the overall stress distribution.

Specifically, the stress distribution, qualitatively speaking, is still influenced at the most proximal points of the subchondral plate, but not as heavily as the peak stress values. Peak von Mises stresses in the subchondral bone

were inversely related to cartilage thickness. This correlation was also found for Tresca (shear) stresses at the interface with the subchondral bone shell, wherein there is a high

sensitivity to increasing the cartilage thickness. The thinnest of the distributed cartilage models had particularly thin edges, which may explain the small Tresca component and that data point may be regarded as unrepresentative of the overall trend. Other sources examining hyperelastic or hypoelastic models of cartilage calculate long-term properties of cartilage with Poisson's ratios of $\nu \approx 0.15-0.2$ (6), but the results of this study support the findings of a previous FE study that showed only weak influence of changing the Poisson's ratio on changes in von Mises stresses (7). The data indicate only a 3% change in von Mises stress for the trabecular elements when going from undistributed 0.5 mm thick cartilage to the thickest distributed cartilage. The bulk of the load is born by, and transferred to the cortical shell. This finding corroborates earlier literature accounts by Wei *et al* that increasing the stiffness of only the subchondral bone had a much greater effect on cartilage shear stress than only increasing the stiffness of the underlying bone in the femoral head while maintaining the same stiffness of subchondral bone.

Conclusion: The data show only a weak effect of cartilage depth mapping on trabecular bone stresses, but depth mapping will have a strong effect on subchondral plate stresses. The assumption of cartilage as linear, isotropic and near-incompressible as a long term property generates unusually high Tresca stresses on the subchondral plate. These equilibrium conditions are unlikely to be experienced *in vivo*, though the Poisson's ratio has minimal influence on subchondral plate stresses. Future studies examining the mechanical behavior at the cartilage/bone interface as well as more complex material models should be investigated.

References: (1)Mow VC and Huiskes R. Basic Orthopaedic Biomechanics and Mechano-Biology. p. 183-227, 2005. (2) Li LP *et al*. Comp Methods Biomech Biomed Eng 5:1:45-52. 2002. (3) Li G *et al*. J Biomech Eng. 123:341-346. 2001. (4). Wei H-W *et al*. Med Engin Physics. 27:295-304. 2005. (5) Donahue TLH *et al*. J Biomech Eng 124:273-280. 2002. (6) Korhonen RK *et al*. J Biomech35:903-905. 2002. (7) Dar FH and Aspden RM. Proc Inst Mech Eng. 217:H:341-348.

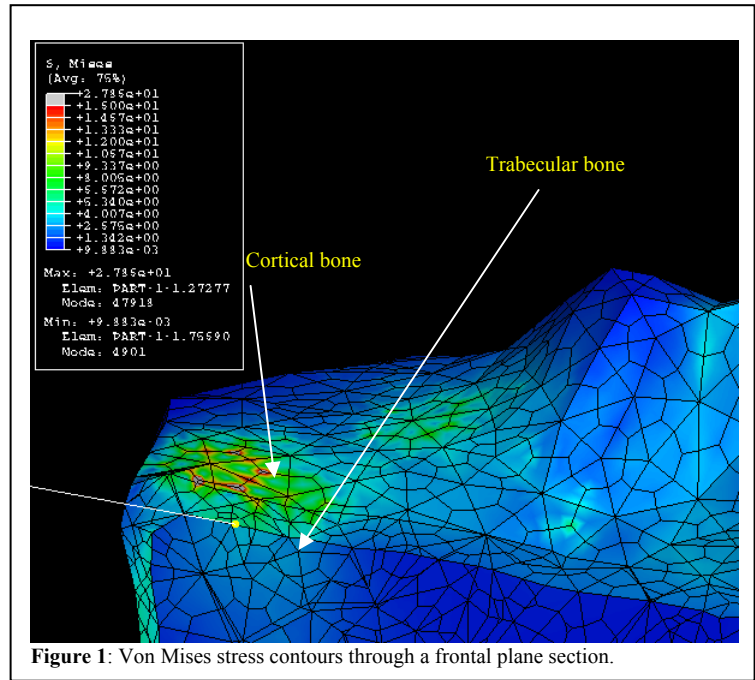


Figure 1: Von Mises stress contours through a frontal plane section.

Model	Ave Thickness (mm)	$E_{cartilage}$ (MPa)	ν	$\sigma_{subchond}$ (MPa)	$\sigma_{trabecular}$ (MPa)	Tresca (MPa)
0.5mm	0.5	15	0.475	5.1140	3.91	7.621
1mm	1	15	0.475	9.3750	3.884	10.77
dist	1	15	0.475	9.6350	3.851	11.06
dist -	0.8	15	0.475	7.5730	3.885	5.043
dist +	1.2	15	0.475	27.8600	4.034	30.76
dist +	1.2	15	0.35	28.83	4.086	31.91
dist +	1.2	15	0.25	29.58	4.124	32.78
dist +	1.2	15	0.15	30.26	4.161	33.66

Table 1 - Cartilage thickness and stress components