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Region-Dependent Material Properties of Human Knee Cartilages and Menisci Determined with Indentation Maps and Machine-Learning

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Abstract

Articular cartilage is an inhomogeneous tissue due to its genetics and adaptation to its mechanical environment. Although the zonal differences in the cartilage thickness direction have been extensively studied, site-specific cartilage differences require further investigation. We have developed a methodology based on machine learning to divide the surface of the knee cartilages into distinct regions to approximate site-specific tissue inhomogeneity across the knee joint. The methodology was initially established on porcine knee cartilages which resulted in several distinct regions on femoral groove, condyle, and tibial cartilages. The objectives of the current study were to 1) apply the methodology to suggest region-dependent material properties of human knee cartilages and the menisci, and 2) identify potential patterns of tissue degeneration. Indentation and thickness mapping data of 24 sets of osteoarthritic human cartilages with mild (n = 12; Kellgren Lawrence, or KL, score: 1-2) and severe (n = 12; KL score: 3-4) degeneration, previously acquired, was analyzed. K-means clustering and Elbow method were used to partition the tested locations into distinct regions based on their 3D coordinates, thickness, and relaxation reaction force data. A Fortran subroutine was used to curve-fit the poromechanical material properties, *i.e.*, the initial (E_0) and stiffening (E_ε) coefficients of fibrillar matrix modulus ($E_f = E_0 + E_\varepsilon \varepsilon$), the proteoglycan matrix modulus (E_m) and the tissue permeability (k), of those regions using the finite element software ABAQUS. A Poisson's ratio of the proteoglycan matrix, $\nu_m = 0.36$, was assumed for simplicity. Since the test data included only 20 s of relaxation data, an artificial neural network was used to predict the relaxation reaction forces for up to 100 s, to facilitate the properties extraction. The preliminary results yielded four distinct regions on each femoral condyle and tibial plateau cartilage, and three regions on each meniscus. Significant variations of material properties were seen among regions within the same cartilage piece, *e.g.*, for joint 01 lateral femoral cartilage regions, they were in the following range: E_0 = 3-14 MPa, E_ε = 1400-3600 MPa, E_m = 1.1-1.49 MPa, k = 0.00018-0.00053 mm^4/Ns. In addition, a partial-subjective partitioning scheme for the tibial cartilages, based on the menisci uncovered area, will be introduced and the extracted properties of both schemes and their capability to predict patterns of degeneration will be compared. The corresponding tissue properties may be used to predict compromised knee joint mechanics with the stage of osteoarthritis.