Depth-Dependent Shear Modulus of TMJ Cartilage relate to Microscale Structure and Composition

Authors: Dong Hwan Yoon*[1], Santiago Peralta[1], Nadine Fiani[1], Gwendolyn Reeve[2], Lawrence J. Bonassar[1]
[1]Cornell University, Ithaca, NY, [2]Weill Cornell Medicine, New York, NY

Introduction: Temporomandibular joint condylar cartilage (TMJ) is a unique tissue that withstands repetitive daily loads over the course of decades.[1,5] Despite containing four different layers, (fibrous surface, proliferative, mature, and hypertrophic)[5], the depth-dependent mechanics of the TMJ cartilage are not fully understood. Previous studies have investigated the depth-dependent shear mechanics of porcine TMJ cartilage[2,7]. To further investigate this theme, canine TMJ, which are known to develop disease, and human cadaver TMJ were investigated to quantify the structural and compositional relationship between the depth-dependent shear mechanics. The aims of this work were (i) investigate the depth-dependent zonal shear modulus profiles in human cadaver, canine, and porcine TMJ cartilage as well as (ii) analyze the relationship between the depth-dependent mechanical properties with microscale structure and composition.

Materials and Methods: Human cadaver TMJ condyles that were IRB approved (Weill Cornell Medicine, New York, NY), canine TMJ condyles from the CARE Tissue Exchange program (Cornell College of Veterinary Medicine, Ithaca, NY), and porcine TMJ condyles (Schrader Farms, Romulus, NY) were obtained. Full thickness cartilage explants (4mm diameter) were obtained from the condyles. Samples were bisected in the posteroanterior direction into hemicylinders and were mechanically tested using a previously established method[3] using confocal elastography. Videos obtained were analyzed using FFT with a custom MATLAB code where orientation index (OI) which represent the relative strength of fiber orientation and the angle of orientation of the fibers were calculated by moving a region of interest per pixel over a horizontal sliding window through the depth of the tissue on the image plane[4]. Furthermore, depth dependent intensity which is proportional to relative matrix density[6] were obtained from the confocal micrographs in ImageJ.

Results and Discussion: The measured shear modulus shows a non-linear relationship through the depth of the cartilage. The relative zonal thickness between the three species starting from the subchondral bone had qualitatively similar shear modulus profiles. The lack of fibrous surface in canine TMJ and lack of fibrous surface and proliferative surfaces in the human TMJ can be explained by the relative age and health of the samples obtained. Relationships between shear modulus and intensity, orientation index, and angle were fit to a log-linear scale. Depth dependent intensity, a surrogate of the extracellular matrix, represents the relative protein content of the tissue. The linear variation between the intensity scales with the log scale shear modulus. Shear modulus and intensity correlations for human and canine were $R = 0.61$ and $R = 0.50$ respectively. Porcine shear modulus and intensity correlation was found to be not significant. Shear modulus and OI show that higher alignment in fibers (higher OI) tend to have a lower shear modulus with correlation of $R = 0.48$ and $R = 0.59$ for human and canine respectively. Shear modulus and angle did not show any significant correlation which aligns with previous findings[1].

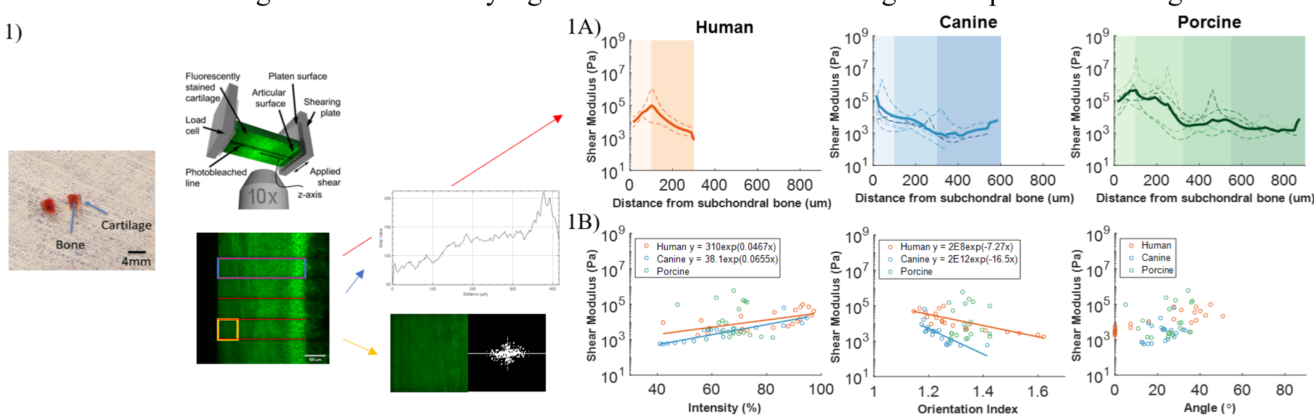

Figure 1. Schematic of experimental process of obtaining shear modulus, intensity, and OI (FFT). 1A) Zonal divided depth-dependent shear modulus. 1B) Correlation plots of shear modulus with intensity, orientation index, and angle.

Conclusion: Results suggest that the shear modulus profiles of the three species show a similar pattern within zones with the human and canine samples lacking zones closer to the surface. Furthermore, microscale structure and composition have a significant effect to the depth-dependent shear modulus of the TMJ cartilage.

References: 1) Silverberg+, Biophysical J. 2014, 107 2) Tanaka+, JOB. 2014, 47 3) Buckley+, JOB. 2008, 41 4) Boys+, ACS. 2019, 11 5) Kuroda+, Osteoarthritis and Cartilage 2009, 17 6) Morikawa+, Scientific reports. 2016, 6 7) Gologorsky+, JOB. 2021, 129