**2016**

**Henak, Ross, Bonnevie, Fortier, Cohen, Kennedy, Bonassar**

**Human talar and femoral cartilage have distinct mechanical properties near the articular surface**

Shear modulus near the interface is indistinguishable between anatomical regions

Variations in depth-dependent shear moduli between anatomical regions occurred within 300 microns of the articular surface

Reports cartilage thickness for different regions

For example, femoral cartilage was 2.16+-0.37 mm thick

**2014**

**Motavalli, Akkus and Mansour**

**Depth-dependent shear behavior of bovine articular cartilage: relationship to structure**

Mature samples

* The stiffest region was located beneath the superficial zone and the most compliant region was found in the radial zone
  + The shear modulus close to the superficial zone was 3-4x greater than that in the radial zone
* Displayed the typical superficial, transitional, and radial zone

Immature samples

* The most compliant region was located in the superficial zone
  + This is quite important, because perhaps the 2014Silverberg paper obtained this result because they used neonatal bovine samples
* Superficial zone was 2x thicker than in mature samples
* Showed two dark zones instead of one, where dark zones are randomly oriented collagen fibers
* Overall more randomly oriented collagen than in mature samples
* Relatively wide region (~400 microns) with a mix of fiber orientations that were not present in group A samples
  + Relatively isotropic region

**2014**

**Silverberg Barrett, Das, Petersen, Bonassar, Cohen**

**Structure-Function Relations and Rigidity Percolation in the Shear Properties of Articular Cartilage**

Weak correlation between shear modulus and collagen fiber orientation

Stronger correlation between shear modulus and the concentration of collagen fibers

Small changes in collagen volume fraction (two fold) lead to orders of magnitude changes in the modulus (100 fold) – scaling by a power law

A spatially localized region was found near the tissue surface with a shear modulus up to 100 times smaller than the typical 1 MPa bulk-averaged value

This region also dissipates up to 90% of the energy imparted during shear

Fibers in the tangential zone (z < 100 microns) were more ordered and were aligned more nearly parallel to the surface in comparison to fibers deeper in the tissue.

Decrease in matrix concentration (collagen fibers) near the articular surface (z < 100 microns) and a constant concentration for (z > 400 microns)

Collagen rather than aggrecan dominates the overall AC shear mechanics

Why do they not recommend a continuum model?

They utilize a power law fit where “the exponent is too large to be consistent with a simple continuum model”

They think “network connectivity tends to be lost in continuum elasticity” and network connectivity is more important than fiber alignment

Kagome Model: The reinforcing medium (matrix) can significantly enhance the shear modulus by suppressing non-affine deformations of the fiber network

**2013**

**Silverberg, Dillavou, Bonassar, Cohen**

**Anatomic Variation of Depth-Dependent Mechanical Properties in Neonatal Bovine Articular Cartilage**

Studied the patellofemoral groove, trochlea, femoral condyle, and tibial plateau

Compliant region within the first 500 micron of tissue where the local shear modulus is reduced by up to two orders of magnitude

Statistically significant differences are localized within the first 50 microns

G\_bulk (similar to G\_plateau) is statistically indistinguishable among all four groups

Anatomic sites experiencing high levels of in vivo loading (FC, TP) were significantly more compliant than sites with low levels of in vivo loading (PFG, TRO)

Differences in biomechanical properties associated with anatomical sites are independent of regional cartilage thickness and coincide with depth-dependent heterogeneity in the AC collagen network

**2013**

**Buckley, Bonassar, Cohen**

**Localization of Viscous Behavior and Shear Energy Dissipation in Articular Cartilage Under Dynamic Shear Loading**

Depth dependent dynamic modulus and phase angles of articular cartilage

Neonatal cartilage is more cellular and less organized than mature tissue

The dynamic shear modulus and phase angle (delta) reach their min and max values respectively 100 microns below the articular surface > the transitional zone

As the frequency of deformation increases above 0.01 Hz the fraction of energy dissipated at low depths increases

Maximal energy absorbing region (MEAR)

Located at 50 < z < 150 microns

Most compliant as well as most viscous

Cartilage is highly effective at absorbing shear energy near the surface because it is both compliant and lossy (high delta)

Capacity is lost at large shear strains

Has chevron-shaped discontinuities (100-300 microns below the articular surface) in compressed specimens

|  |  |  |
| --- | --- | --- |
| Complex dynamic shear mod | < 250 microns | > 250 (deeper into the tissue) |
| Lower frequency | 0.32 +- 0.08 | 1.5+- 0.4 |
| Higher frequency | 0.42 +- 0.08 | 2.1+-0.6 |

**2010**

**Buckley, Bergou, Fouchard, Bonassar, Cohen**

**High-resolution spatial mapping of shear properties in cartilage**

The shear modulus of neonatal bovine and adult human tissue both exhibit a global minimum at a depth of around 100 microns

Note that 2008 Buckley paper reported 125 microns because this study has higher res

Mostly a methodology paper

**2010**

**Wong and Sah**

**Mechanical asymmetry during articulation of tibial and femoral cartilages: local and overall compressive and shear deformation and properties**

Reported axial and shear strains and compressive and shear moduli for femoral condyles (FC) and tibial plateau (TP)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Moduli | Overall | | Articular surface (125 microns) | |
|  | FC | TP | FC | TP |
| Thickness (mm) | 2.20+-0.15 | 2.88+-0.53 |  |  |
| Compressive (MPa) | 0.76 +-0.13 | 0.47+-0.08 | 0.40+-0.19 | 0.24+-0.08 |
| Shear: G0 (MPa) | All slightly higher than Shear (G1) | | | |
| Shear: G1 (MPa) | 0.38+-0.06 | 0.13+-0.01 | 0.22+-0.11 | 0.03+-0.003 |

G0, shear modulus relative to uncompressed cartilage thickness, and G1 is the shear modulus relative to compressed cartilage thickness

G1 and G0 were greater in magnitude for FC than TP, being 80% higher near the surface and 65% overall. (Note: the comparison isn’t that G1 and G0 are higher near the surface but that FC is 80% higher than TP near the surface)

Comparison to 2008 Buckley paper

This paper reported, E and G1 increase with increasing depth being 1.5-2 times lower near the surface and 5-10 times higher near the tidemark than the overall values

Did not report a minimum value right under the articulating surface

> say it is because of methodology because they included sliding and Buckley2008 did not include sliding

> Say they also have lower resolution to their methodology

**2008**

**Buckley, Gleghorn, Bonassar, and Cohen**

**Mapping the Depth Dependence of Shear Properties of Articular Cartilage**

Adult human and neonatal bovine

Shear modulus varied by up to two orders of magnitude across a single sample.

Global minimum 50-250 microns below the articular surface and just below the superficial zone and constant at depths > 1000 microns in the plateau region

Within article: global minimum at 125 microns and constant at depths > 500 microns

The superficial zone is observed to have the most mechanical failure – this study shows that this region is weak to shear

Compression may decrease the vulnerability of articular cartilage to shear-induced damage by lowering the effective strain on individual collagen fibrils

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Plateau strains (%)** | Compressive strains (%) | G\_min (kPa) | G\_plateau (kPa) | G\_min/G\_plateau |
| ***0.6-0.9*** | ***5-6*** | ***68+- 8.6*** | ***650+-140*** | ***~0.11*** |
| ***3.2-4.2*** | ***5-6*** |  |  | ***~0.16*** |
| 0.75 | 5 | 70 | 650 | ~0.11 |
| ***2.0-3.1*** | ***6.0-7.5*** |  |  | ***~0.15*** |
| ***2.0-3.1*** | ***2.0-2.5*** |  |  | ***~0.25*** |
| 3.2-4.2 |  |  |  | ~0.15 |

The region of tissue between the superficial and middle zones became stiffer under increased shear strain and weaker under increased axial strain

Increasing plateau strains increased ratio and increasing compressive strains decreased ratio

Increasing plateau shear strain increased G\_min drastically and increased G\_plateau minimally leading to the increased ratio

Increasing axial/compressive strain decreased the G\_min (incremental) near the surface of the tissue leading to the decreased ratio

Sample variation is significant