ANISOTROPY, INHOMOGENEITY, AND TENSION-COMPRESSION NONLINEARITY OF HUMAN GLENOHUMERAL CARTILAGE IN FINITE DEFORMATION

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INTRODUCTION: The long term hypothesis of this study is that early osteoarthritic degenerative changes in the human glenohumeral joint (GHJ) are dependent on joint congruence, the asymmetric duty cycle in the loading of the glenoid and humeral head, and the state of stress and strain in cartilage. The determination of stresses in the tissue under physiologic loading conditions requires knowledge of its mechanical properties under finite deformation. However, the cartilage mechanical response is known to be complex, exhibiting anisotropy, inhomogeneity through the depth, and tension-compression nonlinearity; previous biomechanical studies have separately reported disparate material properties for human articular cartilage, ranging from 0.5 MPa to 0.7 MPa [3] in compression and 0.7 MPa to 20 MPa [1] in tension. However, to date, there have been no studies comparing tensile and compressive material properties either from adjacent regions or within the same joint. The objective of this study, therefore, was to investigate the nonlinearity of the tensile and compressive properties of GHJ cartilage, and its variance with depth, direction, and joint surface.

MATERIALS AND METHODS: 72 tensile specimens and 42 compressive plugs were tested from cartilage harvested from the GHJ of three fresh-frozen cadaveric shoulders (average age 59). For each joint, twelve tensile strips (4 mm x 8 mm) and seven compressive plugs (6.35 mm in diameter) were harvested from five regions on the humeral head and two regions on the glenoid. Tensile strips were obtained in two orientations, parallel and perpendicular to the split-line directions, from each region in the humeral head (Fig.1). Two serial slices (250 μm thick for tensile testing and 350 μm thick for compressive testing), corresponding to the surface and middle zones of the cartilage layers, were obtained from each tensile strip and each compressive plug. Tensile testing: Each tensile specimen was mounted in an Automated Tensile Apparatus (ATA) and subjected to a sequence of increasing strains, 2%, 4%, 6%, 8%, 10%, 12%, 14%, 16%, 20%, and 25% [1]. Poisson's ratio (ν) was measured for each specimen using a video dimensional analyzer. The exponential function, $\sigma^e = A(e^{B\varepsilon} - 1)$, was used to model the equilibrium stress-strain response [5]. The tensile modulus of each specimen in the limit of 0% (E_0) and at 16% ($E_{0.16}$) strain were calculated. Confined compression testing: Each cylindrical specimen was placed in a confined chamber between two porous filters and loaded in five strain increments of 10 % each, at a rate of 0.025% sec^{-1} on a custom-designed testing apparatus [2]. The aggregate modulus H_{AO} at 0% strain and non-dimensional stiffening coefficient β describing the non-linear stress-strain behavior in compression, were calculated from the axial stress-stretch law derived from the finite deformation biphasic theory [2]. These parameters were then used to predict the stress response using non-linear regression analysis, as well as the aggregate modulus at 16% compressive strain ($H_{A0.16}$). Statistical analysis: The tensile and compressive moduli were analyzed statistically using one-way ANOVA.

RESULTS: Typical plots of equilibrium stress versus strain from tensile and confined compression tests for the center region of the humeral head are provided in Figure 2. Comparisons of tensile and compressive moduli of glenohumeral cartilage are provided in Table 1. E_0 for the humeral head was found to be significantly greater than those in the glenoid (p=0.002). There were also significant differences between the tensile modulus of surface and middle zone specimens at 0% and 16% (p=0.0001) for the humeral head. Significant differences were found in E_0 and $E_{0.16}$ (p=0.039) between specimens taken parallel and perpendicular to the split lines in the human humeral head. Significant differences were found in H_{A0} (p=0.037) and $H_{A0.16}$ (p=0.049) between the surface and middle zones in the humeral head.

DISCUSSION: The finding that human humeral head cartilage, on average, was significantly stiffer than for the glenoid is consistent with our previously reported results for bovine glenohumeral cartilage, and may explain why cartilage lesions appear more frequently on the glenoid [4]. Furthermore, the zonal and directional differences found in the tensile modulus confirm that human GHJ cartilage exhibits anisotropy relative to split line directions and inhomogeneity through the depth. In the confined compressive testing results, H_{A0} and $H_{A0.16}$ are shown to have statistical differences between the two zones (depth inhomogeneity). However, there were no statistical differences between the compressive aggregate moduli of the glenoid and humeral head, nor through the depth on the glenoid cartilage. The tissue stiffness was shown to differ by two orders of magnitude from tension to compression, demonstrating a high degree of tension-compression nonlinearity (Fig. 2). The tensile response also exhibited nonlinear behavior under finite strain, with $E_{0.16}$ four to ten times greater than E_0. This study serves to expose the complexity of the mechanical behavior of human GHJ articular cartilage. In order to accurately determine the state of stress in the tissue under loading, it is necessary to develop a constitutive stress-strain relation which properly accounts for the behavior observed in this study, within a single constitutive law.

REFERENCES: [1] Akizuki S *et al*., *J Orthop Res*, 4:379-92, 1986. [2**]** Ateshian G.A. *et al*, *J Biomechanics*, 11/12:1157-64, 1997. [3] Athanasiou KA *et al*., *J Orthop Res*, 9:330-40, 1991. [4] Huang C-Y *et al*., *ASME Adv Bioengng*, 35:525-526, 1997. [5] Woo S L-Y *et al*., *J Biomechanics* , 9:785-91, 1976.

		Tensile strips		Compressive Plug	
		Parallel	Perpendicular		
Humerus surface zone	E_0^*	7.84 ± 2.73	5.93 ± 2.14	$H_{A0}^\dagger$	0.103 ± .036
	$E_{0.16}^*$	42.8 ± 22.4	26.3 ± 11.9	$H_{A\,0.16}^\dagger$	0.124 ± 0.043
	$\nu^¶$	1.31 ± 0.180	1.33 ± 0.280	$\beta^\dagger$	1.30 ± 0.582
Humerus middle zone	E_0^*	4.22 ± 2.49	3.12 ± 1.39	$H_{A0}^\dagger$	0.145 ± 0.064
	$E_{0.16}^*$	17.2 ± 11.7	12.8 ± 7.10	$H_{A\,0.16}^\dagger$	0.169 ± 0.074
	$\nu^¶$	1.16 ± 0.280	1.03 ± 0.200	$\beta^\dagger$	0.840 ± 0.204
Glenoid surface zone	$E_0^§$	2.63 ± 2.47		$H_{A0}^§$	0.148 ± 0.069
	$E_{0.16}^§$	29.2 ± 42.5		$H_{A\,0.16}^§$	0.175 ± 0.120
	$\nu^\ddagger$	1.14 ± 0.18		$\beta^§$	1.08 ± 0.307
Glenoid middle zone	$E_0^§$	2.21 ± 1.70		$H_{A0}^§$	0.138 ± 0.038
	$E_{0.16}^§$	14.8 ± 17.9		$H_{A\,0.16}^§$	0.162 ± 0.110
	$\nu^\ddagger$	1.18 ± 0.25		$\beta^§$	0.896 ±0.380
Units:	Moduli: MPa, ν,β: non-dimensional *:n=30, §:n=6, †:n=15, ¶:n=20, ‡:n=4				

Table 1.

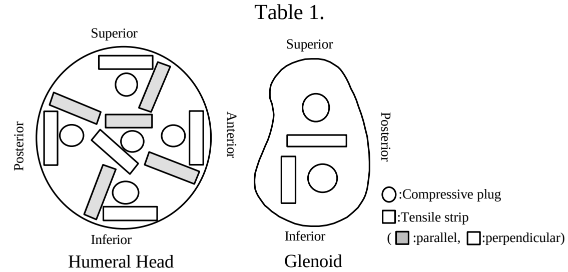

Fig 1. Harvest site.

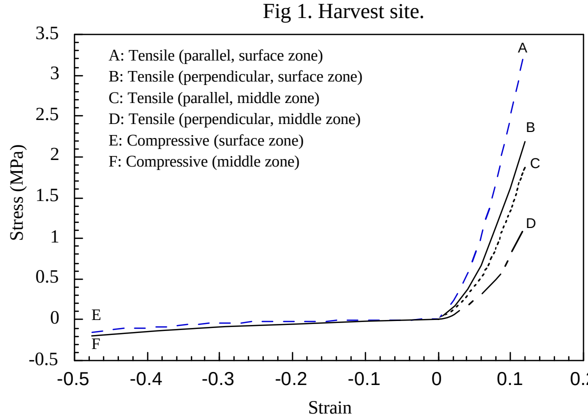

Fig 2. Typical plots of equilibrium stress versus strain from tensile and confined compression tests for the center region of the humeral head

ACKNOWLEGEMENTS: This work was supported by NIH Grant AR42850. The assistance of Mr. Vincent Wang is greatly appreciated.

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