MECHANICAL PROPERTIES OF THE SHOULDER LIGAMENTS UNDER QUASI-STATIC AND DYNAMIC LOADING

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Introduction: The tensile properties of the shoulder ligaments under dynamic loading have not been investigated. A recent finite element model showed the ligaments in the shoulder were subjected to dynamic tensile loading during 8.65 m/s lateral shoulder impact [1]. The mechanical properties of shoulder joints under dynamic loading are needed to better understand shoulder injury mechanisms, to improve shoulder finite element models and to further develop the shoulder of car crash dummies.

Methods: Thirty-three fresh human shoulders were harvested and bone-ligament-bone specimens of acromioclavicular joint, coracoclavicular joint and sternoclavicular joint were obtained. A test fixture and clamps specifically designed for this ligament study and a high-speed Instron machine were used (Fig 1). One quasi-static rate (0.1 %/sec) and two high rates were used in this study. The two high rates (40,000 %/sec and 15,000 %/sec) were determined by analyzing ligament strain rates in the shoulder finite element model [1] subjected to three different test conditions (Heidelberg sled test, FMVSS 214 test, and IIHS side impact test. The acromioclavicular and sternoclavicular ligaments were tubular in cross section and cross sectional area was obtained by measuring the thickness around the ligament circumference with a fine gauged needle and micrometer.

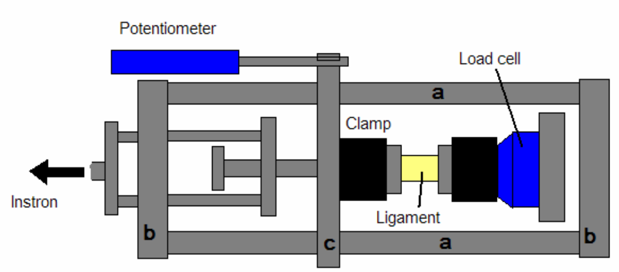

Figure 1. Diagram of the shoulder ligament test setup. Thompson shafts (a) and aluminum plates at the ends (b). The fixture included an additional aluminum plate (c) which was connected and moved with the Instron actuator.

Results: Eighty-three specimens were tested at three different strain rates. By reviewing the high speed camera images, the failure of each specimen was classified as follows: (1) ligament failure, (2) combined ligament failure and bony avulsion fracture (3) bony avulsion fracture. In acromioclavicular joint tests, ligament failure was the most common failure mode. Bone fractures occurred most often at the clavicle rather than acromion. In coracoclavicular joint tests, the majority of specimens failed at the ligament. In these tests, all of the bone fractures occurred at the coracoid. In sternoclavicular joint tests, the specimen failed at the bone in most cases. In acromioclavicular joint and coracoclavicular joint tests, 15,000 %/sec tests and quasi-static tests had more bone fracture cases than 40,000/sec tests. Failure loads, regardless of failure sitefor the acromioclavicular and sternoclavicular joint were greater than for the coracoclavicular jo int. The strains at failure of the sternoclavicular joint were found to be smaller than for acromioclavicular and coracoclavicular joints. The table summarizes mechanical and structural mean values (+/- standard deviation) of 83 shoulder joints at three different strain rates combining all 3 failure modes. The Young's modulus and ultimate load of the three joints were found to be significantly lower in the 0.1 %/sec tests compared to the 15,000 %/sec tests but not significantly different between 40,000 %/sec and 15,000 %/sec tests. There was no significant relationship between the ligament cross sectional area and subject age, height and weight. In addition, there was no significant relationship between mechanical properties of the shoulder joints and anthropometric data.

Discussion: In an attempt to measure the cross sectional area of shoulder ligaments (tubular structure), ultrasound and MRI was used. However, the images were not clear enough to delineate the ligament thickness. The gauged syringe needle method used in this study was validated by comparing with the measured thickness after cutting the ligament. The average age of the specimens in the current study was 72 (+/- 12.4) years and the youngest was 47 years. Only three subjects were under 60 years of age. There could have been an age effect if younger specimens could have been included. This appears to be the first published study describing the mechanical and structural properties of the acromioclavicular ligament and sternoclavicular ligament. The 40,000 %/sec strain rate is the highest published strain rate ever used and analyzed for ligament studies. Overall, the shoulder ligaments showed larger ultimate strain and smaller ultimate stress and Young's modulus than animal or human knee ligament. The acromioclavicular, coracoclavicular and sternoclavicular joint ligaments in this study showed larger ultimate strain, and smaller ultimate stress and Young's modulus than glenohumeral joint ligaments from other studies [2], [3]. The capacity of large ultimate strain as well as the combination of joint movements enables the shoulder to have the largest range of motion in the body and withstand large deflection. With a side impact, 50 % probability of shoulder AIS 2 injury corresponds to 106 mm deflection of the struck shoulder relative to the spine [4].

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Reference: [1] Iwamoto et al., (2000) Proc. 44th Stapp Car Crash Conference. SAE Paper No. 2000-01-SC19 [2] Bigliani et al., (1992) Journal of Orthopedic Research Mar; 10 (2):187-97. [3] Boardman et al., (1996) Shoulder Elbow Surgery 1996 Jul-Aug; 5 (4):249-54. [4] Koh et al., (2001) Proc. 45th Stapp Car Crash Conference, SAE Paper No.2001-01-s49

	Strain rate (%/sec)	Deflection at failure (mm)	Load at failure (N)	Strain at failure (%)	Young's modulus (MPa)
Acromioclavicular ligament (N=32)	40000 (N=13)	15 (+/- 4.0)	696 (+/- 218.3)	105 (+/- 20)	10.6 (+/- 1.7)
	15000 (N=10)	13 (+/- 7.1)	849 (+/-297.1)	81 (+/- 35)	9.6 (+/- 4.5)
	0.1 (N=9)	11 (+/- 2.1)	464 (+/- 101.1)	80 (+/- 17)	6.3 (+/- 1.2)
Coracoclavicular ligament (N=31)	40000 (N=12)	17 (+/- 7.6)	389 (+/- 194.1)	86 (+/- 34)	10.0 (+/- 3.8)
	15000 (N=10)	14 (+/- 4.3)	345 (+/- 132.1)	58 (+/- 18)	9.0 (+/- 3.8)
	0.1 (N=9)	14 (+/- 4.0)	155 (+/- 80.2)	79 (+/- 39)	3.4 (+/- 1.8)
Sternoclavicular ligament (N=20)	40000 (N=5)	12 (+/- 3.5)	670 (+/- 406.9)	62 (+/- 19)	10.2 (+/- 2.8)
	15000 (N=7)	14 (+/- 3.4)	682 (+/- 261.9)	56 (+/- 10)	12.9 (+/- 2.7)
	0.1 (N=8)	8 (+/- 2.4)	334 (+/- 143.7)	39 (+/- 10)	6.2 (+/- 0.6)