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Experimental Study of Variation between Quasi-static and Dynamic Load Deformation Properties of Bovine Medial Collateral Ligaments

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ABSTRACT

In a significant number of automobile crashes involving pedestrians, the knee ligament which controls the stability of the knee often get severely loaded. In lateral impact on knee during automotive crashes, varus-valgus deformities result in failure of ligament by avulsion or rupture. Varus-valgus deformity strains occur mainly in the middle region of ligament and it is known that properties vary in the different regions of the ligament. Experimental measurement of tensile-load elongation behavior of bovine middle region medial collateral ligament properties between strain rate 0.0001/s to 161/s are reported here. The results shows a linear stress-strain response at lower strain rate whereas it is nonlinear and strain rate sensitive in dynamic loading conditions. The objective of this study is to establish a methodology to identify the quasi-static and dynamic properties of ligaments.

INTRODUCTION

In lateral impact the varus-valgus strain results in injuries to the collateral knee ligaments (Kajzer et al. 1990, 1993, Kerrigan et al. 2003). In lateral impact on knee during automotive crashes, varus-valgus deformities results in failure of ligament by avulsion or rupture (Teresinki et al. 2001). Varus-valgus strain occurs mainly in the middle region of the ligament (Kawada et al. 1991) and it is known that the constitutive properties of ligament are not the same in different regions of the ligament (Robinson et al. 2005). There have been limited studies on the structural properties of the ligament (Trent et al. 1976, Kennedy et al. 1976, Kerrigan et al. 2003), whereas some have reported material properties (Butler et al. 1986, Quapp et al. 1988). Reported properties are at lower strain rate, which do not correspond to loading seen in pedestrian automobile crashes. The existing finite element models of human lower extremity lack the accurate constitutive representation of the ligaments. Hence of the variation in between quasi-static and dynamic estimates of stiffness and failure stress would be significant in deciding injury threshold. In present study, nine specimen (n=9) of bovine medial collateral ligament has been tested successfully in quasi-static and dynamic loading at different strain rates.

Investigators usually reported the properties of the combined bone-ligament-bone complex as opposed to only the ligament (Trent et al. 1976, Kerrigan et al. 2003, Robinson et al. 2005). As ligaments are known to be non homogeneous, anisotropic and viscoelastic in nature, regional properties are important in predicting the injury levels in pedestrian automobile collision and FE simulations to study pedestrian kinematics. Ligament functions and propensity for injury are directly related to regional stresses and strains (Phatak et al. 2007). Avulsion failures of the ligament from bony attachment are usually associated with bone weakness at the attachment side due to age of the donor. There has been speculation on the role of inactivity in the period prior to death and normal loss of bone strength with advancing age (Robinson et al 2005). In the present study, the middle region ligament properties are determined in isolation. We also feel that subsequent conversion to stress strain measures through local cross-section area estimates and strain through in-situ marker tracking lead to more statistically consistent measures than in testing bone-ligament-bone complex. Nine (n =9) disease free medial collateral knee ligament has been tested.

EXPERIMENTAL WORK

SPECIMEN PREPARATION

Bovine knee medial collateral ligaments were dissected within one hour after sacrificing the animal. The knee ligament specimens were stored at -20^{0}C prior to test. Thawing of specimen has been done for about two hours to bring the specimen to room temperature. An ambient temperature control unit was used to maintain the temperature of the specimen within ± 1^0 C in quasi-static tests. In quasi-static test, specimen pre-conditioning for 3 cycles for load variation from 0 to 50 N was done. In dynamic test the specimen were preloaded to 15 N (weight of guiding frame). Specimen parameters used for different test are given in the following table.

Table1. Specimen parameters used in tests

Test ID	Gauge length for testing (mm)	Minimum cross sectional area (mm sq)
Quasi-static Tests		
QS-BF-MCL-09	44.5	61.95
QS-BF-MCL-10	39	45
QS-BF-MCL-12	25.1	76.5
Dynamic Tests		
DY-BF-MCL-01	32	61.05
DY-BF-MCL-02	38.3	57
DY-BF-MCL-04	51.1	80
DY-BF-MCL-06	42.4	106.4
DY-BF-MCL-08	37.4	79.6
DY-BF-MCL-12	32.74	73.188

EXPERIMENTAL SET-UP

A custom made quasi-static and dynamic test setups developed are shown in Fig. 1 and Fig. 2. The specimens are held using a cryogenic gripper with liquid nitrogen flowing continuously in cryogenic grippers. A temperature control unit regulates the midpoint temperature of the ligament through thermocouple measurement and on-off control of an hot air flow. The quasi-static setup has been designed to obtain linear speed of screw between 0.5 to 1 mm/min. In dynamic setup a maximum impact velocity of 8 m/sec can be achieved. A strain gauge based transducer; S type load cell (ADI ARTECH) capable of measuring up to 5000 and 7500 N is used in Quasi-static and dynamic test respectively. A laser based sensor is used to determine the elongation of specimen in quasi-static test, with load displacement data are recorded at 1 Hz. In dynamic test, a high speed motion camera (REDLAKE, San Diego, CA, USA) is used to capture the event at 10000 fps. The video is subsequently analyzed to find out the displacement of ligament and initial velocity of the impactor. Load cell sensor data is acquired using an e-DAQ module (SoMat Corporation, Urbana, IL, USA).

Figure1. Quasi-static tensile test set-up

Figure2. Dynamic tensile test set-up

A buffered trigger switch was used to trigger high speed camera and data acquisition system in dynamic test, which synchronizes the displacement data and force data acquired at 10,000 Hz.

Data analysis

The force and laser sensor data in quasi-static tests is acquired with N-Soft™ (N-Code, sheffield, UK) data analysis package. The displacement and velocity data is measured from high speed motion camera by using Image express™ software. Engineering stress reported in the study is calculated from the ratio of force measured and initial minimum cross sectional area. Engineering strain is calculated from the ratio of elongation to the initial length of the specimen.

RESULTS AND DISCUSSIONS

Bovine medial collateral ligament specimens have been tested at 0.0001/s and 0.0003/s in the quasi static setup. In dynamic tests, by setting the drop height, strain rates of 90/s to 164/s have been attained. The load-elongation plot and stress-strain plot are shown in Fig.3 and Fig. 4 respectively. The results of three targeted strain rates are grouped together and plotted for strain rates of 23×10^{-5}/s as quasi-static, 97/s and 136/s for dynamic loading conditions. The strain rates are mean strain rates of three samples each as shown in table 2.

Table: Mean strain rates in quasi-static and dynamic loading

Test ID	Strain rate (1/s)	Strain rate (1/s) Mean ± STD
Quasi-static Tests		
QS-BF-MCL-09	0.0003/s	0.00023 ± 0.0001
QS-BF-MCL-10	0.0003/s	
QS-BF-MCL-12	0.0001/s	
Dynamic Tests		
DY-BF-MCL-02	94.01/s	97.11 ± 8.75
DY-BF-MCL-04	90.33/s	
DY-BF-MCL-06	107/s	
DY-BF-MCL-01	161.4/s	136.13 ± 18.30
DY-BF-MCL-08	147/s	
DY-BF-MCL-12	115/s	

*STD is standard deviation

The load elongation plots in quasi-static and dynamic loading at the mean strain rates is shown in Fig.4.

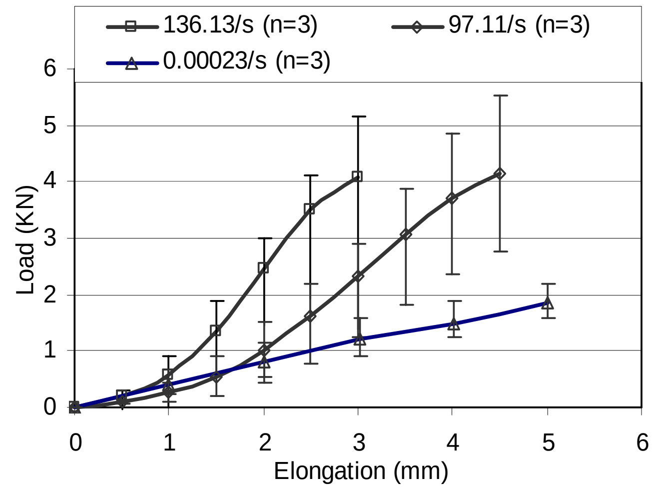

Figure 3 Average load elongation (mean ± standard deviation) plots at mean strain rate in quasi-static and dynamic loading

The stress-strain behavior obtained has been plotted at mean strain rate as shown in Fig 4

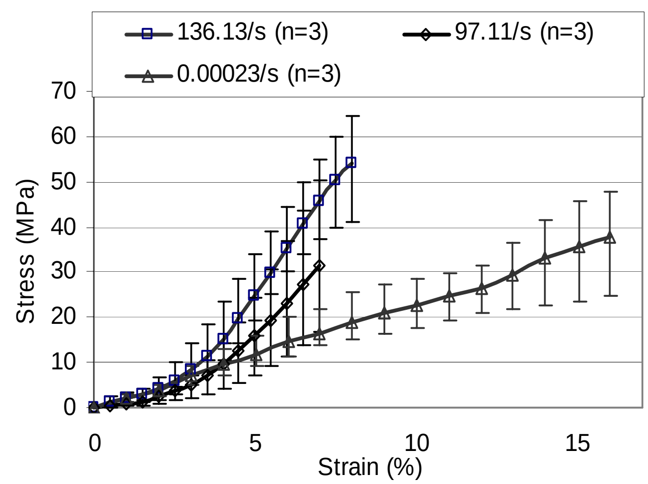

Figure 4 Average stress-strain (mean ± standard deviation) responses at mean strain rate in quasi-static and dynamic loading

The stress-strain curve becomes linear after 4% of strain and again when the load is in excess of 300 N. The elastic modulus was determined from the linear region of the stress-strain curve of the individual tests. (Woo et al. 1992 & Quapp et al 1988).

The ligament properties identified are indicated in table 3.

Table 3: Bovine MCL properties derived from quasi-static and dynamic loading with mean & standard deviation.

	Quasi-static Loading	Dynamic loading	
	Strain rate- $23x10^{-5}$/s (0.0001), n=3	Strain rate- 97.11/s (8.75), n=3	Strain rate- 136.18/s (18.30), n=3
Max strain (%)	20.65± 4.86	10.07±3.08	11.37±3.26
Max. stress (MPa)	34.46±5.99	45.05±6.44	65.38±28.44
Elastic modulus (MPa)	248.92±91.8	513.54±36.4	845.66±109.4

- ( ) indicates standard deviation

These results establish the significance of strain rates in loading of the collateral knee ligament. Regional strain variation is observable as clamp to clamp strain being different from the strain obtained using image analysis of markers placed on the ligament. In the dynamic tests, though the medial strain was tracked, the failure point was not necessarily at the medial region.

CONCLUSION

The bovine medial collateral ligaments properties has been investigated between strain rates $23x10^{-5}$/s to 136/s. The results show substantially linear stress-strain response at very low rate of loading whereas it is nonlinear and strain rate dependant in dynamic conditions. Maximum strain to failure decreases as the strain rate increases, which is the characteristic of viscoelastic material. At a strain rate of about 136/s, the measured elastic modulus is about three times the quasi static value. The failure stress does not exhibit consistent changes with the strain rate. The accurate constitutive representation of human ligament from the properties obtained at high strain rate will help in the precisely predicting the injury level and study the human knee kinematics. It is proposed to populate the data further to establish limits of inter-sample variation, populate the strain range further. The developed procedures and instrumentations are proposed to be extended to measure human knee ligament properties at quasi-static as well as at high strain rate conditions.

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