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VALIDATION OF A NEW FINITE ELEMENT MODEL FOR HUMAN KNEE LIGAMENTS FOR USE IN HIGH SPEED AUTOMOTIVE COLLISIONS

Chiara Silvestri, Louis R. Peck, Kristen L. Billiar, Malcolm H. Ray

Department of Civil Engineering
Worcester Polytechnic Institute
Worcester, MA

Department of Biomedical Engineering
Worcester Polytechnic Institute
Worcester, MA

ABSTRACT

A finite element model of knee human ligaments was developed and validated to predict the injury potential of occupants in high speed frontal automotive collisions. Dynamic failure properties of ligaments were modeled to facilitate the development of more realistic dynamic representation of the human lower extremities when subjected to a high strain rate. Uniaxial impulsive impact loads were applied to porcine medial collateral ligament-bone complex with strain rates up to145 s^{-1}. From test results, the failure load was found to depend on ligament geometric parameters and on the strain rate applied. The information obtained was then integrated into a finite element model of the knee ligaments with the potential to be used also for representation of ligaments in other regions of the human body. The model was then validated against knee ligament dynamic tolerance tests found in literature. Results obtained from finite element simulations during the validation process agreed with the outcomes reported by literature findings encouraging the use of this ligament model as a powerful and innovative tool to estimate ligament human response in high speed frontal automotive collisions.

INTRODUCTION

One of the most common injuries recorded in high speed frontal automotive collisions involves the knee-thigh-hip (KTH) complex. These injuries result often in long term or permanent disabilities with high societal costs. An understanding of the biomechanics and failure mechanisms of the components of the KTH, including ligaments, could help preventing or limiting such types of injuries. Ligaments show a rate dependant and viscoelastic behavior, thus it is possible that their failure properties depend on the rate at which the load is applied. The knowledge of strain rate on the biomechanical properties of ligaments has stimulated great interests in the past years. Few studies, however, investigated the effects of high strain rates on the failure properties of human ligaments. Viano conducted dynamic tolerance tests of the Posterior Cruciate Ligament (PCL) on isolated cadaveric tissues at a loading rate of 1.8 m/sec, finding that a partial ligament failure occurred at a relative tibial-femoral displacement of 14.4 mm and a joint load of 2.02 kN [1]. An ultimate collapse occurred at a relative displacement of 22.6 mm between the femur and the tibia. Mertz recommended an injury threshold level of 15 mm for relative translation between the femur and the tibia at the knee joint for a 50th percentile male to minimize rupture of the posterior cruciate ligament based on the data from Viano [2].

The objective of this study is to determine the failure properties of KTH ligaments subjected to impact conditions presented in high speed frontal automotive collisions. Tests were performed on the medial collateral ligaments (MCL) of pigs and model equations were developed to predict failure stresses based on the initial ligament geometry and the applied strain rate. A partial representation of the 50th percentile male finite element (FE) model developed by Silvestri and Ray was used in this research for validation of a new FE ligament representation including dynamic failure properties [3]. The FE ligament model was validated against Viano experiment results.

METHODS

Porcine knee collateral ligaments were tested at a variety of extension rates consistent with conditions presented in high speed frontal automotive collisions, ranged from 0.005s^{-1} to 145s^{-1}. An axial impulsive impact load was applied to the bone-ligament-bone complex. Data from the impact tests were analyzed to construct predictive model equations capable of forecasting the failure load and failure stress of a ligament subjected to a specific strain rate. Using this information, model equations were developed to predict the failure stresses based on the load and strain rate (Equation 1).

$$P_F = 3.0194 \cdot \varepsilon_{rate} + 1{,}091.5930 \cdot \frac{A_0}{L_0} \tag{1}$$

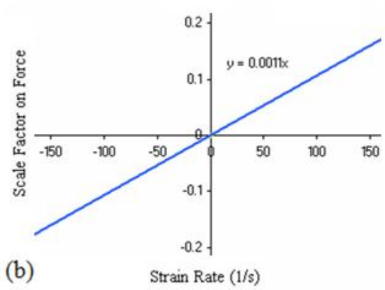
where P_f represents the failure load, ε_{rate} the strain rate applied, while A_0 and L_0 stands for the ligament initial cross sectional area and initial length, respectively.

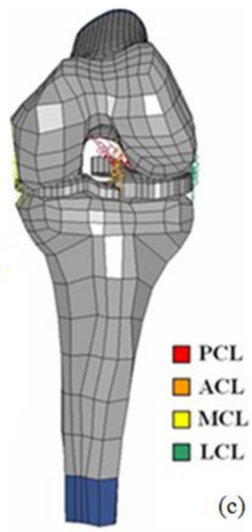
A FE model of the knee human ligaments was then developed. Ligaments length and cross-sectional area were taken from literature (Fig. 1(a)). A spring non-linear elastic material type was chosen in LSDYNA material library because it provides a nonlinear elastic translational and rotational spring with arbitrary force versus displacement curves. Strain rate effects are considered through a velocity dependent scale factor. To define the curve, reproduced in Figure 1(b), the first part of Equation 1 for prediction of the failure load for ligaments was considered. In fact, this relationship can be applied to any ligament knowing its geometrical properties such as its length and initial cross-sectional area. A reduced FE model of the human lower extremity was obtained from the FE KTH model of Silvestri and Ray (Fig. 1(c)) [3]. Patella bone and muscles were not included in the model to conform to the physical tests. Anterior, Lateral, Median and Posterior Cruciate Ligaments (ACL, LCL, MCL, PCL) were modeled. They were split into several discrete elements in order to avoid mesh destabilization problems.

(a)

	Length (mm)	Area (mm^2)
ACL	30.7	5
PCL	35.4	8
LCL	56	10
MCL	38	11

(b)





(c)

Figure 1. FE model of knee ligaments: geometrical inputs (a), scale factor (b) and graphical representation (c).

Experiments conducted by Viano were replicated with finite element simulation in LSDYNA. The mid-femoral shaft was constrained in all directions and rotations. The mid-tibial shaft could move only along direction of the applied velocity. A 1.8 m/sec constant velocity was applied to the bottom mid-tibial shaft in axial direction of the femur.

RESULTS

Results from the FE simulation showed that an initial failure of the PCL occurs at a relative tibial-femoral displacement of 14.24 mm (Fig.2) when the PCL is subjected to 2.97kN force (Table 1). At this point, two of the four discrete elements used to model the PCL fail at their attachment to the condyle indicating an avulsion failure. This was interpreted as a partial ligament failure. An ultimate collapse of the PCL (i.e., all four discrete elements detach) occurs at a relative tibial-femoral displacement of 22.94 mm. Comparison of FE simulation and Viano experimental results are shown in Table 1.

(1

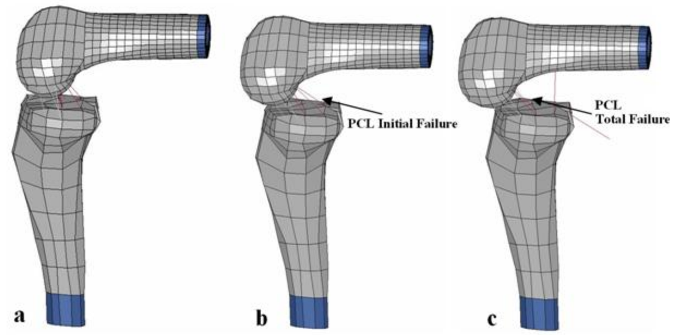


Figure 2. Initial and ultimate rupture of the PCL during FE simulations.

Table 1. FE and Viano test results comparison: tibia displacement relative to fixed femur at PCL first failure and total collapse (a) and PCL force at first failure (b).

		FE (mm)	Viano (mm)
(a)	PCL First failure	14.24	14.4
	PCL Total collapse	22.94	22.6
		FE (kN)	Viano (kN)
(b)	PCL First failure	2.97	2.02

DISCUSSION

As results of uniaxial porcine MCL tests, a relationship connecting the failure load of the ligament with both its initial geometric characteristics and the strain rate applied was established.

Simulation results of a new FE model of human knee ligaments are very similar to the test results obtained by Viano [1]. The simulation results, therefore, fit nicely with both the test data from Viano and the injury criteria recommended by Mertz [2]. According to Anderson, the maximum strain a ligament can tolerate before failure is between 9 and 18 percent [4]. In this case, the two discrete elements failed at a strain of 14.5 and 15.5 percent respectively, which is within the expected range. In conclusion, this validated FE ligament model represents an initial and potential tool for understanding dynamic failure mechanisms of ligaments and avulsion rupture. Future work should be directed to strengthen this FE model to account for mid-ligament failures.

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