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IDENTIFICATION OF VISCOELASTIC PROPERTIES OF HUMAN MEDIAL COLATERAL LIGAMENT USING FINITE ELEMENT OPTIMIZATION

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INTRODUCTION

Current finite element (FE) models of the human lower extremity lack accurate viscoelastic material properties of the knee ligaments, which are needed for computational evaluation of pedestrian injuries [1]. Medial collateral ligament (MCL) is the most frequently injured ligament in lateral impacts. Therefore, the accuracy of the viscoelastic mechanical properties of the MCL FE model is of crucial importance in modeling pedestrian impacts [2]. The focus of this work is to determine the global viscoelastic material properties of MCL using a representative human MCL tested under dynamic and quasi-static loadings.

METHODS

The bone-MCL-bone specimen was extracted and its ends were potted in the fully extended position. The proximal potting cup was rigidly fixed and the distal cup was pulled along the longitudinal axis of tibia. First, the specimen was subjected to a ramp-and-hold test with constant tensile ramp of 3 mm in 30 ms and approximately 600 seconds hold time. The second test was a quasi-static test to failure on the same specimen. In both tests the time histories of force and displacement were recorded. For identification of the material properties, the components of the UVA-GM FE model [2] were used (Figure 1). The insertion sites were modeled using tied contact between bones and ligament. The material model was assumed as transversely isotropic quasi-linear viscoelastic (QLV). The direction of anisotropy (of collagen fibers) was defined in the material definition as the element normal along the insertion sites. First, the quasi-static test was simulated. The material coefficients were optimized using LS-Opt [4], assuming the quasi-static test data as the target values and defining minimization of the root-mean-square (RMS) error as the objective function. The range of values of hyperelastic coefficients (C_1-C_5) used in the optimization process were defined based on the reported data in [5]. The viscoelastic properties of the ligament were then determined from the dynamic ramp and hold test. A three-term Prony series was considered for the relaxation behavior. The long-term Prony coefficients (S3 and T3) were estimated directly from the relaxation data. The two additional Prony coefficients (S1, T1, S2, and T2) were determined by considering both the ramp and hold periods and the same FE optimization procedure described above was conducted.

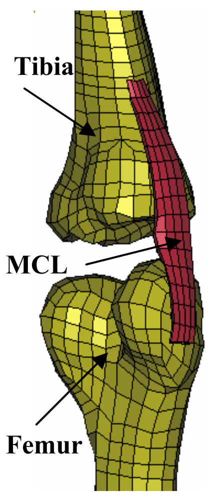

Figure 1: FE Simulation of the MCL Tensile Tests

RESULTS AND DISCUSSION

The material coefficients obtained by FE optimization are provided in Table 1. The results of the simulations of quasi-static failure tests and dynamic ramp-and-hold tensile tests of MCL in comparison with experimental data are shown in Figures 2-a, and 2-b respectively. In the dynamic test with 0.1 mm/ms displacement rate, approximately 15% increase in the peak dynamic force was observed, which suggests that tissue viscoelasticity plays certain role in the response during impact scenarios. The elastic stress-strain relationship in a cubic sample of MCL in tension along the collagen fibers with optimized parameters was compared with the corridor provided in [5]. The current material model was slightly stiffer at strains above 13%. This material model was determined by assuming a homogeneous anisotropic material for the whole MCL and optimizing its global tensile properties. However, MCL is inhomogeneous particularly at the insertion sites, which could explain the difference observed in its local (anterior-central two-third region) and global properties.

Table 1: Optimized MCL material properties

K (GPa)	C_1 (MPa)	C_3 (MPa)	C_4 -	C_5 (MPa)	S_1-
3.75	7.85	0.25	60.4	307.5	0.15
S_2	S_3	T_1 (ms)	T_2 (ms)	T_3 (ms)	λ
0.026	0.348	100	11710	162633	1.055

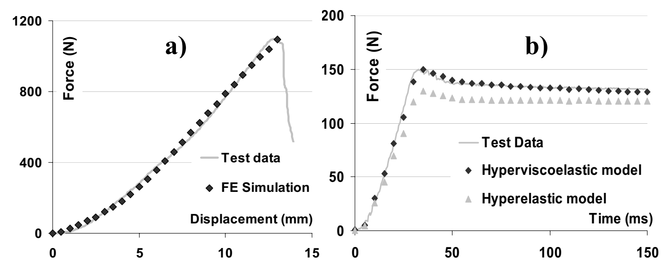

Figure 2: FE Simulation of the MCL Tensile Test

CONCLUSIONS

The global viscoelastic material properties of an MCL specimen were derived by FE optimization. Results showed that tissue viscoelasticity increases the peak dynamic force by 15%. Studies of more specimens are underway and will be reported in the future.

REFERENCES

1. Weiss, J. et al., *Critical Rev. Biom. Eng.* **29**(4): 1-70, 2001
2. Untaroiu, C, et al., *ASME Int. Congress*, Paper 61583, 2004
3. Hallquist, J. O., *LS-Dyna Theoretical Manual*, May 1998
4. Stander, N, et al., “LS-OPT User’s Manual”, LSTC, 2003
5. Quapp, KM, et al., *J. Biomech. Eng.* **120**, 757-763, 1998.