FAILURE PROPERTIES OF CERVICAL SPINAL LIGAMENTS UNDER HIGH-RATE LOADING

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INTRODUCTION

The US Navy is currently developing a finite element model of the human spine to investigate the response of the spine to high-rate loading similar to the input pulse during an aircraft ejection [1]. The University of Virginia Center for Applied Biomechanics is performing experimentation to develop material properties [2] and failure properties of soft-tissues (ligaments and intervertebral discs), which will be implemented into the spine finite element model. This paper presents the failure properties of the anterior longitudinal ligament (ALL), posterior longitudinal ligament (PLL), and ligamentum flavum (LF) in the human cervical spine.

METHODS

Six male and five female human cervical spines were used in this study. The average age of the male and female subjects was 60 yr ± 9 yr and 58 yr ± 6 yr. The average stature and mass were 1749 mm ± 40 mm and 77 kg ± 17 kg for the male subjects and 1626 mm ± 51 mm and 62 kg ± 19 kg for the female subjects. The ALL, PLL, and LF were isolated from each cervical spine at C3-C4, C5-C6, and C7-T1, resulting in a total of 54 male ligaments and 45 female ligaments. Of those, 47 male ligaments and 42 female ligaments were suitable for testing. Ligaments were excluded from testing if they were damaged during specimen preparation. The ligaments were mounted in a universal test machine (Instron, Inc. # 8874 Canton, MA) for uniaxial tests in an orientation that represents physiological conditions. The fixture was enclosed in an environmental chamber to maintain physiological temperature (99 ± 1 ˚F) and humidity (>90%). After the appropriate preconditioning, each ligament was subjected to a battery of material property tests [2], followed by failure tests. The failure tests included step inputs of 75% strain, 100% strain, and 300% strain. A typical strain rate in the failure step tests was 70-150 s^{-1}. Injury risk functions were then generated using a survival analysis on the peak stresses resulting from a 100% step strain input.

RESULTS AND DISCUSSION

The failure analysis was performed using the 100% strain step input tests; therefore, the strain rate (~80 sec^{-1}) did not vary substantially between tests. Otherwise, the viscoelastic nature of the ligaments would result in varying peak stresses depending on the strain rate. A consistent strain rate allows for a direct comparison of peak stress among the ligaments. The engineering stress was calculated using published cross-sectional areas for the ALL, PLL, and LF [3]. The following equations were then used to compute true strain, ε_T, and true stress, σ_T, assuming that the ligaments are incompressible, thus maintaining a constant volume during the tensile loading:

$$\varepsilon_T = \int d\varepsilon = \int_{l_o}^{l_f} \frac{dl}{l} = \ln\frac{(l_o + \Delta l)}{l_o} = \ln(1+\varepsilon_E) \qquad (1a)$$

$$\sigma_T = \frac{F}{A} = \frac{F}{A_0}\cdot\frac{l}{l_0} = \sigma_E(1+\varepsilon_E) \qquad (1b)$$

where F is force, A is cross-sectional area, A_o is initial cross-sectional area, l is length, l_o is initial length, σ_E is engineering stress, and ε_E is engineering strain. Figure 1 and Figure 2 is a representation of the failure strain and corresponding failure stress for each ligament. The similarities of the failure characteristics between genders are consistent with the findings from a statistical analysis of cervical spinal ligament material properties in a previous study by Lucas et al. [2]. From the injury risk functions, the true stress corresponding to a 50% risk of an AIS 3 injury for the ALL, PLL, and LF is 11.6 N/mm^2, 12.6 N/mm^2, and 13.2 N/mm^2.

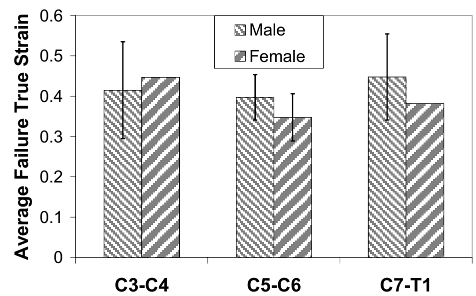

Figure 1: Failure true strain for posterior longitudinal ligament

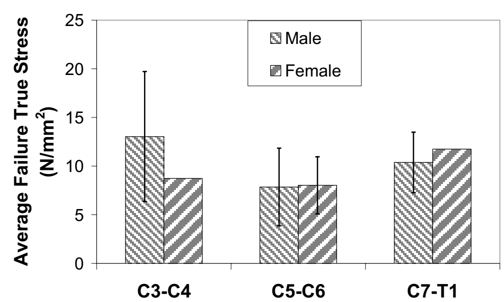

Figure 2: Failure true stress for posterior longitudinal ligament

CONCLUSIONS

The primary objective of this study was to develop failure characteristics of the ALL, PLL, and LF in the human cervical spine under high-rate loading. The injury tolerances are implemented into a finite element model of the cervical spine to assess injury due to aircraft ejection.

REFERENCES

1. Paskoff, G. Influence of Helmet Mass Properties on Head/Neck Forces During High-Speed Ejection. *4th World Congress of Biomechanics*, Calgary, Canada, 2002.
2. Lucas et al. Viscoelastic Characterization of Cervical Spinal Ligaments. *26th ASB Conference*, Portland, OR, 2004.
3. Yoganandan et al. Geometric and Mechanical Properties of Human Cervical Spinal Ligaments. *J Biomech Eng* **122**, 623-629, 2000.