Nonlinear Viscoelastic Behavior of Human Cervical Spine Ligaments
Troyer, KL; Puttlitz, CM
Colorado State University, Fort Collins, CO
puttlitz@engr.colostate.edu

Introduction—Spinal ligaments play an important role in spine biomechanics. Accordingly, a precise understanding of ligament mechanical properties is requisite for accurate modeling of the local and global behavior of the spine. Spinal ligaments exhibit nonlinear stress-strain relationships and viscoelastic material behavior. Current literature on the viscoelastic response of cervical spine ligaments has focused on forces and displacements experienced during trauma and often utilize the quasi-linear viscoelastic (QLV) theory proposed by Fung to describe this behavior. While researchers have shown success using QLV theory to model relaxation behavior of spinal ligaments at a single magnitude of applied strain, this theory does not allow the relaxation function to vary according to the applied strain. Throughout normal spine movements, ligaments undergo varying levels of applied strain. The lack of information about the viscoelastic behavior of spinal ligaments under multiple magnitudes of applied strain prevents the development of mathematical models to accurately approximate spine behavior. This work investigates the viscoelastic behavior of cervical spine ligaments under varying levels of applied strain.

Materials and Methods—Six C5-C6 functional spinal units (FSU) were dissected from frozen human cadaveric cervical spines. The vertebrae of each FSU were transected at the mid-coronal plane of the vertebral body and at the pedicles, separating the posterior elements from the anterior body. The anterior longitudinal ligament (ALL, n=6), posterior longitudinal ligament (PLL, n=6), and ligamentum flavum (LF, n=4) were isolated by carefully removing all nonosteoelagmentous soft tissue, including the intervertebral disc, from each specimen; resulting in a bone-ligament-bone preparation for each ligament. Wood screws were affixed to the superior endplate of the cranial vertebra and to the inferior endplate of the caudal vertebra in the case of the ALL and PLL, and to the superior and inferior surfaces of the articulating processes for the LF. The cranial and caudal bones were potted in polymethylmethacrylate (PMMA). Hydration was maintained throughout specimen preparation via physiologic saline spray. Upon completion of preparation, each specimen was wrapped in saline soaked gauze and frozen at -20 °C in a sealed bag. Before testing, each specimen was thawed overnight to room temperature. All experiments were conducted in an environmental chamber, filled with physiologic saline heated to 37 °C, attached to a translation table (x-y) that was rigidly fixed to the base of a servo-hydraulic materials testing machine (Bionix 858, MTS, Minneapolis, MN).

A single degree of freedom load cell was placed between the MTS actuator and a custom upper fixture that attached to the cranially potted vertebral bone. After attaching the caudally potted bone to the environmental chamber, the upper fixture was lowered close to but not contacting, the cranially potted bone and the load cell force was zeroed. The upper fixture was then attached to the cranially potted vertebra and the crosshead was moved to the zero force configuration for 1 hr for specimen equilibration. After equilibration, the specimen was compressed to 25 N and the displacement zeroed. The specimens were ramped at 0.05 mm/s to 5 N of pretension. The resulting displacement was used as the reference configuration.

Relaxation experiments were conducted at varying levels of strain. Each ligament was preconditioned at 10% engineering strain, applied at 1 Hz for 120 cycles, and was returned to its reference configuration for 600 s. Each ligament was subsequently subjected to a randomized application of 4, 6, 8, 10, 12, 14, 16, 18, 20 and 25% engineering strain applied at 5 mm/s. Every strain level was held for 100 s then returned to the reference configuration for 600 s before the application of the next strain magnitude. Force relaxation data were recorded at 60 Hz. Statistical analysis was performed using the SAS PROC MIXED (SAS Institute, Inc., Cary, NC) procedure with α=0.05.

Results—Relaxation data were fitted to the following power relationship:

\[ F(t) = A t^n \]  

where \( A \) is the initial force magnitude (N), \( t \) is time (sec), and \( n \) is the relaxation rate (dimensionless). Eq. (1) approximated the response well, with the average (and standard deviation) \( r^2 \) across all strain levels being 0.983 (0.019), 0.901 (0.191), and 0.873 (0.162) for the ALL, PLL, and LF, respectively.

Statistical analysis indicated a significant interaction between strain magnitude and ligament type for both \( log(A) \) and \( n \) (\( p=0.0001 \)). Also, a significant interaction existed between the square of the strain and the ligament type for \( log(A) \) (\( p=0.0013 \)) and for \( n \) (\( p=0.0001 \)).

Discussion—Researchers have traditionally used QLV theory to describe the mechanical behavior of spinal ligaments. While this approach works well for describing the relaxation behavior at a single strain, it does not allow the relaxation function to vary according to the magnitude of the applied strain. This inherent shortcoming prevents QLV models from accurately describing the ligament response throughout the spine’s physiological range of motion.

The data presented herein shows a strong correlation between the magnitude of the initial force and the applied level of strain. More importantly, the relaxation rate for these ligaments was strongly dependent on the applied strain level. All tested ligaments showed an increase in relaxation rate as the strain increased. This indicates that QLV theory is not robust enough to describe the range of tested strain levels and thus a more general, nonlinear viscoelastic theory should be used to fully characterize these ligaments.


Acknowledgements—James zumBrunnen for statistical consulting.