COMPUTATIONAL ANALYSIS OF THE MECHANICAL BEHAVIOR OF LIGAMENTS

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INTRODUCTION

Ligaments play a variety of roles in the behavior of the lumbar spine as well as other joints. They limit movement, store energy, and provide stability to the joint. As a result, any computational biomechanical model that attempts to explain injury pathway(s) in the lumbar spine must use an accurate depiction of the ligament behavior if it is to describe the spinal loads reliably. For biomechanical models, the material properties are the parameters that have the greatest effect on the behavior.

The inherent variability of biological tissue leads to a range of properties, not a single, known or estimated value. Moreover, the limited existing material property data varies widely from study to study. To present, no study has systematically investigated the effect of varying the material properties within their feasible range. The goal of this presentation is to show the effect of the material property variations and strain rate on the cyclic behavior of ligaments, as well as their importance in biomechanical modeling.

METHODS

A nonlinear Kelvin-Voight model was developed in this study to represent the hysteretic ligament behavior. The spring and dashpot behavior is strain dependent and is governed by

$$E = \{1.0 + \tanh(\psi\,[\varepsilon - \varepsilon_0])\}\, E_{active}/2$$

where E is the current spring or dashpot coefficient, E_{active} is the coefficient when the ligament is fully active, ψ is a parameter defining the shape of the transition between the active and inactive states, ε is the current strain, and ε_0 is the strain at center of the modulus transition zone (activation strain).

Experimental data from different loading cycles (Tkaczuk, 1968) and at different strain rates (Solomonow, 2004) were considered a starting point for an investigation into the effect of loading rate and the material properties of the ligament on the behavior. An analysis of each parameter has been performed to determine their influence on the model output. Hysteretic energy dissipation is used as a damage measure in many areas of mechanics, and is calculated herein for both the first and third cycles of a testing sequence.

RESULTS AND DISCUSSION

The maximum stress was calculated for a wide range of strain rate, activation strain, and viscous coefficient. The activation strain was found to have a considerable effect on the overall ligament behavior, and faster rates of load application were associated with the higher stress levels, with the effect being more pronounced in the first loading cycles. Increasing strain rate from 25 to 100%/sec resulted in the maximum stress increasing by 31%. The maximum stress decreased by 19.5% as the activation strain varied from 2.5% to 15%. Experimental results also indicate increased stiffness and earlier activation with cycling.

Energy dissipation exhibited a nonlinear dependence on the viscoelastic parameters and increased as much as five-fold with strain rates from 12.5%/sec to 100%/sec. Conversely, larger activation strains (from 5% to 15%) lead to a 60% decrease in the energy dissipation. These effects were present at a smaller scale, but were no less important, at the third and later cycles, as seen in Figure 1.

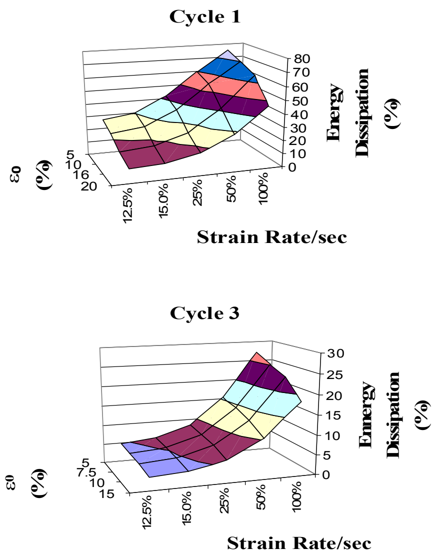

Figure 1: Energy dissipation at first and third cycle as a function of ε_0 and strain rate.

An examination of the results indicates that faster movement rates lead to higher tensile stresses and more energy dissipation in the ligaments. This fact, coupled with the rapid decrease in energy dissipation from the first to later cycles, reinforces commonly held beliefs about injury prevention. The results suggest that one strategy for reducing the risk of injury to the spine due to repetitive loading is to start slowly with smaller loads, and to increase the load and loading rate gradually to the desired level.

CONCLUSIONS

In conclusion, this study showed that small variations in even a single parameter can result in large changes in the ligament behavior. The results underline the importance of understanding the relationship between the work environment, material testing, and modeling on the prediction of injury. In order to be truly useful, the parameters for biomechanical models must come from both the real world and the laboratory, and the material testing must be performed under realistic conditions.

REFERENCES

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