PROELASTIC FINITE ELEMENT MODEL TO PREDICT THE FAILURE PROGRESSION IN A LUMBAR DISC DUE TO CYCLIC LOADING

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INTRODUCTION

The intervertebral disc is susceptible to ruptures and degenerative processes. Autopsy studies have shown that the formation of annular tears, dehydration of the nucleus pulposus, and fissure formation in the cartilage endplate are the main early macroscopic features that characterize disc degeneration. Understanding how failure originates and progresses in a motion segment subjected to cyclic loading conditions is thus important to understand the process of disc degeneration.

Initiation and propagation of different types of events that lead to disc degeneration and the effect of the degenerative process on the disc mechanical performance is difficult to study by experimental techniques. Therefore, the aim of this investigation is to model the development of annular tears and endplate fissures and study the propagation of these degenerative processes in a lumbar motion segment subjected to cyclic loading that correspond to a certain heavy physical work activity. The hypothesis of this study is that the failure progression due to cyclic loading increases exponentially as the drained elastic modulus of the failed disc components decreases (as compared to modulus of the intact portion) due to presence of failure.

METHODS

A previously validated three-dimensional poro-elastic finite element model of the L4-L5 motion segment including biological parameters (swelling pressure and strain dependent permeability and porosity) was used [1]. Elastic and poro-elastic material properties for the nucleus, inner annulus and outer annulus were varied regionally according to values taken from the literature. The annular fibers were modeled using several layers of large number of “re-bar” elements that accurately model the bulging of the annulus due to large compression and shear loads experienced during the heavy physical work activities.

Failure initiation and progression was modeled using a “user-supplied-material” function available in the finite element code (ADINA). Failure initiation and progression in all the disc components was modeled as follows: due to the applied load if at any integrating point in an element representing the disc the von-Mises stress is greater than the corresponding failure stress, the drained elastic modulus of material at that integrating point is reduced by an assumed percentage of the intact elastic modulus value and used for subsequent analyses. This method allows prediction of the location of failure initiation in any component of the disc and follows the failure progression continuously as the cyclic loading continues.

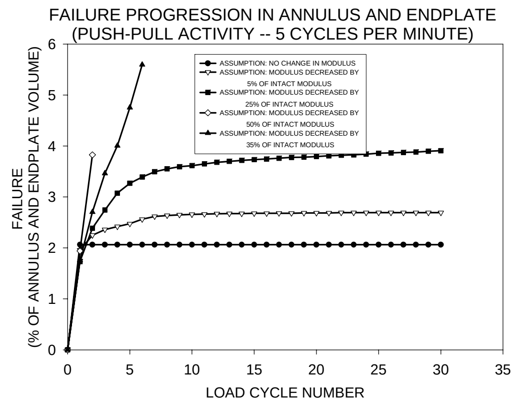
The physiological loading conditions used in this investigation involved pulling a box with a force of 140 N using a handle at 142 cms above the ground. A muscle optimization model using EMG and kinematics data collected in a lifting laboratory was used to calculate spinal loads as a function of time. Five cycles of activity per minute was modeled in the current study. During each cycle, push-pull activity was completed in 5 seconds followed by a rest for 7 seconds. The rest period was simulated by applying an axial compressive load of 400 N.

The number of integrating points where failure occurred in various elements representing different components of the disc was collected at the end of each load cycle. Percentage of disc failure volume at the end of each load cycle was calculated by dividing the number of failed integrating points by the total number of integrating points in the disc.

RESULTS

The failure initiated both in the endplate and annulus during the first load cycle. Annular failure initiated on the interface surface between the bottom endplate and inner annulus. On the other hand, endplate failure initiated at the top endplate. Both annular and endplate failure initiations occurred in the right lateral quadrant of the disc. As the load cycle increased, endplate failure progressed towards the center of the endplate as well as along the anterior quadrant of the top endplate. Failure in the annulus progressed outward as the number of load cycles increased.

There was no change in disc failure volume as the load cycle increased (Figure) when it was assumed that the drained elastic modulus of failed disc components were not altered (due to failure) in the subsequent load cycle analyses. On the other hand, when the drained elastic modulus of the failed disc components were decreased in the subsequent analyses by 30% of the corresponding intact drained elastic modulus, failure was found to propagate. The analyses also showed that the rate at which the disc failure volume increased as the load cycle progressed (slope of the curve) was greater as the assumed decrease in drained elastic modulus due to failure increased. The result showed that the disc failure volume increased exponentially as the reduction in drained elastic modulus at the failure locations in the disc components increased.



SUMMARY/CONCLUSIONS

The results of the current study support our hypothesis that the failure progression due to cyclic loading exponentially increases as the assumed drained elastic modulus of the failed disc components decrease. Since the failed portion of the disc was able to carry a much smaller share of the load (due to larger percentage reduction in drained elastic modulus in such regions) progression of failure was exponential. The results presented here is a conformation that the current concepts used in modeling the failure progression in a lumbar disc are reasonable.

REFERENCES

1. Natarajan, R. N., Williams J. R., and Andersson G. B. J., 2004, “Recent Advances in Analytical Modeling of Lumbar Disc Degeneration”, *Spine*: 29(23), pp. 2733-2741.

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