THE EFFECT OF COUPLED MOTIONS AND LIFTING TASKS ON HUMAN LUMBAR NUCLEUS PRESSURES AND ANNULUS FIBROSUS STRESSES IN A MUSCLE-LOADED FINITE ELEMENT MODEL

1 Benjamin C Gadomski, 2 John Rasmussen, 3 Pavel Galibarov, and 1 Christian M Puttlitz
1 Colorado State University, Fort Collins, CO; email: puttlitz@engr.colostate.edu
2 Aalborg University, Aalborg, Denmark
3 AnyBody Technology A/S, Aalborg, Denmark

INTRODUCTION
Approximately one-fifth of occupational injuries are related to low back problems. Coupled motions involving a combination of flexion, lateral bending, and axial rotation have been linked to increased incidence of low back disorders [1]. The role of lifting in low back injuries has been well established, but many of the underlying mechanisms behind low back pain remain unclear. Until recently, the inability to accurately determine musculature recruitment patterns with respect to force magnitude and timing has hindered advancement in this area. New musculoskeletal modeling techniques have provided insight into these details, which are especially important in determining the role of the spinal musculature on the mechanical parameters of the relevant osseous and soft tissues. The aim of the current study was to evaluate the effect of muscle-driven coupled rotations and lifting on key mechanical parameters such as annulus fibrosus stresses and intradiscal pressures of the human lumbar spine.

METHODS
Lumbar muscle forces were applied to L1 through L4 on a previously validated nonlinear finite element lumbar spine model. An anisotropic strain energy function was utilized for the constitutive modeling of the annulus fibrosus, where the total energy density was the sum of the matrix and fiber terms [2]. Muscle forces were determined using the AnyBody Modeling System [3] (AnyBody Technology A/S, Aalborg, Denmark) for the postures of 40° forward flexion (Sacrum-L1), maximum lateral bend (30° Sacrum-L1), and maximum axial rotation (20° Sacrum-L1). A total of 135 discrete forces were simulated in the muscle model. Each muscle force was applied to the model via a surface node set and a coupling constraint. The erector spinae assembly consists of the longissimus thoracis pars lumbarum, iliocostalis lumbarum pars lumbarum, longissimus thoracis pars thoracis, and iliocostalis lumbarum pars thoracis components. Eight fascicles of longissimus thoracis pars lumbarum and eight fascicles of iliocostalis lumbarum pars thoracis components. Eight fascicles of iliocostalis lumbarum pars lumbarum were attached to the medial and lateral transverse processes respectively. A significant force is exerted by the eleven fascicles of longissimus thoracis pars thoracis and eight fascicles of iliocostalis pars thoracis components, but have no direct attachment site on the lumbar portion of the spinal column. These forces were applied via a node in the area posterior to the pars lumbarum connections in the center of the erector spinae aponeurosis. The attachment points of the thirty fascicles of the multifidus muscle were located on the spinous processes and mamillary processes. A single fascicle of psoas major was attached to each lateral face of the vertebral bodies of L1 through L4 for a total of eight fascicles. Four fascicles of the quadratus lumborum were attached to the anterior portion of the spinous process at the L1 and L3 levels. The transversus abdominal muscle force was applied to the anterior face of each vertebral body from a node located in the center of the abdominal cavity. The 21 fascicles of the semispinalis were connected to the transverse processes at the L1, L2, and L3 levels. In vivo range of motion and intervertebral disc pressures were compared to those obtained by the finite element model in flexion, lateral bending, and axial rotation to ensure correct muscle attachment.

The cases of forward flexion (30°) with and without a 15 kg load and forward flexion (30°) combined with lateral bending (15°) with and without a 15 kg load were simulated on the AnyBody model. The resultant muscle forces were implemented on the lumbar spine finite element model. Average annulus fibrosus von Mises stresses and intradiscal pressures were compared between simulations.

RESULTS AND DISCUSSION
Intradiscal pressures for the various movements are presented in Figure 1. The pressures for all loading scenarios increased inferiorly along the spinal column and were highest at the L4-L5 level. The combination of flexion and lateral bending with and without lifting (loaded and unloaded respectively) generated higher nucleus pressures at all levels than the respective flexion with axial rotation simulations.

Figure 1: Intradiscal nucleus pressures for the various loading scenarios.
The combination of flexion and axial rotation increased nucleus pressures from 75% at the L1-L2 level to 100% at the L4-L5 level when the lifting load was applied, while the combination of 30° forward flexion with 15° of lateral bending experienced an average nucleus pressure increase of 60% when the 15 kg load was incorporated (Figure 2).

The average von Mises stresses in the annulus fibrosus for all simulations were lowest at L1-L2, while the average annulus stresses for the remaining three levels were nearly constant. Stresses were highest at the posterior region of the annulus for all levels except L1-L2 in all loading scenarios. Stresses at the L1-L2 level were highest at the right lateral region of the annulus, opposite the direction of lateral bend. This effect was greatly increased with the addition of the lifting load. The flexion with lateral bending scenarios with and without lifting produced higher average annulus fibrosus stresses than the respective flexion with axial rotation simulations.

The flexion with lateral bending loading scenario annulus stresses increased between 75% and 110%. Average annulus stresses for the flexion with axial rotation lifting combination increased between 110% and 190%. These increases were greatest in the posterior annulus regions, but were minimal in the remaining regions of the annulus. Changes in annulus stresses were highest at the superior levels and lowest at the inferior levels. The large increases in pressures and stresses experienced by the spinal column under axial rotation indicate that this combination of twisting and flexion offers less stability than lateral bending and flexion.

The nucleus pressures predicted for the lifting simulations are in agreement with previously reported in vivo lifting measurements [4]. These data suggest that the spinal column experiences increased loading as a result of greater muscle activation in response to a lifting task. In this study, the spinal musculature invoked increased activation in order to retain constant intervertebral rotation. This resulted in a dramatic increase in nucleus pressures and annulus fibrosus stresses. Also, the low nucleus pressures and annulus stresses experienced under flexion with axial rotation suggest that, of the three main principal loading directions, flexion is the main driving force behind intervertebral disc pressure and stress generation, followed by lateral bending and axial rotation. Both nucleus pressures and annulus stresses increased with the addition of a lifting load. Nucleus pressures were highest in the anterior region. Annulus stresses typically peaked in the posterior region of the disc, demonstrating the annulus fibrosus’s high stress response to tensile loading.

**CONCLUSIONS**

Nucleus pulposus pressures and annulus fibrosus stresses increased greatly with the addition of a 15 kg lifting load. The annulus experienced the highest stresses in areas under tensile loading, while nucleus pressures were greatest in areas under compression. These results demonstrate the increased loading placed on the lumbar spine during lifting tasks, and provide quantitative evidence of the high risk of failure of the posterior annulus fibrosus (i.e. herniation or tearing) under lifting conditions.

**REFERENCES**