INTRODUCTION:
Nerve root compression is a key factor in symptomatic progression of degenerative disc disease. Degenerative changes of the cervical spine in the form of bone spurs and disc space narrowing secondary to DDD affect the area available for the nerve roots and the space available for the spinal cord. The area is greatly affected by the posture of the spine.

Traditional techniques to evaluate the foraminal dimension have used direct measurement by caliper and blunt probe and measurement using CT scans in static postures. The goal of this study was to assess the neural foramen and canal dimension of intact cervical spine specimens throughout the flexion-extension range of motion.

MATERIALS & METHODS
Specimens
Nine C3-T1 cervical spine specimens (42±10.5 yrs).

Experimental Protocol
- Spine specimens were instrumented with radiopaque markers (Figure 1).
- A 3-dimensional (3-D) specimen-specific anatomical model was reconstructed using axial CT scans (slice thickness: 0.63mm) (Figure 2).
- Kinematic response was measured in flexion-extension.
- A 3-D motion of each vertebral body was tracked using optoelectronic motion sensors (Figure 3).
- A digital link between the CT markers and the 3-D motion was made by digitizing the radiopaque markers relative to the motion targets (registration).
- The 3-D vertebral motion data obtained during the flexibility test was used to drive the 3-D CT anatomical model. As a result, 3-D motion of any anatomical landmark on the specimen could be assessed in response to the loads applied during flexibility testing.
- Canal Area was calculated by digitally tracing the C5 posterior inferior endplate edge and neural arch and the C6 posterior superior endplate edge and neural arch. These points were projected onto a plane defined by the C6 superior endplate and the area was calculated in this plane (Figure 4).
- Foraminal area was calculated by tracing the isthmus of the C5-C6 neural foramen and projecting onto a plane oriented at 45 degrees from the sagittal plane of C6. The area was calculated in this plane (Figure 5).

RESULTS:
The model was used to visualize and quantify the canal overlap area and foraminal area throughout the entire range of motion in flexion-extension (Figures 6 & 7).

The foraminal and canal areas were processed to obtain the percent change relative to the neutral posture. Linear regression analysis was performed on percent change in canal and foraminal areas vs. C5-C6 angular motion from neutral posture.

In flexion-extension, the canal and foraminal areas for all specimens increased in flexion and decreased in extension. Regression analysis showed a significant correlation between percent change in canal area and angular motion ($R^2=0.89$, $p<0.05$) as well as percent change in foraminal area and angular motion ($R^2=0.87$, $p<0.05$) (Figures 8 & 9).

The canal and foraminal areas changed by 1.5% and 1.0% respectively per degree of flexion - extension angular motion.

DISCUSSION
The increase in foraminal and canal space in flexion as demonstrated in this study is consistent with the treatment modalities used in manipulation and physical therapies to relieve radicular symptoms associated with foraminal and canal stenosis. The specimen specific model used in this experiment allowed evaluation of these areas over the full flexion-extension range of motion.

Although not presented in this analysis, the model allows similar assessment in other modes of motion and at all cervical levels. The 3-D CT-based specimen-specific models allow assessment of spine kinematics not previously possible in the ex vivo setting.

SIGNIFICANCE
This is the first work to evaluate foraminal area and canal overlap area of the cervical spine in response to kinematic range of motion in flexion-extension.