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Intervertebral Motion After Incremental Damage to the Posterior Structures of the Cervical Spine

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Study Design. Compare intervertebral motion after incremental damage to posterior cervical structures in whole cadavers to motion in asymptomatic subjects.

Objective. Determine if damage to the posterior structures of the cervical spine can be detected by quantitative analysis of flexion-extension radiographs.

Summary of Background Data. Simulated damage to the posterior structures of the cervical spine can change intervertebral motion, if intervertebral motion before damage is known. It is not known if intervertebral motion measured from flexion-extension radiographs can be used to detect damage to the posterior structures if motion before damage is not known.

Methods. Incremental injury to posterior ligaments and facet joints was simulated in 12 whole cadavers. Intervertebral motion was measured from flexion-extension images using validated and clinically applicable software. Measurements were compared to previously published measurements for asymptomatic subjects.

Results. Extensive damage could be simulated in all the cervical spines without intervertebral motion exceeding the 95% confidence limits for asymptomatic subjects. After sectioning all posterior ligaments, destroying both facet joints, and then sectioning the posterior longitudinal ligaments, intervertebral motion exceeded the 95% confidence intervals in 69% of the cadavers. Intervertebral shear decreased with incremental damage to posterior structures.

Conclusions. Radiographic assessment of the cervical spine may not be sufficient to exclude even extensive damage to the posterior structures of the cervical spine.

Key words: cervical spine, injury, radiographic, diagnosis. **Spine 2005;30:E503–E508**

Understanding instability is critical for the appropriate treatment of many types of spinal disorders. Nonoperative as well as surgical decisions are made regularly for a variety of conditions based on the clinician's judgment of stability. Although dozens of studies addressing spinal stability have been reported, validated diagnosis and treatment guidelines that use objective measurements of spinal stability do not exist.

Numerous investigators have addressed the challenge of diagnosing physical damage to the cervical spine of trauma patients. The clinical working hypothesis is that damage to the intervertebral ligaments can lead to abnormal motion between vertebrae, which can, in turn, lead to neurovascular damage and symptoms. Computerized tomography is clearly the best modality for assessing malalignment or fractures but only provides a static view. Flexion-extension radiographs have been advocated as a method to assess the dynamic stability of the spine. Unfortunately, there is relatively little known about the degree of damage that can be detected in the absence of knowledge of intervertebral motion before the injury. Despite the efforts of many researchers, clinical tests that can accurately and reliably detect injuries to the intervertebral ligaments of the cervical spine have never proved to be sensitive or specific. Such tests would be of significant clinical benefit.

A test to detect damage to the spine requires scientifically valid data to identify both normal and abnormal test results. Toward this end, several investigators have reported on the motion of normal, intact cervical spines *in vivo* using radiographic and fluoroscopic images.[1–7] Much of this research was summarized in a recent review article.[8] Laboratory studies have shown that simulated trauma to the cervical spine or sequential sectioning of the intervertebral ligaments alters the pattern of intervertebral motion.[9–15] Although these studies have provided valuable information, their findings have not been translated to routine clinical diagnostic use. In addition, the initial models consisted of cervical spines stripped of their surrounding soft tissues, with the exception of the immediately adjacent muscles, ligaments, and joint capsules. More recent models have attempted to account for dynamic muscle forces by developing a series of pulley systems to simulate dynamic muscle actions.[16,17] In this study, we have used a more direct model for assessing biomechanics, that being the entire, intact cadaver with physiologic motion.

The purpose of this study was to improve our understanding of cervical spine motion and instability following injury to posterior structures in an otherwise intact cadaver using a new biomechanical testing model. The central hypothesis was that damage to specific intervertebral ligaments would result in predictable and measurable changes in the pattern of intervertebral motion. A secondary hypothesis was that even if changes in intervertebral motion can be detected, the measured motion after damage to posterior structures may not be outside the ranges measured for asymptomatic patients and would, therefore, not be detectable in clinical practice. To enhance the clinical relevance of the study, interver-

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tebral motion was measured using a validated method that is used in routine clinical practice.

Methods

There were 12 intact human cadavers obtained from the Baylor College of Medicine Department of Anatomy evaluated after rigor mortis had completely subsided. None of the cadavers had prior cervical spine surgery, congenital cervical vertebral fusion, advanced degenerative changes, neoplastic changes, and the second through seventh cervical vertebra could be visualized on lateral flexion and extension fluoroscopic images. Each cadaver was secured in a custom apparatus designed to hold the body in an upright, seated position inside a fluoroscope (Figure 1). Because these were intact specimens, no simulation of the weight of the head or the neck was necessary. A helmet was fixed to the head, accommodating a strap attached to a tensiometer. The force applied to the helmet was always applied in a direction tangential to the helmet surface, thereby providing reproducible flexion and extension moments for all trials. This load control model provided a consistent moment, and a full range of flexion and extension motion. In a model such as this, load control was absolutely necessary. A motion control model would have placed constraints on absolute motion, and, thus, would limit the ability to detect any developing instability should it occur. Weights were attached to both arms to depress the shoulders to allow better visualization of the lower cervical vertebra. A goniometer was attached to the helmet to allow for the recording of overall motion during the testing process. Straps were placed across the pelvis and across the chest under the axilla to secure firmly the torso during testing.

Figure 1. Cadaver positioned to obtain lateral radiographic images of the cervical spine in flexion (**A**) and in extension (**B**).

Lateral fluoroscopic images were obtained during flexion and extension of the head with the cadaver completely intact. Using a posterior approach, the muscles were then dissected longitudinally away from the posterior elements but otherwise were left intact. Incremental sectioning was then performed at the C4–C5 interspace in the following sequence: (1) supraspinous and interspinous ligaments, (2) ligamentum flavum, (3) right facet capsule, (4) left facet capsule, (5) right facet joint, (6) left facet joint, and (7) posterior longitudinal ligament (PLL) along with fibers of the posterior anulus fibrosis (Figure 2).

Following each of these sectioning steps, fluoroscopic images in the maximally flexed and extended positions were obtained. Four intervertebral motion parameters were calculated using Food and Drug Administration approved motion-tracking software (RAD QMA, Medical Metrics, Houston, TX). This software has been validated to measure intervertebral motion, with an average accuracy of 0.5° and 0.5 mm.[18] The 4 sagittal plane intervertebral motion parameters included rotation, shear, anterior displacement between vertebrae, and posterior displacement between vertebrae, as previously described.[19] Because the ratio of shear per degree of rotation has been studied as an indicator of cervical spine motion, this was also calculated.[7]

In addition to evaluation of the motion segment undergoing ligamentous sectioning, the segments above and below C4–C5 were also evaluated. Intervertebral motion data were analyzed using 1-way analysis of variance with *post hoc* multiple comparison tests and compared to the 95% confidence limits from a previous study of intervertebral motion in 140 asymptomatic subjects.[19] At completion of the experiment, the incision in the neck was sutured closed, and the body was returned for embalming and further anatomic use.

Results

Sectioning of the ligaments had no significant effect on intervertebral motion at the adjacent levels, with $P > 0.74$ for all 4 intervertebral motion measurements in this cadaver model. Sagittal plane intervertebral rotation of intact specimens averaged 14.0° between flexion and extension. Shear of intact specimens was a mean of 12.2% of the vertebral body width. These rotations and shear measurements are consistent with measurements obtained for 140 asymptomatic subjects, with mean rotation of 16.9° (standard deviation 3.75°) and shear of 16.2% (standard deviation 5.56%).[19] This observation indicated that at least for the intact specimens, the cadaveric model accurately represented the *in vivo* condition.

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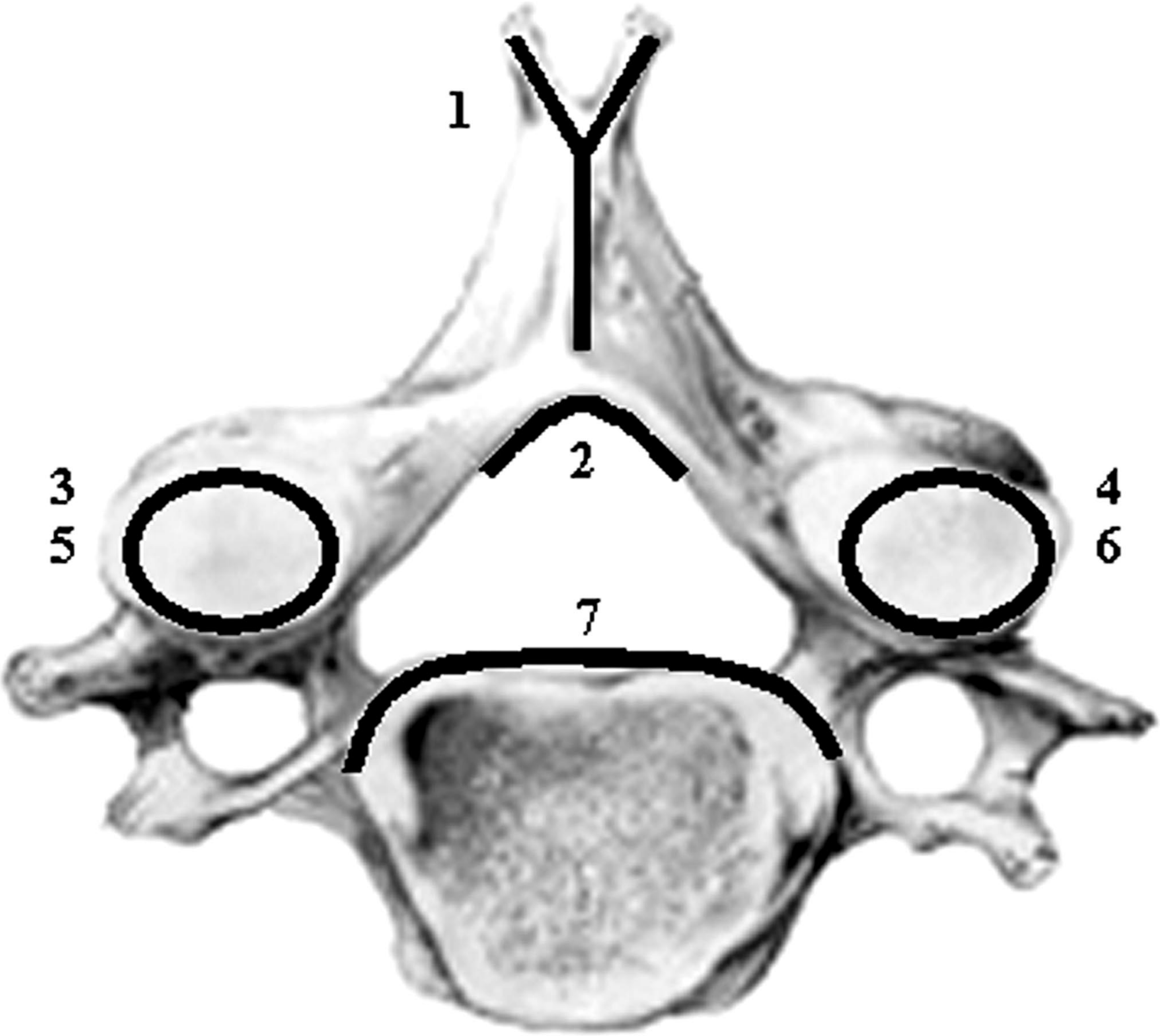

Figure 2. Representation of the sequence of incremental damage to posterior structures of the cervical spine. Supra and infraspinous ligaments (**1**). Ligamentum flavum (**2**). Right facet capsule (**3**). Left facet capsule (**4**). Osteotomy right facet joint (**5**). Osteotomy left facet joint (**6**). PLL and posterior aspect of anulus fibrosis (**7**).

Relative changes in rotation, shear, and displacements at the C4–C5 interspace are summarized in Figure 3. Intervertebral rotation tended to increase with sequential posterior ligament sectioning (Figure 3A). Until simulated injury to a single bony facet, intervertebral rotation in all cadavers was never higher than the 95% confidence interval (CI) measured in 140 asymptomatic subjects.[19] Intervertebral rotation increased to more than the 95% CI after sectioning the first facet capsule in only one cadaver. In 2 additional cadavers, intervertebral rotation was more than the 95% CI after simulated injuries were created to the bone of the left and right facets. After PLL disruption, intervertebral rotation was more than the 95% CI in 69% of the cadavers.

Shear between vertebrae tended to decrease as progressively more damage occurred to the posterior structures (Figure 3B), but none of the changes was significant. Following release of the PLL, mean shear at the C4–C5 interspace was 87% of what it was in the intact spine. Posterior displacements and anterior displacements showed trends similar to rotation as ligaments were sequentially sectioned, and the change in posterior displacements was more pronounced than for any of the other motion parameters (Figures 3C, D). However, on average, the change in posterior displacements was only significantly different (compared to intact) after the PLL was sectioned. After the bone of 1 facet was damaged, 42% of cadavers had posterior displacements more than the 95% CI for asymptomatic subjects. After sectioning the PLL, 85% of cadavers had posterior displacements higher than the 95% CI.

The ratio of shear to rotation more clearly showed changes in intervertebral motion associated with ligament sectioning (Figure 4). The ratios calculated for the

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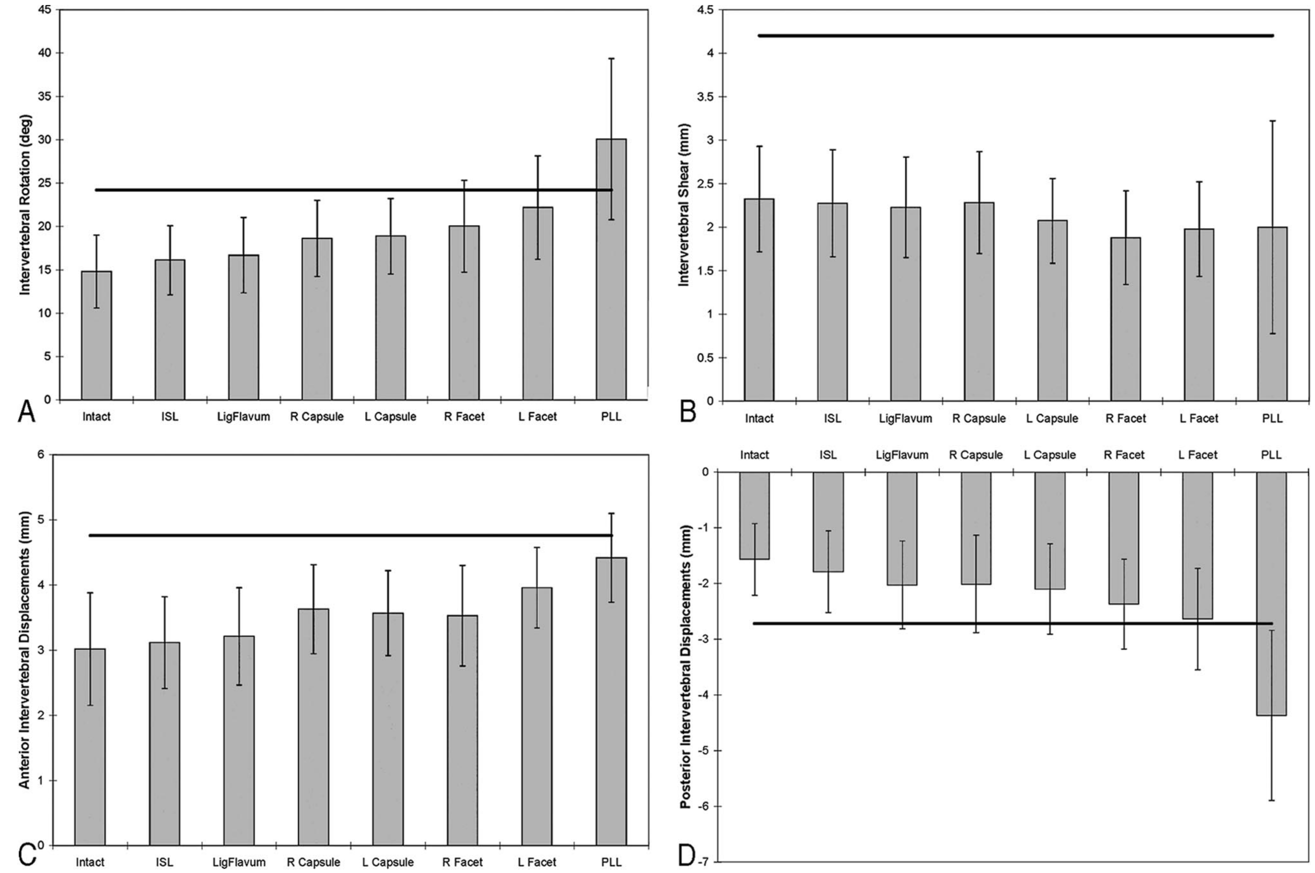

Figure 3. Changes in C4–C5 intervertebral motion (full flexion to full extension) after sequential sectioning of posterior structures. Changes in intervertebral rotation (**A**). Changes in sagittal plane anterior-posterior displacement (shear) (**B**). Changes in the anterior displacements (**C**). Changes in the posterior displacements (**D**). In all graphs, the solid line above (or below for posterior displacements) the bars shows the upper end of the 95% confidence interval for the measurement when made in 140 asymptomatic subjects. deg, degree; ISL, interspinous ligament; L, left; Lig, ligamentum; R, right.

intact spines in the current study were very similar to those reported for 140 asymptomatic subjects[19] or those reported for a different population of asymptomatic subjects.[20]

■ Discussion

Clinical instability of the spine has been defined as the loss of ability of the spine to maintain, under physiologic loads, its pattern of displacement so that there is no initial or additional neurologic deficit, no major deformity, and no incapacitating pain.[21] Several studies have been conducted to define and understand better instability in the spine, particularly as it relates to trauma patients. However, despite significant contributions and advances, knowledge is still limited, and it remains unclear if flexion and extension and radiographs can be used to rule out injury or "clear" the cervical spine acutely in trauma patients. This study simulates acute injury to the posterior structures of the cervical spine by sequential sectioning of intervertebral ligaments in an attempt to determine if any resulting abnormal intervertebral motion can be detected from flexion-extension radiographs. Although several previous investigators have shown that changes in intervertebral motion can be detected following ligament sectioning, there is only limited evidence to document whether posterior injuries can be detected in the absence of knowledge of intervertebral motion before the injury. In clinical practice, determining if intervertebral motion measurements in a patient indicate the

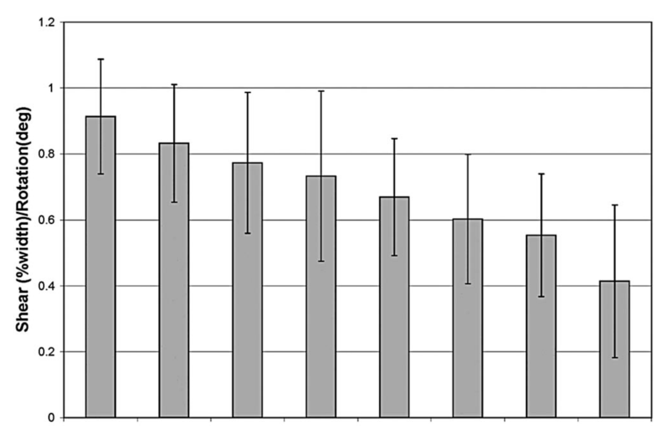

Figure 4. Changes in intervertebral sagittal plane displacement between vertebrae (shear, calculated as a percent of the antero-posterior width of the C5 vertebra), per degree of intervertebral rotation, after sequential sectioning of posterior structures.

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presence of an injury requires a quantitative definition of what constitutes both normal and abnormal ranges of motion.

Initial efforts to achieve a quantitative understanding of spinal stability focused on intervertebral motion in normal individuals. Dvorak *et al*[3] performed passive flexion and extension lateral radiographs of 44 asymptomatic adults and found that mean rotation was 21° and mean translation was 3.6 mm at the C4–C5 level. Several other groups have also contributed to our current understanding of normal intervertebral motion.[4,22] In the present study, intervertebral motion in the cadavers was compared to data from 140 asymptomatic subjects because those data were obtained using the same measurement technology and are within the ranges of motion reported by other investigators.[19]

Panjabi *et al*[23] performed the initial attempts to quantify changes in cervical intervertebral motion with serial sectioning of intervertebral ligaments. There were 17 single motion segments, stripped of soft tissues, potted in polyester resin, and gauges measured horizontal and vertical displacement of the upper vertebra. "Physiologic" flexion and extension loads were placed on the upper vertebra. They reported that initial, intact motion at each individual segment was less than 10.7° of rotation and less than 2.67-mm horizontal displacement. After many components were sectioned, the displacement with full load was often still physiologic, which is consistent with our findings. Angular displacement increased with serial sectioning, and failure did not occur until the PLL was sectioned.

Numerous other sectioning studies have been completed.[10] Goel *et al*[15] found significantly increased rotation with flexion and extension following sectioning of the facet capsular ligaments. Zdeblick *et al*[24] reported a statistically significant increase in rotation and displacement after resection of 75% facet capsules bilaterally. Their earlier work had shown a nonsignificant increase in motion following 50% unilateral facetectomy in 12 cervical spines.[25] Although Goel[15] and Zdeblick[24] *et al* were able to find a statistically significant increase in rotation after injury to the facet capsule, that was not found in the present study, possibly because of the effects of surrounding, intact tissues. Several other investigators have shown various changes in rotation following posterior soft tissue sectioning.[11,26,27]

Abnormality in intervertebral motions *in vivo* has also been studied. Dvorak *et al*[28] reported "hypermobility" in a population of volunteers following whiplash injuries. A close review of their findings revealed an increase in rotation at some levels, while translation was actually decreased in the subaxial cervical spine. Approximately one third of patients with chronic whiplash had quantifiable instability in another study,[7] although they found an increase in the ratio of shear to rotation, while this ratio decreased in the cadaver model.

In the present cadaver study, almost complete posterior disruption was necessary to detect rotational motion higher than what was found in an asymptomatic population.[19] Intervertebral shear actually decreased as the spine became progressively more damaged posteriorly. These data suggest that at least in the acute stage of an injury, dynamic imaging may not be very sensitive to posterior disruption and that if abnormal motion is seen, substantial damage likely exists.

The observed significant decrease in shear motion contradicts observations of Panjabi[23] and Zdeblick[24] *et al*, although they are supported by other studies.[3,27] It can be hypothesized that following posterior injury through the posterior anulus, intervertebral translations would not change because the anterior longitudinal ligament and anulus fibrosis could be sufficient restraints to translation. However, chronically, intervertebral shear may increase as the remaining anterior restraints are overloaded and attenuate.

A relatively novel cadaver model was used in addition to an intervertebral motion measurement tool that is used clinically to evaluate intervertebral motion. This model is limited by the lack of dynamic stabilizing muscular forces. This model may also not represent the patterns of damage that actually occur with cervical trauma, although it does represent normal passive restraints and the forces resulting from the weight of the head. The cadaver model does not include the effect of muscle spasms or muscle activity associated with pain. Therefore, the model may represent a best-case scenario in that if abnormal motion cannot be detected in this model, it is even more unlikely to be detected in a patient with an injury. These data appear to provide valuable information regarding the role and effectiveness of the passive restraints, which are primarily accountable for cervical stability. The similarity in motion of the intact cadaver compared to asymptomatic volunteers *in vivo* also supports the efficacy of this model.

There may be some concern that cadaveric motion was limited relative to *in vivo* motion, and, therefore, component motions may be underrepresented. We did not find this to be true. We measured overall gross flexion and extension, and found that this compared favorably with known values of flexion and extension in asymptomatic volunteers.[19] This is consistent with results from laboratory studies that showed postmortem tissue properties are stable after 36–72 hours and that with a few preconditioning cycles, tissues are slightly more flexible than before death.[29] Finally, the effects of damage to posterior structures may be different at other levels in the cervical spine, and this could be the subject of further investigation.

Conclusions

Data were acquired using a clinically validated measurement tool in a novel cadaveric model that likely allows for accurate biomechanical evaluation of the passive restraints of the cervical spine. Near complete destruction of posterior structures was required to create interverte-

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bral motion more than the 95% confidence limits for asymptomatic subjects. There is no direct evidence that results from this and previous cadaver models can be applied in clinical practice. However, these results clearly do not support the use of flexion-extension radiographs to "clear" the spine of injury acutely following trauma because the sensitivity for substantial injury will likely be very low. In addition, the presence of instability in motion studies acutely suggests potentially significant injury and should initiate further appropriate clinical assessment. It is also possible that after substantial damage to intervertebral ligaments or facet joints, follow-up motion studies may identify instability. This result could be true during the subacute period following injury after reduction in protective dynamic muscle guarding or in the chronic situation in which the remaining intact passive restraints become gradually overloaded and attenuate with time.

■ Key Points

- Intervertebral motion from maximum flexion to maximum extension was measured in whole cadavers before and after incremental damage to the posterior structures.
- Substantial damage must be done to the posterior structures before intervertebral rotation at the damaged level becomes more than the 95% CI for asymptomatic subjects.
- This study suggests that flexion and extension x-rays exhibit poor sensitivity for detection of posterior cervical spine injury, and thus does not support the routine use of these x-rays to clear the cervical spine in acute trauma patients.

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