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Basic Science

Reference data for assessing widening between spinous processes in the cervical spine and the responsiveness of these measures to detecting abnormalities

Aaron C. Eubanks, MD, John A. Hipp, PhD*, Ran Lador, MD, Peleg J. Ben-Galim, MD, Charles A. Reitman, MD

Department of Orthopedic Surgery, Baylor College of Medicine, 1709 Dryden Rd, 12th Floor, Houston, TX 77030, USA

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Abstract

BACKGROUND CONTEXT: Traumatic injury to the spine is evaluated and treated based on the perceived stability of the spine. Recent classification schemes have established the importance of evaluating the discoligamentous complex to fully comprehend stability. There are a variety of techniques to evaluate the discoligamentous complex, including assessment of interspinous distance. However, there currently are no clinically validated methods to define and assess abnormal interspinous widening.

PURPOSE: The purpose of the study was to provide reference data and evidence to support the objective use of spinous process widening in the diagnosis of cervical spine injury and instability.

STUDY DESIGN: The study was designed to be biomechanical and observational.

METHODS: Distances between spinous processes were measured from lateral flexion-extension X-rays of 156 skeletally mature asymptomatic subjects who reported never having had neck symptoms as well as 12 whole human cadavers before and after creating increasingly severe damage to posterior structures. Cervical interspinous distances were measured and then normalized to the width of the C4 vertebral end plate. The change in the distance from flexion to extension was also calculated.

RESULTS: Descriptive statistics, including the 95% confidence intervals for each cervical level were tabulated for 863 levels in 149 analyzable asymptomatic volunteers. In the simulated cadaver model, interspinous widening was highly specific and mildly sensitive for detecting damage to the posterior structures of the cervical spine.

CONCLUSIONS: This study provides reference data that can be used to quantitatively assess interspinous process widening in the cervical spine. Application of the reference data to a cadaver model of cervical trauma suggests that although objective evidence of abnormal widening may be uncommon, when present, it is suggestive of extensive damage to the cervical spine. Derived from this data were two ''rule of thumb'' criteria to identify abnormal interspinous widening in flexion X-rays; when greater than 30% relative to an adjacent level (40% between C1–C2 and C2–C3) or greater than 50% of the anterior-posterior width of the C4 vertebral body (30% for C2–C3).

Keywords: Spinous processes widening; Cervical spinal stability; Normal measurements; Stability assessment criteria

Introduction

Reliable and validated test methods are essential for accurate diagnosis of injuries and disease and for use in selecting and evaluating treatment protocols. For injuries and pathology of the spine, many diagnostic tests focus on the alignment of and motion between vertebrae. In clinical practice, assessment of alignment and motion is

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* Corresponding author. Department of Orthopedic Surgery, Baylor College of Medicine, 1709 Dryden Rd, 12th Floor, Houston, TX 77030, USA. Tel.: (832) 651-7083.

E-mail address: jhipp@bcm.edu (J.A. Hipp)

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frequently based on subjective assessment of medical imaging, in part because of lack of reliable, validated, and accessible quantitative measurement tools. Quantitative measurements also require reference data to determine whether a measurement is normal.

Traumatic injury to the spine is evaluated and treated based on the perceived stability of the spine. Vaccaro et al. [1] recently described a comprehensive classification system that defines stability based on three variables, including osseous and discoligamentous integrity as well as neurological status. This system has uniquely focused attention on the discoligamentous complex and the soft-tissue component of stability in particular. Although computed tomography is generally accepted as highly reliable for evaluating fixed deformity or fracture, the ability to identify soft-tissue injuries with computed tomography is less precise. Magnetic resonance imaging is currently thought to be the gold standard for assessment of acute soft-tissue injury, but well-known challenges exist when using magnetic resonance imaging in the acute setting. In addition, magnetic resonance imaging can be misleading in trauma cases with limited sensitivity to certain types of soft-tissue injuries [2] and can be less accurate in subacute or chronic conditions. If there are alignment abnormalities, computed tomography or radiographs can infer the loss of soft-tissue integrity. These abnormalities can be seen anteriorly between the vertebral bodies or posteriorly between the lamina and spinous processes. However, validated and practical methods to identify abnormal interspinous widening are lacking.

Thus, the goals of this study were to first establish a database of normal interspinous process widening in an asymptomatic population, and then to use a whole cadaver model to study a cohort with known damage to posterior structures to determine whether abnormal widening can be reliably detected. Furthermore, the final objective was to provide practical guidelines that could be used to identify abnormal interspinous process widening in clinical practice.

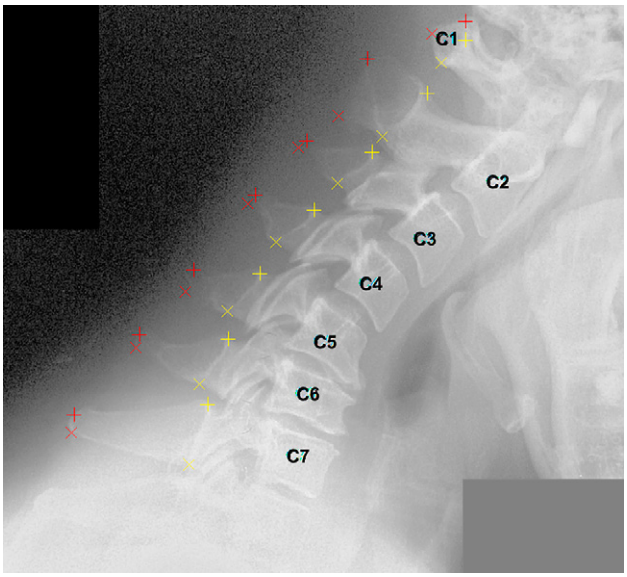

Fig. 1. An example of how landmarks were placed on the tips of the spinous processes and on the interlaminar lines.

Table 1
Mean distances between the tips of the spinous processes in the cervical spines of an asymptomatic population, measured from radiographs with the spine in flexion, and normalized to the width of the superior end plate of the fourth cervical vertebra

Level	Mean	SD	N	LL	UL	SD/mean
C1–C2	114	27.9	140	59.6	169	0.24
C2–C3	84	24.9	147	35.0	133	0.30
C3–C4	108	26.3	148	56.8	160	0.24
C4–C5	110	26.3	146	58.5	162	0.24
C5–C6	120	32.4	144	56.4	183	0.27
C6–C7	133	26.8	132	80.1	185	0.20
Average	112			57.8	165	

SD, standard deviation; LL, lower limit for the 95% confidence interval; UL, upper limit for the 95% confidence interval.

Materials and methods

To establish a database that can be used to define normal interspinous widening, dynamic relationships of the posterior elements were analyzed from an asymptomatic population of 156 skeletally mature subjects. The data were retrieved from flexion-extension radiographs that were previously collected to define intervertebral motion in the cervical spine of asymptomatic individuals [3]. There were 83 females and 66 males. Ninety-two subjects were under the age of 44 years, 30 in the 44 to 63 year age group, and 27 over 64 years. Potential volunteers had been excluded from the study if they ever reported having neck pain necessitating a visit to a physician.

The injury cohort data were also retrieved from a previous intervertebral motion study of 12 whole human cadavers [4]. In this study, complete sectioning of all posterior intervertebral structures was performed at the C4–C5 level in eight sequential steps, ultimately resulting in complete sectioning from the posterior longitudinal ligament to the posterior aspect of the annulus fibrosis.

Table 2
Distances between the interlaminar lines of the spinous processes in the cervical spines of an asymptomatic population, measured from radiographs with the spine in flexion, and normalized to the width of the superior end plate of the fourth cervical vertebra

Level	Mean	SD	N	LL	UL	SD/mean
C1–C2	74.3	18.7	140	37.6	111.0	0.25
C2–C3	40.8	12.1	147	17.1	64.4	0.30
C3–C4	52.2	12.6	148	27.4	76.9	0.24
C4–C5	53.1	13.5	146	26.7	79.6	0.25
C5–C6	54.4	16.4	144	22.3	86.5	0.30
C6–C7	51.7	16.8	132	18.7	84.8	0.33
Average	54.4			25.0	83.9	

SD, standard deviation; LL, lower limit for the 95% confidence interval; UL, upper limit for the 95% confidence interval.

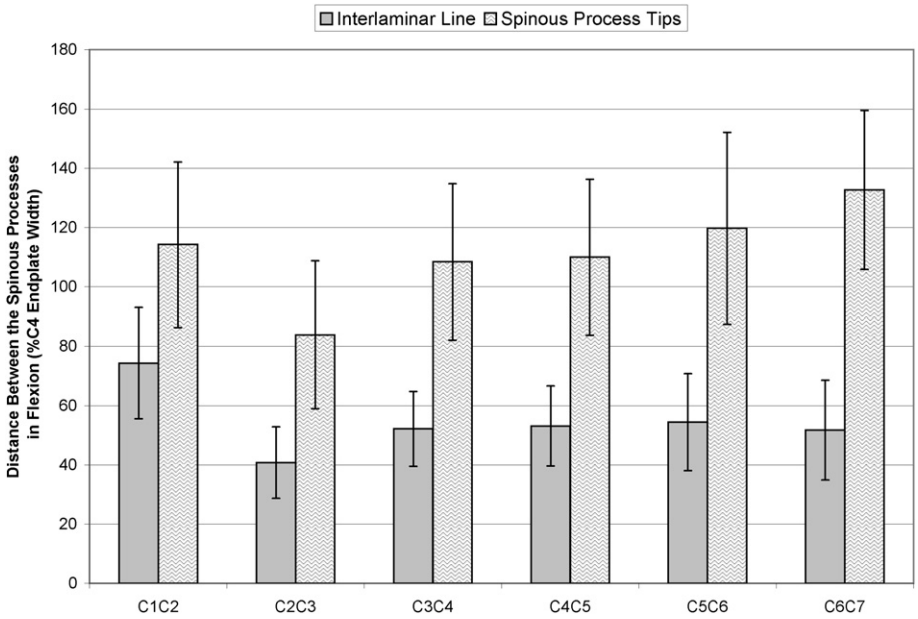

Fig. 2. The mean and standard deviations for the distance between the spinous processes, measured in the flexion images only, at the tips of the spinous processes and at the interlaminar lines, for each level in the cervical spine, normalized to the widths of the C4 end plate.

All these studies had been previously tracked using a validated computer-assisted method (QMA; Medical Metrics, Inc., Houston, TX, USA) for the purpose of quantitative analysis of intervertebral motion between flexion and extension [5]. For the present study, the flexion and extension images were reanalyzed for the specific purpose of evaluating interspinous widening. The distances between the spinous processes in flexion and extension were determined by placing landmarks on the most cephalad and caudal aspects of the spinolaminar line and also to the most cephalad and caudal aspects of the tips of the spinous process (Fig. 1). Using the QMA software, distances were calculated from the relative position of the landmarks at each intervertebral level from C1 to C7.

To make the measurements applicable when the magnification in a radiograph is not known, the distances were normalized to the anterior-posterior width of the superior end plate of C4. The change in interspinous process distance from flexion to extension was also calculated. The change in interspinous widening between flexion and extension was also used to calculate a ratio of the percent of widening at each level with respect to widening at the adjacent levels.

All radiographs were also evaluated for the amount of associated degenerative changes. Radiographs were graded using a four-point scale to characterize the degree of degeneration at each intervertebral level using a published plain radiographic classification system [6]. The parameters of height loss, sclerosis, and osteophyte formation were analyzed to determine the classification level. A disc was reported as normal if there were no height loss, no sclerosis, and no osteophytes. The sum of these variables was used to classify disc disease as normal, mild, moderate, or severe.

Spinous process distance and displacement measurements from the flexion-extension X-rays in the cadaver study were classified as normal or abnormal using the 95% confidence intervals (CIs) established using the data for the asymptomatic volunteers.

Results

Seven sets of images from the 156 flexion/extension studies of asymptomatic subjects could not be analyzed because of generally insufficient contrast to allow reliable identification of the spinous process landmarks. In addition, the landmarks could not be reliably identified at some additional levels, most commonly at C6–C7. The 149 analyzable subjects provided 863 cervical levels for analysis.

The distances between spinous processes, measured in the flexion image and then normalized to width of the anterior-posterior width of the superior end plate of C4, are

Table 3
Change in distance between the tips of the spinous processes from extension to flexion, normalized to the anterior-posterior width of the superior end plate of the fourth cervical vertebra

Level	Mean	SD	N	LL	UL	SD/mean
C1–C2	29.7	16.8	140	−3.3	62.7	0.57
C2–C3	34.2	13.4	149	7.8	60.5	0.39
C3–C4	54.5	18.0	148	19.2	89.8	0.33
C4–C5	62.3	20.6	146	22.0	102.6	0.33
C5–C6	60.1	26.5	144	8.2	112.0	0.44
C6–C7	53.5	27.1	133	0.3	106.7	0.51
Average	49.1			9.0	89.1	

SD, standard deviation; LL, lower limit for the 95% confidence interval; UL, upper limit for the 95% confidence interval.

Table 4
Change in distance between the interlaminar lines of the spinous processes from extension to flexion, normalized to the anterior-posterior width of the superior end plate of the fourth cervical vertebra

Level	Mean	SD	N	LL	UL	SD/mean
C1–C2	30.9	14.0	140	3.5	58.3	0.45
C2–C3	14.4	7.2	147	0.4	28.5	0.50
C3–C4	25.4	10.4	148	5.0	45.8	0.41
C4–C5	28.3	12.4	146	3.9	52.7	0.44
C5–C6	26.1	15.1	144	−3.5	55.8	0.58
C6–C7	23.2	15.1	132	−6.5	52.9	0.65
Average	24.7			0.5	49.0	

SD, standard deviation; LL, lower limit for the 95% confidence interval; UL, upper limit for the 95% confidence interval.

provided in Tables 1 and 2 and in Fig. 2. In the subaxial spine, the observed interspinous motion was consistently greater than the interlaminar motion. However, the tips of the spinous processes were more difficult to identify in some images, so the interlaminar line distances were considered more reliable. Based on one-way analysis of variance, there was a significant difference in interlaminar distances between levels (p less than .001). If only levels below C2 and C3 were included, there were no significant differences between levels (p=.32).

Tables 3 and 4 and Fig. 3 provide the displacements of the spinous processes between flexion and extension, normalized to the width of the superior C4 end plate. The mean widening at the interlaminar lines ranged from 14% at C2–C3 to 31% at C1–C2. There were significant differences between levels (p less than .0001). When interspinous widening was expressed as the difference between the index and adjacent levels, there were significant differences between levels based on interlaminar distance measurements or based on spinous process tip measurements (p less than .0001; Fig. 4 and Tables 5 and 6).

Radiographically apparent degeneration was recorded in 335 of the 865 vertebral levels from the asymptomatic volunteers, but moderate and severe degeneration was only seen in 74 and 22 levels, respectively. Based on multivariate analysis of variance/covariance tests, the amount of degeneration was not a significant factor in interspinous distances or displacements (p greater than .1).

In the cadaver study, interspinous process widening in the intact necks in the cadaver spines averaged slightly less but was well within the 95% CI for live asymptomatic volunteers (compare Figs. 2 and 5). The sequential sectioning resulted in abnormal widening in only a few specimens. Sensitivity and specificity were calculated for the data in two ways: to assess the utility of spinous process widening and to detect mild and severe injuries. Calculations were first made with the spine considered to be truly damaged if any of the sectioning steps had been performed in the whole cadaver model. A second set of calculations was done with a spine considered to be truly injured only if all posterior structures had been sectioned or damaged, up to and including the posterior longitudinal ligament.

The specificity of the widening measures was high for all measures and all scenarios (Table 7), suggesting that spinous process widening will almost always be within the expected 95% CI in a healthy spine. For detecting differences from mild to severe damage, the sensitivity of any measure of spinous process widening was poor. The changes in widening at C4–C5 are summarized in

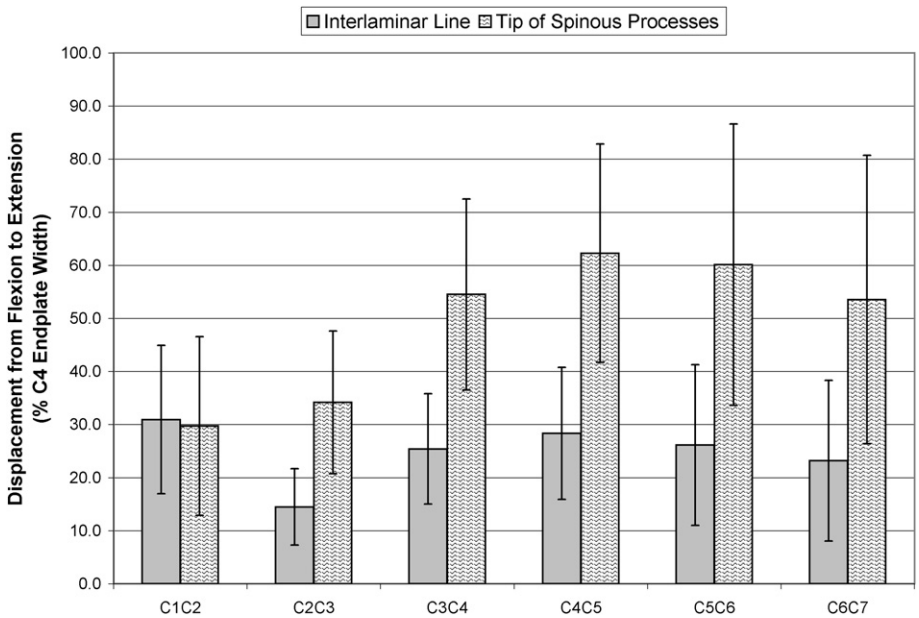

Fig. 3. Mean and standard deviations for the change in interspinous and interlaminar distances between flexion and extension for each level in the cervical spine, normalized to the widths of the C4 end plate.

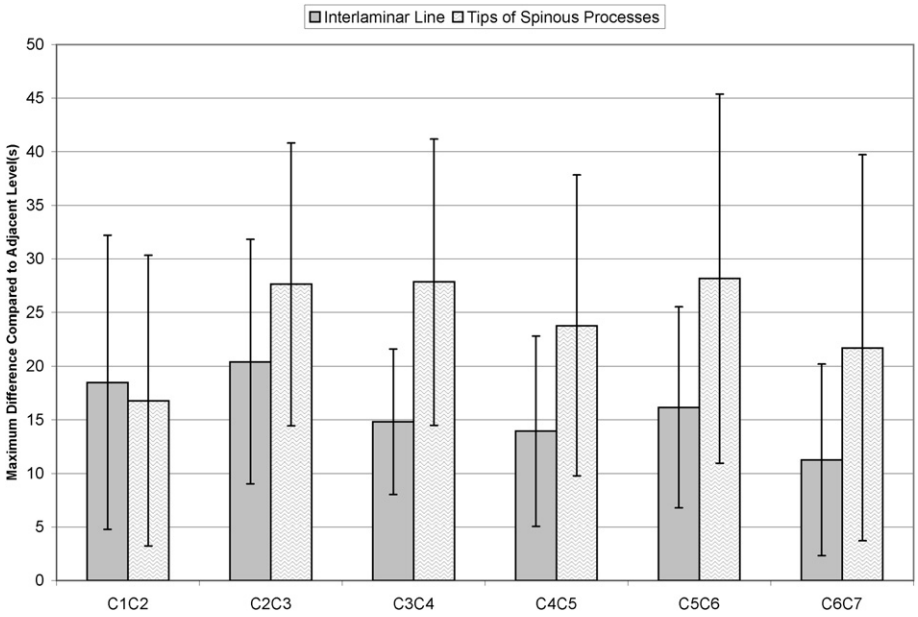

Fig. 4. Mean and standard deviations for the change in interspinous and interlaminar distances between flexion and extension, expressed as the maximum difference between the index level and adjacent level(s).

Figs. 5 and 6. Interspinous widening tended to increase with each step in the sequential posterior column damage but only became significantly greater than the 95% CI in a few spines. Abnormal widening only occurred after all posterior structures up to and including the posterior annulus were sectioned. Interspinous process widening, expressed as a percent of the adjacent level, was the least sensitive measure but also had the least variation.

Discussion

Many published studies and others cited in these publications, focused on sagittal plane intervertebral rotation measured from flexion and extension radiographs [3,7–12]. Computer-assisted imaging techniques can now be used to reduce errors in the analysis of cervical spine motion, and reference data for interpreting intervertebral rotations and translations have been published [3,13]. Interspinous widening is also commonly used as a marker of disease or injury to the spine particularly for injuries or degeneration of posterior structures and evaluation of pseudoarthrosis [14–18], again with no validated criteria for these measurements. This lack of standardization limits the ability to interpret and compare data in the clinical settings and across studies [19].

First and foremost, this study provides a normative database of interspinous distances to assist the clinician in interpretation of lateral X-ray studies of the cervical spine.

Table 5
Interspinous process widening measured as change in the distance between the tips of the spinous processes between flexion and extension minus the change in distance at adjacent levels

Level	Mean	SD	N	LL	UL	SD/mean
C1–C2	16.8	13.5	139	−9.8	43.3	0.81
C2–C3	27.6	13.2	147	1.8	53.5	0.48
C3–C4	27.8	13.3	148	1.7	54.0	0.48
C4–C5	23.8	14.0	146	−3.7	51.3	0.59
C5–C6	28.2	17.2	143	−5.6	61.9	0.61
C6–C7	21.7	18.0	132	−13.6	57.0	0.83
Average	24.3	14.9		−4.9	53.5	

SD, standard deviation; LL, lower limit for the 95% confidence interval; UL, upper limit for the 95% confidence interval.

Data are expressed as the percent difference.

When superior and inferior adjacent levels were available, the maximum difference was used.

Table 6
Interspinous process widening measured as change in the distance between the interlaminar lines of the spinous processes between flexion and extension minus the change in distance at adjacent levels

Level	Mean	SD	N	LL	UL	SD/mean
C1–C2	18.5	13.7	140	−8.4	45.4	0.74
C2–C3	20.4	11.4	147	−1.9	42.8	0.56
C3–C4	14.8	6.8	148	1.5	28.1	0.46
C4–C5	13.9	8.9	146	−3.5	31.4	0.64
C5–C6	16.2	9.4	143	−2.2	34.5	0.58
C6–C7	11.3	8.9	132	−6.3	28.8	0.79
Average	15.9	9.8		−3.4	35.2	

SD, standard deviation; LL, lower limit for the 95% confidence interval; UL, upper limit for the 95% confidence interval.

Data are expressed as the percent difference.

When superior and inferior adjacent levels were available, the maximum difference was used.

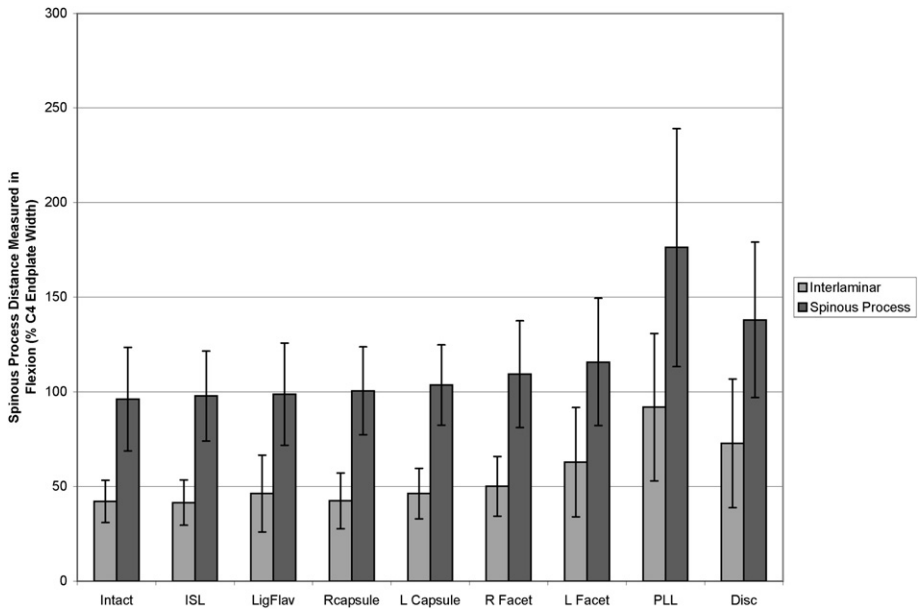

Fig. 5. Distances between spinous processes at the level of the simulated injury, from a cadaver model of cervical trauma. Distances were measured in the intact spines and after increasingly severe damage to the spine. ISL—interspinous ligament cut, LigFlav—ligamentum flavum cut, R capsule and L capsule—right and left facet capsules sectioned, R facet and L facet—right and left facet joints destroyed, PLL—posterior longitudinal ligament sectioned, and Disc—posterior half of the intervertebral disc and uncovertebral joints destroyed.

Validated criteria facilitate interpretation of interspinous distances and can be used to help detect soft-tissue injury and cervical instability, with the potential of influencing clinical management.

Derived from these data are two criteria that could be used as ''rule of thumb'' screening methods for discoligamentous complex injury detection (Table 8). The first requires comparison of the distance between interlaminar lines in flexion to the distance at adjacent levels. In asymptomatic volunteers, the difference between adjacent levels was less than 30% except at C1–C2 and C2–C3, where the normal difference was less than 40%. The second rule was a comparison of the distance between interlaminar lines in flexion to the width of the C4 end plate. Anything greater than 50% was abnormal except for C2–C3, where the distance was less than 30%.

Comparing vertebral motion with the adjacent levels has the theoretical advantage of accounting for generalized differences between individuals, such as those with high mobility at all levels. However, it was observed that general hypermobility is less likely to result in false interpretation than a hypomobile segment causing the appearance of relative greater motion at the adjacent level. Thus, when using this method to interpret the data, care must be taken to critically look for the existence of hypomobility as a source of error.

Application of these criteria to detecting the result of ligament damage in the cadaver model resulted in 99% specificity but only 53% sensitivity for severe damage. This suggests that interspinous widening may be an unreliable assessment, as false negatives may be likely. However, the high specificity provides confidence that when abnormal widening is detected, a severe soft-tissue

Table 7
Sensitivity and specificity of spinous process distance and displacement measurements for detecting mild to severe damage or only severe damage to posterior structures

	Detecting mild to severe damage to posterior structures		Detecting only severe damage to posterior structures	
Description	Sensitivity	Specificity	Sensitivity	Specificity
Spinous process distance in flexion	0.08	0.99	0.47	0.99
Spinous process displacement from flexion to extension	0.13	0.98	0.60	0.98
Spinous process displacement from flexion to extension as % adjacent level	0.04	0.96	0.10	0.96
Interlaminar distance in flexion	0.14	0.99	0.53	0.99
Interlaminar displacement from flexion to extension	0.14	0.98	0.60	0.98

Table 8
Simplified clinical guidelines

Measurement	Simplified guideline to identify abnormalities	Limitations
Distance between interlaminar lines in flexion	>30% adjacent levels	>40% for C1–C2 or C2–C3
Distance between interlaminar lines in flexion	>50% C4 end plate width	>30% for C2–C3
Displacement between spinous processes from flexion to extension	>50% adjacent levels	>60% for C5–C6
Distance between spinous processes in flexion	>170% C4 end plate width	>135% for C2–C3
Distance between interlaminar lines in flexion	>80% C4 end plate width	
		>110% for C1–C2
		>65% for C2–C3
Displacement between spinous processes from flexion to extension	>110% C4 end plate width	
		>60% for C1–C2 or C2–C3
		>90% for C3–C4

These guidelines are adapted from the data in Tables 1–6.

injury is likely and management should proceed accordingly.

Prior radiographic criteria for abnormal interspinous widening have been published using frontal plane X-rays [14,20]. The criteria proposed by Naidich et al. [14] required that the interspinous distance at any level exceed one and half times the interspinous distance of both the level above and below the suspected level. This criteria was based on the observation that at least one individual exceeded the motion in the adjacent level by more than 50%. That result is generally consistent with data in Table 5 of the present study.

As reported based on a prior study [4], all posterior structures up through the posterior disc had to be damaged before intervertebral motion in flexion-extension was greater than the 95% CI for asymptomatic subjects. Interspinous process measurements provide no improvement in sensitivity for detecting progressive damage to the posterior cervical spine over the previously reported methods. This continues to support the notion that flexion/extension studies are poor screening tests, and at least for the acute setting, significant injury can occur without being detected by dynamic radiographs [4,21].

In summary, despite routine use in clinical practice, there are currently no clinically validated criteria for evaluating interspinous widening on lateral X-ray studies of the cervical spine. Flexion/extension X-rays are generally insensitive to soft-tissue damage, although they are highly specific. The present study provides data and methods that can be used to better quantify and analyze interspinous motion, both in the acute and chronic settings. Simple rules can be applied to quickly assess interspinous widening, which would be abnormal when greater than 30% of the adjacent level (40% between C1–C2 and C2–C3) or greater

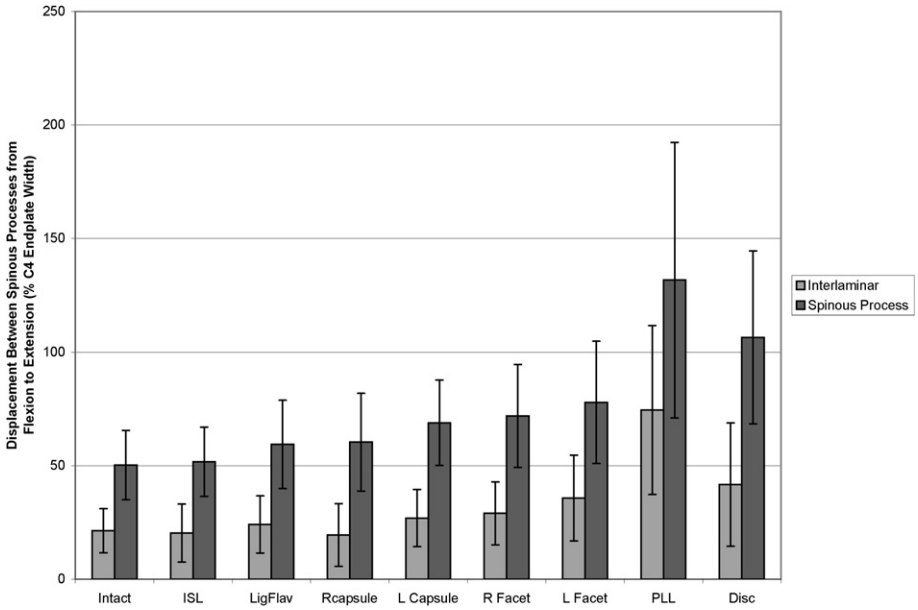

Fig. 6. Displacements between spinous processes at the level of the simulated injury from a cadaver model of cervical trauma. Distances were measured in the intact spines and after increasingly severe damage to the spine. Key to the x-axis labels as in Fig. 5.

than 50% of the length of the C4 vertebral body (30% for C2–C3).

References

[1] Vaccaro AR, Hulbert RJ, Patel AA, et al. The subaxial cervical spine injury classification system: a novel approach to recognize the importance of morphology, neurology, and integrity of the disco-ligamentous complex. Spine (Phila Pa 1976) 2007;32:2365–74.

[2] Goradia D, Linnau KF, Cohen WA, et al. Correlation of MR imaging findings with intraoperative findings after cervical spine trauma. AJNR Am J Neuroradiol 2007;28:209–15.

[3] Reitman CA, Mauro KM, Nguyen L, et al. Intervertebral motion between flexion and extension in asymptomatic individuals. Spine 2004;24:2832–43.

[4] Brown T, Reitman CA, Nguyen L, Hipp JA. Intervertebral motion after incremental damage to the posterior structures of the cervical spine. Spine 2005;30:E503–8.

[5] Zhao KD, Yang C, Zhao C, et al. Assessment of noninvasive intervertebral motion measurements in the lumbar spine. J Biomechanics 2005;38:1943–6.

[6] Kettler A, Rohlmann F, Neidlinger-Wilke C, et al. Validity and interobserver agreement of a new radiographic grading system for intervertebral disc degeneration: Part II. Cervical spine. Eur Spine J 2006;15:732–41.

[7] White AA 3rd, Johnson RM, Panjabi MM, Southwick WO. Biomechanical analysis of clinical stability in the cervical spine. Clin Orthop Relat Res 1975;109:85–96.

[8] Bogduk N, Mercer S. Biomechanics of the cervical spine. I: Normal kinematics. Clin Biomech (Bristol, Avon) 2000;15:633–48.

[9] Ferrario VF, Sforza C, Serrao G, et al. Active range of motion of the head and cervical spine: a three-dimensional investigation in healthy young adults. J Orthop Res 2002;20:122–9.

[10] Frobin W, Leivseth G, Biggemann M, Brinckmann P. Sagittal plane segmental motion of the cervical spine. A new precision measurement protocol and normal motion data of healthy adults. Clin Biomech 2002;17:21–31.

[11] Lind B, Sihlbom H, Nordwall A, Malchau H. Normal range of motion of the cervical spine. Arch Phys Med Rehabil 1989;70:692–5.

[12] Kristjansson E, Leivseth G, Brinckmann P, Frobin W. Increased sagittal plane segmental motion in the lower cervical spine in women with chronic whiplash-associated disorders, grades I-II: a case-control study using a new measurement protocol. Spine 2003;28:2215–21.

[13] Piche M, Benoit P, Lambert J, et al. Development of a computerized intervertebral motion analysis of the cervical spine for clinical application. J Manipulative Physiol Ther 2007;30:38–43.

[14] Naidich JB, Naidich TP, Garfein C, et al. The widened interspinous distance: a useful sign of anterior cervical dislocation in the supine frontal projection. Radiology 1977;123:113–6.

[15] Pennecot GF, Leonard P, Peyrot Des GS, et al. Traumatic ligamentous instability of the cervical spine in children. J Pediatr Orthop 1984;4:339–45.

[16] Kuhns LR, Strouse PJ. Cervical spine standards for flexion radiograph interspinous distance ratios in children. Acad Radiol 2000;7:615–9.

[17] Penning L. Functional pathology of the cervical spine: radiographic studies of function and dysfunction in congenital disorders, cervical spondylosis and injuries. In: Penning L, ed. Functional radiographic examination. Baltimore, MD: Williams & Wilkins, 1968:1–27.

[18] Cannada LK, Scherping SC, Yoo JU, et al. Pseudoarthrosis of the cervical spine: a comparison of radiographic diagnostic measures. Spine 2003;28:46–51.

[19] Chen J, Solinger AB, Poncet JF, Lantz CA. Meta-analysis of normative cervical motion. Spine 1999;24:1571–8.

[20] Pennecot GF, Gouraud D, Hardy JR, Pouliquen JC. Roentgenographical study of the stability of the cervical spine in children. J Pediatr Orthop 1984;4:346–52.

[21] Subramanian N, Reitman CA, Nguyen L, Hipp JA. Radiographic assessment and quantitative motion analysis of the cervical spine after serial sectioning of the anterior ligamentous structures. Spine 2007;32:518–26.