

STIFFNESS PROPERTIES AND GEOMETRY OF LUMBAR SPINE POSTERIOR ELEMENTS

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Abstract—This paper reports measurements made in five fresh cadaver lumbar spine motion segments of the load-deformation properties of the posterior element soft tissues. These properties were measured and the stiffnesses corresponding to them were calculated for loading in anterior, posterior and lateral shear; in longitudinal tension and compression; and in flexion, extension, lateral bending and axial torsion.

In addition, measurements were made in six motion segments of the positions of the inferior facet joint centers relative to the vertebral body centers, and of the orientations of the facet joint surfaces.

INTRODUCTION

Discussions of the 'facet syndrome' which appear in the clinical literature (for example, Mooney and Robertson, 1975) suggest that the facet joints of the lumbar vertebrae can be sites of low back pain. The lumbar facet joints are known to be profusely innervated (Wyke, 1967). Some physical activities tend to aggravate low back pain while others do not. To examine facet joint involvement, we need to know what kinds of physical activities tend to load those joints.

The total loads imposed on lumbar motion segments by a variety of physical task performances can be calculated without consideration of segment soft-tissue properties. This can be done through biomechanical model analyses, and those loads are now fairly well-known (for example, Schultz *et al.*, 1983). The distribution of these total loads among the intervertebral disc, the facet joints and the various ligaments of the motion segment can also be calculated through model analyses, but the outcome of this load-sharing calculation is dependent on soft tissue stiffness properties and bony structure geometries. The stiffness properties of the soft tissues have been well-documented in intact lumbar motion segments and documented to some extent in motion segments with posterior elements removed (for example, Berkson *et al.*, 1979). Few data are available on the stiffness properties of the posterior element tissues themselves, or of their individual substructures, including the tissues of the facet joints. The aim of this investigation was to obtain stiffness and geometry data adequate for use in calculation of load distributions within lumbar spine motion segment substructures.

MATERIALS AND METHODS

Six lumbar spine motion segments were obtained at autopsy following accidental deaths from fresh ca-

davens of ages 18-35 yr (Table 1). When not in use these were sealed in plastic bags and stored at -20°C . Facet joint geometry data were obtained from all six and load-deformation data from five of these specimens.

The specimens were first radiographed. Then the anterior and posterior longitudinal ligaments and the intervertebral disc were excised from each motion segment. The ligamentum flavum, interspinous ligament and facet joint capsule soft tissues were kept intact. The transverse process of both vertebrae were removed to allow for mounting. The supraspinous ligament was kept intact if possible, but was excised in some specimens where it interfered with specimen mounting. The height of the superior vertebral body of each motion segment was measured.

Measurement of load-deformation behavior

Specimens were thawed and kept moist throughout preparation and testing. The superior vertebral body was mounted, using screws and acrylic cement, into a superior bracket designed so that loads could in effect be applied on an axis passing through the centers of the right and left facet joints (Fig. 1). The lower vertebral body was mounted into an inferior bracket using screws, cement and an anchoring rod threaded through the inferior spinous process. The inferior bracket was secured to the base of the testing machine (Fig. 2).

Loads were applied to the superior bracket in four increments, using weights, cords and a low friction pulley system. Forces up to 60.4 N were applied in tension, compression, and in anterior, posterior and lateral shear. Pure moments up to 3 Nm were applied

Table 1. Lumbar spine motion segment specimens

Specimen number	Level	Age (yr)	Sex
1	L4-5	18	Male
2	L2-3	19	Male
3	L2-3	24	Female
4	L3-4	18	Male
5	L4-5	—	—
6	L1-2	35	Male

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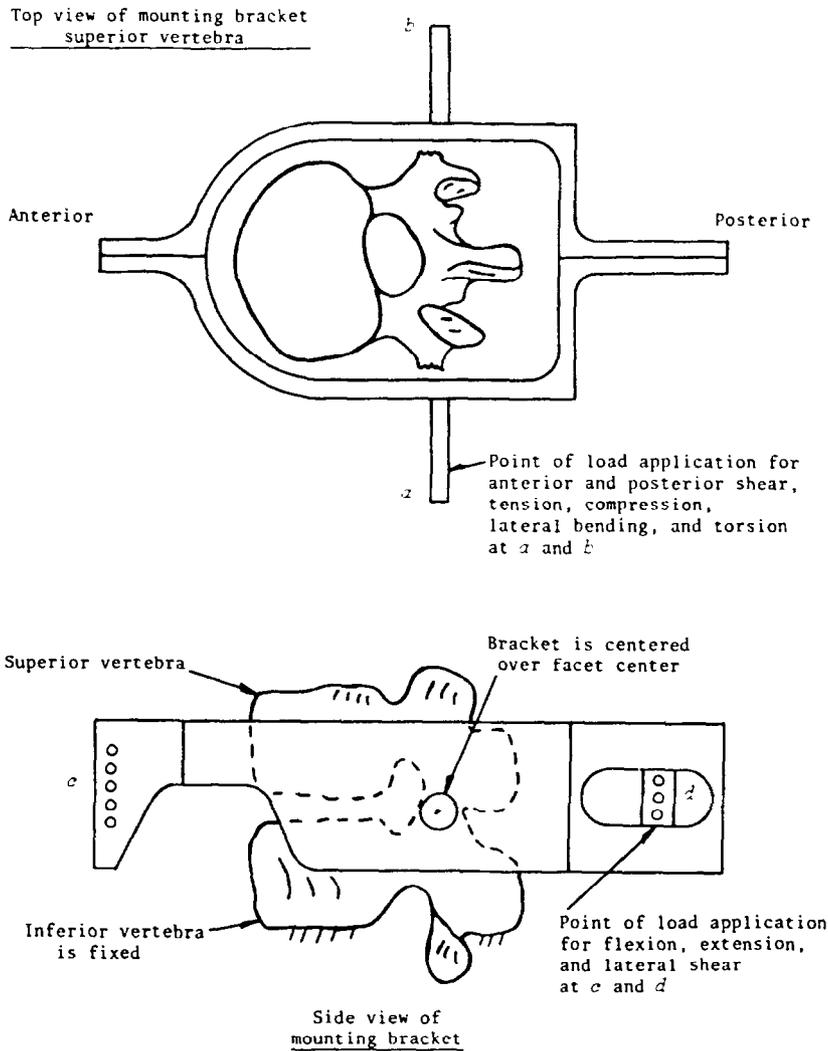


Fig. 1. Schematic diagram of the superior mounting bracket and the points of load application.

in lateral bending and torsion, and up to 2 Nm in flexion and extension. To produce these moments, two equal weights were used acting over a moment arm which ranged from 76 to 140 mm, depending on the size of the superior vertebra and the test mode. Tests were made in the following order: anterior shear, left lateral bending, flexion, left lateral shear, torsion, tension, posterior shear, extension and compression. Each load was maintained for 30 s.

The three linear and three angular displacements that resulted from application of these loads were measured at a point fixed to the upper surface of the superior vertebral body, approximately 1 cm superior to the center of that surface (Fig. 2). They were measured by three linear variable differential transformers and three angle-measuring potentiometers. The three potentiometers were attached to the measuring point by linkages capable of buckling, so that translations of the superior vertebra were not impeded by the measuring instruments yet the rotations were transmitted. The potentiometers were pre-loaded by

30 g weights to take up slack in the linkages. The linear displacement transducers were connected by 30 cm long, thin, mutually perpendicular flexible rods that united at the point of measurement. The union pivoted about the measuring point so that these instruments would produce no moment impeding the rotations of the superior vertebra while they transmitted the linear displacements.

The instruments were calibrated prior to testing so that the relationship between change in linear or angular displacement vs change in transducer output voltage was known. The linear displacement transducers were calibrated using a micrometer, and the potentiometers were calibrated by rotating their shafts through known increments. Transducer output signals were recorded at a rate of 470 ms per channel using a data acquisition system.

After testing was completed, the ligamentum flavum and interspinous and supraspinous ligaments were severed, leaving only the facet joint capsules. The test sequence was then repeated.

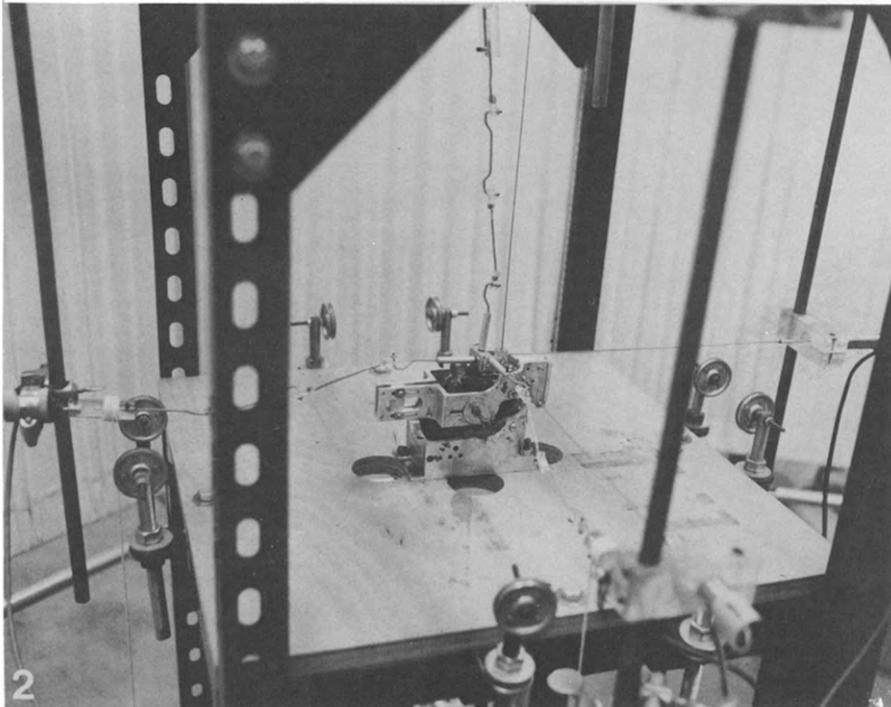
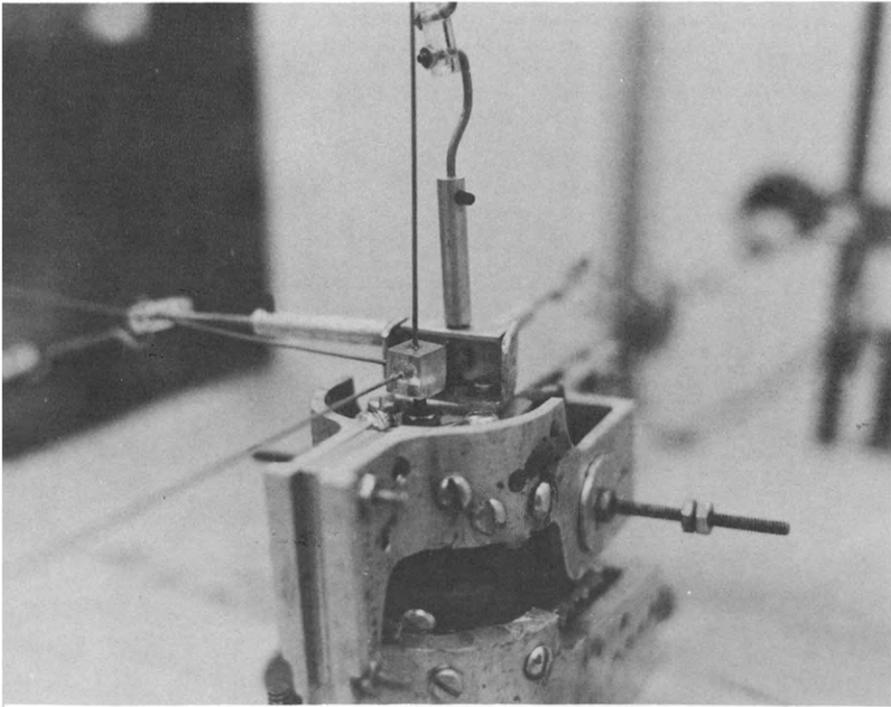


Fig. 2. View of superior bracket with mounted motion segment (upper photograph). Displacement and rotation measuring instruments attached to specimen and testing machine (lower photograph).

Assuming small rotations and using the theory of rigid body kinematics plus specimen geometry data gathered as will be described, the displacements at the inferior facet joint centers of the superior vertebra were calculated from the measured displacement and rotation data.

Measurement of facet geometry

After load-displacement testing was completed, the specimen was cleaned of all mounting cement. A wooden shim was inserted in the intervertebral disc space and acrylic cement was used to fill the gap so as to reproduce approximately the original disc height. The radiographs guided the achievement of this. The superior surface of the superior vertebra was centered at the base of a mold. Acrylic cement was poured into the mold until it covered the inverted motion segment. After the cement had cured, five holes were drilled parallel to the longitudinal axis of the specimen; one in each of the four corners of the casting, and the fifth through the center of the superior vertebral body. The casting was then sectioned transversely with a band saw having a cut thickness of 0.76 mm. Section thickness ranged from 1.0 to 4.0 mm. Each section was numbered, aligned on a grid using the drilled holes, and its inferior and superior surfaces photographed. Sections that contained portions of the facet joints were segregated and rephotographed.

The centers of both left and right facet joint surface intersections on both the inferior and superior faces of each transverse section were marked on each photograph. The location of these intersection centers relative to the intervertebral body center was then determined. The orientation in each transverse plane of the facet joint surfaces was found by measuring on the photographs the angle included between the posterior axis and a line tangent to the surface of the facet joint in that plane.

From these data, facet joint geometry was reconstructed. Geometry was described in terms of the location of the inferior facet joint centers relative to the superior vertebral body center; the length and width of the facet joint surfaces; and the approximate orientations of the facet joint surfaces. Orientations were described in terms of three unit vectors at the facet joint center: \bar{T}_L , the vector along the length of the surface; \bar{T}_W , the vector across the width of the surface; and \bar{T}_N , the outward-directed normal to the surface (Fig. 3). Full details of the geometrical reconstruction procedure are given by Skipor (1983).

RESULTS

Mean measured load-deformation and stiffness data

In response to 30.2 N loads applied in anterior, posterior, or lateral shear, or in tension or compression, the mean displacements of the inferior facet joint centers of the superior vertebral body ranged from 0.5 to 1.8 mm. Moments of 1.0–1.6 Nm applied in flexion, extension, lateral bending or torsion produced mean rotations ranging from 4.1 to 10.2° (Table 2).

Excision of the interspinous and supraspinous ligaments and the ligamentum flavum increased the mean displacements so that they ranged from 0.7 to 2.8 mm. Ligament excision resulted in mean rotations ranging from 3.7 to 11.3° in response to moments ranging from 0.8 to 1.3 Nm (Table 2).

With the posterior elements intact the mean linear stiffness, defined as the applied common load (30.2 N) divided by the mean of the displacements over all tests in that mode at that load, ranged from 29.7 to 58.8 N mm⁻¹. Upon ligament excision, mean stiffnesses ranged from 11.0 to 43.0 N mm⁻¹. In bending and torsion, in contrast to the shear and compression modes, there was no load common to all tests. Of the

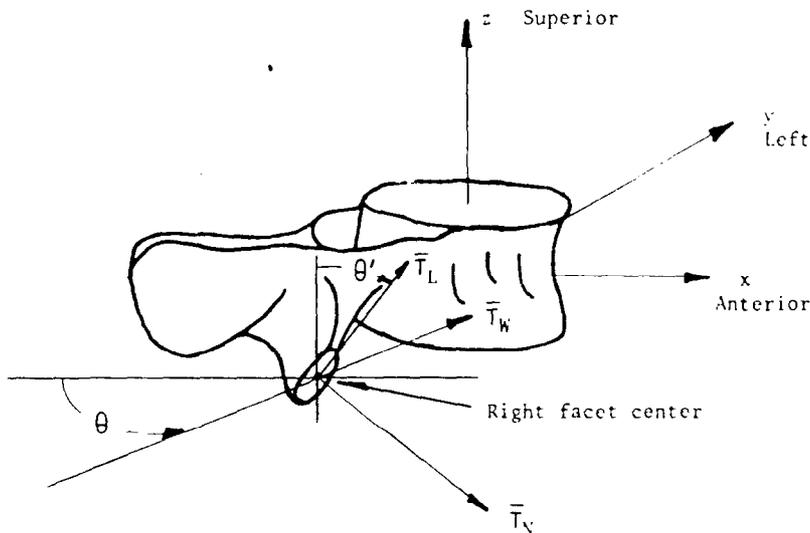


Fig. 3. Inclination angles and orientation vectors of the inferior facet joint surfaces. (Superior facet joints not shown.)

Table 2. Posterior element mean load-deformation data

Test mode	Mean displacements (mm) due to 30.2 N force	
	Posterior ligaments intact	Posterior ligaments except capsule excised
Anterior shear	0.64 (0.3)	1.2 (1.2)
Posterior shear	1.83 (1.4)	2.8 (2.4)
Left lateral shear	-1.02 (1.5)	-1.7 (1.4)
Tension	0.54 (0.6)	1.7 (2.1)
Compression	0.51 (0.6)	0.7 (0.2)
	Mean moments (Nm)/mean rotations (degrees)	
Flexion*	1.6 (0.03)/10.2 (6.4)	0.9 (0.10)/ 8.4 (8.3)
Extension	1.0 (0.03)/ 8.2 (4.2)	0.8 (0.30)/11.3 (3.0)
Lateral bending	1.3 (0.13)/ 4.1 (1.8)	1.3 (0.13)/ 5.8 (2.1)
Counter clockwise torsion	1.0 (0.30)/ 1.5 (1.1)	1.3 (0.13)/ 3.7 (2.8)

*Two specimens only.

Negative sign indicates net displacement to right.
Standard deviations are given in parentheses.

four loads applied in each bending and torsion mode, the load nearest 1 Nm was chosen and divided by that load's resulting rotation. The mean bending and torsion stiffness data were obtained by computing the mean of these values. Mean bending and torsion stiffnesses ranged from 0.13 to 1.31 Nm degree⁻¹ with posterior elements intact, and from 0.07 to 0.81 Nm degree⁻¹ with ligaments excised (Table 3). The standard deviations for the displacements, rotations, and the stiffness were large (Tables 2 and 3), reflecting the considerable variation often found in the measured properties of biological materials.

The posterior element tissues were nearly half again as stiff in flexion as in extension (Table 3). This seems reasonable since in flexion the interspinous and supraspinous ligaments are taut while in extension they are slack and can provide little resistance. In extension, stiffness decreased when the ligamentum flavum, interspinous and supraspinous ligaments were severed.

In lateral bending and lateral shear the decrease in stiffness upon severing the posterior ligaments was probably due primarily to the excision of the ligamen-

tum flavum and supraspinous ligament. The interspinous ligament is thin and membranous and probably provided little resistance.

In torsion the ligamentum flavum is twisted and the supraspinous and interspinous ligaments are stretched. When these tissues were severed there was a marked increase in rotation.

When tension is applied to the motion segment the posterior soft tissues are placed in tension. Severing the posterior soft tissues other than the joint capsule led to a 2.7-fold increase in superior displacement.

In compression, severing the posterior tissues led to an increase in displacement, but the effect was not as large as that in tension. The interspinous ligament and the supraspinous ligament provide little resistance to compression because they are slack in this mode. The facet capsules and perhaps bony impingement provide considerable resistance, and the ligamentum flavum may provide some resistance to compression.

Posterior shear resistance decreased when the posterior soft tissues were severed. The facet capsules provided 67% of the stiffness in posterior shear.

Table 3. Posterior element mean stiffness data

	Posterior ligaments intact	Posterior ligament except capsule excised
Linear stiffness (N mm ⁻¹) due to 30.2 N force		
Anterior shear	47.2	25.6
Posterior shear	16.5	11.0
Left lateral shear	29.7	18.0
Tension	47.8	17.7
Compression	58.8	43.0
Bending stiffness (Nm degree ⁻¹) a moment of approximately 1 Nm.		
Flexion*	0.19 (0.12)	0.23 (0.24)
Extension	0.13 (0.05)	0.07 (0.02)
Lateral bending	0.38 (0.17)	0.25 (0.12)
Counter clockwise torsion	1.31 (1.02)	0.81 (0.80)

*Two specimens only.

Standard deviations are given in parentheses.

The resistance to anterior shear decreased after the posterior soft tissues were excised.

Extreme values of measured load-deformation and stiffness data

Knowledge of the extreme values of the measured displacements and rotations may be useful in quantifying posterior element stability clinically. The largest and smallest values of the stiffnesses measured are also of interest to load-sharing studies. These will be referred to as the 'low-stiffness' and 'high-stiffness' data sets. The largest displacements of the facet joint center were in the range of 0.97–3.34 mm in response to a 30.2 N load. The largest rotations produced in response to moments from 1.15 to 1.58 Nm were 2.41 to 14.8 degrees (Table 4). Based upon these data, the low-stiffnesses ranged from 9.04 to 31.1 N mm⁻¹ in linear motions, while in bending and torsion the low stiffnesses ranged from 0.08 to 0.48 Nm degree⁻¹.

The smallest displacements of the inferior joint center ranged from 0.14 to 0.38 mm in response to the 30.2 N load. In bending the smallest rotations ranged from 0.29 to 5.73° in response to moments ranging from 0.77 to 1.62 Nm. Based upon these data the high-stiffnesses ranged from 35.0 to 216 N mm⁻¹ for linear motions, while in bending and torsion the high-

stiffnesses ranged from 0.2 to 2.59 Nm degree⁻¹.

These high and low stiffness values encompass the extremes found when the posterior elements were intact.

Motion segment geometry

The geometric measurements obtained from the specimens showed a mean superior vertebral body height of 26.2 mm, and a mean location of inferior facet joints centers, relative to the center of the superior vertebral body, of 31 mm posterior, 17 mm inferior, and 14 mm lateral (Table 5). With respect to the center of the intervertebral disc, the facet joint centers ranged from 11 mm superior to 10 mm inferior, while the transverse axis through the facet centers lay between 6 mm anterior and 5 mm posterior.

The orientation vector along the facet joint length, T_L , had a mean flexion tilt of 18° relative to the superior axis (Table 6). This ranged from a 28° extension to a 53° flexion tilt. The vector along the width, T_W , had a mean orientation of 30° measured clockwise (left facet) and counterclockwise (right facet) in the transverse plane relative to the posterior axis. Its orientation ranged from 12 to 58°. The orientation of the facet joints to the transverse plane was quite

Table 4. Posterior element extreme load-deformation data and stiffnesses corresponding

Test mode	Largest displacement (mm) due to 30.2 N force	Smallest displacement (mm) due to 30.2 N force	Linear stiffness (N mm ⁻¹)	
			Low	High
Anterior	1.10	0.38	27.7	77.4
Posterior shear	3.34	0.38	9.0	77.4
Left lateral shear	-3.30	-0.36	9.1	35.0
Tension	0.97	0.29	31.1	104.0
Compression	1.40	0.14	21.6	216.0
	Largest rotation (degrees) due to [indicated] load (Nm)	Smallest rotation (degrees) due to [indicated] load (Nm)	Bending stiffness (Nm degree ⁻¹)	
Flexion*	14.8 [1.58]	5.37 [1.62]	0.11	0.28
Extension	14.7 [1.14]	5.30 [0.78]	0.08	0.15
Lateral bending	6.65 [1.27]	2.06 [1.28]	0.19	0.62
Counterclockwise torsion	2.41 [1.15]	0.27 [0.75]	0.48	2.59

*Two specimens only.

Table 5. Motion segment geometry: inferior facet joint data

Direction	Range of inferior facet joints center locations (mm)		
	Minimum	Mean	Maximum
Posterior to superior vertebral body center	25	31	50
Inferior to superior vertebral body center	7	17	28
Lateral, relative to mid-sagittal plane	12	14	16

Table 6. Motion segment geometry: inferior facet joint orientation data

Specimen number	Flexion tilt (degrees) of vector T_L relative to superior axis		Angle (degrees) between vector T_ψ and posterior axis: counterclockwise (left facet) clockwise (right facet)	
	Left facet	Right facet	Left facet	Right facet
Minimum	5.1	-27.9	12.0	16.0
Maximum	53.0	47.4	39.0	58.0
Mean	22.2 (18.0)	13.8 (25.2)	27.5 (10.2)	32.5 (17.4)
Overall mean	18.0 (22.0)		30.0 (13.8)	

Standard deviations are given in parentheses.

variable. The surfaces of the facet joints sometimes were curved, but mostly those surfaces were flat across the width of the joints.

DISCUSSION

Load-deformation and stiffness data

No prior direct measurements of load-deformation response of lumbar spine posterior element soft tissues were found reported in the literature. The data collected here showed considerable variation, a result often found in measurement of the mechanical properties of biological materials.

The displacement data in left lateral shear showed net facet joint displacements in all five specimens that were opposite to the direction of the applied load. This may have resulted because the loads were applied superior to the inferior facet joint center of the superior vertebrae. This causes left lateral bending of the superior vertebra about an axis superior to the facet center, so that the facet joint center displaces to the right.

The mean stiffnesses of the posterior element soft tissues measured here can be compared to those reported for the disc using the stiffness data for motion segments with posterior elements destroyed reported by Schultz *et al.* (1979) and Berkson *et al.* (1979). The mean posterior element stiffnesses were, compared to those mean disc stiffnesses; 16% in anterior shear, 6% in posterior shear, 8% in lateral shear, 7% in compression, 24% in flexion, 10% in extension, 34% in lateral bending, and 47% in torsion. These figures alone suggest that the posterior elements are capable of sharing significant proportions of at least some types of loads applied to a lumbar motion segment.

The mean stiffness in flexion of the posterior elements with the ligaments excised was higher than with these tissues intact, the opposite of what might be expected. Only two specimens were tested in the flexion mode. Ligament excision apparently substantially altered segment kinematics.

Lin *et al.* (1978) investigated the mechanical response of the lumbar intervertebral joint under loading. Subtracting the anterior and lateral shear stiffness of their motion segments with posterior elements destroyed from that of their intact motion segments

resulted in a mean (S.D.) stiffness of the posterior elements in anterior shear of 136 (31) N mm^{-1} and in lateral shear of 220 (5) N mm^{-1} . These values were obtained from their plot of shear force vs horizontal deflection, for two motion segments in each mode at a 100 N shear force. The current investigation showed that for a 30.2 N shear force the mean stiffness of the intact posterior elements was 47.2 N mm^{-1} in anterior shear and 29.7 N mm^{-1} in lateral shear. These differences may be due in part to the fact that their load level was more than three times larger than the one used for our stiffness calculations.

Farfan *et al.* (1970) investigated the torsional load at fracture of motion segments. When the mean torque strength of their normal motion segments with posterior elements removed was subtracted from the mean torque strength of their whole normal motion segments, the intact posterior elements stiffness was 1.94 Nm degree^{-1} . In the present investigation, the mean stiffness for intact posterior elements at loads well below failure was 1.31 Nm degree^{-1} . From the data of Schultz *et al.* (1979) the mean stiffness, at loads well below failure levels, of intact posterior elements found in a manner similar to that used here was 4.1 Nm degree^{-1} due to a 4.7 Nm moment. Thus, the torsional stiffness data found in the present experiments seem to be consistent with those reported earlier.

It was also found from the data reported by Schultz *et al.* (1979) that the differences in stiffness of whole motion segments and those with posterior elements removed in flexion and extension was 0.12 Nm degree^{-1} and 0.93 Nm degree^{-1} , respectively. The present study found that the stiffness of intact posterior elements was 0.19 Nm degree^{-1} in flexion and 0.13 Nm degree^{-1} in extension. Thus the flexion and extension stiffness data found in the present study seem roughly consistent with those reported earlier.

An approximate idea of the correspondence of the loads used in these tests to those acting on whole lumbar motion segments *in vivo* can be gained by examining motion and stiffness data (Table 7). For example, a typical 30 N compression load applied in the present experiments produced a mean facet center displacement of approximately 0.5 mm. Berkson *et al.*

Table 7. Loading on whole lumbar motion segments required to produce posterior element mean motions observed

Test mode	Posterior elements only		Intact motion segments*	
	Load applied	Resulting motion	Mean stiffness	Load needed for same motion
	(N)	(mm)	(N mm ⁻¹)	(N)
Anterior shear	30.2	0.64	120	77
Posterior shear	30.2	1.83	171	313
Lateral shear	30.2	1.02	145	145
Compression	30.2	0.54	784	423
	(N cm)	(Degree)	(N cm degree ⁻¹)	(N cm)
Flexion	160	10.2	192	1958
Extension	100	8.2	355	2911
Lateral bending	130	4.1	201	824
Torsion	100	1.5	707	1061

*Data from Berkson *et al.* (1979) and Schultz *et al.* (1979).

(1979) report whole lumbar motion segment compression stiffnesses on the order of 800 N mm⁻¹. So, it would require a 400 N compression force to produce a 0.5 mm vertebral body center motion in a whole segment. By analogous calculations, a 30 N shear load applied here would correspond roughly to 100–300 N shear loads, and the approximately 100–150 Ncm moments applied here would correspond roughly to 800–2900 Ncm moments applied to whole lumbar motion segments. In other words, the loads used in the present experiments seem to correspond reasonably to loads probably frequently experienced *in vivo* when small to moderate segment motions occur.

Specimen mounting considerations dictated removal before testing of intertransverse ligaments and sometimes of supraspinous ligaments. How much removal of those structures might have influenced the property data gathered here is unknown. However, previously reported differences in behavior between whole motion segments tested intact and tested with all posterior elements removed (Berkson *et al.*, 1979; Schultz *et al.*, 1979) are not very pronounced. It seems likely that removal of the structures would not have major effects on mechanical behavior, particularly when compared to the variation in mechanical behavior found here.

Motion segment geometry

It was assumed when gathering the facet geometry data that the articulating facet surfaces of adjacent vertebrae were parallel to each other and that the facet joint centers were coincident.

The facet joint geometry data compare well with data reported by others. Miller *et al.* (1983) reported posterior offsets of the facet joint centers of 42 lumbar motion segments relative to the center of the intervertebral discs ranging from 23 to 40 mm, with a mean of 31 mm. In this study posterior offset ranged from 25 mm to 36 mm, with a mean of 31 mm. In that 41 motion segment sample, Miller *et al.* found the most superior and most inferior position of the facet joints

relative to the superior vertebral body center were 9 mm and 33 mm, with a mean of 21 mm. Here, that range was from 7 to 28 mm, with a mean of 17 mm. No data seem available to check the present measurements of lateral offset.

The width vector \bar{T}_w had a mean (S.D.) orientation of 30(18)° measured clockwise (left facet) and counter-clockwise (right facet) in the transverse plane relative to the posterior axis. This number compares favorably with that computed from the data of Cyron and Hutton (1980) on eighteen lumbar spine vertebrae; 41 (9)°. The orientation vector T_L , along the length of the inferior facet joint, had a mean flexion tilt of 18 (22)° away from the superior axis. Miller *et al.* (1983) made similar measurements and found a range of 6–18°.

SUMMARY AND CONCLUSIONS

Three dimensional load–deformation data of intact posterior elements and isolated facet joint capsules of five lumbar motion segments were obtained. Considerable variability was observed among specimens.

The load–deformation data showed that in response to 30.2 N loads applied in anterior, posterior or lateral shear, or in tension or compression, the mean displacements of the inferior facet joint centers of the superior vertebral body ranged from 0.5 to 1.8 mm. Moments of 1.0–1.6 Nm applied in flexion, extension, lateral bending or torsion produced mean rotations ranging from 4.1 to 10.2°.

Excision of the interspinous and supraspinous ligaments and the ligamentum flavum increased the mean displacements so that they ranged from 0.7 to 2.8 mm. Ligament excision resulted in mean rotations ranging from 3.7 to 11.3° in response to moments ranging from 0.8 to 1.3 Nm.

With the posterior elements intact, the mean linear stiffnesses ranged from 29.7 to 58.8 N mm⁻¹, while upon ligament excision they ranged from 11.0 to

43 N mm⁻¹. Mean bending stiffnesses ranged from 0.13 to 1.31 Nm degree⁻¹ with posterior elements intact, and from 0.07 to 0.81 Nm degree⁻¹ with ligaments excised.

Geometry measurements in six lumbar motion segments showed a superior vertebral body height of 26.2 mm; and a mean location of inferior facet joint centers relative to the center of the superior vertebral body of 31 mm posterior, 17 mm inferior and 14 mm lateral. The vector along the length of the inferior facet joint had a mean flexion tilt of 18° relative to the superior axis. This tilt ranged from 28° extension to 53° flexion. The vector along the width had a mean orientation of 30° measured clockwise (left facet) and counterclockwise (right facet) in the transverse plane relative to the posterior axis. This orientation ranged from 12 to 58°.

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