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Mechanical function of facet joints in the lumbar spine

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Summary

Sections of human cadaver lumbar spines consisting of the L_3, L_4 and L_5 vertebrae and the intervening discs and ligaments were tested mechanically to determine the effects of simulated spondylolysis and of facet joint fusion. Compression, flexion and extension, lateral bending, axial rotation forces and torques were applied to intact specimens and then after unilateral and bilateral division of the pars interarticularis, and, in a separate group of specimens, after unilateral and bilateral immobilization of the facet joints.

Division of the pars interarticularis caused a large increase in axial rotation, and a lesser increase in lateral bending. Other motions were not statistically significantly changed. Facet fixation caused a statistically significant decrease in flexion and extension only. The average anterior or posterior shear motion across the intervertebral discs was less than 1 mm in magnitude in intact specimens, and none of the interventions produced statistically significant changes in this motion accompanying the angular motion.

Relevance

These findings from cadaver specimens demonstrate how the motion of the lumbar spine may be affected acutely by spondylolysis fracture and by facet fusion *in vivo*. They show that a major role of intact facet joints is limitation of axial rotation motion. Probably it is the flexibility of the neural arch which permits substantial motion between vertebrae after immobilization of facet joints.

Key words: Lumbar spine, Facet joints, Biomechanical testing, Spondylolysis, Fusion

Introduction

The lumbar motion segment (the articulation between two vertebrae consisting of disc, facet joints and ligaments) has been described as a three-joint complex with six degrees of freedom. When a torque or force is applied to the motion segment, motion in several of the six possible degrees of freedom may result. The nature of the resulting motion is variable between specimens[1,2] and probably results from a complex interaction of the stiffnesses of the components of this three-joint complex. Especially at the end range of motion, ligaments control the motion[3,4,5].

The relationship between motion of intervertebral joints and painful symptoms is not clear[6,7]. It is probable that any motion which overloads or overstretches tissue components of the joint is painful. Hypermobility may be present in the initial stage of the degenerative process of intervertebral joints[8]. Motion in intervertebral joints consists of potentially three rotational and three translational components, and these may be 'coupled' so that one tends to accompany another[9]. Thus, degeneration might result in abnormal motion such as anterior shear accompanying a primary or intentional motion such as flexion[7,10,11]. Laboratory[10] and radiological studies[7,11] have reported abnormally large shear motion accompanying flexion in the degenerating lumbar spine. The kind of motion abnormality has been termed 'segmental instability', although this terminology has not been well defined. Mechanically, instability implies that large motion results from a small change in the applied forces. Since only the spinal motion can be easily observed clinically, this term can easily be misapplied to hypermobility of spinal segments. Segmental fusion has been used to treat the painful symptoms[8]. If such abnormal motions occur with degenerative changes in the spine, it is not clear whether initially there are changes in the disc, placing increased stress upon the facet joints, or vice versa[12]. However, it is to be expected that altered mechanical properties of one component will affect other components of the joint complex. In particular, the facet joints apparently guide the motion of intervertebral joints, so that mechanical changes in the facet

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joints might alter the motion of other components, including the disc.

This is a report of a study of mechanical behaviour of cadaveric spinal specimens, under conditions intended to simulate *in vivo* conditions. Changes in the mechanical behaviour of lumbar motion segments resulting from simulated spondylolysis (created by cutting the pars interarticularis unilaterally and bilaterally) were measured. In a separate group of specimens, the effects of immobilizing facet joints by transfixing them with a screw were determined. The purpose of the study was to determine how these interventions would change the magnitude of compression, flexion and extension, lateral bending and axial rotation motion and in addition to determine whether changes in the anterior shear component of motion in the disc would occur.

Method

Sections of 21 cadaveric lumbar spines were studied. Ten were studied in an experiment to determine the effects of division of the pars interarticularis, and 11 in the study of effects of facet fusion. The specimens consisted of the vertebrae L_3, L_4 and L_5 and the two intervening motion segments. The lumbar spines were removed at autopsy, wrapped in plastic and in protective layers and stored at −20°C until testing. Details of the specimens are shown in Table 1. The mean age at death was 67·5 years (36–87 years).

Table 1. Details of spinal specimens

Specimen no.	*Age (years)*	*Sex*	*Grade**	*Cause of death†*
1	89	F	2	CAD
2	73	M	4	CVA
3	80	F	4	CAD
4	80	F	2	CAD/pneumonia
5	57	F	4	Gastrointestinal bleeding
6	38	F	1	Sepsis
7	69	F	3	MI
8	45	M	1	MI
9	70	M	3	CVA
10	76	F	4	MI
11	36	M	1	Aorta laceration
12	74	M	3	Cardiac arrhythmia
13	52	F	2	Pneumonia
14	50	M	2	CAD/MI
15	78	F	3	Liver failure
16	68	M	2	MI
17	83	F	2	CVA
18	65	M	2	MI/CAD
19	79	F	3	Bowel infarct
20	87	F	4	MI/CAD
21	74	F	2	Pneumonia

Specimens 1–10 were studied in spondylolysis simulation; 11–21 in fusion simulation
* According to method of Galante[23]
† Cause of death: CAD=coronary artery disease; MI=myocardial infarct; CVA=cardiovascular aneurysm

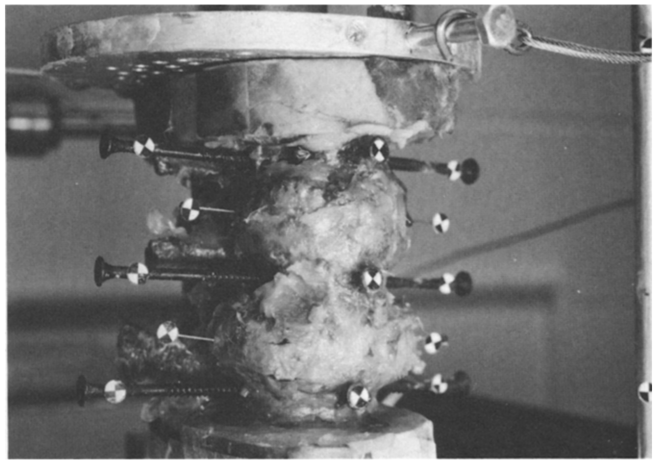

Figure. View through one stereo-photogrammetric camera, showing three vertebrae mounted in end-fittings with three photogrammetric targets inserted into each vertebra.

For testing, the specimens were thawed to room temperature, dissected free of extraneous muscle and the upper half of the vertebra L_3 and the lower half of the vertebra L_5 were embedded in epoxy resin to connect these vertebrae rigidly to end fittings. Three screws were then inserted into each of the vertebral bodies (see Figure 1). Photogrammetric targets were attached to the ends of these pins. These then served as markers for stereo photogrammetric measurement of the motion of the vertebrae by a technique based on that described by Stokes[13]. Two cameras were used to record the positions of the markers. The cameras were positioned at the same horizontal level, with a subtended angle of approximately 60° between them. Prior to testing of the spinal specimen, a calibration jig was positioned in place of the specimen and photographed by both cameras. During each test, the positions of the specimens in each loading condition were photographed. After developing of the films, they were projected onto a 500 mm square flat-bed digitizing tablet.

The position of each target was digitized and the coordinates transmitted to a computer file. Additionally, fiduciary marks at the edge of each frame were used to determine an image axis system. The direct linear transformation program of Marzan[14] was used to compute the three-dimensional coordinates of each target point, based on its positions recorded by the two cameras. Since there were three measured target points on each vertebra, the three-dimensional, 6 degree of freedom motion of each vertebra was calculated. The method of Panjabi and White[15] was used to calculate the flexion or extension, lateral bend, axial rotation and three-dimensional position of each vertebra. A coordinate transformation giving the coordinates of markers on a vertebrae, based on an axis system fixed in the vertebra below, was used to determine the relative motion between adjacent vertebrae, again described by 6 degrees of freedom. The coordinate system for measurement of intervertebral motion was established by reference to two further photogrammetric targets on the ends of pins inserted into the discs. The targets were aligned visually so that the mid-point between them was at the geometric centre of the disc. These points served as a local origin of axes. The axes system was further defined by having its y coordinate vertical and the z coordinate in the plane of symmetry of specimen (sagittal plane). Translation motion between vertebrae was referred to this origin of axes. The accuracy of measurement of the resulting motion was assessed by photographing a frozen specimen in 16 slightly different orientations. For each orientation, the positions of the landmarks were digitized and the apparent motion between vertebrae calculated. Since the specimen was frozen, any apparent motion was due to measurement error. The standard deviations of these motions were 0·3° for angular motion, 0·15 mm for compression and 0·4 mm for anterior and lateral shear motion.

Each specimen was tested under eight different loading states: unloaded, with 1000 N compression load, with 11·12 Nm of flexion moment, 11·12 Nm of extension moment, 11·12 Nm of left and right lateral bending and with 16·13 Nm of clockwise and counter-clockwise axial rotation. The position of application of the compressive load was such that the resulting motion was pure compression without visible rotations accompanying it. The magnitudes of the applied torques were chosen to achieve a physiological range of motion in each articulation. These torques were applied by means of equal and opposite forces transmitted from deadweights through cables and pulleys.

Because of viscoelastic and creep behaviour, the motion produced by a given force or torque was not necessarily repeatable. Therefore, precautions were taken to ensure consistent conditions of testing. For each type of loading, two cycles of loading were applied, and the specimen was unloaded between these. The second load application was recorded. Each load application lasted about 30 seconds, as did the unloaded period between them. Photographs were taken at the end of the loading period, just prior to unloading.

In 11 specimens, fusion of the facet joints was simulated by passing a steel self-tapping screw through both facets. This was done initially on the right side at L_3/L_4 and on the left side at L_4/L_5. After completing mechanical testing in this condition, both facets at both levels were 'fused', and mechanical testing was repeated. The bony defect of the neural arch in spondylolysis was simulated in a separate group of ten specimens by cutting through the pars interarticularis initially on one side only (unilaterally) and then bilaterally, with a dental burr.

Results

Intact lumbar spinal specimens, tested as described above, were found to deform by an average of 0·72 mm in compression, 5·6° in flexion, 4·2° in extension, 3·6° in lateral bending to each side and 3·1° in axial rotation to each side at each intervertebral motion segment. From this baseline of motion, changes in the magnitude of motion resulting from the two separate interventions were analysed. Table 2 gives the mean values of the

Table 2. Compression and angular displacements of specimens in the intact state, and changes after simulation of spondylolysis and fusion

	Compression (mm)	*Flexion* (deg)	*Extension* (deg)	*Lat. Bend* (deg)	*Axial Rot'n* (deg)
Intact (n=42)					
Primary Motion	0·72 (0·39)	5·6 (2·07)	4·2 (1·56)	3·6 (1·12)	3·1 (1·62)
Shear	–	0·65 (0·66)	−0·25 (0.57)	0·05 (0·64)	0·31 (0·71)
Unilateral fusion (n=22)	−0·07 (n.s.)	−1·9 (34%)	−0·44 (−10%) n.s.	−0·07 (−2%) n.s.	−0·27 (−9%) n.s.
Bilateral fusion (n=22)	−0·18 (n.s.)	−3·0 (−53%)	−1·1 (−26%)	−0·24 (−7%) n.s.	0·50 (16%) n.s.
Unilateral spondylo. (n=10)	+0·03 (n.s.)	+0·7 (12%) n.s.	−0·56 (−13%) n.s.	+1·8 (28%)	+1·6 (51%)
Bilateral spondylo. (n=10)	0·0 (n.s.)	+1·01 (18%) n.s.	−0·02 n.s.	+0·9 (26%)	+2·1 (70%)

For the intact state, the mean and standard deviation of each measure are given. For changes after interventions, negative values signify a reduction in the corresponding range of motion. Percentages give the mean change in deformation expressed as a percentage of the corresponding mean deformation in the intact state. Since measurements were obtained from both L_{3-4} and L_{4-5} in the intact state and after fusions, the number of observations is twice the number of specimens tested changes in compression and angular displacements subsequent to the intervention of simulating fusion or spondylolysis.

After 'fusing' one facet joint at each interspace by insertion of a metal screw, there was a 34% reduction (1·9°) in the range of flexion motion. Small reductions in all other motion directions, including a 10% reduction in the extension motion, were not statistically significant. After fusing both levels, flexion was reduced by 53% (3°) and extension by 26% (1·1°). Other motions were reduced, but the reduction was not statistically significant. Thus, although fusing one or both of the facet joints reduced the range of movement in the motion segment, the reduction was relatively small.

Unilateral division of the pars interarticularis produced small increases in the range of motion (12% increase for flexion (n.s.), 13% for extension (n.s.), 28% for lateral bend and 51% increase in axial rotation). For axial rotation the mean increase was 1·6° from a mean initial range of 3·1° to each side. After bilateral cutting of the pars, the increase in axial rotation was 70% of the original (increase of 2·1°), while motion in the other directions did not show statistically significant further increase beyond that produced by the unilateral intervention.

Very small magnitude of shear motion in the intervertebral disc accompanied the induced motion in compression, flexion, extension, lateral bending and axial rotation. In all cases, in the initial intact state, the mean shear motion was less than 0·5 mm, except in flexion when a mean of 0·65 mm was recorded. None of the interventions produced a statistically significant change in the range of this shear motion recorded during these tests. A pilot study in one specimen was performed in order to determine the magnitude of shear motion resulting from shear forces applied to the intervertebral joints. In this experiment, the end-fittings (with L_3 and L_5 vertebrae) were fixed in the testing machine and a horizontal force of 200 N was applied to the L_4 vertebra by means of a deadweight, cable and pulley. The mean resulting shear motion at both interspaces was less than 0·5 mm for both anteriorly and posteriorly directed forces.

Discussion

These measurements emphasize the important role of the facets in the lumbar spine for limiting axial rotation motion and show a large increase in this potentially injurious motion after division of the pars interarticularis. However, motion in other directions was not substantially changed by this intervention, which simulated the acute effects of the spondylolysis defect. These findings are in agreement with other studies of the effects of facet removal from cadaver spines[2,3,4]. The long-term changes, *in vivo*, would be influenced by adaptive changes in the spine, so this study with cadaver specimens was limited by its inability to take account of tissue healing and other biological responses which occur *in vivo*. Another limitation of studies with cadaver specimens is that they do not necessarily involve realistic loadings of the spinal segments, since the anatomic structures (muscles etc.) which normally apply the loads have been removed. Radiographic studies of motion of lumbar spines of living subjects with spondylolysis[16,17] and with clinical and radiologic signs of 'segmental instability,[18] have shown very little abnormality of the motion, although other studies have described groups of patients with a large shear component accompanying voluntary motion[7,11]. Degenerative changes may be necessary before abnormal motion occurs[12].

The small magnitude of shear motion accompanying angular motion was especially surprising in the case of the interventions simulating spondylolysis. In these tests, which did not apply any direct shear forces to the disc, the amount of shear motion was not statistically significantly altered by the stabilizing effect of fusion or by the de-stabilizing effect of the pars interarticularis defect. However, direct shear forces of 145 N magnitude applied to motion segments by Berkson[1] produced shear motions less than 1 mm, which increased to just over 1 mm after removal of posterior elements.

The amount of shear motion measured depends critically on the point to which this motion is referred. In this study the centre of the intervertebral disc was chosen as a reference point. In this way the method was similar to that of Tencer et al.[19] and differed from that of Schultz et al.[2], Panjabi et al.[9] and Berkson[1], who referred linear motions to the mid-point in the upper vertebral body.

Attempted fusion of the facet joints of specimens tested here by passing a screw through them was found subjectively to produce a substantial reduction of motion when the specimens were manipulated by hand. In one specimen it was found that there was in excess of 2 mm of motion in one joint after the completion of testing, so this specimen was rejected and a new specimen was tested. All other specimens remained 'rigid' by manual examination after testing. Thus, it was surprising how little reduction of motion was achieved when the specimens were tested objectively and with substantially greater forces than could be achieved manually. This failure to reduce intervertebral motion by posterior fusion has been noted previously *in vitro*[20,21] and *in vivo*[6,22]. It appears to be due to the inherent flexibility of the neural arch, together with the relative proximity of the axis of rotation of the motion segment to the facet joint[10,20].

Conclusions

Based on testing of cadaver specimens, it was confirmed that the major mechanical role of the facet joints of the lumbar spine is limitation of axial rotation motion, and that immobilization of facet joints only reduces flexion and extension motion of the lumbar spine to a significant extent. The anterior and posterior shear motion accompanying compression and the three principal angular motions was less than 1 mm under conditions of testing, and was not statistically significantly changed by division of the pars interarticularis or facet fusion.

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