A Biomechanical Analysis of the Clinical Stability of the Lumbar and Lumbosacral Spine

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Eighteen Functional Spinal Units (FSU), representing three levels of human lumbar and lumbosacral spine, were tested using preload forces that corresponded to the clinical situation of a person lying supine or standing while subjected to maximum physiologic flexion or extension forces. Sagittal plane displacements were measured using linear variable differential transformers (LVDTs) and a MINC-11/03 minicomputer. Sequential transection of components in the posterior-to-anterior and anterior-to-posterior directions until failure occurred allowed measurements of the displacement sagittal plane translation and rotation of the intact and transected FSU. [Key words: lumbar spine, stability, flexion, extension, preload]

THE SURGEON is often faced with the dilemma of determining whether or not the lumbar or lumbosacral spine is clinically stable. This problem may be encountered following trauma, tumor, infection or a particular surgical procedure. In some circumstances, the answer may be obvious, but often the decision is very difficult. There are few specific guidelines for making this determination. For the stable spine, treatment may be relatively inconsequential, involving only a few days of bed rest or an orthosis for several weeks. However, for the unstable spine, treatment may involve extensive surgery or prolonged bed rest, and a number of physicians think that all unstable spines require surgical stabilization. In any case, the diagnosis of instability is a critical one and should be made with as much accuracy as possible. This study was done because reliable quantitative data about the biomechanics of the lumbar and lumbosacral spine will improve clinical judgement about stability.

Clinical instability has been defined by White and Panjabi as "the loss of the ability of the spine under physiologic loads to maintain relationships between vertebrae in such a way that there is neither initial damage nor subsequent irritation to the spinal cord or nerve roots and, in addition, there is no development of incapacitating deformity or pain due to structural changes."[38] Holdsworth classified fractures and fracture dislocations into stable and unstable groups, and wedge compression and bursting compression fractures were considered unstable.[13] The study by Kaufer and Hayes concluded that all lumbar dislocations and fracture dislocations were unstable and required surgical fusion,[16] whereas only half of the cases described

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by Smith and Kaufer required surgical intervention.[33] A review of the clinical experience at the Massachusetts General Hospital by Pierce suggested that early surgical intervention was indicated in a significant number of cases.[27] White and Panjabi, in order to better define instability of the lumbar spine, have suggested a checklist giving point values to different criteria.[38] However, the authors suggested that this could be greatly improved with the help of some appropriately designed experiments. This paper reports on an *in vitro* study of the lumbar and lumbosacral spine designed to yield quantitative information to help define clinical instability.

Junghanns defined a motion segment as consisting of two adjacent vertebrae and all intervening soft tissues.[15] More recently, this has been renamed the functional spinal unit (FSU), representing the smallest mechanical unit of the spine involving kinetics as well as kinematics.[38] Components of an FSU refer to the ligaments, apophyseal joints, and disc joining the two adjacent vertebrae.

At first, research on spinal mechanics concentrated either on the individual components or spinal segments as a whole. Tkaczuk[34] studied the mechanical properties of the longitudinal ligaments, while Galante,[7] Horton,[14] and Hirsch and Nachemson[11] studied the disc. Other authors studied either the motion of intact individual FSUs or entire segments of the spine under various loading conditions.[2,6,17,24,30,35]

More recent studies designed to improve judgement about clinical stability have concentrated on the mechanics of an FSU as a function of its components. These studies were done on the cervical spine, using flexion and extension forces, by White et al[36] and Panjabi et al[22] and on the cervical spine, using tensile forces, also by Panjabi et al.[25] Similar experiments have been done on the thoracic spine, using flexion and extension forces, again by Panjabi et al.[26]

In our present work, we have studied the mechanics of the lumbar and lumbosacral region of the spine as a function of the transection of its components using flexion, extension, and preload forces, alone and in combination. Two different data reference systems are used for presentation of data and the discussions that follow. The coordinate system referred to in the description of the experiment set up and for the initial data reduction is the one recommended by White and Panjabi and illustrated in Figure 1.[37] As shown, the three axes in the coordinate system are denoted X, Y, Z. A second coordinate system (X^c, Y^c, Z^c) is used later for the presentation of clinically useful data. Representing the data in this way permits accurate collection of experimental data which are then transformed to a convenient, reliable technique for more quantitative definition of the clinical instability of the lumbosacral spine. To our knowledge, no such experimentation has yet been done to provide this type of information for this portion of the spine.

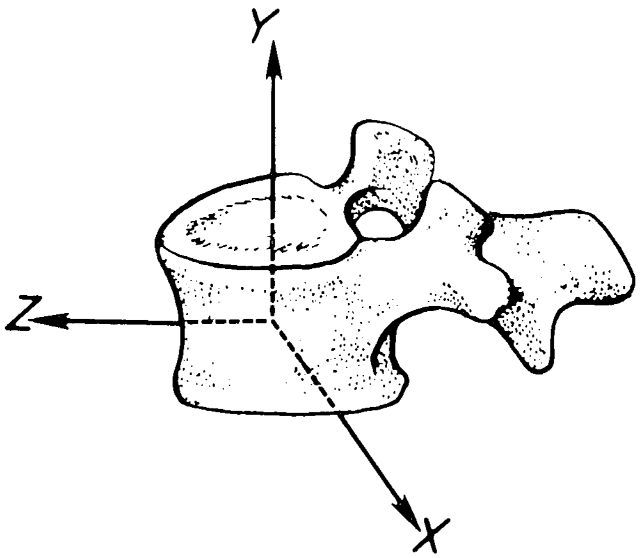

Fig 1. For each FSU, a space-fixed experimental coordinate system was established at the center of the upper vertebral body in its initial position, with the axes oriented as shown.

CLINICAL RELEVANCE

Guidelines are given for displacements of the intact FSU as well as displacements corresponding to a threshold of clinical instability. The guidelines are presented in the form of checklists designed for direct and immediate clinical application. These checklists insure a systematic approach to improve accuracy and reproducibility in the important and difficult area of clinical judgement concerning the stability of the lumbar and lumbosacral spine.

ANATOMY

This is a brief review of the salient anatomic points that are cogent to clinical stability. The structures are divided into anterior and posterior groups. The posterior longitudinal ligament and all ligaments anterior to it are referred to as the anterior elements. Similarly, all elements posterior to the posterior longitudinal ligament are referred to as posterior elements (Figure 2).

The most superficial fibers of the anterior longitudinal ligament join several vertebrae, while the deepest fibers connect only adjacent vertebrae.[8] In the area of the lumbar spine, the average width is 2 to 2.5 cm, and the average thickness is 2 mm narrowing to 1 mm at the L2 level.

The annulus fibrosis is strongly attached to both anterior and posterior longitudinal ligaments.[12] Superiorly and inferiorly, the fibers attach to the bony endplates peripherally by means of Sharpey's fibers, and centrally they mesh with the hyaline cartilage endplates.

The posterior longitudinal ligament is composed of longitudinally running fibers that are generally denser

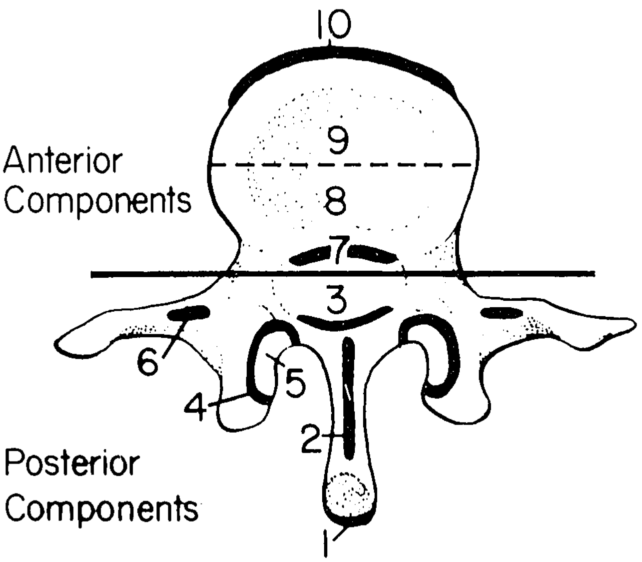

Fig 2. Schematic representation of the components of a functional spinal unit of the lumbar spine. (1) Supraspinous ligament, (2) interspinous ligament, (3) ligamentum flavum, (4) facet capsular ligament, (5) facet joints, (6) intertransverse ligament, (7) posterior longitudinal ligament, (8) posterior one-half of disc, (9) anterior one-half of disc, (10) anterior longitudinal ligament.

and more compact than the anterior longitudinal ligament. However, this ligament is usually thinner, narrower, and weaker than the anterior longitudinal ligament.[34] The most superficial fibers run the length of several vertebrae, while the deeper layers join adjacent vertebrae.[8] The width ranges from 1.1 to 1.4 cm at the disc level and from 0.6 to 0.8 cm at the vertebral level, while the thickness averages 0.9 to 1.4 mm.[34] The intertransverse ligaments are interposed between the transverse processes and are generally considered to be thin and membranous.[8] The ligamentum flavum is 4 to 6 mm thick, narrowing in the L5–S1 space to as little as 1.5 mm.[9] It is thicker towards the midline, narrowing in its lateral extent. The ligamentum flavum is mainly composed of elastic fibers representing the largest and heaviest of all elastic tissue structures, with the highest percentage of elastin in the human body.[28,3]

The interspinous ligament is quadrilateral in shape, with the largest dimension located ventrally. The fibers run from posterosuperior to anteroinferior with a thickness averaging 1 to 2 mm in the upper lumbar region and 2 to 3 mm in the lower lumbar region.[29]

The supraspinous ligament, which is usually 5 to 7 mm thick and 6 to 8 mm wide, is not present in 95% of FSUs of the lumbar spine below L4.[29]

MATERIAL AND METHODS

Anatomic Material. Seven fresh lumbar spines T12–S1 were obtained within 12 hours of death from autopsies at regional hospitals. The medical records were screened, and information was obtained including sex, age, height, weight, cause of death, and most recent medical history (Table 1). Attempts were made to determine the weight prior to terminal illness. Spines were not obtained if there was any chronic history of back pain, spinal surgery, or disease. The spines were double-wrapped in plastic bags and frozen at −20 C. This method of storage has been shown not to significantly affect the mechanical properties of the bone (Sedlin and Hirsch[32]), the annulus (Hirsch and Galante[10]), or the longitudinal ligaments (Tkaszuk[34]). All spines were roentgenographed in the anteroposterior (AP) and lateral planes to rule out any bone pathology or anatomic anomalies.

Functional Spinal Unit Test Apparatus. Eighteen FSUs were tested to determine their response to flexion, extension, and preload forces using a test

Table 1. Specimen Data

Spine no.	Levels	Disc*	Transection† (P-A/A-P)	Age (years)	Sex (M/F)	Weight (kg)	Height (cm)	Cause of death	Radiologic evaluation
3	L3–L4	1	P–A	59	F	51.5	153	Myocardial infarction	No degenerative changes
4	L1–L2	1	A–P	46	M	58.7	175	Adenocarcinoma, lung	Minor degenerative changes
	L3–L4	1							
	L5–S1	1							
13	L1–L2	1	A–P	45	F	54.5	170	Gastric carcinoma	No degenerative changes
	L3–L4	1							
	L5–S1								
16	L1–L2	0	P–A	27	M	52.3	150	Lymphoma	No degenerative changes
	L3–L4	0							
	L5–S1	0							
18	L1–L2	1	P–A	46	M	58.4	183	Pancreatic carcinoma	No degenerative changes
	L3–L4	1							
	L5–S1	1							
21	L1–L2	0	P–A	18	F	47.7	150	Sepsis	No degenerative changes
	L5–S1	0							
23	L1–L2	1	A–P	52	M	58.0	165	Renal failure	No degenerative changes
	L3–L4	1							
	L5–S1	1							

* Disc refers to level of disc degeneration: 0 = normal; 1 = minimal changes.
† P–A = posterior to anterior; A–P = anterior to posterior.

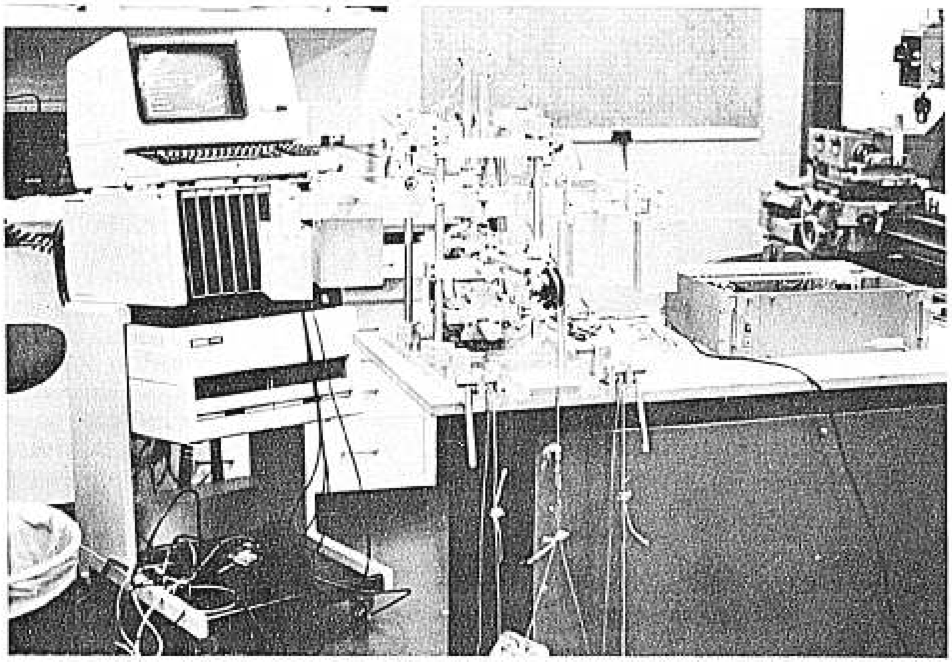

Fig 3. Laboratory set-up: the apparatus in the center shows the position of the LVDTs, the preload bar with four out of a possible ten aluminum boxes, and the pulley for the flexion force. The MINC-11/03 minicomputer is on the left, and the signal conditioner for the LVDTs is on the right.

apparatus built for this experiment. The apparatus had six main component groups: (a) specimen support and base, (b) pulley stand (for AP loading), (c) load frame and preload lifting mechanism, (d) preload bar, (e) specimen top plate, and (f) displacement transducers. The test apparatus and the MINC-11/03 computer data acquisition system are shown in Figure 3.

The specimen support assembly securely held the test specimen and oriented the specimen with respect to the applied loads and the displacement transducers. As shown in Figure 4, the support group consisted of a specimen box, the tilt table, and the X–Z stage (which is attached to the base plate). The FSU to be tested was mounted in the specimen box and secured to the tilt table and and the X–Z stage. The tilt table was designed so that the middisc plane of the FSU specimen could be made parallel to the base plate by rotating the specimen to the proper orientation and locking it in place. Similarly, by adjusting the X–Z stage, the specimen was positioned laterally so that the flexion or extension forces could be applied in the true AP direction.

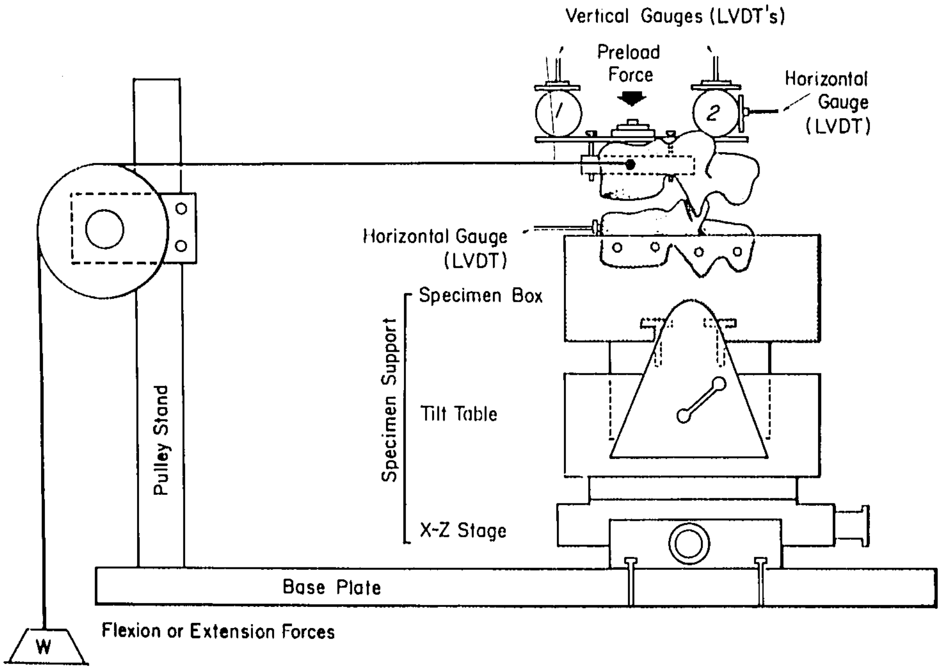

Fig 4. The experimental set-up: (1) and (2) are the measuring balls attached to the top plate which is attached via a cyclindrical aluminum piece to the upper vertebrae. The figure shows an FSU being subjected to preload and flexion forces with transection of components from posterior to anterior. The specimen is reversed 180° for testing with an extension force.

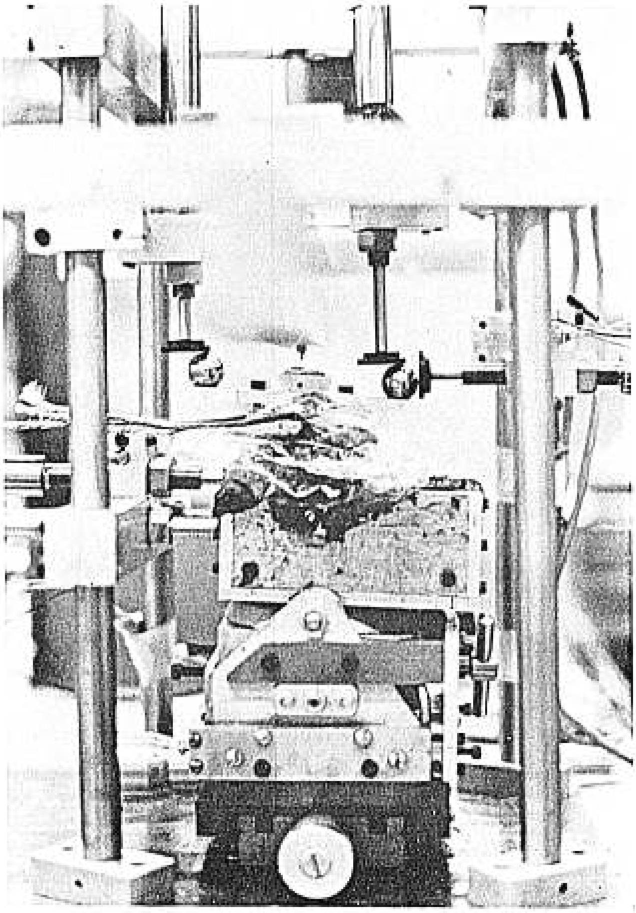

Fig 5. Close-up view of the experimental set-up. This is the initial position prior to testing for a flexion sequence.

The pulley stand, also shown in Figure 4, was used to facilitate the application of the flexion or extension forces. A pulley with needle bearings was attached to this post, and, by means of a steel cable, the flexion of extension forces were applied via lead weights suspended over the edge of the table. The steel cable was attached to a bolt through the center of the upper vertebral body. The vertical position of the pulley was adjusted so that the application of the flexion or extension force was parallel to the base plate. Specially designed lifters slowly applied the flexion or extension force. Stop mechanisms for both the preload and flexion or extension forces acted to protect the linear variable differential transformer (LVDT) displacement transducers from damage when failure occurred.

A load frame was attached to the base plate as shown in Figure 5. This frame consisted of four vertical steel posts with four cross members at the top to which were attached the lifting and holding devices for the preload bar. By means of the lifting devices, the preload weight could be lowered slowly and made to rest in the hole in the adjustment device on the specimen top plate. Adjustments could be made via the top plate adjustment device to minimize movement of the upper vertebrae when the preload was applied.

The preload bar could be loaded with ten aluminum boxes that could exert a total maximum weight of approximately 900 newtons. This could be centered so as not to constrain the motion of the upper vertebrae. In order to control the point of application of the preload force, a conical hole was drilled in the center of the adjustment device on the top plate.

The specimen top plate attached rigidly to the superior vertebral body of the test specimen. This is shown in Figure 4. This top plate was designed to effectively transmit the load and allow for both fine and gross adjustments of the point of application of the load.

The displacement of the superior FSU due to the applied loads was measured using a set of transducers interfaced with a MINC-11/03 computer. Four LVDTs* were positioned, two vertically and two horizontally, to measure movement in the sagittal plane of the two steel balls of the top plate and a screw in the anterior superior lip of the lower vertebrae. This arrangement is also illustrated in Figure 4.

Preparation of the FSU for Testing. Prior to testing, each spine was thawed slowly at room temperature in a humidification chamber that maintained 100% humidity and 27 C. The spine was then carefully cleaned of all muscle tissue and separated into three functional spinal units: L1–L2, L3–L4, and L5–S1. The two FSUs that were not going to be immediately tested were rewrapped in double plastic bags and stored at 0 C.

The inferior vertebrae of the FSU, with several bolts through it, was placed in the specimen box and fixed in position with fast-setting Polyester resin, † using the box as a mold. Three bolts were also set in the resin to attach the specimen box to the tilt table. Care was taken while setting the resin to keep the specimen aligned correctly in all directions and to prevent the resin from contacting the ligaments involved in the FSU. When the resin was firm enough so that no movement would occur, the exposed tissues were wrapped in cool saline-soaked sponges and placed in a freezer at −20 C for ten to 15 minutes to prevent damage to the tissues by the exothermic process of the setting resin (up to 90 C).

After the resin had completely set, the top plate was attached. A cylindrical piece of aluminum was placed through the upper vertebrae. The top plate was attached to the aluminum piece with two screws, with the upper vertebral bolt going through the aluminum piece as well. This method of fixation created a rigid body of the top plate, upper vertebrae, and upper vertebral bolt through which flexion or extension forces were applied. No loosening was detectable throughout the experiment, and the geometry could be accurately delineated for the data reduction. A round-

*Model number PCA-117-1000 made by Schaevitz Engineering, Pennsauken, New Jersey.

† Polyester resin with Benzyol peroxide hardener made by Dynatron Corporation, Atlanta, Georgia.

headed cancellous screw was placed in the anterior upper lip of the lower vertebral body to allow for measurement of any horizontal motion of the lower vertebral body.

The specimen box was finally attached to the tilt table, and the specimen was aligned in the test coordinate system. The proper orientation of the FSU was achieved by first visually aligning the specimen using the tilt table so that the middisc plane was parallel to the plane of the aluminum base plate. This was confirmed with measurements from a portable x-ray plate. Corrections were made and the specimen set-up radiographed until the middisc plane was parallel to the base plate to an accuracy of within 1°. The specimen was wrapped in saline-soaked gauze sponges and wrapped in plastic to prevent drying. Periodically, the sponges were moistened with additional saline solution.

The preload bar was adjusted to minimize the movement of the upper vertebrae when the preload was applied. It was found that, when a preload of 190 newtons was applied, the preload could be adjusted to minimize movement of the FSU either slightly forward or slightly backward. This displacement was recorded for each experiment. The average displacement (± 1 SD) with a preload of 190 newtons was .073 (± .095) mm in the sagittal direction. The specimen was then ready for testing.

There were only two differences in the method for testing posterior-to-anterior, as opposed to anterior-to-posterior transection sequences: first, the entire specimen was reversed when comparing one transection sequence set-up to the other, and second, the LVDT measuring the horizontal displacement of the lower vertebral body was either placed in the front or the back of the apparatus, depending upon the position of the specimen.

TESTING PROCEDURES

Eighteen functional spinal units from seven lumbar spines were tested. Originally, six lumbar spines were chosen for testing. However, bony, as opposed to ligamentous, failure occurred in one test, rendering the data unacceptable for purposes of this study. Therefore, an FSU from a seventh lumbar spine was used to replace these data. Table 1 lists the autopsy information for these specimens.

Two different modes of testing were used in this study. In one mode, the specimen was loaded with a series of flexion and preload forces, while the ligaments were serially transected from posterior to anterior until failure occurred. In a second mode, the specimen was loaded with a series of extension and preload forces while the ligaments were serially transected from anterior to posterior until failure occurred. Table 2 lists the order of transection of ligaments. Failure was defined by a sudden and total giving away of the upper vertebral body in relationship to the lower vertebral body.

Table 2. Order of Transection of Components

Posterior to anterior (P–A)	*Anterior to posterior (A–P)*
1. Supraspinous ligament	1. Anterior longitudinal ligament
2. Interspinous ligament	2. Anterior one-half of disc
3. Ligamentum flavum	3. Posterior one-half of disc
4. Facet capsular ligament	4. Posterior longitudinal ligament
5. Facet joints	5. Intertransverse ligament
6. Intertransverse ligament	6. Facet capsular ligament
7. Posterior longitudinal ligament	7. Facet joint
8. Posterior one-half of disc	8. Ligamentum flavum
9. Anterior one-half of disc	9. Interspinous ligament
10. Anterior longitudinal ligament	10. Supraspinous ligament

Similar experimentation on the cervical and thoracic spine conducted previously by White et al[36] and Panjabi et al[22,26] included two additional transection sequences, ie, transection from posterior to anterior with an extension force and transection from anterior to posterior with a flexion force. These sequences were not included in the present study for several reasons. First, it is known from previous studies, as well as preliminary trials related to this work, that the FSU will remain stable, ie, not fail until nearly all but one ligament has been transected. This suggests that, for a given FSU, there would be stability in flexion but gross instability in extension. The converse would be true when the direction for transection components and loading is reversed. Clearly, either condition is an untenable situation clinically. Second, the ligaments in these two methods of testing are placed in compression rather than in tension, with bone-to-bone grating in opposition providing the major component of this otherwise precarious stability. Since the ligaments are not typically loaded in this situation, the data could not be related to the flexibility and stiffness characteristics of the spinal ligaments. Finally, because of the value of the FSUs, as well as the time and expense required to study them, it did not seem that these particular portions of the experiment were in any way cost-effective. For these reasons, it was determined that these two traditional sequences would be eliminated from the design of this study.

Six specimens were tested at each of the three lumbar levels L1–L2, L3–L4, and L5–S1, with three specimens being transected from anterior to posterior and three from posterior to anterior. Thus, the total number of specimens tested in this study was 18.

Each specimen was loaded with a series of flexion or extension forces and preload forces based upon body weight and FSU level. Table 3 lists the percentages of body weight that were used. The flexion or extension force percentages were based on data by Ruff that

Table 3. Percentage of Body Weight for Applied Forces*

Level	Force 1	Force 2	Preload 1	Preload 2
L1	50%	75%	66%	132%
L3	56%	84%	70%	140%
L5	60%	90%	73%	146%

* Force refers to flexion and extension forces.

estimated the proportion of body weight above a certain spinal level.[31] The second force (force 2) was set equal to 1.5 times the first force (force 1), based on our estimation that this represents the maximal physiologic range. The percentages for preload were based on data by Nachemson relating intradiscal pressures to preloads.[18] Using intravital measuring techniques, he was able to determine that the load on L3 while reclining is approximately 70% body weight, while the preload during standing is approximately 140%.[19,20] Therefore, the choice of the preload of 70% body weight comparable to lying in bed and 140% body weight comparable to standing is clinically appropriate. We also varied the preload by increasing it from L1 to L5 as suggested by Nachemson's data.[19] Panjabi, in testing the effect of preload on spinal motion, used similar preload values of 60% and 145% body weight in this study.[24]

Each specimen was loaded with a single force, single preload, or combination of force and preload for four minutes before a datum measurement was taken. The specimen was then unloaded and allowed to rest for four minutes, and a second measurement was recorded to determine the residual displacement. Four minutes was chosen as the time interval for each measurement to allow the tissues to creep. As shown by Panjabi et al, practically all deformation due to creep is complete after four minutes.[23]

During testing, voltages from the LVDTs were automatically acquired and stored using a minicomputer.* The computer clock was then used to determine the four-minute interval prior to data acquisition. The order of loadings was slightly different for posterior-to-anterior as opposed to anterior-to-posterior transections in order to apply the loads in an increasing manner. Table 4 lists the order of application of loads. The difference is reflected in the fact that the preload acted in concert with the flexion force because of moments generated when the FSU was transected from posterior to anterior, while the preload acted in opposition to the extension force when the FSU was transected from anterior to posterior. Using this method of testing, a minimum of 60 and a maximum of 128 data points were collected for each of the 18 FSUs studied. Each point represented a load-displacement pair for a given loaded or unloaded state. Care was taken to keep the specimen well hydrated during the six to 12 hours required to prepare and test each specimen.

*MINC (Modular Instrument Computer) - 11/03 minicomputer was made by Digital Equipment Corporation, Maynard, Massachusetts.

After failure, the specimen was inspected to insure experimental acceptability. A portable x-ray film was taken to confirm that fracture had not occurred. Prior to disassembling the set-up, measurements were done to confirm the geometric relationship of the two steel balls, the upper vertebral bolt (through which the flexion or extension force was applied), and the point at which the preload was applied. These measurements were then used in the data reduction. The LVDTs were calibrated over their entire range before and after each experiment using the Emco Milling Machine with a micrometer screw accurate to .025 mm.

Subsequent to failure of the functional spinal unit, the degree of degeneration of the disc was determined macroscopically, according to the classification employed by Rolander and a number of other investigators.[30] All the discs in this study were graded either 0 or 1 (Table 1), representing either normal or slightly degenerated discs.

DATA REDUCTION AND ANALYSIS

The reduction of data obtained in this experiment can be organized into five steps of analysis, beginning with the treatment of the raw data and ending with a proposed spinal stability evaluation technique.

The five steps, which are presented in more detail below, were:

A. The measured motions of the top plate attached to the FSU specimen were recorded and converted to displacements of the superior vertebral body in the Y, Z, Θ coordinate system.

B. Statistical analyses were performed on the data in the Y, Z, Θ coordinate system to determine the significance of key parameters (ie, vertebral level and transection condition) for various loadings. The means and standard deviations for appropriate groups were then calculated.

C. The data were mathematically transformed from the experimental Y, Z, Θ reference system to a clinically useful Y^c, Z^c, Θ^c reference system.

D. The statistical means and standard deviations of the displacements in the Y^c, Z^c, Θ^c system for the intact specimens and the transected specimens prior to failure were calculated.

E. An evaluation technique based on this last set of

Table 4. Order of Application of Loads

Type of transection	Forces*	Preload 0	Preload 1	Preload 2
Posterior to anterior		1	2	4
	Force 1	3	6	8
	Force 2	5	7	9
Anterior to posterior	0	1	2	3
	Force 1	8	4	6
	Force 2	9	5	7

* Force refers to flexion and extension forces.

statistical values was suggested, and the numerical values used with this technique were calculated.

Measurement of the Y, Z, Θ Motions. The relation of the measured motion of the top plate to the displacement of the superior vertebra of the test specimen in the experiment coordinates was determined.

The voltages of the LVDT displacement transducers were converted to millimeter displacements using an average of the pre- and postcalibration data. The resolution of an LVDT in conjunction with a MINC-11/03 minicomputer was .014 mm. Corrections were made on the horizontal measurements for any displacement of the specimen box when a flexion or extension force was applied. This was usually zero but in some cases ranged up to .03 mm. Three parameters were calculated from the LVDT data: angular displacement of the upper vertebrae (Θ) in degrees and vertical and horizontal displacement (Y and Z) of the geometric center of the upper vertebrae in millimeters. Angular displacement was calculated using the method described by Panjabi et al, based on the formula:

$$\Theta = \arc \sin (\Delta/A + \sin \alpha) - \alpha$$

where Θ is the angular displacement, Δ is the difference in the two vertical LVDT readings, A is the distance between the ball's centers and α is the initial angulation prior to loading.[22] The horizontal displacement of ball number 2 (Figure 4) was first determined as the difference in the horizontal LVDT readings. A geometric analysis of the actual specimen and x-ray studies determined the relationship between the positions of the balls and the center of the upper vertebral body. The horizontal displacement of the center of the body could then be determined based on the geometric analysis and the assumption that the vertebral body and measuring balls constituted a rigid body. An analogous procedure was used to determine the vertical displacement.

Statistical Analysis of Original Data. The data were analyzed for significant statistical differences between the intact and maximum displacements and anatomic level by analysis of variance and Duncan's tests. Maximum displacements were defined as the maximum displacement prior to the transection of the component that produced failure. The measurements were grouped in flexion and extension groups for each of the eight individual force loads. The means and standard deviations were determined using a normal distribution to represent the data.

Mathematic Transformation to Clinical Reference Coordinates. The data were mathematically transformed from the Y-Z-Θ representation to the clinical coordinate system denoted Y^c-Z^c-Θ^c (Figure 6). This coordinate system is defined by drawing the Z^c axis along the superior end-plate of the inferior vertebra, with the Y^c axis drawn perpendicular to the Z^c axis above the posterior–superior corner of the vertebral body, as shown. Then, for any point in the Y-Z-Θ axis, the corresponding representation is

$$Y^c = (Y+h+d) \times \cos(\beta/2) + (Z+e) \times \sin(\beta/2)$$

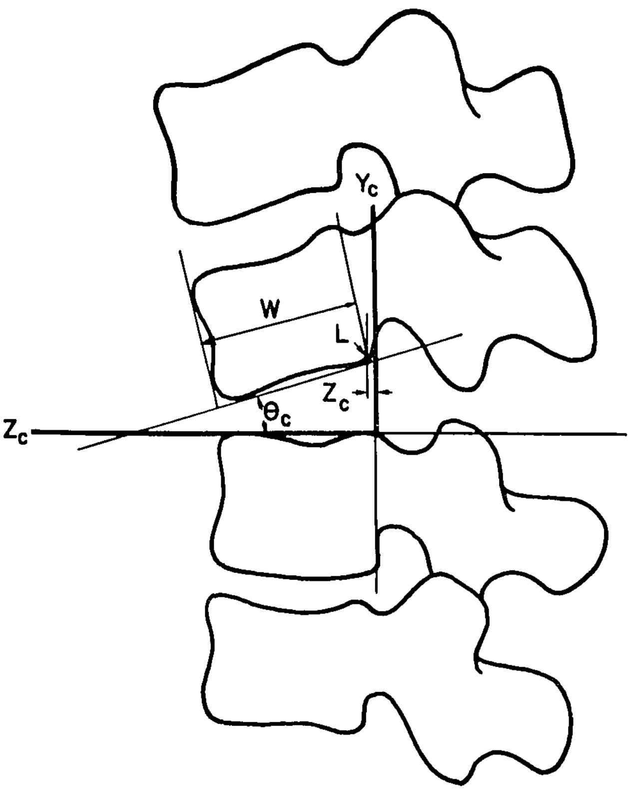

Fig 6. The deflection of an FSU can be clinically determined from x-rays by drawing a set of axes (Y^c and Z^c) along the superior surface of the vertebral body below the level in question. The percentage horizontal displacement is the distance of the posterior-inferior lip of the superior vertebral body (labelled L) from the Y^c line divided by the width W, of the superior vertebra multiplied by 100. The angle Θ^c, here shown in a negative sense, is the angle of the intervertebral disc.

$$Z^c = -(Y+h+d) \times \sin(\beta/2) + (z+e) \times \cos(\beta/2)$$

where the parameter d is the distance from the origin of the Y^c–Z^c axis to the inferior–posterior corner of the superior vertebra (the point L in Figure 6), h is the distance from point L to the center of the superior vertebral body measured along the Y axis and e is the distance of the point L from the Y axis measured along the Z axis. The angle Θ^c is merely the disc angle measured relative to the Z^c axis. The position of the point L relative to the Y^c–Z^c axes and the angle Θ^c can then be used to evaluate spinal stability.

The means and standard deviations of Θ^c and the Z^c position of L for the intact and the transected unstable specimen are used to determine test values to represent the threshold of clinical stability. This is not a simple matter statistically. As stressed by both Armitage and Colton, the rate of false positives (the FSU tests as unstable but is really stable) and false negatives (the FSU tests as stable but is really unstable) depends not only on the value chosen as the test value, but also on the actual incidence of both populations, stable and unstable.[1,4] Because of the great difficulty and expense in obtaining and testing these specimens, the groups are small in number and statistically may not represent the "true" population. With these reser-

vations in mind, we elected to equalize the two populations and determined the test value so that the rate of false positives and false negatives would be equal. If T represents the test value, $\bar{x}_I \pm s_I$ represents the mean ± SD of the displacements of the intact specimens, and $\bar{x}_M \pm s_M$ represents the mean ± SD of the maximum displacements prior to failure, then the value of T is given by the following equation:

$$T = (s_I\bar{x}_M + s_M\bar{x}_I) / (s_I + s_M)$$

The rate of false positives or false negatives designated as percent error of diagnosis in Tables 6–8 can then be determined by normalizing either group of measurements to determine a C value where:

$$C = \frac{T - \bar{x}_I}{s_I} = \frac{T - \bar{x}_M}{s_M}$$

Using this C value, T, and a standard table of a normal distribution, the rate of false positives or false negatives is determined.

To facilitate the reading of the displacements from x-ray information, an additional parameter was calculated. The horizontal displacement was divided by the actual horizontal width, W, of the upper vertebral body measured at its center to give a percentage horizontal displacement, $Z^c\%$ (Figure 6). This method was described by Dickson et al, except that he used the width of the lower vertebral body.[5] Appropriate comparison testing of vertebral body widths showed no significant differences among the various levels.

The data were analyzed and presented in terms of percentage horizontal displacement for clinical convenience in that this method eliminates the problem of x-ray standardization and magnification.[38]

RESULTS

Table 5 lists the components transected prior to failure and the number of specimens failing after each component. In the flexion sequences with transection from posterior to anterior, all specimens failed when all posterior components plus one anterior component had been transected. In the extension sequences with transection from anterior to posterior, all specimens failed when all anterior components plus two posterior components had been transected. In other words, in flexion testing all specimens were stable if the anterior components plus two additional components were intact, while in extension testing all specimens were stable if the posterior components plus one additional component were intact.

The forces producing failure varied among the specimens without any recognizable pattern, and therefore are not presented in detail. However, the mode of failure was similar among the specimens. In the flexion experiments, the intertransverse and posterior longitudinal ligaments failed with separation of their fibers, while the disc failed with the cartilaginous end-plate pulling off the vertebral body (three upper and six lower). In the extension experiments, the intertransverse ligament again failed with separation of its fibers, while the apophyseal capsule and ligamentum flavum pulled off their attachments to bone (seven lower and two upper).

Table 5. Component Transected Prior to Failure

	Component	*Number of specimens*
Flexion	Facet joint	1
	Intertransverse ligament	3
	Posterior longitudinal ligament	5
Extension	Posterior longitidinal ligament	5
	Intertransverse ligament	2
	Facet capsule	2

The motion of the FSUs prior to failure referenced to the experimental coordinate system (X, Y, Z) is illustrated by six graphs, Figures 7–12. All graphics were done with the MINC-11/03 minicomputer in conjunction with the Tektronix terminal and hard copy unit.* The ordinate represents the experimental horizontal (mm) and experimental angular (degrees) displacement, while the abscissa represents the component transected. The forces and component sequences are also shown. The displacements when forces were applied, as well as the residual displacements after the forces were removed, are graphed. The same three load patterns, ie, force 2 alone, force 2 with preload 1 in combination, and force 2 with preload 2 in combination, were chosen and displayed in these figures for one FSU in flexion and one in extension. These represented typical behavior for each group of FSUs.

The behavior of the FSUs with a flexion force and posterior-to-anterior transection showed a progressive increase in horizontal and angular displacement after transection of each component. After the apophyseal joints were removed, there was a slight increase in the displacements with a greater increase in the residual displacements. All FSUs failed after transection of the posterior longitudinal ligament. However, many FSUs tolerated some additional load sequence prior to failure. In addition, after the posterior longitudinal ligament was cut, there was a large increase in displacement.

The behavior of the FSUs with an extension force and anterior-to-posterior transection was very different than the behavior for the flexion sequence. When extension force was applied alone (Figure 10) without preload, there was a progressive increase in displacement as each component was transected in a manner similar to that seen in the flexion sequences. However,

*Graphics Display Terminal 4010-1 with Hard Copy Unit 4631 made by Tektronix, Beaverton, Oregon.

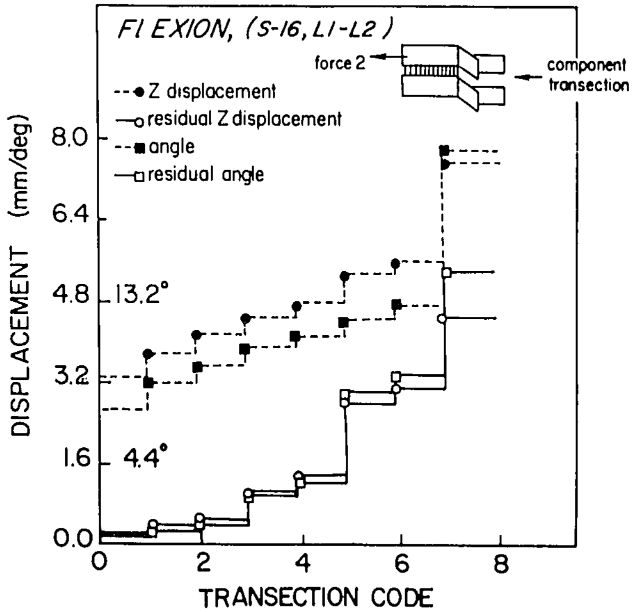

Fig 7. A flexion force of 75% body weight was applied with component transection from posterior to anterior. Horizontal and angular displacements are graphed as a function of component transection. Residual displacements result after the force is removed.

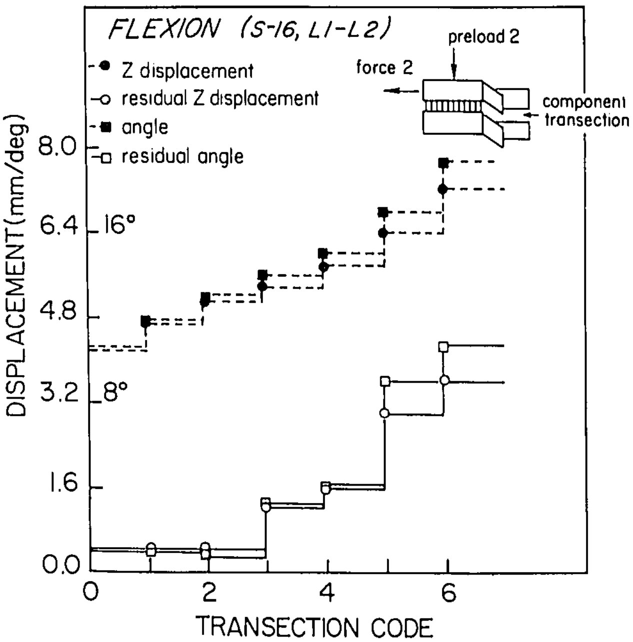

Fig 9. A flexion force of 75% body weight and a preload of 132% body weight (corresponding to a person standing with a maximum physiologic flexion force) were applied with component transection from posterior to anterior. Horizontal and angular displacements are graphed as a function of component transection. Residual displacements result after the force is removed.

the combination of extension force and preload yielded horizontal displacements that progressively increased with transection of components but angular displacements that in some cases increased and in some cases decreased. This occurred because the preload counteracted the tendency of the extension force to rotate the upper vertebral body. After sectioning of the disc, the FSU was unstable to preload forces alone in that the FSU could rotate laterally in either direction in the X–Z plane outside the range of 2.54-cm

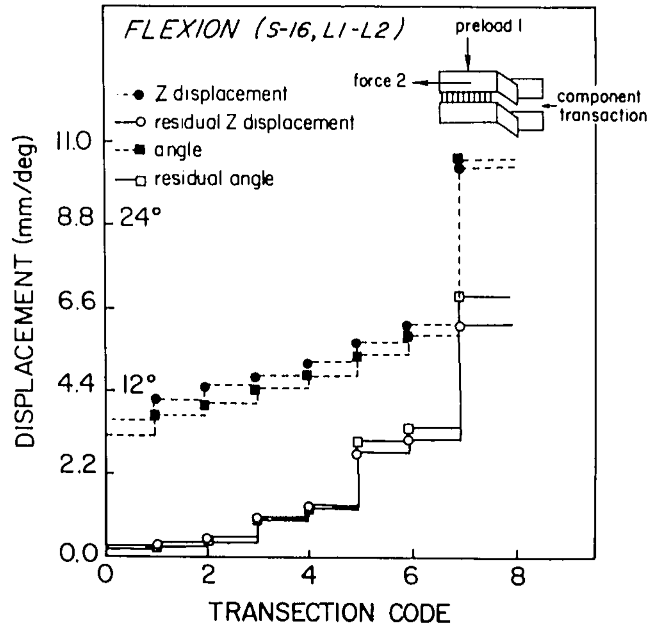

Fig 8. A flexion force of 75% body weight and a preload of 66% body weight (corresponding to a person lying supine with a maximum physiologic flexion force) were applied with component transection from posterior to anterior. Horizontal and angular displacements are graphed as a function of component transection. Residual displacements result after the force is removed.

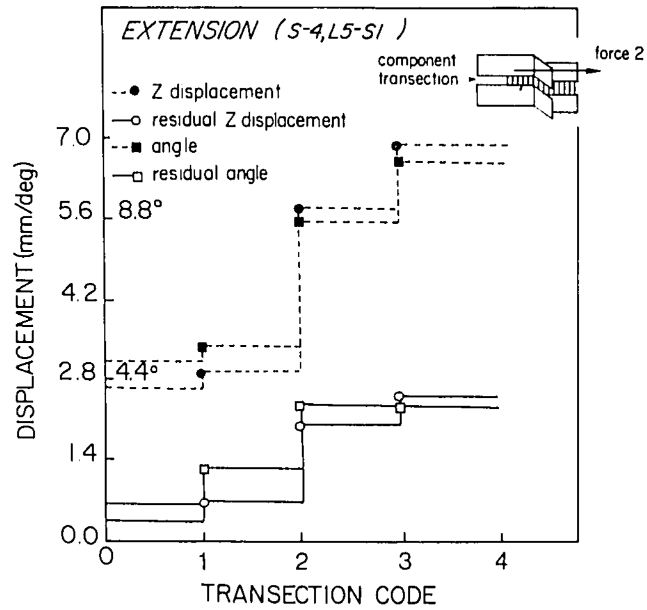

Fig 10. An extension force of 60% body weight was applied with component transection from anterior to posterior. Horizontal and angular displacements are graphed as a function of component transection. Residual displacements result after the force is removed.

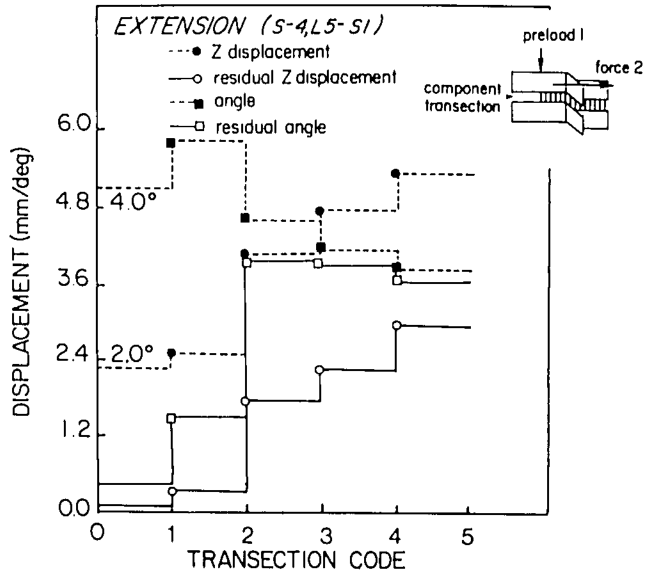

Fig 11. An extension force of 60% body weight and a preload of 73% body weight (corresponding to a person lying supine with a maximum physiologic extension force) were applied with component transection from anterior to posterior. Horizontal and angular displacements are graphed as a function of component transection. Residual displacements result after the force is removed.

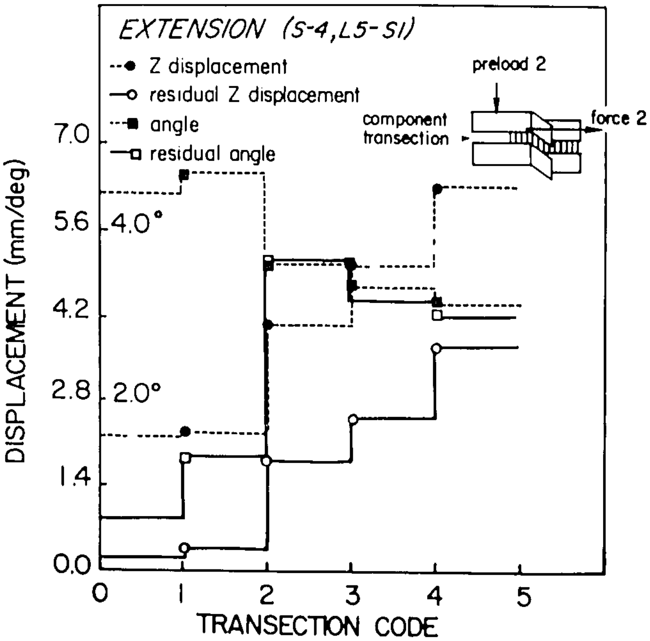

Fig 12. An extension force of 60% body weight and preload of 146% body weight (corresponding to a person standing with a maximum physiologic extension force) were applied with component transection from anterior to posterior. Horizontal and angular displacements are graphed as a function of component transection. Residual displacements result after the force is removed.

flat-end contact points used to contact the measuring balls.

The means ±SD of the intact and transected displacements in the clinical coordinate system (centered at the posterior superior corner of the lower vertebrae) are tabulated (Tables 6–8) for three of the eight force loads, force 2, force 2 with preload 1, and force 2 with preload 2. These forces were chosen for presentation because force 2 represents the traditional loading force used in experiments on FSU motion, while the combinations of force 2 with preload 1 or force 2 with preload 2 represent, respectively, the clinical situation of a person either supine or standing with a flexion/extension force applied.

Statistical analysis of the data showed a significant difference between the combined L1–L2/L3–L4 levels and the L5–S1 level for all flexion sequences, whereas no significant difference was found between the L1–L2

Table 6. Clinical Displacements for Application of Force 2*

	Level	*Intact*†	*Maximum*†	*Test value*	*Percent error of diagnosis*
Flexion					
Z^c (mm)	L1–L2 L3–L4	1.5 ± 0.6	3.5 ± 1.0	2.2	10
	L5–S1	0.7 ± 1.2	2.1 ± 1.0	1.5	27
Z^c% (%)	L1–L2 L3–L4	5.0 ± 2.0	11.7 ± 3.6	7.4	11
	L5–S1	2.8 ± 4.9	7.2 ± 3.6	5.4	30
σ^c (degrees)	L1–L2 L3–L4	−3.1 ± 2.8	−13.3 ± 6.2	−6.3	13
	L5–S1	10.3 ± 6.0	1.2 ± 10.1	6.8	28
Extension					
Z^c (mm)	L1–L2 L3–L4 L5–S1	2.1 ± 0.7	5.0 ± 2.2	2.8	15
Z^c% (%)	L1–L2 L3–L4 L5–S1	6.6 ± 2.2	15.2 ± 5.3	9.1	12
σ^c (degrees)	L1–L2 L3–L4 L5–S1	16.4 ± 9.6	23.7 ± 9.8	20.0	35

* Force 2 corresponds to a maximum physiologic flexion or extension force without any preload forces applied.
† Mean ± 1 SD.

Table 7. Clinical Displacements for Application of Force 2 and Preload 1*

	Level	Intact†	Maximum†	Test value	Percent error of diagnosis
Flexion					
Z^c (MM)	L1–L2	1.6 ± 0.6	4.0 ± 2.1	2.1	18
	L3–L4				
	L5–S1	1.0 ± 1.1	2.4 ± 1.8	1.6	32
Z^c% (%)	L1–L2	5.4 ± 2.0	13.4 ± 7.1	7.2	19
	L3–L4				
	L5–S1	3.9 ± 4.5	8.6 ± 6.4	5.8	33
σ^c (degrees)	L1–L2	−4.2 ± 3.0	−16.1 ± 9.0	−7.2	16
	L3–L4				
	L5–S1	8.2 ± 6.5	−3.5 ± 12.2	4.1	27
Extension					
Z^c (mm)	L1–L2	1.7 ± 0.8	5.6 ± 2.7	2.6	13
	L3–L4				
	L5–S1				
Z^c% (%)	L1–L2	5.2 ± 2.5	17.1 ± 6.7	8.5	10
	L3–L4				
	L5–S1				
σ^c (degrees)	L1–L2	15.9 ± 9.7	17.4 ± 10.6	N.S.	
	L3–L4				
	L5–S1				

* Force 2 and preload 1 corresponds clinically to a person lying supine with a maximum physiological flexion or extension force applied.
† Mean ± 1 SD.

and L3–L4 levels. It also showed a significant difference between intact and transected displacements for all groups except angular displacement in the extension sequences when a combination of force 2 and preload 1 or 2 was applied.

The test values representing the threshold of clinical stability were determined based on the means ±SD as previously described. The results of these determinations are also presented in Tables 6–8. The last column of figures in Tables 6–8 is the projected error of diagnosis which could be expected using the assumptions presented in the preceding section. The smaller the error, the better the corresponding test value should be relative to distinguishing an intact from transected types of conditions. An error value of 50% would indicate that there was statistically no significant difference between initial and maximum displacements. The extremes of wall test values found are summarized in Table 9.

Using these criteria, we can now update and improve the checklists to evaluate lumbar and lumbosacral spine clinical stability, as suggested by White and Panjabi.[38] As x-ray magnifications will vary quite sensitively with the distances between the x-ray tube, patient, and plate, it is recommended that percentage horizontal displacement based on upper vertebral

Table 8. Clinical Displacements for Application of Force 2 and Preload 2*

	Level	Intact†	Maximum†	Test value	Percent error of diagnosis
Flexion					
Z^c (mm)	L1–L2	1.7 ± 0.6	3.2 ± 1.0	2.3	17
	L3–L4				
	L5–S1	1.0 ± 1.2	1.6 ± 1.4	1.3	41
Z^c% (%)	L1–L2	5.8 ± 2.1	10.8 ± 3.5	7.7	19
	L3–L4				
	L5–S1	3.8 ± 4.5	5.8 ± 4.9	4.7	42
σ^c (degrees)	L1–L2	−5.6 ± 3.7	−14.0 ± 5.6	−8.9	18
	L3–L4				
	L5–S1	4.9 ± 7.3	−5.0 ± 11.9	1.1	30
Extension					
Z^c (mm)	L1–L2	1.6 ± 1.0	6.0 ± 3.1	2.6	14
	L3–L4				
	L5–S1				
Z^c% (%)	L1–L2	4.9 ± 3.1	18.3 ± 7.7	8.7	11
	L3–L4				
	L5–S1				
σ^c (degrees)	L1–L2	15.6 ± 10.4	16.4 ± 10.1	N.S.	
	L3–L4				
	L5–S1				

* Force 2 and preload 2 correspond clinically to a person standing with maximum physiological flexion or extension forces applied.
† Mean ± SD.

Table 9. Extreme Test Values to Define Clinical Thresholds of Stability

	Flexion		
	Lumbar (L1–L5)	Lumbrsacral (L5–S1)	Extension (L1–S1)
Z^c (maximum)	2.3 mm	1.6 mm	2.8 mm
Z^c% (maximum)	8%	6%	9%
Θc (minimum)	−9°	1°	*

* No test value is given for Θ with extension forces since there was no significant difference between intact and maximum displacements when the FSU's were physiologically loaded with preload and extension forces.

Table 10. Checklist for the Diagnosis of CLinical Instability in the Lumbar (L1–L5) Spine

Element	Point value*
Cauda equina damage	3
Relative flexion sagittal plane translation >8% or extension sagittal plane translation >9%	2
Relative flexion sagittal plane rotation <−9°	2
Anterior elements destroyed	2
Posterior elements destroyed	2
Dangerous loading anticipated	1

* Total of 5 or more = clinically unstable.

width be used instead of actual horizontal displacements (Figure 6). Because of the significant differences between the observations on the lumbar and lumbosacral spine, two checklists are presented, Tables 10 and 11.

DISCUSSION

Previous studies have concentrated on the motion of the intact FSU, with and without preload forces applied, or the motion of the FSU as a function of transection of its components with only flexion or extension forces applied and no preload. The present study is different in that it involves study of the motion of both the lumbar and lumbosacral spine as a function of transection of components with both preload and flexion/extension forces applied. Although the muscles of the lumbar region play a role in the stability of the spine, knowledge of the contribution of the osseous and ligamentous structures can contribute greatly to the understanding of clinical stability of the spine. This is especially relevant when the forces studied correlate with those known to exist in the clinical situation. We have reported the results for three of the eight force conditions that we studied, where force 2 corresponds to a maximum physiologic flexion or extension force applied; force 2 and preload 1 corresponds to a person lying supine with a maximum physiologic flexion or extension force applied, and force 2 and preload 2 correspond to a person standing with a maximum physiologic flexion or extension force applied.

Two different reference coordinate axes were used to present the displacement data of the specimens due to load. The first coordinate system was used in the experimental measurement of motion and angulation. In this sytem of axes, the orientation of the loaded specimen is compared with the initial unloaded position to determine displacements. In the clinical situation, however, there is insufficient information available to reliably describe the no-load position of the vertebra. Therefore, a second reference system is required for clinical application to describe the absolute position of the two vertebra in the FSU relative to each other. This method of measurement can be used to differentiate intact spine conditions from transected-type conditions, with a slight decrease in statistical significance due to the variability of the geometric characteristics of each FSU.

The results of the study of the intact lumbar spine by Nachemson et al[21] were obtained using similar loading and displacement measurement techniques and therefore may be comparable with the results of our present study. The reference coordinates used in both cases were experimental axes detailed above. The horizontal displacements due to the flexion/extension loads measured in our study were approximately three times as large as those measured by Nachemson et al. This difference most likely results from the difference in the flexion/extension forces and preloads that were applied and possibly from the relatively short time, 15 seconds, allowed in that study for the specimen to creep. Panjabi et al showed that the displacements of a specimen will continue to increase under the action of a constant load for significant periods of time and that four minutes is an appropriate period of time to allow for creep to occur.[23]

The displacement measurements for the intact spine when subjected to loads yield important data for the clinician faced with the decision of fusion in a patient with pain in his low back region. Guidelines can be defined for the normal motion of the intact spine. These clinical guidelines are different for the lumbar (L1–L5) and lumbosacral (L5–S1) regions when flexion and preload forces are considered. These values, for both preload and flexion/extension forces, are summarized in Table 12. These intact maximal ranges certainly ought to be considered before a clinical decision to fuse a lumbar or lumbosacral spine for pain

Table 11. Checklist for the Diagnosis of CLinical Instability in the Lumbosacral (L5–S1) Spine

Element	Point value*
Cauda equina damage	3
Relative flexion sagittal plane translation >6% or extension sagittal plane translation>9%	2
Relative flexion sagittal plane rotation <1°	2
Anterior elements destroyed	2
Posterior elements destroyed	2
Dangerous loading anticipated	1

* Total of 5 or more = clinically unstable.

Table 12. Clinical Guidelines to Define Displacements of the Intact FSU

	Flexion (mean ± 1 SD)		Extension (mean ± 1 SD)
	Lumbar	Lumbosacral	
Z^c (maximum)	1.7 mm ± 0.6 mm	1.0 mm ± 1.2 mm	2.1 mm ± 0.7 mm
Z^c% (maximum)	6% ± 2%	4% ± 4%	7% ± 2%
Θ^c (minimum)	−6° ± 4°	5° ± 7°	16° ± 10°

due to "instability" is made. This is obviously a rather complex clinical point. The authors simply wish to emphasize that displacements of this magnitude can occur in a physiologically loaded, *intact* spine. Therefore, it may be illogical to assume that displacements of this magnitude indicate clinical instability.

The significant difference between displacement measurements of the lumbar and lumbosacral regions in the flexion sequences most probably results from the orientation of the apophyseal joint and the thickness of the disc.[38] The apophyseal joints at the L5–S1 level are oriented more in the frontal or X–Y plane, while higher in the lumbar spine they are oriented in the sagittal or Y–Z plane. The L5–S1 disc is also thicker than the other discs, which would allow for additional motion. It should also be noted that in our particular specimens the aponeurosis of the longissimus muscle was not preserved for testing so that the transection sequence for the L5–S1 data with a flexion force began with the ligamenta flava. Therefore, the intact displacements are likely to be slightly greater than for the true population.

Motion of the FSU generally demonstrates a gradual progressive displacement as components are transected. There is a more marked increase with transection of the apophyseal joint and posterior longitudinal ligament for the flexion sequences. Flexion and extension forces, when studied alone or in combination with different preloads, yield patterns of motion which are markedly similar. The only major difference is the rotation of the upper vertebral body when a preload force and an extension force are applied. In this case, there is no statistically significant difference in displacement as components are transected. This suggests that *in vitro* when preload is applied the spine is more stable with the anterior components destroyed, and an extension force is applied, as opposed to when the posterior components are destroyed and a flexion force is applied. Failure in all cases was sudden and complete, with specimens failing when all posterior components plus one additional anterior component were transected in the flexion sequence, and all anterior plus two additional posterior components were transected in the extension sequence.

Since the most clinically relevant outcome of this work is the two clinical stability checklists, an explanation of the rationale behind them is appropriate. They are designed to have the clinician utilize all relevant information in making the decision about stability. The lists are intended to include some internal checks and balances so that no particular criterion or unit of information determines the decision, and the relative importance and reliability of the units are weighted. The weighting is achieved by assigning numbers to the individual criteria based on their significance. Finally, the user has the option of giving some portion of the full weighting, that is, a 1 instead of a 2 or 3, when there is a borderline finding or interpretation.

Cauda equina damage due to displacement is included and heavily weighted for the following reasons. If there has been significant enough displacement to allow damage to these structures which lie in an area where there is usually some free space, then presumably there must have been significant damage to the spinal components. Moreover, we assume that some degree of displacement is at risk of recurring. Table 10 is different from Table 11 because of the statistically significant differences in motion of the lumbar and lumbosacral spines when flexion and preload forces are applied. In cases where extensive vertebral body compression occurs, as opposed to "pure" dislocations, the disc angle is usually not altered. The criteria used would then only include the percentage translation and not the angulation.

Identification of anterior and posterior elements destroyed or unable to function is based on the qualitative analyses presented in Table 5. This is determined by interpretation of the roentgenograms and/or the history. We recall that trauma, surgery, or tumor may result in the loss or failure of function of either all the anterior elements or all the posterior elements. We know, for example, that when there is obvious malpositioning of the lumbar spine spinous processes there is a great probability that the posterior elements are damaged and unable to function, due to dislocation, fracture, or fracture dislocation of the posterior element.

Finally, we come to the concept of dangerous loads anticipated. In the definition of instability, the term "physiologic loads" is used. It is sometimes the case that for a given patient the physiologic loads are going to be dangerously high, as with an interior lineman on a football team or a weight lifter. In these and similar

circumstances, an additional 1 should be scored in the checklist. A total of 5 or more constitutes a diagnosis of clinical instability, and the patient must be managed with full recognition of this diagnosis.

SUMMARY

We have studied lumbar and lumbosacral Functional Spinal Units (FSUs) under conditions that simulate maximum physiologic flexion and extension under preloads which are analogous to lying and standing. The sagittal plane translations and rotations of transected FSUs have been measured and compared with the measurements of the intact FSU. The following conclusions may be drawn based on the data collected:

1. There are no statistically significant differences between the motion of the L1–L2, the L3–L4, and the L5–S1 FSUs, when loaded with both physiologic preload and extension forces.
2. There are statistically significant differences in the motion of the intact FSUs in the lumbar (L1–L5) and in the lumbosacral (L5–S1) spines, when loaded with both physiologic preload and flexion forces.
3. In the tests to failure with flexion simulated and components being destroyed from posterior to anterior, all FSUs failed when all the posterior components plus one anterior component had been destroyed.
4. In the extension sequences with destruction of components from anterior to posterior, all FSUs failed when all the anterior components plus two posterior components were destroyed.
5. The site of failure of the anterior elements was at the disc, with the annulus fibers and the cartilaginous end-plate pulling off the vertebral body.
6. The site of failure of the posterior elements was at the attachment of the ligaments to the bone.
7. In extension loading with sequential component destruction as compared with flexion, the preload appeared to protect the FSU from excessive extension sagittal plane rotation.
8. In flexion sequences, the preload added to the excessive flexion sagittal plane rotation.

The findings of the experiments are incorporated into two checklists for the evaluation of clinical stability in the lumbar and the lumbosacral spines, respectively.

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CONFERENCE ON SPINAL DISORDERS

"Spinal Disorders in Children," a St. Louis University Medical Center conference, will be held October 29–30, 1982 at the St. Louis Sheraton Hotel, St. Louis, Missouri. Sponsored by the department of orthopedic surgery at the medical center and Cardinal Glennon Memorial Hospital for Children, St. Louis, the conference is designed for orthopedic surgeons and other physicians involved with the treatment of spinal disorders in children. Topics to be discussed include spinal trauma, spinal deformities, infections, tumors and other spinal disorders.

Faculty from across the country will be speaking and include Marc A. Asher, MD, University of Kansas Medical Center; Edgar G. Dawson, MD, UCLA School of Medicine; Robert W. Gaines, MD, Shannon Stauffer, Southern Illinois University-Springfield; Lyle J. Micheli, MD, Harvard Medical School, Perry L. Schoenecker, MD, Washington University School of Medicine and Robert B. Winter, MD, University of Minnesota. For further information, contact Behrooz A. Akbarnia, MD, Department of Orthopedic Surgery, St. Louis University Medical Center, 1325 S. Grand Blvd., St. Louis, MO 63104, tel. (314) 577-5646.

SCOLIOSIS AND KYPHOSIS CONGRESS

The First European Congress on Scoliosis and Kyphosis will be held in Dubrovnik, Yugoslavia, October 5–9, 1983. The Chairman is P. Stagnara, France; the President of the Scientific Committee is A. L. Nachemson, Sweden; the President of the Organizing Committee is M. Pećina, Yugoslavia. For information, contact:

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