

A BIOMECHANICAL STUDY OF THE LIGAMENTOUS STABILITY OF THE THORACIC SPINE IN MAN

MANOHAR M. PANJABI¹, JEFF N. HAUSFELD¹ & AUGUSTUS A. WHITE, III²

¹Engineering Laboratory for Musculoskeletal Diseases, Division of Orthopaedic Surgery, Yale Medical School, New Haven, CT and ²Department of Orthopaedic Surgery, Beth Israel Hospital and Harvard Medical School, Boston, MA, USA

An *in vitro* study was conducted to establish the thresholds of thoracic spine stability. Flexion or extension producing horizontal forces of 43 percent body weight were applied to fresh two-vertebrae spine specimens. Spine components were transected in two different sequences until failure. Load-displacement curves were measured.

Intact spine exhibited average inter-vertebral horizontal translatory displacement of 1.0 mm (s.d. = 0.4) and sagittal plane rotation of 1.4 degrees (s.d. = 0.8). Just prior to failure these average displacements increased to 2.4 mm (s.d. = 1.4) and 4.1 degrees (s.d. = 1.7). A horizontal displacement of 2.5 mm (on lateral X-ray) or 5 degrees of angulation of one vertebra with respect to the other may indicate an unstable spine. This information, together with other clinical indicators of spine instability discussed here, will be helpful in the clinical judgment regarding an injured spine.

Key words: biomechanics; extension stability; flexion stability; spine biomechanics; spine stability; thoracic spine

Accepted 12.x.80

Quantitative assessment of clinical stability of the spine in an injured patient is of paramount importance. Once the information becomes available, appropriate clinical judgment can be made to decide if the patient is to have minor treatment such as a brace or perhaps major treatment in the form of surgery such as spinal fusion. At this time, precise methods of quantification of clinical stability of the thoracic spine after injury are not available although some interesting biomechanical studies have been done.

The Functional Spinal Unit (FSU), consisting of two vertebrae and the interconnecting soft tissue, may be considered as the smallest working unit of the spine. *In vitro* stability studies of the spine may, therefore, be advantageously conducted using the FSU. There have been several

biomechanical studies of the individual soft tissue components of the FSU (Hirsch & Nachemson 1953, Galante 1967, Nachemson & Evans 1968, Silver 1954, Tkaczuk 1968). However, there are only a few studies describing the functional roles of the various components in providing stability to the spine. Munro (1965) referred to spine stability but made no experimental studies. Farfan et al. (1969) determined experimentally the torsional behavior of the lumbar spine segments and estimated the functional contribution of the disc, facet joints, capsular ligaments, and interspinous ligaments to the rotational stability of the spine. White & Hirsch (1971) and Markolf (1972) reported increased rotatory motion of the thoracic spinal units subjected to torsion with transection of the posterior elements. Panjabi et al. (1975)

and White et al. (1975) described the stability of the cervical FSU under flexion and extension loads. Panjabi et al. (1978) described the sequential contribution of the various ligaments of the cervical spine (five vertebrae segments) subjected to distraction forces. To our knowledge, there have been no biomechanical studies dealing with the stability of the thoracic spine.

The purpose of this presentation is to describe an *in vitro* experiment where thoracic functional spinal units were loaded to failure under the application of either a flexion or an extension producing horizontal force. Various ligaments were sequentially transected and biomechanical parameters recorded. The results provide precise information concerning the mechanical stability of the thoracic spine as a function of the various ligaments, disc and facet joints for the loading conditions used. This will help to provide a better understanding in the decision making process concerning an injured spine.

METHODS

Specimen preparation

The spine specimens were obtained from fresh cadavers. At the time of removal, care was taken not to destroy the transverse processes and to save about 3 cm of ribs on either side. Only spines free from diseases that affect the soft and hard tissues were included in the study. The spines were double-bagged and placed in the freezer at -20°C for storage. It has been shown that such storage does not significantly affect the physical properties of bone (Sedlin & Hirsch 1966), the annulus fibers of the disc (Hirsch & Galante 1967), or the longitudinal ligaments (Tkaczuk 1968).

At a subsequent date the spine specimen was thawed to room temperature and divided into appropriate functional spinal units. Each FSU was cleaned of all musculature. X-rays were taken and the geometrical center of the upper vertebral body was established, as described by Panjabi et al. (1976). A 6.35 mm diameter threaded steel rod was threaded through a hole drilled into the geometric center. The rod was placed so that it lay in a horizontal plane in the medial-lateral direction. Screws and pins were threaded into the lower one half of the lower vertebra prior to molding into a quick setting resin cast (AB Plastic Padding, Gothenburg, Sweden). Also molded into the resin cast were two 6.35 mm diameter 7.5 cm long bolts, 5 cm apart. Care was taken to align the mid-disc plane horizontally, at the time of molding. The spine specimen was refrozen for storage and subsequent testing.

Testing apparatus

Figure 1A shows schematically the test apparatus while Figure 1B shows the actual equipment. The prepared specimen was fixed to the test table with the help of the two 6.35 mm diameter bolts. The test table was surrounded by a plexiglass chamber supplied with air of 100 percent relative humidity at room temperature (20°C) to preserve the physical properties of the specimen. A specially constructed measuring jig, consisting of two spherical balls mounted on a plate, was fixed on the superior surface of the upper end plate. On one end of the test table there was a set of pneumatic cylinders that could apply tensile force to the FSU specimen in the horizontal direction. The force was applied to the upper vertebral body of the FSU via two plexiglass bars connecting the pneumatic cylinders to the medial-lateral steel bar. To apply a flexion or extension producing force, the FSU specimen was appropriately turned in the horizontal plane.

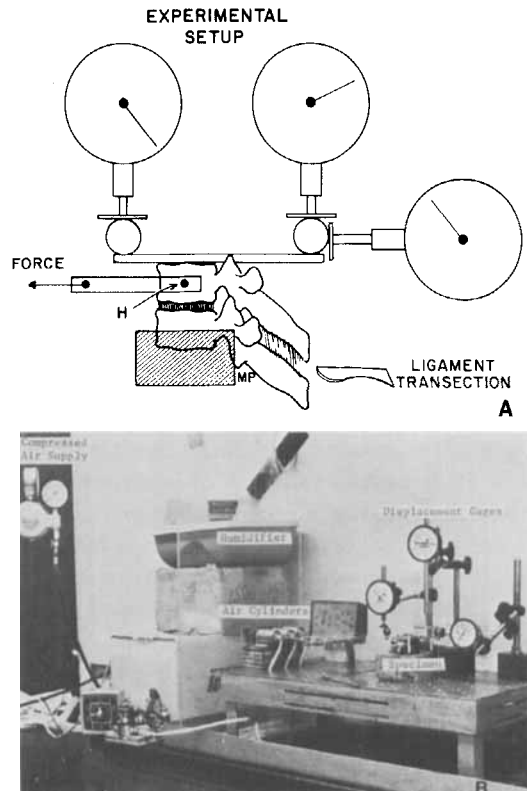


Figure 1. A. Schematics of the experimental set-up. A functional spinal unit specimen is shown being subjected to flexion-type load and its ligaments transected from posterior to anterior. Three dial gages were used to measure the complete sagittal plane motion.

B. Photograph of the experimental set-up.

Table 1. Cutting sequences

ANTERIOR TO POSTERIOR	POSTERIOR TO ANTERIOR
I - Intact	I - Intact
ALL - Anterior Long. Lig.	ISL - Inter- and supra-spinous lig.
AHD - Anterior half of Disc	LF - Ligamentum flavum
CVJ - Costo-Vertebral Joint	CL - Capsular Lig.
PHD - Posterior half of Disc	FJ - Facet joint
PLL - Posterior Long. Lig.	CTL - Costo-transverse Lig.
CTL - Costo-transverse Lig.	PLL - Posterior Long. Lig.
CL - Capsular Lig.	PHD - Posterior half of Disc
FJ - Facet Joint	CVJ - Costo-Vertebral Joint
LF - Ligamentum flavum	AHD - Anterior half of Disc
ISL - Inter- and supra-spinous Lig.	ALL - Anterior Long. Lig.

The sagittal plane motion was measured with the help of three mechanical displacement gages (resolution 0.01 mm) arranged as shown in Figures 1A and 1B. The gages had flat plates that contacted the spherical balls. The overall accuracy of the displacement measuring system was determined by a preliminary experiment in which a given motion was compared to its measurement. Results indicate an overall accuracy of the measurement system of better than ± 0.08 mm for horizontal translation and ± 0.07 degrees for rotation.

The actual *in vivo* load vectors applied to the spine during flexion or extension are not known. We estimated a load of 43 percent body weight applied horizontally in the sagittal plane to be a reasonable physiological load encountered by the thoracic spine in either flexion or extension. This rough estimate was arrived at in the following manner. It is known that the weight of the head and neck is about 10 percent body weight while the weight of the body above L1 is about 60 percent body weight (Ruff 1950). Assuming a linear weight distribution in the thoracic spine the corresponding weight above the T8 vertebra would be about 43 percent body weight. As the actual load vectors are as yet unknown, we believe the chosen value is a reasonable estimate.

Experimental procedure

An initial load of 12 newtons was followed by four load increments so as to obtain loads of 11, 21, 32, and 43 percent body weight for each specimen. The FSU specimen was oriented with respect to the loading system so as to be subjected to either a flexion or an extension load. Two types of ligament cutting sequences were studied: anterior to posterior and posterior to anterior. Details of the two cutting sequences are given in Table 1. The mnemonics used in the table are indicated in Figure 2. Thus, there were a total of four test groups: flexion with anterior to posterior cutting (FAP); flexion with posterior to anterior cutting (FPA); extension with

anterior to posterior cutting (EAP); and extension with posterior to anterior cutting (EPA). A given functional spinal unit was assigned to one of these four test groups.

Steps involved in the testing of a FSU were the following. First a load cycle consisting of five load increments, as described earlier, was applied to the intact FSU. Readings were taken following each load increment application after 3 minutes of waiting so as to allow for creep. At the end of the fifth load increment, the load was removed. The first ligament to be transected was cut and the FSU was subjected to the next load cycle. This was followed by the cutting of the next ligament and so on until failure of the FSU took place. The failure was defined arbitrarily as a complete sep-

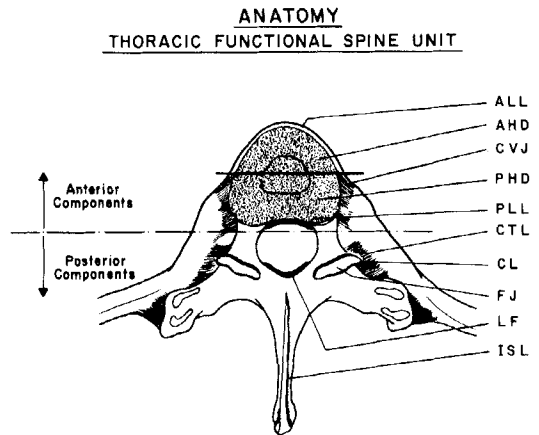


Figure 2. Anatomy of the thoracic functional spinal unit showing the various spine components (ligaments, facets and disc) whose role in providing spine stability was studied. Also indicated is an imaginary boundary, dividing spine components into anterior and posterior groups.

aration of the upper vertebra from the lower vertebra or a movement of the upper vertebra of an amount greater than 10 mm of translation, or 45 degrees of rotation.

Disc degeneration rating

Subsequent to the failure of the functional spinal unit, the degree of disc degeneration was determined macroscopically. The discs were rated according to the criteria presented among others by Rolander (1966). Briefly, these were: grade 0 represents an annulus and a nucleus that are shiny white; grade 1 represents a disc with slightly fibrous nucleus and a distinct boundary between the nucleus and annulus; grade 2 defines a nucleus that is dry and discolored with fissures in the annulus; and grade 3 represents a degenerated nucleus and annulus.

Analysis of data

A lateral X-ray of the functional spinal unit and the measuring jig was taken to provide the coordinates of the centers of the spherical balls with respect to the load application point on the vertebra. Computer programs were written to transform the displacement gage readings into three motion parameters that completely defined the planar motion of the upper vertebra at its point of loading with respect to the lower vertebra. Displacement-load curves were plotted for both the horizontal translation and rotation of the upper vertebra. As load was the independent variable, it was plotted on the horizontal axis. For a given specimen, multiple displacement-load curves were plotted on one and the same graph; thus describing the progressive changes in the behavior of a FSU from intact to its failure.

RESULTS AND DISCUSSION

A total of 19 functional spinal units were tested: four in Flexion, Anterior to Posterior cutting; five in Flexion, Posterior to Anterior cutting; six in Extension, Anterior to Posterior cutting; and four in Extension, Posterior to Anterior cutting. Details of each of the FSU specimens tested and its behavior until failure are presented in Tables 2 to 5. The first five columns in each table describe the spine specimen data: number, vertebral level, subject age, subject weight and the disc grade, respectively. Next is the maximum load (43 percent body weight) used for the particular FSU. Intact maximum load displacement of the FSU is presented in columns 7 and 8 followed by "Prior-to-Failure" behavior presented in columns 9 and 10. The last column shows the "failure ligament" which when cut resulted in failure of the FSU specimen as well as "Prior-to-Failure" ligament in parenthesis.

Typical displacement-load curves for the four test groups are presented in Figures 3 through 6. Each figure has two parts, A and B, showing respectively the horizontal translation-load and rotation-load curves. Mnemonics used for the various curves are explained in Table 1 and Figure 2. Besides the intact and the ligament cut indicators, we have also marked the "Prior-to-Failure" (PtF) curves.

Table 2. Flexion, Anterior to Posterior cutting (FAP)

#	SPINE				Max. Load N	INTACT		PRIOR-TO-FAILURE		Failure* Ligament (PtF Ligament)
	Level	Age yrs	Weight kg	Disc Grade		Horiz. T mm	Rotation deg	Horiz. T mm	Rotation deg	
1**	T11-12	60	64	3	270	0.81	1.96	1.1	2.32	FJ (CL)
4	T 5-6	25	75	0	316	1.17	1.76	1.80	3.50	FJ (CL)
5	T 6-7	66	59	1	249	1.02	1.24	1.17	1.76	FJ (CL)
6	T 4-5	65	60	2	253	0.55	0.5	1.01	0.89	FJ (CL)

* For ligament mnemonics, see Table 1.

** Displacement-load curves of Functional Spinal Unit 1, T11-12, are presented in Figure 3.

Table 3. Flexion, Posterior to Anterior cutting (FPA)

SPINE					Max. Load N	INTACT		PRIOR-TO-FAILURE		Failure* Ligament (PtF Ligament)
#	Level	Age yrs	Weight kg	Disc Grade		Trans. mm	Rotat. deg.	Trans. mm	Rotat. deg.	
1	T 9-10	60	64	3	270	0.53	0.98	0.93	1.83	CVJ (PHD)
3	T 4-5	59	64	3	270	0.78	0.55	1.18	1.90	CVJ (PHD)
4	T 1-2	25	75	0	316	1.94	3.39	3.63	5.99	PHD (PLL)
5**	T12-L1	66	59	1	249	1.05	2.05	1.86	4.93	CVJ (PHD)
6	T 8-9	65	60	2	253	0.67	0.47	0.81	1.80	CVJ (PHD)

* For ligament mnemonics, see Table 1.

** Displacement-load curves of Functional Spinal Unit 5, T12-L1, are presented in Figure 4.

Table 4. Extension, Anterior to Posterior cutting (EAP)

SPINE					Max. Load N	INTACT		PRIOR-TO-FAILURE		Failure Ligament* (PtF Ligament)
#	Level	Age yrs	Weight kg	Disc Grade		Trans. mm	Rotat. deg.	Trans. mm	Rotat. deg.	
1	T 7-8	60	64	3	270	0.87	0.81	2.04	4.08	PLL (PHD)
2**	T 8-9	35	48	0	202	0.74	1.35	1.83	5.02	PLL (PHD)
2	T12-L1	35	48	0	202	0.79	1.17	2.74	4.07	PLL (PHD)
5	T 4-5	66	59	1	249	1.39	1.34	1.87	3.95	PHD (CVJ)
5	T10-11	66	59	1	249	1.05	1.82	3.88	4.49	PLL (PHD)
6	T 2-3	65	60	2	253	1.04	0.88	2.64	6.98	PLL (PHD)

* For ligament mnemonics, see Table 1.

** Displacement-load curves of Functional Spinal Unit 2, T8-9, are presented in Figure 5.

The data given in Tables 2 to 5 are condensed in the form of means and standard deviations and presented in Table 6. Displacements due to maximum load when FSU is Intact and "Prior-to-Failure" are shown in columns A and B. Column C shows the "change" in the displacement from Intact to "Prior-to-Failure". The same change expressed in percentage is shown in Column D.

Comparing the results of the four test groups with each other as is seen in column D, we observe that there were greater changes produced in the groups FPA and EAP as compared to the other two test groups. Therefore, clinically these are the more important test groups. We have combined the results of these two groups FPA and EAP and these are presented in the last row of

Table 5. Extension, posterior to anterior cutting (EPA)

#	SPINE				Max. Load N	INTACT		PRIOR-TO-FAILURE		Failure * Ligament (Pt F Ligament)
	Level	Age yrs	Weight kg	Disc Grade		Trans. mm	Rotat. deg.	Trans. mm	Rotat. deg.	
2	T10-11	35	48	0	202	0.62	0.65	0.67	0.86	AHD (CVJ)
4 **	T 3-4	25	75	0	316	1.43	1.29	1.72	2.83	AHD (CVJ)
5	T 8-9	66	59	1	249	1.26	1.08	1.17	1.54	AHD (CVJ)
6	T 6-7	65	60	2	253	0.65	0.44	1.09	0.54	AHD (CVJ)

* For ligament mnemonics, see Table 1.

** Displacement-load curves of Functional Spinal Unit 4, T3-4, are presented in Figure 6.

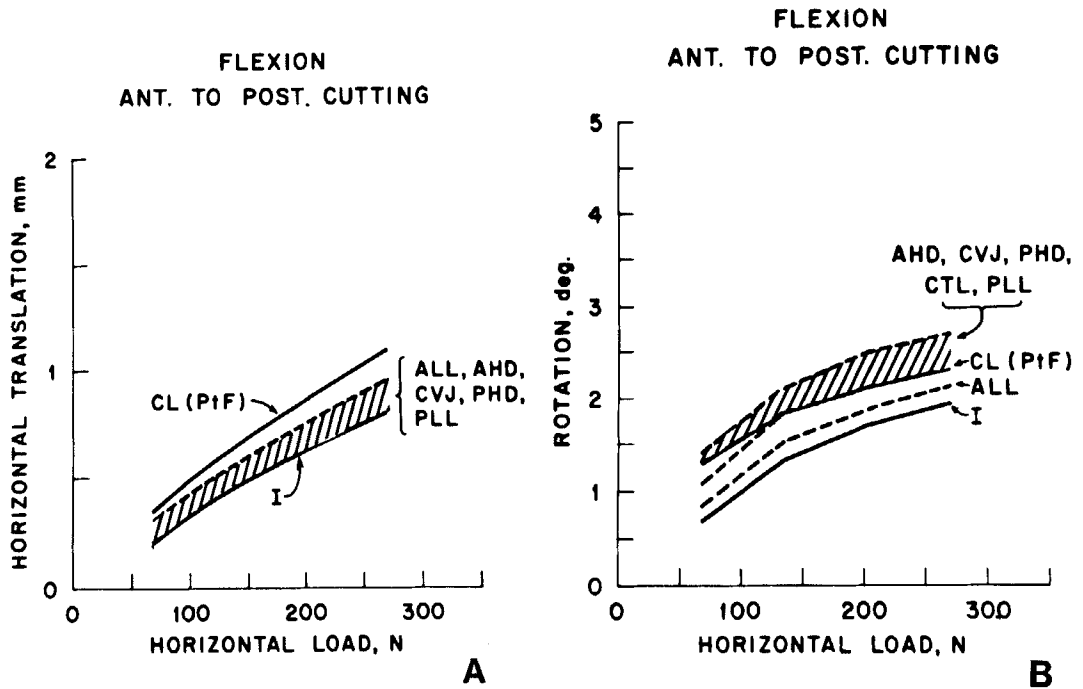


Figure 3. An example of displacement and load curves for flexion load with anterior to posterior cutting. The curve labeled I represents the intact specimen while PtF is the prior-to-failure curve. For mnemonics of the ligaments transected, see Figure 2. (A) Horizontal translation. (B) Rotation.

Table 6. To establish the thresholds of displacement that would separate the stable spines from the unstable ones, we identify the corresponding situations in our study, as the Intact and the "Prior-to-Failure", respectively. In the test

groups showing small changes, i.e. FAP and EPA shown in Tables 2 and 5, there was a large overlap between the Intact and the "Prior-to-Failure" displacements. However, in groups showing large changes, i.e. FPA and EAP shown

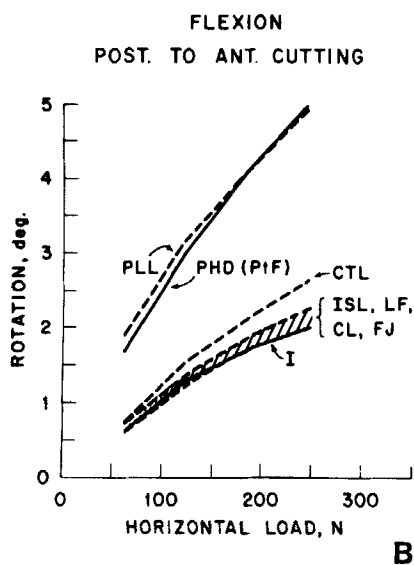
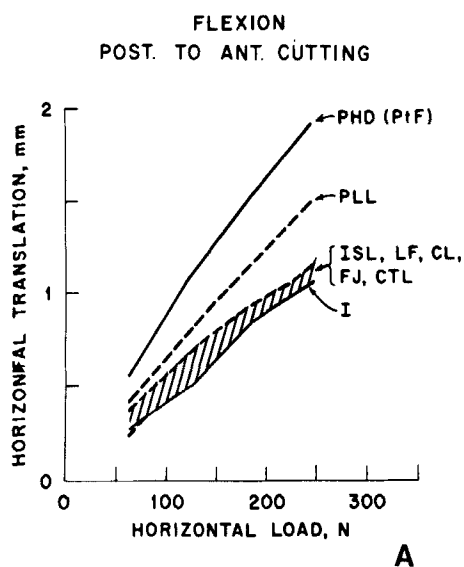


Figure 4. An example of displacement and load curves for flexion load with posterior to anterior cutting. The curve labeled I represents the intact specimen while PtF is the prior-to-failure curve. For mnemonics of the ligaments transected, see Figure 2. (A) Horizontal translation. (B) Rotation.

in Tables 3 and 4, despite the overlap, there were sufficient differences. An attempt was therefore made to establish the thresholds of stability using the latter data. Under the assumption of normal distribution of the data, it was possible to com-

pute the thresholds of instability and the corresponding judgment errors that would be involved, if these thresholds were the only criteria that were used to make a clinical judgment of spine stability. Details of the methodology are given in the Appendix.

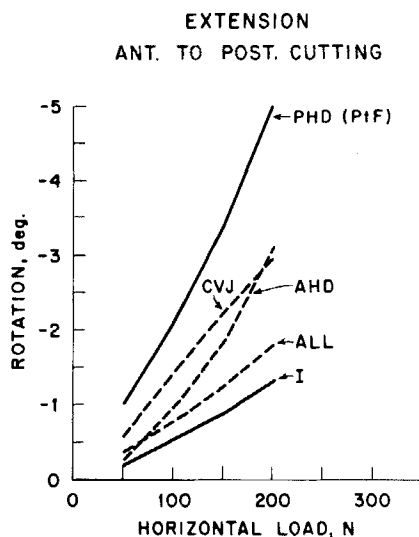
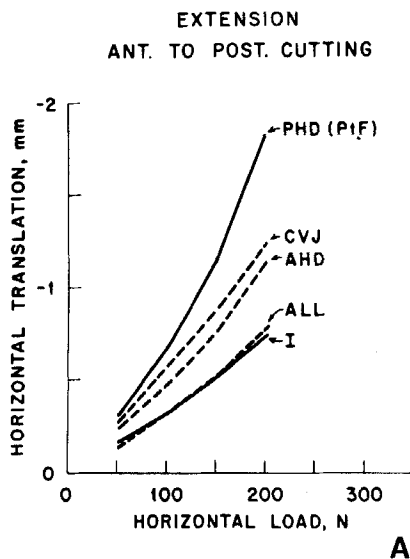


Figure 5. An example of displacement and load curves for extension load with anterior to posterior cutting. The curve labeled I represents the intact specimen while PtF is the prior-to-failure curve. For mnemonics of the ligaments transected, see Figure 2. (A) Horizontal translation. (B) Rotation.

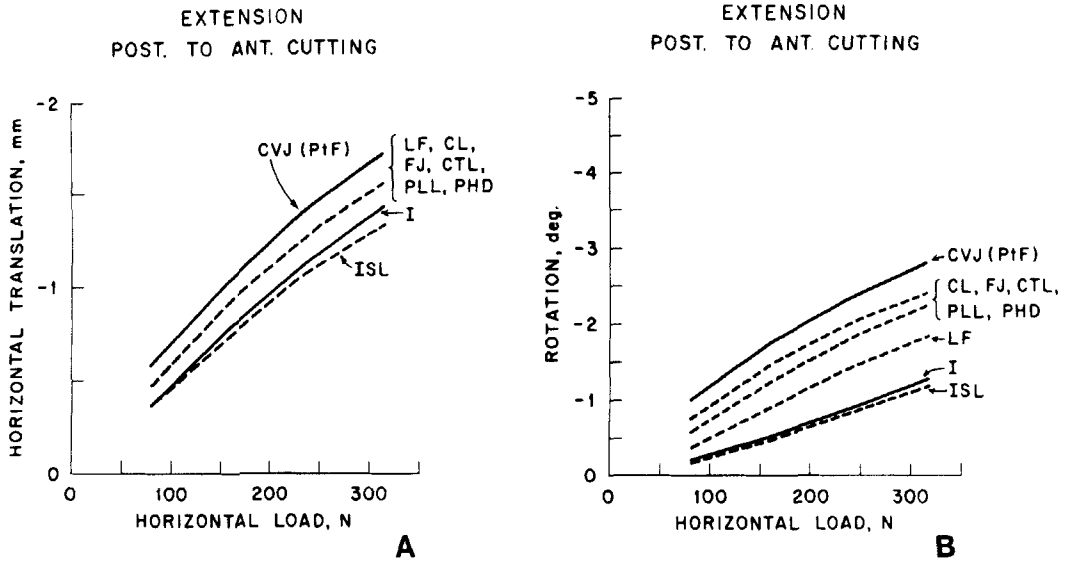


Figure 6. An example of displacement and load curves for extension load with posterior to anterior cutting. The curve labeled I represents the intact specimen while PtF is the prior-to-failure curve. For mnemonics of the ligaments transected, see Figure 2. (A) Horizontal translation. (B) Rotation.

Combining the results of Tables 3 and 4, frequency curves for distribution of Intact and "Prior-to-Failure" data were plotted. Figures 7A and 7B show respectively the results for horizontal translation and rotation in the sagittal

plane. Thresholds of stability or "cut-off points" were established as 1.9 mm of horizontal displacement and 5 degrees of rotation.

A horizontal displacement greater than 1.9 mm (2.5 mm on lateral X-ray accounting for 30 per-

Table 6. Summary of results based upon those given in Tables 2 to 5. Average and (standard deviation) of horizontal translation T and body rotation R of FSU due to a horizontal force of 43 percent body weight are given below. Note especially the results of the clinically important combined group FPA and EAP. The letters, F, E, A, P stand for Flexion, Extension, Anterior and Posterior respectively

Test Groups	Table No.	A. Intact		B. Prior to Failure		C. Change = (B - A)		D. % Change = $\frac{(B - A)}{A} \times 100$	
		T,mm	R,deg.	T,mm	R,deg.	T,mm	R,deg.	T,%	R,%
FAP	2	0.9 (0.3)	1.4 (0.7)	1.3 (0.4)	2.1 (1.1)	0.4	0.7	44	50
FPA	3	1.0 (0.6)	1.5 (1.2)	2.3 (1.9)	3.3 (2.0)	1.3	1.8	130	120
EAP	4	1.0 (0.2)	1.2 (0.4)	2.5 (0.8)	4.8 (1.2)	1.5	3.6	150	300
EPA	5	1.0 (0.4)	0.9 (0.4)	1.2 (0.4)	1.4 (1.0)	0.2	0.5	20	56
FPA & EAP	364	1.0 (0.4)	1.4 (0.8)	2.4 (1.4)	4.1 (1.7)	1.5 (1.2)	2.7 (1.5)	145	201

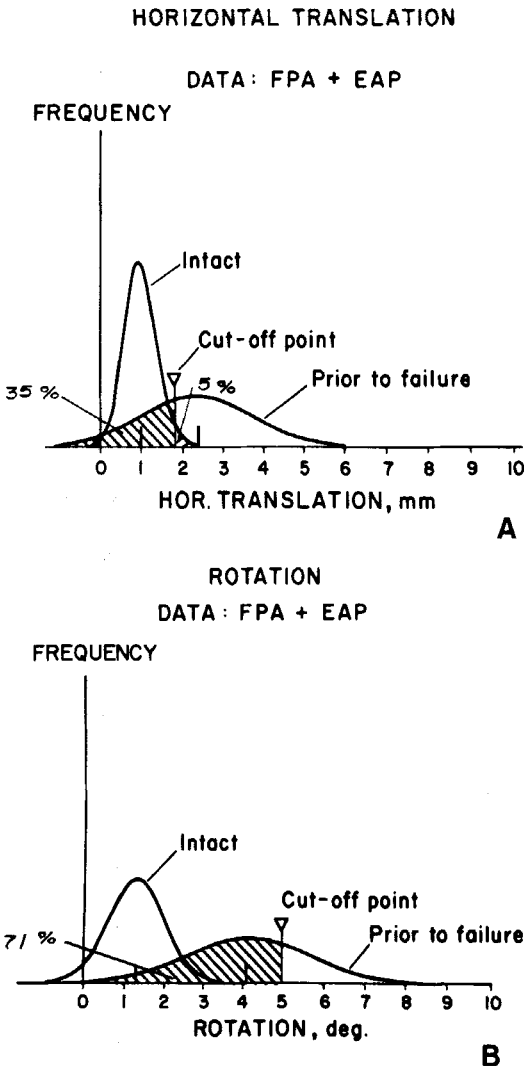


Figure 7. Expected frequency distributions of horizontal translation (A) and rotation (B) for combined test groups FPA and EAP are shown. Normal distribution curves are plotted for intact and prior-to-failure spine specimens. These are based upon normal distribution of the two populations. Also shown are the cut-off points. For details see text.

cent magnification) or rotation greater than 5 degrees of one vertebra with respect to the other in the sagittal plane are suggested as indicators of mechanical instability. The measurement of 1.9 mm was chosen as it represented the upper range of any intact spine tested. The measurement of 5 degrees was chosen on more arbitrary grounds. It

was considered as the minimum angle that may be practical to measure in the clinical set-up. As seen in Tables 2 to 5, the upper range of the intact spine rotation was less than 3.5 degrees.

The use of above thresholds as cut-off points to divide the two populations of Intact and "Prior-to-Failure", will entail certain errors in the classification of both the intact and the injured spines. Assuming normal distributions for the behavior of the Intact and "Prior-to-Failure" functional spinal units, results of the two test groups showing the greatest changes in the mechanical behavior due to injury are shown in Figures 7A and 7B. As seen, the frequency distributions of the two populations for the horizontal displacement are not completely distinct; there is an overlap. Also shown in Figure 7 are the chosen thresholds. If measurements were taken from the lateral X-rays of injured patients and the patients were divided solely on the basis of the chosen stability thresholds, into the stable and unstable populations, then there will be certain errors of judgment. Using the horizontal displacement cut-off threshold only, 5 percent of intact spines will be misclassified as unstable while about 35 percent of injured spines will be misclassified as stable spines. Similarly, using the rotation criteria, Figure 7B, although none of the intact spines will be misclassified nearly 71 percent of the injured spines will be misclassified as stable. In other words, the limitations of using a single criterion, such as the displacement of one vertebra with respect to the other, as the sole indicator of spine instability are obvious. Other factors such as anterior or posterior components destroyed or made non-functional; costovertebral articulations disrupted or made non-functional; or spinal cord or cauda equina damaged, must be taken into account to arrive at the clinical decision. Based upon this type of reasoning, White & Panjabi (1978) have suggested a spine instability checklist which includes several other factors, besides the biomechanical.

Another observation that can be made from the data presented in Tables 2 to 5 and summarized in Table 6 concerns the *minimum* requirements of spinal components for a stable FSU under physiological loads. The test groups that were most unstable, as shown by the per-

centage change due to cutting of ligaments "Prior-to-Failure", were the Flexion with Posterior to Anterior cutting and Extension with Anterior to Posterior cutting. For these two test groups, the ligaments that produced "Prior-to-Failure" situations are indicated in parenthesis in the last columns of Tables 3 and 4. Thus, under flexion loads, the thoracic spine FSU is on the threshold of instability when all ligaments *posterior to and including* the posterior half of the disc (PHD) are cut. Similarly, under extension load, referring to Table 4, the FSU is on the verge of instability when all ligaments *anterior to and including* the posterior half of the disc (PHD) have been cut. To put it in another way, consider the FSU as being made of two sets of components, anterior and posterior (see Figure 2). Results indicate that the spine is on the threshold of instability when either all the posterior set of components *plus* PLL and PHD are cut or all the anterior components *minus* PLL are cut.

The present study was done *in vitro* on fresh cadaver functional spinal units. It is well known that the neuro-musculature control *in vivo* increases the stability of the spine significantly. The stability is also increased when the contribution of the thorax is considered. Andriacchi et al. (1974) have shown that there is an increase of 27 percent in flexion and of 132 percent in extension with the addition of the rib cage. The biomechanical criteria of instability presented here in the form of vertebral displacements as seen on lateral X-rays must be tested and evaluated by clinical experience. The stability checklist which incorporates the biomechanical criteria, once validated by suitable clinical trials, has the potential of providing objective parameters for the determination of clinical stability of the spine in an injured patient.

CONCLUSIONS

We have studied *in vitro* thoracic spine two-vertebrae functional spinal units (FSU) regarding their stability when subjected to either flexion or extension produced by horizontal forces of 43 percent body weight. Effect of cutting the various spinal components, e.g. ligaments, disc and facet

joints, on the stability was investigated for Anterior to Posterior and Posterior to Anterior cutting sequences.

The following conclusions may be drawn from the study.

1. Intact spines exhibited more rotary motion in flexion: 1.4 (0.9) degrees as compared to extension: 1.0 (0.4) degrees. However, the translatory motion was about the same: 1.0 (0.4) mm.
2. Out of the four possible load/injury combinations, the FSU was least stable for the combination of posterior injury with flexion load and anterior injury with extension load.
3. Recommended thresholds of mechanical stability are: 2.5 mm of horizontal translatory displacement, as seen on a lateral X-ray, and 5 degrees of rotatory displacement of one vertebra with respect to the other.
4. The thoracic spine FSU is on the brink of instability (a) under flexion load, when all ligaments posterior to and including the posterior half of the disc are transected and (b) under extension load, when all ligaments anterior to and including the posterior half of the disc are transected.

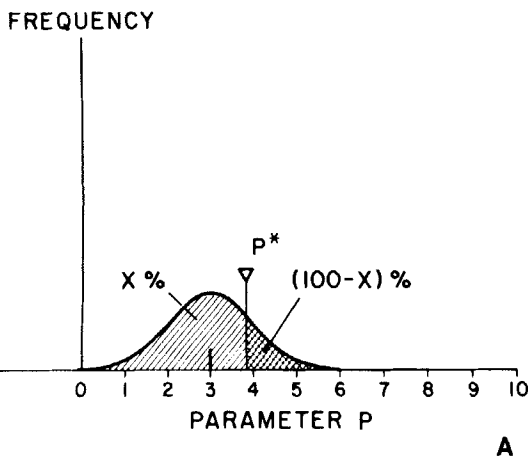
APPENDIX

Frequency distribution of a normally distributed parameter P is shown in Figure 8A. On the horizontal axis is plotted the parameter P and on the vertical axis is its frequency distribution. The curve is mathematically defined by its values of standard deviation and mean. The total area under the curve is 100 percent. The entire population of the parameter P may be divided by a cut-off threshold P^* into two parts: X percent and (100-X) percent, as shown in Figure 8A.

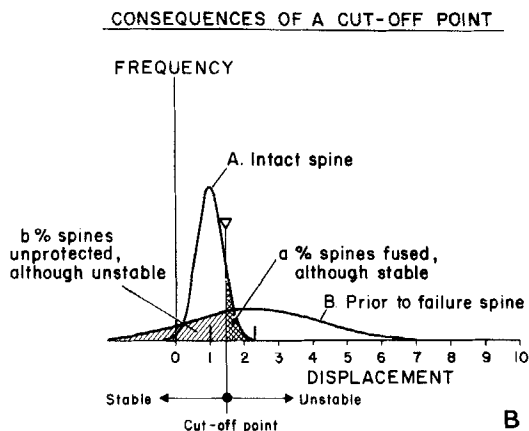
Now consider two overlapping populations A and B, for example: Intact and "Prior-to-Failure" spine populations, as shown in Figure 8B. A cut-off point will divide the two populations such that there will be some parts of populations A, which will be misclassified as belonging to population B, and similarly there will be a certain percentage of population B that will be misclassified as belonging to population A. These are the errors as a result of division of the two populations by a single cut-off point.

Standard Z-transformation and the table of areas of one-tail of the standard normal curve may be used to compute the above errors involved in the division of the two overlapping populations. Details are provided in Colton (1974). As an example of such errors in two normally distributed populations of Intact and Prior-

to-Failure spines the respective errors are indicated by shaded areas in Figure 8B. There will be "a-percent" of stable normal spines that will be misclassified as unstable. On the other hand, there will be "b-percent" of unstable spines that will be labeled as stable.



A



B

Figure 8. A. Area under the frequency distribution curve represents 100 percent of the population. A cut-off point P^* divides this population into X and $100-X$ parts. B. Two overlapping distributions of populations A and B, for example, representing the intact and prior-to-failure spines, respectively. With one cut-off point dividing the two populations, there will be errors of judgment. If the treatment provided was based solely on this cut-off point, a certain percentage of spines (a -percent), although stable, will be fused unnecessarily, and a certain percentage (b -percent), although unstable, will be unprotected. See text for details.

ACKNOWLEDGMENTS

The support for this project was provided by U.S. Public Health Grant NS-19174 and Research Career Development award KO4 AM 00299.

REFERENCES

Andriacchi, T. P., Schultz, A. B., Belytsko, T. B. & Galante, J. O. (1974) A model for studies of mechanical interactions between the human spine and rib cage. *J. Biomech.* **7**, 497-507.

Colton, T. (1974) *Statistics in medicine*. Little, Brown & Company, Boston.

Farfan, H. F. (1969) The effect of torsion on the intervertebral joints. *Canad. J. Surg.* **12**, 336-341.

Galante, J. O. (1967) Tensile properties of the human lumbar annulus fibrosus. Thesis. *Acta Orthop. Scand.*, Suppl. 100.

Hirsch, C. & Galante, J. O. (1967) Laboratory conditions for tensile tests in annulus fibrosus from human intervertebral discs. *Acta Orthop. Scand.* **38**, 148-162.

Hirsch, C. & Nachemson, A. (1953) New observations on the mechanical behavior of lumbar discs. *Acta Orthop. Scand.* **23**, 254-283.

Markolf, K. L. (1972) Deformation of the thoracolumbar intervertebral joint in response to external loads: A biomechanical study using autopsy material. *J. Bone Joint Surg.* **56-A**, 511-533.

Munro, D. (1965) The factors that govern the stability of the spine. *Paraplegia* **3**, 219-228.

Nachemson, A. & Evans, J. (1968) Some properties of the third human lumbar interlaminar ligament. *J. Biomech.* **1**, 211-220.

Panjabi, M. M., White, A. A. & Johnson, R. M. (1975) Cervical spine mechanics as a function of transection of components. *J. Biomech.* **8**, 327-336.

Panjabi, M. M., Brand, R. A. & White, A. A. (1976) Mechanical properties of the human thoracic spine: As shown by three-dimensional load-displacement curves. *J. Bone Joint Surg.* **58-A**, 642-652.

Panjabi, M. M., White, A. A., Keller, D., Southwick, W. O. & Friedlaender, G. (1978) Stability of the cervical spine under tension. *J. Biomech.* **11**, 189-197.

- Rolander, S. D. (1966) Motion of the lumbar spine with special reference to the stabilizing effect of posterior fusion *Acta Orthop. Scand.*, Suppl. 90.
- Ruff, S. (1950) Brief acceleration: Less than one second. *German Aviation Medicine, World War II*, Washington, DC, USA Government Printing Office, 584–597.
- Sedlin, E. & Hirsch, C. (1966) Factors affecting the determination of the physical properties of femoral cortical bone. *Acta Orthop. Scand.* **37**, 29–48.
- Silver, P. H. S. (1954) Direct observations of changes in tension in the supraspinous and interspinous ligaments during flexion and extension of the vertebral column in man. *J. Anat. (Lond.)* **88**, 550–551.
- Tkaczuk, H. (1968) Tensile properties of human lumbar longitudinal ligaments. Thesis. *Acta Orthop. Scand.*, Suppl. 115.
- White, A. A. & Hirsch, C. (1971) The significance of the vertebral posterior elements in the mechanics of the thoracic spine. *Clin. Orthop.* **81**, 2–14.
- White, A. A., Johnson, R. M., Panjabi, M. M. & Southwick, W. O. (1975) Biomechanical analysis of clinical stability in the cervical spine. *Clin. Orthop.* **109**, 85–96.
- White, A. A. & Panjabi, M. M. (1978) *The clinical biomechanics of the spine*. J. B. Lippincott Co., Philadelphia, PA.

Correspondence to: Manohar M. Panjabi, Dr. Tech., Department of Surgery, Yale Medical School, New Haven, CT 06510, USA.