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Measurement of Cadaver Lumbar Spine Motion Segment Stiffness

Mark D. Brown, MD, PhD, David C. Holmes, MS, and Anneliese D. Heiner, PhD

Study Design. Prospective.

Objectives. To measure lumbar spine motion segment stiffness and relate it to the degree of disc degeneration.

Summary of Background Data. The association between the instability of the lumbar spine motion segment and disc degeneration remains unclear. The traditional method for determining motion segment instability at the time of decompressive surgery is a manual test performed by the surgeon. To quantify instability of the lumbar spine, a vertebrae distractor was developed in the authors' laboratory to measure motion segment stiffness by applying a defined load at a constant rate.

Methods. Lumbar stiffness was measured by subjecting cadaver lumbar spine motion segments to a constant rate flexion-traction load and recording the magnitude of the resistance to distraction *versus* the range of motion. Disc degeneration was measured by pressure-volume discography and by grading of disc morphology.

Results. Motion segment stiffness decreased with the initial stages of disc degeneration and then increased with severe disc degeneration. This measure of motion segment stiffness correlated well with a manual stiffness measure.

Conclusions. The observed results follow an accepted hypothesis of motion segment instability associated with disc degeneration. [Key words: degenerative disc disease, discography, joint instability, lumbar spine, motion segment, spinal diseases, surgical instruments] **Spine 2002; 27:918-922**

Knuttson,[12] Friberg and Hirsch,[7] and Stokes et.al[18] implied that the mechanically unstable lumbar spine motion segment (MS) can originate from degeneration of the nucleus pulposus of the intervertebral disc through a loss of its hydrodynamic properties. A degenerated nucleus, with diminished water content, leads to disc space narrowing, loss of viscoelastic properties, and the subsequent transfer of compressive loads to the anulus fibrosus and facet joints.[2,10,15-17] Disc space narrowing results in a loss of pretension in the ligamentum flavum and longitudinal ligaments, laxity of the facet joint capsule ligaments, and subluxation of the facet processes, leading to an abnormal response to loading of the MS.[1,3,14,18]

The MS usually stiffens as a result of an osteoarthritic reaction to disc degeneration; however, this reaction can be inhibited by repeated injury or exhausted by the degenerative process itself.[11] Progressive disc degeneration can lead to an unstable MS. This instability is defined as an abnormal response to normal loads and is characterized by motion of the MS beyond normal constraints.[8] The excessive motion can be abnormal in quality, *i.e.,* abnormal coupling patterns, or in quantity, *i.e.,* an abnormal increase in motion.[20] The association between clinical instability of the lumbar spine MS and disc degeneration remains unclear. Kirkaldy-Willis observed that in the early stages of disc degeneration the MS becomes relatively unstable and that in the later stages of disc degeneration, with reactive osteophyte formation, the MS becomes stiffer than normal.[11]

The traditional method for determining MS instability at the time of decompressive surgery is a manual test performed by the surgeon. The surgeon places a clamp or towel clip on each of the adjacent spinous processes of the MS and then distracts and relaxes the vertebrae along the axis of the spine. Variations of this method of distraction may include elevation of the spinous processes, assessment of rotational stiffness, or a combination of these tests. From the tactile feedback given by the resistance to distraction and the observed range of distraction, the surgeon assigns a relative stiffness grade to the MS, *i.e.,* loose, normal, or fused.

Lubin et al [13] used a modified laminar spreader to measure the force required to distract adjacent lumbar vertebrae in cadavers. The distraction force and displacement between the vertebrae were recorded for MSs with normal and degenerative discs. Differences in MS stiffness did not correlate with degrees of disc degeneration. The lack of correlation was attributed to using a manually operated distractor where rate of distraction and force applied could not be controlled. Ebara et al[4] reported a correlation between MS stiffness and disc degeneration using a manual lumbar spinal spreader; however, statistical significance was not mentioned. A device for measurement of cervical MS stiffness using Caspar pins has also been reported.[5,6] Most recently, the use of a spinal mobility tester has been described in porcine lumbar spines. [19]

To quantify clinical instability of the lumbar spine, a vertebrae distractor was developed in the authors' laboratory to measure MS stiffness by applying a defined load at a constant rate.[9] Stiffness was measured by distracting the two adjacent vertebrae of an NIS along the axis of the

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From the Department of Orthopaedics and Rehabilitation, University of Miami School of Medicine, Miami, Florida.
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SSG at the Base of the Spinous Processes

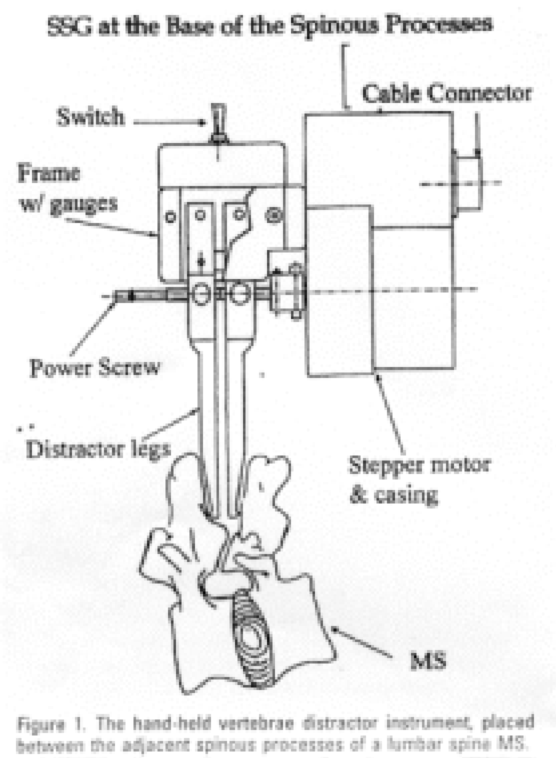


Figure 1. The hand-held vertebrae distractor instrument, placed between the adjacent spinous processes of a lumbar spine MS.

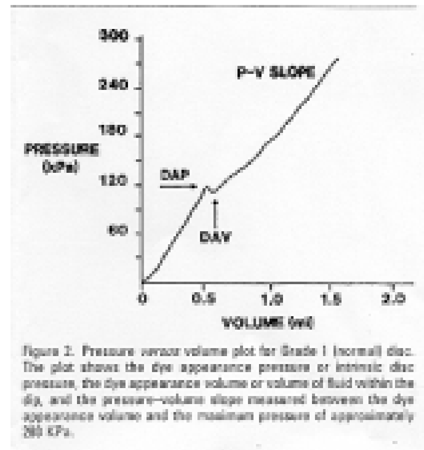


Figure 2. Pressure *versus* volume plot for Grade 1 (normal) disc. The plot shows the dye appearance pressure or intrinsic disc pressure, the dye appearance volume or volume of fluid within the dip, and the pressure-volume slope measured between the dye appearance volume and the maximum pressure of approximately 280 KPa.

spine. The force required to distract the vertebrae and the resulting displacement were recorded.

The objective of this study was to determine the correlations among MS stiffness (measured by the manual test and with the vertebrae distractor), pressure-volume discography measurements of disc degeneration, and morphologic grades of disc degeneration (macroscopically). The pressure-volume test is a proven technique for identifying degenerated discs[2,15-17] and thus provides a numerical measure of the degree of disc degeneration and a basis for comparison of the distraction measurements.

Materials and Methods

A total of 50 MSs from 12 cadavers ranging in age from 21 to 67 years were tested. The spines were removed from cadavers within 24 hours postmortem and were tested immediately or stored at -70 C and thawed to room temperature before testing. The supraspinous and interspinous ligaments were removed along with small sections of the spinous processes to seat the arms of the distraction instrument at the junction of the base of the spinous process with the lamina.

The apparatus for recording simultaneous force-displacement data consists of a hand-held motorized vertebrae distractor (stepper motor model no. 45H-24A56S, Airpax Inc., Chesire, CT) and strain gauges, interfaced to a signal conditioning circuit, computer system and power supply, and connecting cables. The vertebrae distractor is designed to impart to the MS a load along the axis of the spine, similar to that exerted by the surgeon during the manual clamp test described earlier: The distractor arms are placed at the base of the spinous processes (Figure 1). Constant rate rotation of the stepper motor distracts the vertebrae at a constant rate, to a maximum load of 200 N. On reaching the maximum load, the stepper motor reverses direction and the distractor arms close, thus allowing the vertebrae to return to the original starting position and zero load. The rate of distraction was 1.02 mm/sec and the data sampling rate was 20 Hz.

The apparatus for the pressure-volume tests consisted of an infusion/withdrawal pump (Harvard Apparatus, Millis, MA), 30 mL plastic syringe, hydraulic line (2.0 mm I.D.), spinal needle (70 mm, 20 gauge), pressure transducer (model no. p743, Schaevitz Engineering Inc., Pennsauken, NJ), and volume transducer (a linear slide potentiometer attached to the infusion pump), interfaced to the same computer and signal conditioning system. This apparatus has been used previously by the first author.[17] The fluid in the hydraulic system (total volume

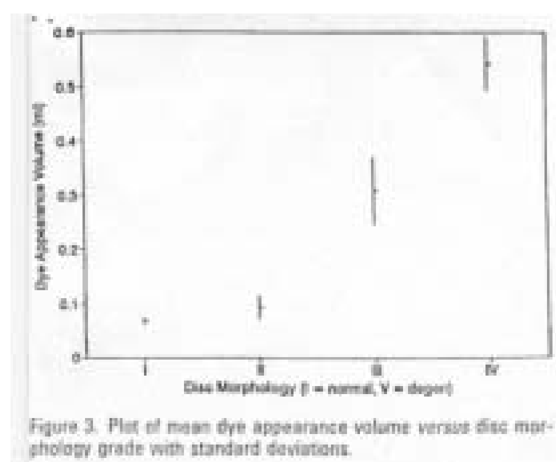


Figure 3. Plot of mean dye appearance volume *versus* disc morphology grade with standard deviations.

Table 1. Mean Values of the MS Stiffness (Load-Displacement Slope), Maximum Displacement, Hysteresis Area, and Kocher Clamp Test Value

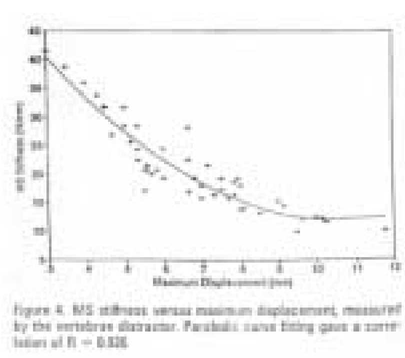
	Mean	Standard Error	Range	n
MS stiffness (N/mm)				
All levels	21.1	1.1	9.9-41.4	50
L5-S 1	19.1	2.2	11.7-35.9	9
L4-L5	17.8	1.9	9.9-28.3	10
L3-L4	21.6	2.8	12.2-41.4	10
L2-L3	20.5	1.8	12.5-31.5	10
L1-L2	25.9	2.1	14.1-38.6	11
Maximum displacement (mm)				
All levels	6.74	0.3	3.00-11.77	50
L5-S 1	7.26	0.6	4.00-10.25	9
L4-L5	7.56	0.7	5.00-11.77	10
L3-L4	6.42	0.6	3.00-9.67	10
L2-L3	7.03	0.5	4.50-10.00	10
Ll-1_2	5.60	0.4	3.50-8.08	11
Hysteresis area (mmZ)				
All levels	505	20.8	217-873	50
L5-S1	451	40.8	299-661	9
L4-L5	559	46.3	341-873	10
L3-L4	457	41.4	217-720	10
L2-L3 . 542		53.2	277-861	10
L1-L2	508	39.0	299-730	11
Kocher clamp test value	.			
All levels	7.4	0.2	2-10	50
L5-S1	6.2	0.7	2-10	9
L4-L5	6.7	0.5	4-9	10
L3-L4	7.6	0.3	6-9	10
L2-1_3	7.7 ,	0.3	6-9	10
LI-L2	8.7	0.2	7-10	11

approximately 50 mL) had a concentration of 20 parts radiopaque dye (Renographin no. 76, 37% iodine) to 1 part of methylene-blue dye. The dye infusion rate of the pump was 1.48 mL/min. The data sampling frequency for pressure and volume was 50 Hz.

The stiffness of each of the five lumbar MSs was,first evaluated by the surgeon (M.D.B.) using the manual clamp test and assigned a stiffness grade between 1 and 10. Grade 1 was defined as so loose that the facet joints dislocate on distraction, and Grade 10 was defined as no relative motion between the vertebrae (functionally fused). The stiffness of each MS was then measured with the vertebrae distractor. Applied force and resulting distraction were recorded simultaneously. The vertebral distraction test gives a plot of applied force *versus* displacement. The plot shows both the distraction and relaxation curves for the MS. The amount by which the legs bend is calculated with beam equations and factored into the force-displacement plot by the system software. The stiffness of the MSU was calculated between the 22 and 67 N force levels of the curve, and the maximum displacement was measured at the maximum applied load of 200 N. Hysteresis was measured as the area between the distraction and relaxation curves, between the 22 and 67 N force levels. The 22-67 N joint loading range was determined as that portion of the curve containing the most repeatable and consistent information. The surgeon who evaluated MS stiffness using the manual clamp test was blinded to the results of the vertebral distractor test.

On completion of the stiffness tests, pressure-volume measurements were made.[17] The spinal needle was inserted anteriorly into the center of the nucleus. The needle position was verified by fluoroscopy. Dye was infused at a constant rate; the subsequent increase in pressure and corresponding volume of infused fluid were recorded simultaneously (Figure 2). The parameters extracted from the plot were the pressure at which the dye entered the nucleus pulposus, representing the intrinsic disc pressure, termed dye appearance pressure, and the slope of the second pressure-volume curve, termed P-V slope. The rise in pressure before the dye appearance pressure represents the compliance within the hydraulic system.

After the pressure-volume tests, the discs were sectioned through the transverse midplane and graded visually based on the morphology of the anulus and nucleus. Morphology grades were assigned as follows: Grade 1 = dye contained within a normal shaped nucleus; Grade 2 = irregularly shaped nucleus;



Maximum Displacement (mm)

Figure 4. MS stiffness *versus* maximum displacement, measured by the vertebrae distractor. Parabolic curve fitting gave a correlation of R = 0.926.

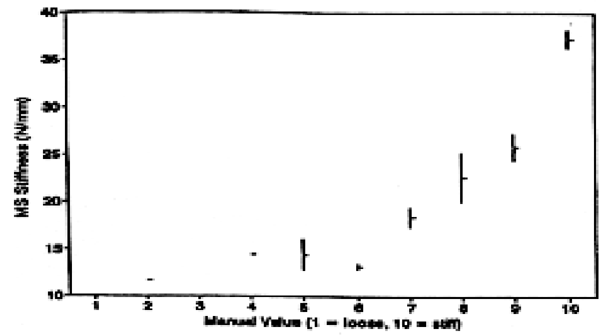


Figure 5. Plot of mean MS stiffness, measured by the vertebrae distractor, *versus* manual clamp test value with standard deviations. This association is linear (R = 0.67)

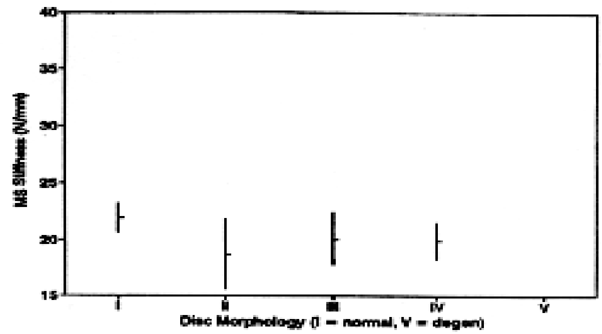


Figure 6. Plot of mean MS stiffness (force–displacement slope) *versus* disc morphology grade with standard deviations.

Disc Morphology (I = normal, V = degen)

Figure *5.* Plot of mean MS stiffness, measured by the vertebrae distractor, *versus* manual clamp test value with standard deviations. This association is linear (R = 0.671).

Figure *6.* Plot of mean MS stiffness (force-displacement slope) *versus* disc morphology grade with standard deviations.

Grade 3 = anular tears, nucleus herniation, or leakage of dye from the confines of the disc; Grade 4 = severe degeneration of the nucleus pulposus; and Grade 5 = severe degeneration involving the nucleus pulposus and the anulus fibrosus.

• Results

Of the 50 cadaver MSs, 46 were successfully tested with the pressure-volume apparatus. Of these, 26 were Grade 1 (normal) as determined by gross morphology, 6 were Grade 2, 10 were Grade 3, and 4 were Grade 4. There was a statistically significant linear correlation (R = 0.79) between the dye appearance volume and the disc morphology grade (Figure 3).

The mean, standard deviation, and range of the MS stiffness (force-displacement slope), maximum displacement, and hysteresis of the MS stiffness curve were determined for the MSs as a whole and for each MS level (Table 1). There was an inverse, nonlinear association ($y = 0.485x^2 -- 10.361x + 67.130$, R = 0.926) between the stiffness and the maximum displacement for the MSs (Figure 4). There was no significant difference in stiffness, maximum displacement, or hysteresis between the MS levels. No statistical correlation was found between the measured hysteresis area and the lumbar level, stiffness, or maximum displacement. There was a linear correlation (R = 0.67) between MS stiffness and the values from the manual clamp test (Figure 5).

MS stiffness was plotted for each disc morphology grade (Figure 6) to enable identification of the parabolic behavior of MS stiffness in relation to degeneration of the intervertebral disc, as measured by gross morphology. The MS stiffness first decreased, then increased, with the increasing disc degeneration. This pattern may represent a loss of MS stability with the initial stages of disc degeneration and an increase in MS stability with increasing degrees of disc degeneration. However, an analysis of variance test revealed that there was no significant difference in MS stiffness between the disc morphology grades (P = 0.46). Disc morphology Grade 5 was not included in the statistical analysis because this group consisted of only one data point.

• Discussion

The easiest way to measure MS stiffness was to use the slope of the force-displacement curve, as opposed to maximum displacement or hysteresis. The inverse association between the MS stiffness and the maximum displacement (Figure 4) implies that the stiffness measurement is proportional throughout the full range of motion. A very stiff MS has a limited range of motion between the vertebrae, and a loose MS has an excessive range of motion.

Kirkaldy-Willis hypothesized that there are three major phases of MS degeneration.[11] In Phase 1 (dysfunction; this study's Grade 2), the MS does not function normally but morphologic changes are small. In Phase 2 (instability; this study's Grade 3), the MS shows abnormal increased motion when subjected to flexion-extension, lateral bending, or axial rotation; the disc has diminished contents and a bulging anulus. In Phase 3 (restabilization; this study's Grades 4 and S), disc degeneration, fibrosis in the facet joint capsules and disc, and osteophyte formation result in minimal movement between the vertebrae.

The nonlinear association between MS stiffness and disc morphology grade (Figure 6) quantitatively substantiates Kirkaldy-Willis's hypothesis that an association exists between MS stiffness and the degree of disc degeneration. The MS stiffness decreased with the initial stages of disc degeneration (Grades 2 and 3) and increased with increasing degrees of disc degeneration (Grades 4 and 5). Measurements of abnormal motion from lateral bending and axial rotation are beyond the scope of this device and undoubtedly contribute to spinal instability.

• Conclusions

The vertebrae distractor stiffness measure correlated well with the surgeon's subjective stiffness measure. Motion segment stiffness appears to be dependent on disc morphology and fits Kirkaldy-Willis's description[11] of the three stages of disc degeneration; MSs in the initial stages of disc degeneration are more compliant, and those with advanced stages of disc degeneration are stiffer and more stable.

■ Key Points

- To quantify instability of the lumbar spine, a vertebrae distractor was developed to measure motion segment stiffness by applying a defined load at a constant rate.
- The vertebrae distractor stiffness measure correlated well with the surgeon's subjective manual stiffness measure.
- The nonlinear association between motion segment stiffness and disc morphology grade quantitatively substantiates Kirkaldy-Willis's hypothesis that an association exists between. motion segment stiffness and degree of disc degeneration.

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Address correspondence to

Mark D. Brown, MD, PhD
University of Miami School of Medicine
Department of Orthopaedics and Rehabilitation (R-2)
P.O. Box 016960
Miami, FL 33101
E-mail: mbrown@med.miami.edu