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The Role of the Sternum, Costosternal Articulations, Intervertebral Disc, and Facets in Thoracic Sagittal Plane Biomechanics

A Comparison of Three Different Sequences of Surgical Release

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Study Design. Eighteen human torsos were used in three experiments (A, B, and C) to determine the changes in sagittal motion due to three different sequences of three surgical releases.

Objectives. To investigate the relative effects of releasing the intervertebral disc, the costosternal joint, the sternum, and the facet joints on sagittal thoracic motion and the consequences of altering the sequence of the releases.

Summary of Background Data. The biomechanics of the thoracic spine are different from the cervical and lumbar spine particularly due to the ribs and sternum, which contribute to stability and control motion. The role of the sternum and costosternal articulation in the biomechanics of thoracic sagittal motion has not been well studied. The effects of releasing each of these structures, whether alone or with discectomy and/or facetectomy, is potentially relevant in the surgical correction of thoracic deformities, such as severe kyphosis, and in the biomechanics of thoracic fracture.

Methods. In Experiment A, the release sequence was back to front: total facetectomy (T4–T8), then radical discectomy (T4–T8), then costosternal release, then sternal osteotomy. In Experiment B, the release sequence was front to back: sternal osteotomy, then costosternal release, then radical discectomy, and finally total facetectomy. In Experiment C, the release sequence was: radical discectomy, then sternal osteotomy, then costosternal release, then total facetectomy. The different sequences allowed separate analysis of each component and the synergistic patterns. In each of the three experiments, the torso was flexed then extended each time by an applied force (25 N) before and after each release. The extent of flexion and the extent of extension were measured each time and compared with the intact condition, after each release.

Results. The results obtained for sternal osteotomy were combined with the results obtained for costosternal release to give "sternal release." Radical discectomy provided the greatest increase ($P < 0.05$) in range of motion (ROM) compared with the other two single releases, no matter what the sequence. For paired release combinations, the radical discectomy and sternal release (as in Experiments B and C) provided a significant ($P < 0.05$) increase in total sagittal ROM compared with the combination of radical discectomy and total facetectomy (Experiment A). In Experiment A, sternal release accounted for 42% of the total sagittal ROM compared with only 26% related to the total facetectomy (Experiment B). In general, all of the releases allowed more extension than flexion.

Conclusions. Sagittal plane motion in the thoracic spine is influenced by all three structures tested in this experiment. Overall, the radical discectomy provides the greatest increase in total ROM and in extension compared with the other two releases. The second most influential release is the combination of sternal osteotomy plus costosternal release (*i.e.*, sternal release), particularly in extension (correction of kyphosis). When two releases are done in sequence, radical discectomy plus sternal release provides the greatest increase in total ROM and in extension. Overall, total facetectomy is the least effective release. These data have relevance for surgical strategies in the correction of thoracic kyphosis or lordosis and suggest a potential role for sternal osteotomy and costosternal release in severe and rigid upper thoracic kyphosis.

Key words: biomechanics, thoracic spine, intervertebral disc, sternum, costosternal joint, facet joint, osteotomy, release, sternal fracture. **Spine 2005;30:2014–2023**

In terms of anatomy and biomechanics, the thoracic spine is different from the cervical and lumbar spine. In addition to the disc, facet joints, related capsules, and ligaments, the ribs and sternum play an important role in controlling and restricting motion. The sternum and costosternal joints are obviously critical in respiratory mechanics but are also potentially important structures in the biomechanics of thoracic fracture and thoracic deformity correction. Spine surgeons tend to perform facetectomy or discectomy in correcting thoracic deformity, with the sternum and its costal articulations usually not addressed in the treatment strategy.

In a previous report, the authors demonstrated that radical discectomy (the combination of rib head resection and total circumferential discectomy) allows the greatest increase in thoracic range of motion (ROM)

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compared with facetectomy or standard discectomy.[1] Kaneda *et al* reported on the clinical results of surgical treatment in scoliosis patients and concluded that rib head resection combined with discectomy allowed better spine correction and better reduction of the rib hump.[2] Posterior element release has been reported to allow an increase in motion of the thoracic spine in both the sagittal plane and axial rotation.[3] However, the ribs and sternum, which could also significantly restrict motion, were not included as releases in those experiments.

Many authors think that the functional spinal unit of the thoracic spine includes not only the two adjacent vertebrae and the interconnecting soft tissue, but also the sternal-rib complex.[4–6] Golpalakrishnan and el Masri reported that sternal fracture is almost always associated with severe spinal injury.[7] Berg postulated that the sternum and ribs represent a "fourth column" of structural thoracic spine support.[4] Given the observations that the sternum is linked to spinal stability in fracture patients, it could follow that it may also play an important role in thoracic deformity and in correction of severe rigid sagittal plane pathology. Anderson and Horton reported the use of sternal osteotomy plus costosternal release in a patient with severe fixed thoracic kyphosis which could not be corrected after anterior radical discectomy alone.[8] After sternal release, the fixed deformity could be corrected from 110° to 50°.

These reports suggest that the costosternal complex is important in thoracic fracture mechanics and releasing it may be clinically useful in rigid kyphosis. Unfortunately, there is almost no biomechanical work specifically addressing the role of the costosternal complex in spinal function or how this might be applied to spinal deformity. We therefore decided to carry out three separate biomechanical experiments to investigate the effects on sagittal ROM of releasing critical structures that restrict motion of the thoracic spine, and the consequences of changing the sequence of the releases.

■ Materials and Methods

Specimen Preparation. Eighteen fresh human cadaveric torsos (C7–L1), with the intact spine, rib cage, and sternum were obtained from cadavers (average age, 73.6 years; range, 65–82 years). There were no deformities on gross examination and no spine or chest abnormalities on plain radiographs. All specimens were stored at −20 C. Each torso was slowly thawed at room temperature 24 hours before testing. The torso was carefully dissected to preserve costovertebral joints, costosternal joints, facet joints, intercostal muscles, and all ligaments. Both ends of the specimens were cut through the axis of the disc, the remaining disc was removed from the endplate, and all soft tissues were freed from both ends. Three long screws were driven into each of the vertebral bodies of C7 and L1 in a multiplanar direction, with 2 cm of each screw protruding from its vertebra. Each end of the specimen was potted up to its midbody in a 10-mm-diameter polyvinylchloride end cap using dental cement. The screws that protruded from the bodies of C7 and L1 allowed secure fixation between the vertebral body and the cement; thus, C7 and L1 were constrained, but T1–T12 were unconstrained.

Two short screws were then fixed into the upper and lower parts of the sternum and were later used as markers for measuring the length of the sternum at various stages during the biomechanical testing. Throughout the entire subsequent testing procedure, the specimens were kept moist using saline.

Testing Apparatus. The specimen was positioned in the upright posture and a force of 25 N was applied perpendicular to the long axis of the spine by loading a spring balance attached to the C7 end cap, to produce flexion or extension (Figure 1) as appropriate. To record the extent of both flexion and extension, a digital goniometer (Pro Smart Level, Wedge Innovations, San Jose, CA) was attached on top of the C7 end cap. A digital electronic caliper (Starrett Co., Athol, MA) was used to measure the distance between the two screws in the sternum at the extent of extension and at the extent of flexion when the 25-N force was applied (Figure 1). A force of 25 N was chosen after some earlier pilot experiments as appropriate magnitude, allowing the specimen to return to its original, upright position, without irreversible damage.

The force was applied manually until 25 N was reached on the spring balance and the goniometer reading was taken after 5 seconds to allow for equilibrium. We applied the load 6 times and took 6 readings to ensure repeatability. On the sixth loading cycle, the sternum-screw distance was also measured. Three people were required to carry out the experiment.

Experimental Procedures. The 18 torsos were divided into three groups of six specimens each (Experiment A, Experiment B, and Experiment C). Before testing, each specimen was flexed and extended 10 times (each time with a 25-N force as described above). This was done to precondition the soft tissues. The last preload cycle was always flexion, and the specimen was allowed to return to its resting position. The datum only changed about 1° between the time we mounted the specimen and after the 20 preconditioning cycles. We deliberately kept our force at a low value (25 N) (over our long testing procedure) so that we were not permanently deforming the specimen. After this preload session was completed, the datum value from the digital goniometer was recorded as representing the zero position. This position was used for all calculations on a

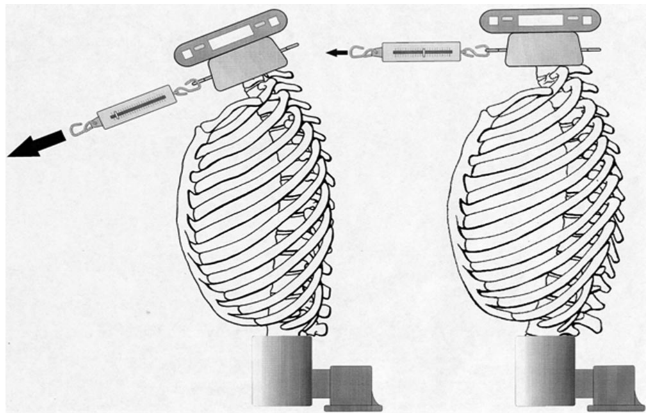

Figure 1. A cadaveric torso is shown clamped in the erect posture. A digital goniometer was attached to the upper end cap. In this left lateral view the torso is being flexed under the application of the 25 -N force applied manually through a spring balance.

particular spine to represent the zero equilibrium, or neutral, upright position between extension and flexion. The specimen was kept moist using saline during the subsequent experiments. The sequences of surgical releases and testing were different for each of the three experiments as follows:

Experiment A (surgical release sequence: total facetectomy, radical discectomy, costosternal release, sternal osteotomy). The specimen was first tested intact. A force of 25 N was applied to produce extension, which was measured using the digital goniometer. The force was always applied perpendicular to the long axis of the spine. The length of the sternum, as measured by the distance between the two screws in the sternum, was measured using the digital caliper when the specimen was at the limit of extension. The specimen was then unloaded and allowed to return to the zero equilibrium position. This procedure of extending the specimen under the action of 25 N was repeated six times to ensure repeatability, and the reading on the digital goniometer was taken each time. Then, a 25-N force was applied to produce flexion, which was measured using the goniometer, and the length of the sternum was again measured when the specimen was at the limit of flexion. This procedure of flexing the specimen was also repeated six times to ensure repeatability, and the reading on the digital goniometer was taken each time. Once the intact specimen had been measured in extension and flexion, the first surgical release (total facetectomy) was carried out.

1) Total facetectomy. Four levels of total facetectomy were then performed from T4–T8 as follows. A laminotomy was carried out using a Kerrison rongeur. The inferior articular processes were excised with a 5-mm osteotome at the level of the caudal border of the transverse process, and a 3-mm Kerrison rongeur was used to remove the superior articular processes. This provided complete excision of the four facet complexes (Figure 2). Each interspinous and supraspinous ligament was left intact and was examined to confirm that there is no calcification bridging between spinous processes. The procedure of applying a 25-N force and measuring the extent of extension and flexion (six times each) was then repeated as described above. The length of the sternum was measured while the specimen was at the limit of extension and again at the limit of flexion. The next surgical release (radical discectomy) was then done:

2) Radical discectomy. Four levels of radical discectomy (T4–T8) were carried out using a standard anterior approach. Thoracotomy was done through a right T4–T5 intercostal space. Rib head resection was performed by incising the parietal pleura over the rib head. The pleura was elevated superiorly and inferiorly with a Cobb elevator. After circumferential subperiosteal exposure of the rib, a Kerrison rongeur was used to divide the rib lateral to the tip of the transverse process. The costovertebral and costotransverse ligaments were divided with a scalpel and curved curette, and the rib head was disarticulated *en bloc*. Hereafter each discectomy was performed removing the anulus and nucleus pulposus with curettes and rongeurs; at the same time, the anterior longitudinal ligament was cut. Care was taken to remove cleanly all accessible disc material, including the posterolateral corner, but the posterior longitudinal ligament was preserved (Figure 3). The procedure of applying a 25-N force and measuring the extent of extension and flexion (six times each), and the length of the sternum was then repeated, as described for the intact specimen. The next surgical release (sternal osteotomy) was then carried out.

3) Costosternal release. Six levels of the anterior costosternal joint (third to eighth ribs) were resected bilaterally in the vertical plane using a scalpel (Figure 4). The procedure of applying a 25-N force and measuring the extent of extension and flexion (six times each) and the length of the sternum was then repeated, as described above. The last surgical release (sternal osteotomy) was then carried out.

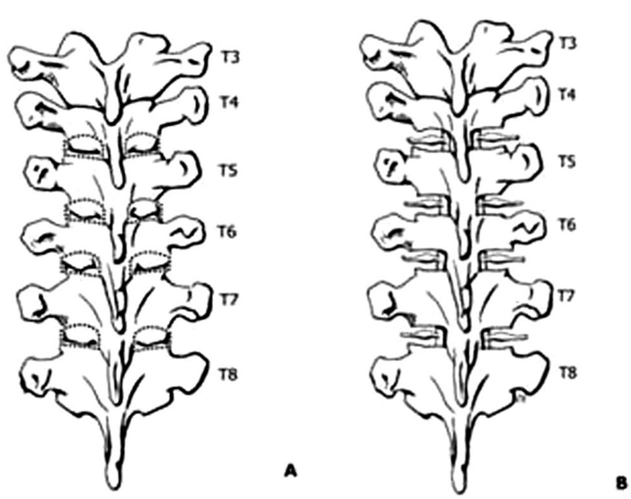

Figure 2. A diagrammatic representation of the posterior view of a thoracic spine from T3-T8. **A,** Intact T4-T8 (the areas designated for total facetectomy are marked with dotted lines.); **B,** After total bilateral facetectomy.

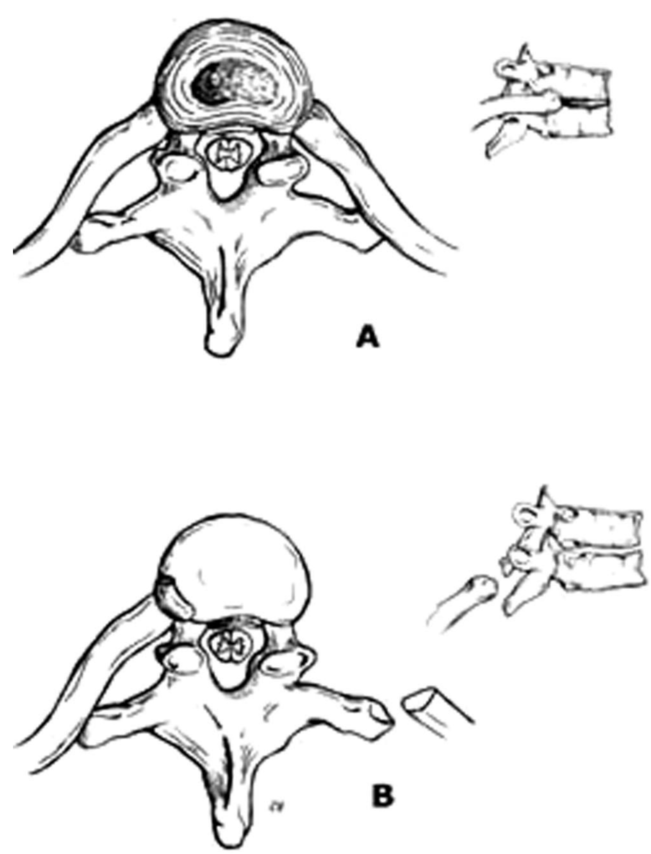

Figure 3. A diagrammatic representation of an axial view of a thoracic vertebra and a lateral view of a motion segment. **A,** While intact; **B,** After rib head resection and radial discectomy.

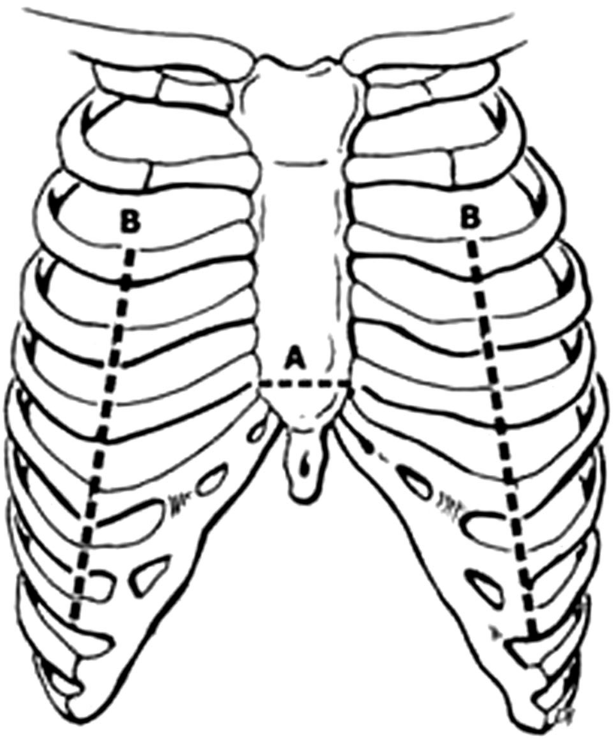

Figure 4. A diagrammatic representation of anterior view of a thoracic cage. Sternal osteotomy at T5–T6 was performed (see dotted line at A). Costosternal releases were carried out from T3–T8 (see dotted lines at B). X denotes the location of the marker screws.

4) Sternal osteotomy. Sternal osteotomy between the fifth and sixth ribs was carried out using a 3-mm Kerrison rongeur cutting in the transverse plane (Figure 4). The procedure of

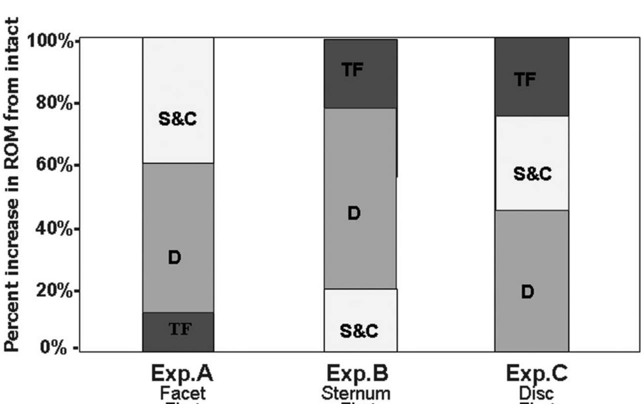

Figure 5. The percent total ROM (i.e., extension plus flexion) for each release in each of the three experiments A, B, and C. Note: 0% represents the ROM for the intact condition. Additional motion following each release is shown as a percentage increase. One hundred percent represents the increase in ROM after all three releases. Radical discectomy provided a significantly greater ($P < 0.05$) percentage increase in total ROM than either total facetectomy or sternal release. The combination of radical discectomy and sternal release (Experiments B and C) provided a significantly greater ($P < 0.05$) percentage increase in total ROM as compared to the radical discectomy and total facetectomy (Experiment A). TF = total facetectomy, D = discectomy, S&C = sternal osteotomy plus costosternal release.

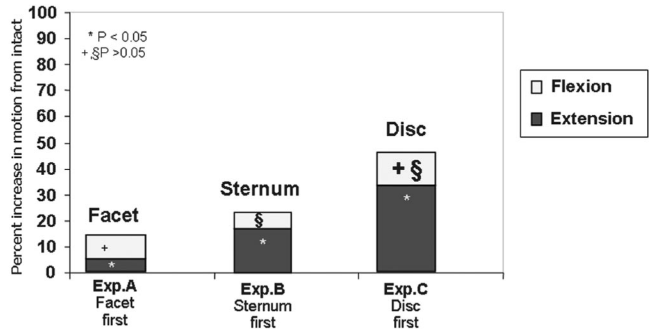

Figure 6. The percent increase in ROM (flexion plus extension) after the **first** surgical release in each of the experiments. Note 0% represents ROM for the intact condition. Additional ROM following the first release is shown as a percentage increase from intact. When radical discectomy was performed first (Experiment C) it provided a significantly greater ($P < 0.05$) increase in extension as compared to either total facetectomy (Experiment A) or sternal release (Experiment B) when performed first. In flexion, there was no significant difference in the increase in flexion between radical discectomy (Experiment C) and total facetectomy (Experiment A) ($P > 0.05$) when either was carried out first. However, radical discectomy when performed first provided a significantly greater ($P < 0.05$) increase in flexion as compared to sternal release when carried out first.

applying a 25-N force and measuring the extent of extension and flexion (six times each) and the length of the sternum was then repeated, as described above.

Experiment B (surgical release sequence: sternal osteotomy, costosternal release, radical discectomy, facetectomy). The procedure of applying a 25-N force and measuring the extent of extension and flexion (six times each) and the length of the sternum after each surgical release, as described for Experiment A, were repeated exactly for all remaining specimens in Experiment B, only the sequence of surgical releases was different. In Experiment B, after testing the intact specimen, a sternal osteotomy between the fifth and the sixth ribs was carried out. This was followed by costosternal releases of third to eighth

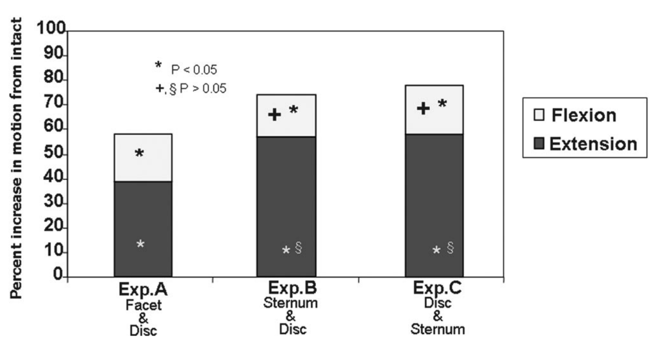

Figure 7. The percent increase in ROM (flexion plus extension) after the **first two** surgical releases in each of the experiments. Note 0% represents the ROM for the intact condition. Additional motion following the first two releases is shown as a percentage increase from intact. The combination of radical disectomy plus sternal release (Experiments B and C) provided significantly more extension ($P < 0.05$) as compared to radical discectomy and total facetectomy (Experiment A). In flexion, there was no significant difference in the results obtained ($P > 0.05$) among any of the three experiments. There was no significant difference between Experiment B and Experiment C ($P > 0.05$).

Table 1. Relative Range of Motion After Back to Front Sequential Releases in Experiment A*

	ROM (°) of Intact Spine		Increase in ROM (°) After Sequential Releases								
			Total Facetectomy			Radical Discectomy			Sternal Release		
	Flexion	Extension	Flexion	Extension	ROM (%)	Flexion	Extension	ROM (%)	Flexion	Extension	ROM (%)
Torso 1	16.6	16	3.2	2.1	5.3 (17.3)	3.2	11	14.2 (46.3)	2.8	8.4	11.2 (36.5)
Torso 2	17.8	20.2	1.7	1.4	3.1 (12.9)	5.7	6.8	12.5 (51.9)	2.8	5.7	8.5 (35.3)
Torso 3	10.3	13.4	1.4	0.7	2.1 (14.2)	1.1	5.6	6.7 (45.3)	2.8	3.2	6 (40.5)
Torso 4	10	8	1.6	0.4	2 (20.8)	0	3.5	3.5 (36.5)	1.1	3	4.1 (42.7)
Torso 5	12.4	14.9	0.9	0.2	1.1 (4.3)	4.2	9.5	13.7 (53.9)	3	7.6	10.6 (41.7)
Torso 6	14.2	16.4	1.2	0.3	1.5 (6.6)	0.6	7.6	8.2 (36.1)	1.3	11.7	13 (57.3)
Mean	13.6	14.8	1.7	0.8	2.5 (12.7)	2.5	7.3	9.8 (45.0)	2.3	6.6	8.9 (42.3)

ROM (%) = range of motion (percent in parentheses). Each of the values of ROM represents the average of six measured values. The standard deviations of these six values are not shown, in order to avoid congestion of the table. However, the average standard deviation of these values when calculated in percent of the mean is 3.6% (range, 0.8%–6.9%).
*Release sequence: intact, total facetectomy, radical discectomy, sternal release.

ribs, followed by four levels of radical discectomy (T4–T8), and finally total facetectomy (T4–T8).

Experiment C (surgical release sequence: radical discectomy, sternal osteotomy, costosternal release, facetectomy). The procedure of applying a 25-N force and measuring the extent of extension and flexion (six times each) and the length of the sternum after each surgical release were repeated exactly for the six specimens in Experiment C, only the sequence of releases was different. After testing the intact specimen, four levels of radical discectomy (T4–T8) was carried out, followed by sternal osteotomy between the fifth and the sixth ribs, then costosternal releases of the third to eighth ribs, and finally total facetectomy (T4–T8), respectively.

Data Analysis

Calculation. Each set of six readings taken for extension was averaged to give a mean value for extension for that particular release. Similarly, each set of six readings taken for flexion was averaged to give a mean value for flexion for that particular release. The mean value of flexion or extension obtained for the intact spine (our datum value) was then subtracted from each mean value to give the net increase in extension or flexion after each release. Using these methods, we were able to obtain the relative motion between T1 and T12 for the intact spine and again after each sequential surgical release. Each specimen served as its own internal control, to account for any interspecimen variations in flexibility.

The ROM was calculated for each release by adding the flexion and extension values for each torso for each of the three releases: facetectomy, discectomy, and sternal plus costosternal. The total increase in ROM for all the releases was calculated by adding up the increase in ROM after each sequential release (*i.e.*, for discectomy, facetectomy, sternal plus costosternal). The percent increases were calculated by using the increased ROM for a specific sequential release divided by the total increase in ROM for all three releases (Figures 5–7).

Statistical Analysis. Because of the small sample size ($n = 6$) in each of the experiments, nonparametric tests were used to make the relevant comparisons. To test whether there were any significant differences between the three experiments in the increase in ROM for each release, a nonparametric test (the Kruskal-Wallis test) was used. This tested whether there are any significant differences between three independent experiments (A, B, and C). When the overall Kruskall-Wallis test was significant at the 0.05 level, pairwise comparisons were evaluated using the Mann-Whitney U-test; otherwise, pairwise comparisons were not investigated. To test whether there were significant differences in the increase in ROM between a pair of releases within the same experiment, a nonparametric test (the Wilcoxon Signed Rank test) was used. The Wilcoxon Signed

Table 2. Relative Range of Motion After Front to Back Sequential Releases in Experiment B*

	ROM of Intact Spine		Increase in ROM (°) After Sequential Releases								
			Sternal Release			Radical Discectomy			Total Facetectomy		
	Flexion	Extension	Flexion	Extension	ROM (%)	Flexion	Extension	ROM (%)	Flexion	Extension	ROM (%)
Torso 7	13.9	11.5	1.8	2.8	4.6 (17.2)	2.2	6.8	9 (33.5)	3.5	9.7	13.2 (49.3)
Torso 8	21.5	30.7	2.3	4.2	6.5 (20.9)	2.9	14.6	17.5 (56.3)	2.5	4.6	7.1 (22.8)
Torso 9	17.2	26.5	1.7	4.9	6.6 (22.8)	2.5	12.9	15.4 (53.3)	2	4.9	6.9 (23.9)
Torso 10	6.1	17.2	1.5	4.6	6.1 (25.8)	3.1	12	15.1 (64.0)	1.6	0.8	2.4 (10.2)
Torso 11	9.6	18.1	2.1	3.6	5.7 (27.0)	1.8	10.6	12.4 (58.8)	0.4	2.6	3 (14.2)
Torso 12	16	14.7	1.3	3.4	4.7 (20.8)	2.5	7.6	10.1 (44.7)	2.1	5.7	7.8 (34.5)
Mean	14.1	19.8	1.8	3.9	5.7 (22.4)	2.5	10.8	13.3 (51.8)	2.0	4.7	6.7 (25.8)

ROM (%) = range of motion (percent in parentheses). Each of the values of ROM represents the average of six measured values. The standard deviations of these six values are not shown, in order to avoid congestion of the table. However, the average standard deviation of these values when calculated in percent of the mean is 2.3% (range, 0.6%–5.6%).
*Release sequence: intact, sternal release, radical discectomy, total facetectomy.

Table 3. Relative Range of Motion After Sequential Releases in Experiment C, Where the Radical Discectomy Was Done First*

	ROM of Intact Spine		Increase in ROM (°) After Sequential Releases								
			Radical Discectomy			Sternal Release			Total Facetectomy		
	Flexion	Extension	Flexion	Extension	ROM (%)	Flexion	Extension	ROM (%)	Flexion	Extension	ROM (%)
Torso 13	15.5	23.5	4.3	8	12.3 (49.8)	2.3	5	7.3 (29.55)	2	3.1	5.1 (20.6)
Torso 14	10.4	15.1	2.5	5.3	7.8 (40.4)	1.2	6	7.2 (37.3)	1.8	2.5	4.3 (22.3)
Torso 15	11.2	14.2	1.8	6.1	7.9 (50.3)	0.4	3.6	4 (25.5)	1.2	2.6	3.8 (24.2)
Torso 16	10.5	16	1.6	7.3	8.9 (38.4)	1.8	6.3	8.1 (34.9)	2	4.2	6.2 (26.7)
Torso 17	12.2	15	2.3	8.8	11.1 (48.7)	1.6	5.9	7.5 (32.9)	1.8	2.4	4.2 (18.4)
Torso 18	12.8	14.4	3.5	6	9.5 (39.9)	1.8	7.2	9 (37.8)	2.1	3.2	5.3 (22.3)
Mean	12.1	16.4	2.7	6.9	9.6 (44.6)	1.5	5.7	7.2 (33.0)	1.8	3	4.8 (22.4)

ROM (%) = range of motion (percent in parentheses). Each of the values of ROM represents the average of six measured values. The standard deviations of these six values are not shown, in order to avoid congestion of the table. However, the average standard deviation of these values when calculated in percent of the mean is 2.1% (range, 0.7%–4.5%).
*Release sequence: intact, radical discectomy, sternal release, total facetectomy.

Rank test was also used to test for differences between flexion and extension. A 5% level was used to declare statistical significance for all these tests.

Results

In the following, we combined the results of sagittal motion after sternal osteotomy with the results after costosternal release to give sternal osteotomy plus costosternal release (or "Sternal release"). We felt that this made less complicated reading and did not detract from the main message. The results are shown in Tables 1, 2, and 3. Each of the values for flexion or extension represents the average increase (of six values) over intact after the specific release. For example, in Table 1, Torso 1, after total facetectomy the average increase in flexion (19.8° − 16.6° = 3.2) and extension (18.1 − 16° = 2.1°) were summed to give the average increase in ROM of 5.3°. The standard deviation for each of the six individual averages are not given to avoid congestion in the tables. Table 4 gives the averages for the increase in ROM for each experiment (A, B, and C) as well as the overall; the results shown in Table 4 were pulled from Tables 1, 2, and 3.

Experiment A

The increase in ROM for both extension and flexion after each respective release is shown in Table 1 and graphically in Figure 5. Radical discectomy allowed the greatest increase in ROM (9.8°, or 46%) with the increase in extension greater than in flexion (extension 7.3° [74%], and flexion 2.5° [26%]). The sternal release accounted for almost the same amount of motion (8.9°, or 42%) with extension again greater than flexion (extension 6.6° [74%], and flexion 2.3° [26%]). Total facetectomy, which was performed first, allowed an increase of only 2.5° (or 12%) with the increase in flexion being greater than extension (flexion 1.7° [68%], and extension 0.8° [32%]). The ROM obtained after facetectomy was significantly less than after either discectomy or sternal release ($P > 0.05$).

Radical discectomy provided a slightly greater contribution to the overall increase in ROM compared with the sternal release; however, it was not significantly different (46% *vs.* 42%) ($P > 0.05$).

Experiment B

The increase in ROM after each respective release is shown in Table 2 and graphically in Figure 5. Radical discectomy allowed the greatest increase in ROM (13.3°, or 52%) with the increase in extension greater than flexion (extension 10.8° [81%], and flexion 2.5° [19%]). Total facetectomy allowed an increase of 6.7° (or 26%) with extension greater than flexion (extension 4.7°

Table 4. Average and Standard Deviation of the Percent Increase in ROM (Extension + Flexion) for Each Experiment and Overall

	% Increase in ROM			
	Experiment A	Experiment B	Experiment C	Overall Average (SD)
Facetectomy	12.7 (6.3)[a,b,g]	25.8 (14.3)	22.4 (2.9)[d,e,g]	20.3 (10.3)[g]
Discectomy	45.0 (7.5)[b]	51.8 (11.0)[c]	44.6 (5.6)[e,f]	47.1 (8.5)[g]
Sternal release	42.3 (7.9)[a,h,i]	22.4 (3.6)[c,h,j]	33.0 (4.8)[d,f,i,j]	32.6 (9.9)[g]

Based on the Mann-Whitney U-test, facetectomy is significantly different between Experiment A (facet first) and Experiment C (facet last). Sternal release is significantly different between Experiments A and B, A and C, and B and C. No significant differences were found between experiments for discectomy. The P value was calculated comparing the percent release between the three variables within each experiment. Hence, there were significant differences using the Wilcoxon signed rank test, between sternal release and facetectomy for both Experiments A and C, between discectomy and facetectomy for both Experiments A and C, and between sternal release and discectomy for both Experiments B and C. Note that two superscripts having the same letter indicate a significant difference at the 5% level.

[70%], and flexion 2.0° [30%]). The sternal release together allowed 5.7° (or 22%) with extension greater than flexion (extension 3.9° [68%], and flexion 1.8° [32%]).

Radical discectomy provided a significantly greater ($P < 0.05$) contribution to the overall increase in ROM compared with the other two releases in this sequence.

Experiment C

The increase in ROM after each respective release is shown in Table 3 and graphically in Figure 5. Radical discectomy allowed the greatest increase in ROM (9.6°, or 44%) with extension greater than flexion (extension 6.9° [72%], and flexion 2.7° [28%]). The sternal release allowed an increase of 7.2° (or 33%) with extension greater than flexion (extension 5.7° [79%], and flexion 1.5° [21%]). Total facetectomy increased the ROM by 4.8° (or 22%) with extension greater than flexion (extension 3° [63%], and flexion 1.8° [37%]).

Radical discectomy provided a significantly greater ($P < 0.05$) contribution to the overall increase in ROM compared with the other two releases in this sequence.

Single Release

When only a single release (*i.e.*, the first release) is considered (Figures 5, 6), radical discectomy (Experiment C) provided a significantly greater ($P < 0.05$) increase in extension and total ROM than either total facetectomy (Experiment A) or sternal release (Experiment B). The sternal release (Experiment B) provided a significantly greater ($P < 0.05$) increase in extension and total ROM than total facetectomy (Experiment A). In flexion, radical discectomy (Experiment C) provided a significantly greater ($P < 0.05$) increase in flexion than sternal release (Experiment B); however, there was no significant difference in flexion between radical discectomy (Experiment C) and total facetectomy (Experiment A).

Two Single Releases in Sequence

When only the first two releases for each sequence are considered (Figures 5, 7), the combination of radical discectomy and sternal release (as in Experiment B and Experiment C) provided a significant ($P < 0.05$) increase in extension and total ROM compared with the combination of radical discectomy and total facetectomy (Experiment A); however, there was no significant difference in flexion between three of them. There were no significant differences ($P > 0.05$) in increase of extension, increase of flexion, and total ROM between Experiment B (sternal release followed by radical discectomy) and Experiment C (radical discectomy followed by sternal release), suggesting internal consistency in the experiment method.

Total Releases

There are no significant differences ($P > 0.05$) in the percentage increase compared with intact in total ROM between each experiment when all three releases were completed (Experiment A, 73%; Experiment B, 80%; Experiment C, 77%).

When radical discectomy was carried out first, it had a slightly lesser effect on ROM (44% in Experiment C) than when it was carried out last (46% in Experiment A and 52% in Experiment B); however, these differences were not significant at the 5% level (Table 4). When sternal release was carried out first, it had a significantly ($P < 0.05$) lesser effect on ROM (22% in Experiment B) than when it was carried out following discectomy (42% in Experiment A and 33% in Experiment C). When total facetectomy was carried out first, it also had a lesser effect on ROM (12% in Experiment A) than when it was carried out last (26% in Experiment B, $P < 0.06$; and 22% in Experiment C, $P < 0.05$.

For all the 18 specimens in the three experiments, the average length of the sternums in the zero position was 13.2 cm (range, 12.25–13.5 cm). The average increase in length after releasing of all the structures from zero position to full extension was 1.55 cm (range, 1–1.75 cm) ($P < 0.05$).

■ Discussion

Our goal with this project was to gain a fundamental understanding of the role the sternum and ribs play in sagittal thoracic stability and to determine how surgical osteotomy of these structures may compare with other commonly used strategies such as discectomy and facetectomy in the correction of thoracic deformity.

The main points to emerge from this study are:

1. Radical discectomy provided the greatest increase in ROM compared with the other two releases, no matter what the sequence (Figure 6, $P < 0.05$). Radical discectomy is potentially the most effective single release for correction of thoracic kyphosis or lordosis.
2. The sternal release (sternal osteotomy plus costosternal release) gives significantly greater increase in motion in extension compared with facetectomy (Figure 6, $P < 0.05$) and could be relevant in the correction of kyphosis.
3. When two releases were carried out in sequence (Figure 7), the combination of radical discectomy and sternal release provided significantly greater increase in both extension and total ROM compared with the combination of radical discectomy and facetectomy ($P < 0.05$).
4. In general, all of the releases allowed for significantly more extension than flexion ($P = 0.002$ using Wilcoxon-Signed Rank test).
5. The average increase in length of the sternum from the zero position to full extension following release was 1.55 cm ($P < 0.05$).
6. If the sternal osteotomy and costosternal release had not finally been carried out (in Experiment A), nearly 42% of the ultimate total ROM would not have been gained. This contribution of the sternal release was significant ($P < 0.05$).

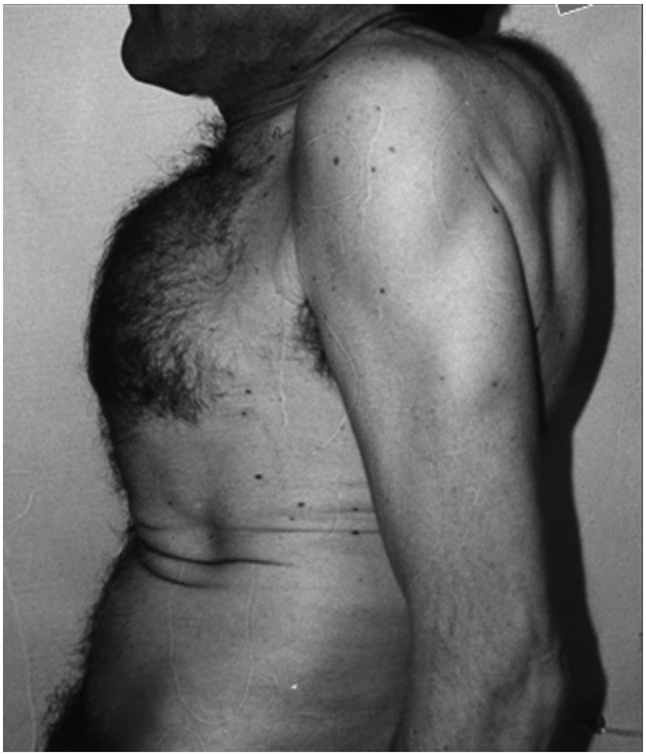

Figure 8. A lateral photograph of a patient with severe upper thoracic kyphosis and associated sternal deformity (arrow).

In the surgical treatment of kyphotic deformity, there is a growing interest in posterior multiple facetectomies with posterior shortening.[9–11] This strategy is particularly successful in moderate kyphosis (60°–90°), especially when the apex is below T5 or T6. However, with more severe and rigid kyphosis over 90° and particularly in kyphosis with an apex at or above T5, correction has proven particularly difficult. Our data show that facetectomy alone provides a minimal release effect compared with discectomy or sternal release, producing only 0.8° of motion in extension under experimental conditions. Both the sternal release alone and the radical discectomy provided significantly greater motion in extension (3.9° and 6.9°, respectively). Thus, our data suggest that radical discectomy would be the single best release for the correction of severe kyphotic deformity and that the sternal release will perform significantly better than the commonly used facetectomy. The data also indicate that the combined radical discectomy and sternal release gives significantly more extension motion than the combination of discectomy with facetectomy. This experimental finding correlates with the clinical experience reported by Anderson and Horton.[8] In their paper, a severe 110° kyphosis with myelopathy did not correct adequately after radical discectomy alone but did significantly improve after the subsequent sternal osteotomy was added. That clinical report and the biomechanical data of this study both indicate that a combined discectomy and sternal release would be the most effective strategy for correcting severe and rigid upper thoracic kyphosis.

It has been noticed clinically that some severe kyphotic deformities are accompanied by deformation of the sternum itself (Figure 8). The clinical observation of a sternal deformity may further increase the indication to consider sternal osteotomy in severe kyphosis. We would emphasize that the sternal osteotomy in this experiment was performed experimentally at the T5–T6 interval, but it would be possible to base the osteotomy more cephalad in position, and this would depend on the apex of any deformity to be treated. It would appear, however, that sternal release would only be reasonable to consider for deformities that span between T2 and T6, where the most fixed segments of costosternal articulations exist.

The correction of thoracic lordosis has also proven to be clinically very difficult, especially in the rigid scoliosis case with hypokyphosis. Our data indicate why such a correction may be challenging, since none of the tested structures allowed for a dramatic increase in segmental flexion compared with the increase that was observed in segmental extension. However, the radical discectomy still proved to be the most effective strategy for producing segmental flexion, and this suggests it may be the most appropriate strategy for the treatment of thoracic lordosis.

Our understanding of fracture mechanisms is also enhanced by these data. In Experiment A, when the facet and disc were totally disrupted, only 58% of the potential total ROM was manifested, with the intact sternal complex clearly still providing an important stabilizing effect (Table 1). This phenomenon is suggested by the report of Stahlman *et al* of a late sternomandbrial dislocation following a thoracic burst fracture, indicating significant load transmission through the sternum.[12] An additional 42% of the total ROM in Experiment A was seen after the release of the sternal complex ($P < 0.05$); this suggests the important contribution of the sternal complex to the thoracic spine. These data support the fourth column concept of fracture biomechanics as described by Berg[4] and that the coexistence of a sternal fracture may account for more than 40% to the overall instability of the spine, so sternal reconstruction may therefore be worth considering in certain cases.

Orthopedic traumatologists and spine surgeons of orthopaedic or neurosurgical background are typically not so familiar with the sternum and retrosternal anatomy. It is clear from the paucity of biomechanical information or clinical reports regarding the association of the sternum to spinal pathology that the sternum has not figured prominently in clinical concepts of thoracic biomechanics, instability, or deformity correction. Cardiac and thoracic surgeons routinely perform sternal osteotomy with low morbidity.[13] In a population including adults, sternal osteotomy with costosternal release and chest wall reconstruction results in 97% patient satisfaction, and improved cardiopulmonary function and exercise tolerance in 90% to 91% of cases.[14–16] Our study confirms that the sternum and costosternal complex plays a significant role in stabilizing the thoracic spine, and suggests that spine surgeons should consider the sternal complex in evaluation and strategies for the management of thoracic deformity and thoracic trauma.

A clinically important observation regarding the sequencing of surgical releases emerges from these data. Radical discectomy had a consistent effect on ROM no matter where in the sequence it was performed (46% Experiment A, 52% Experiment B, 44% Experiment C). There was no statistical difference in the effect of discectomy whether done first or done following other releases. However, the sternal release and facetectomy were much more influenced by sequence. Sternal release gave significantly more ROM when it followed discectomy ($P < 0.05$). Likewise, the facetectomy provided significantly more motion when done last compared with first (22% Experiment C *vs.* 12% Experiment A). This suggests that the discectomy is the release to consider first. The others are more effective as supplemental releases with the sternal release being more effective than facetectomy.

In this study, sternal release resulted in an average of 1.55 cm of lengthening under experimental conditions. One would assume that even greater lengthening could be accomplished with direct sternal distraction and reconstruction. Campbell *et al* demonstrated a significant increase in thoracic volume using the expansion thoracoplasty method.[17] Sternal osteotomy and lengthening with reshaping of the height and anteroposterior dimensions of the thorax may similarly increase thoracic volume and potentially improve overall respiratory mechanics. Significant improvements in cardiopulmonary function following sternal reshaping for pectus surgery have been reported.[18,19] In thoracic kyphosis, Culham *et al* showed a significant decrease of vital capacity, inspiratory capacity, and total lung capacity in patients who were diagnosed with osteoporosis and thoracic kyphosis.[20] Sternal lengthening may allow more effective correction of thoracic kyphosis, and allow for improvements in thoracic volume and pulmonary function.

We acknowledge that this experimental model is an *in vitro* study of static structures. *In vivo* thoracic biomechanics are far more complex with additional dynamic stabilizers such as spinal extensor muscles, abdominal muscles, intercostal muscles, and the diaphragm, which have not been studied in this experiment. Furthermore, we did not attempt to simulate lateral bending or torsional motion in our evaluation of the costosternal complex, and these future assessments may also have value in the further understanding of the scoliotic deformity and subsequent chest torsion. There may also be relevant influences from the viscera, and pressures within the chest and abdominal cavities.

The testing method did not use a preloading compressive force down the long axis of the spine, and this force could be considerable in normal upright body postures. Such compressive force would influence potentially both the disc and the facet joints in close apposition. We decided against a preload as it would have been extremely difficult to apply a physiologically valid compressive force to a full length specimen without muscles, since the specimen would tend to buckle. Furthermore, any surgical releases would be carried out on an unconscious, muscle-relaxed patient, lying not standing, with no such compressive force.

We also acknowledge that any test of an entire human thoracic specimen has inherent difficulties of specimen consistency. All specimens were carefully screened by history and radiologic examination, and randomization of the specimens resulted in three groups that were statistically similar with respect to their intact condition. The average standard deviation for the three groups was also very close, being 3.6%, 2.3%, and 2.1%, in Groups A, B, and C, respectively. These data suggest that the three groups are similar and statistically equivalent for appropriate comparison. However, with only six specimens in each group the power is weak.

Previous reports have shown poor results with conservative treatment for patients who sustained multiple wedge compression fractures with associated rib and sternal fractures.[21,22] This often resulted in malunion of the sternum and progressive kyphotic deformity of the spine. The results of our experiment provide substantiating evidence regarding the magnitude of stability provided by the sternum and rib cage as an important stabilizer for the thoracic spine. The instability resulting from vertebral fracture and sternal fracture together may be more than the sum of the two injuries, as suggested by our data. This clinical appreciation may significantly enhance treatment algorithms of "simple compression fractures."

In a previous study, we demonstrated that unilateral total facetectomy was ineffective as a release for influencing thoracic ROM.[1] In this current study, we did find that bilateral total facetectomy could increase thoracic ROM, which is in keeping with reports previously published by many authors.[3,5] However, it is important to stress that our data show the total thoracic facetectomy, which is commonly used clinically, has a relatively limited influence on overall ROM (particularly on thoracic extension), when compared with the other releases tested. In the thoracolumbar and lumbar spine, where the constraints of the rib cage and sternum are not present, total facetectomy may be expected to have a more positive effect as a surgical release allowing for more motion than what was observed in the thoracic spine.

We would like to emphasize that the radical discectomy as performed in this experiment does include a rib head resection and total disc removal. Radical circumferential discectomy should be considered in large or rigid deformities, while the rib head resection may be added for additional release or for thoracoplasty. Surgeons who perform a more limited standard discectomy without a total circumferential disc excision or without rib head removal will not see the same increase in motion as is demonstrated in this experiment. Indeed, the relative effect of a sternal release observed here might appear even more significant when compared with a standard discectomy without circumferential disc release or rib head resection.

Conclusion

Sagittal plane motion in the thoracic spine is influenced by all three structures tested in this experiment. Overall, the radical discectomy provides the greatest increase in total range of motion and in extension compared with the other two releases. The second most influential release is the sternal osteotomy with costosternal release, particularly in extension (correction of kyphosis). When two releases are done in sequence, the combination of radical discectomy and sternal complex release provides the greatest increase in total range of motion and in thoracic extension. Overall, the total multilevel facetectomy is the least effective release. These data have relevance for thoracic trauma and for surgical strategies in the correction of thoracic kyphosis or lordosis, and suggest a potential role for sternal osteotomy and costosternal release in severe and rigid upper thoracic kyphosis.

Key Points

- Radical discectomy provides the greatest increase in sagittal range of motion.
- The combination of radical discectomy and sternal release provides the most effective paired release.
- In general, all of the releases allowed more extension than flexion.
- The sternum provides substantial thoracic stability even after discectomy and facetectomy.
- Sternal osteotomy and costosternal release may have roles in correcting severe thoracic kyphosis.

References

1. Feiertag MA, Horton WC, Norman JT, et al. The effect of different surgical releases on thoracic spinal motion. *Spine* 1995;20:1604–11.
2. Kaneda K, Shono Y, Satoh S, et al. Anterior correction of thoracic scoliosis with Kaneda anterior spinal system: a preliminary report. *Spine* 1997;22:1358–68.
3. White AA III, Hirsch C. The significance of the vertebral posterior elements in the mechanics of the thoracic spine. *Clin Orthop* 1971;81:2–14.
4. Berg EE. The sternal-rib complex: a possible fourth column in thoracic spine fractures. *Spine* 1993;18:1916–9.
5. Oda I, Abumi K, Lu D, et al. Biomechanical role of the posterior elements, costovertebral joints, and rib cage in the stability of the thoracic spine. *Spine* 1996;21:1423–9.
6. Tekeuchi T, Abumi K, Shono Y, et al. Biomechanical role of the intervertebral disc and costovertebral joint in stability of the thoracic spine: a canine model study. *Spine* 1999;24:1414–20.
7. Gopalakrishnan KC, el Masri WS. Fractures of the sternum associated with spinal injury. *J Bone Joint Surg Br* 1986;68:178–81.
8. Anderson TM, Horton WC, Whitesides TE, et al. Sternal release and advancement with thoracotomy and osteotomy for idiopathic osteopenia. *Ann Thorac Surg* 1995;60:437–8.
9. Lowe TG. Scheuermann disease. *J Bone Joint Surg Am* 1990;72:940–5.
10. Tribus CB. Scheuermann's kyphosis in adolescents and adults: diagnosis and management. *J Am Acad Orthop Surg* 1998;6:36–43.
11. Hosmas AJ, Langeloo DD, de Kleuver M, et al. Analysis of the sagittal plane after surgical management for Scheuermann's disease: a view on overcorrection and the use of an anterior release. *Spine* 2002;27:167–75.
12. Stahlman GC, Wyrsch RB, McNamara MJ, et al. Late-onset sternomanubrial dislocation with progressive kyphotic deformity after a thoracic burst fracture. *J Orthop Trauma* 1995;9:350–3.
13. Grossi EA, Culliford AT, Krieger KH, et al. A survey of 77 major infectious complications of median sternotomy: a review of 7,949 consecutive operative procedures. *Ann Thorac Surg* 1985;40:214–23.
14. de Matos AC, Bernardo JE, Fernandes LE, et al. Surgery of chest wall deformities. *Eur J Cardiothorac Surg* 1997;12:345–50.
15. Shamberger RC, Welch KJ. Surgical repair of pectus excavatum. *J Pediatr Surg* 1988;23:615–22.
16. Tjan TD, Semik M, Rotering H, et al. Pectus excavatum: special surgical technique, perioperative management and long-term results. *J Cardiovasc Surg (Torino)* 1999;40:289–97.
17. Campbell RM Jr, Smith MD, Mayes TC, et al. The characteristics of thoracic insufficiency syndrome associated with fused ribs and congenital scoliosis. *J Bone Joint Surg Am* 2003;85:399–408.
18. Fonkalsrud EW, Dunn JCY, Atkinson JB. Repair of pectus excavatum deformities: 30 years of experience with 375 patients. *Ann Surg* 2000;231:443–8.
19. Shamberger RC, Welch KJ. Cardiopulmonary function in pectus excavatum. *Surg Gynecol Obstet* 1988;166:383–91.
20. Culham EG, Jimenez HAI, King CE. Thoracic kyphosis, rib mobility, and lung volumes in normal women and women with osteoporosis. *Spine* 1994;19:1250–5.
21. Klasse JM, Zimmerman KW, Veldhuis EF. Increased kyphosis by a combination of fractures of the sternum and thoracic spine. *Eur Spine J* 1998;7:69–71.
22. Lund JM, Chojnowski A, Crawford R. Multiple thoracic spine wedge fractures with associated sternal fracture: an unstable combination. *Injury* 2001;32:254–5.