A biomechanical study on the effects of rib head release on thoracic spinal motion

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Abstract

Purpose Idiopathic scoliosis is generally treated by surgical derotation of the spine. A secondary goal of surgery is minimization of the “rib hump” deformity. Previous studies have evaluated the effects of surgical releases such as disectomy, costo-vertebral joint release, facetectomy, and costoplasty on spine mobilization and overall contribution to thoracic stability. The present study was designed to evaluate the biomechanical effects of the rib head joints alone on axial rotation, lateral bending, and segmental rotation, without disectomy or disruption of anterior or posterior elements.

Methods Four female cadaver thoracic spines with intact sternums and rib cages were mounted in an Instron servohydraulic bi-axial MTS. In a 12-step sequence, the costo-vertebral and costo-transverse ligaments were released, first unilaterally from T10–T7, then bilaterally until complete disarticulation between the rib heads and the vertebral bodies. After each release, biomechanical testing, including axial rotation and lateral bending, was performed. Vertebral body displacement was also measured using electromagnetic trackers.

Results We found that rib displacement during axial rotation was significantly increased by unilateral rib head release, and torque was decreased with each successive cut. We also found increased vertebral displacement with sequential rib head release.

Conclusions Our results show that sequential costo-vertebral joint releases result in a decrease in the force required for axial rotation and lateral bending, coupled with an increase in the displacement of vertebral bodies. These findings suggest that surgical release of the costo-transverse and costo-vertebral ligaments can facilitate segmental correction in scoliosis by decreasing the torso’s natural biomechanical resistance to this correction.

Keywords Rib head release · Scoliosis · Thoracic spine · Vertebrae · Costo-vertebral release

Introduction

The biomechanics of the thoracic spine have been studied extensively over the past 20 years, largely because the thoracic spine differs greatly from the cervical and lumbar spine. This difference is primarily due to the presence of the ribs and costo-vertebral joints. Several studies have examined the thoracic spine in detail to determine which elements provide the greatest spinal stability. Much of the research on the biomechanics of the thoracic spine has focused on studying the mechanical constraints involved with derotation of the scoliotic spine [1–7].

Cases of scoliosis that manifest in the thoracic region of the spine are particularly difficult to treat because of the stiffness associated with rotational deformity of the ribs. By convention, scoliosis is largely treated in one of two ways; the spine can be approached by anterior or posterior techniques to

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install either screws and a rod system [8] or a hook and rod system [9]. However, as the spine is straightened during surgery to correct the three-plane curvature, the ribs are consequently forced to rotate as well. This results in an increased prominence of the “rib hump” deformity associated with thoracic scoliotic rotation of the spine. Although this prominence is largely cosmetic, it is a significant complaint of patients and plays an important role in patient satisfaction [2]. The rib hump deformity is generally corrected with costoplasty [10] or facetectomy [4]. A costoplasty minimizes the rib prominence by selectively lengthening or shortening the ribs, and a facetectomy relieves stress posteriorly, allowing the ribs to rotate. Recently, Suzuki and Kono [11] have described successful correction of thoracic rib hump deformity using a technique that involves bilateral release of the costovertebral ligamentous connections from T5 to T10 followed by rod and hook derotation maneuvers.

While choosing a technique for rib hump correction, it is important to consider the biomechanical effects of the treatment on thoracic stability. Several studies have examined the biomechanical effects of costovertebral joint resection in a variety of models, including canine cadaver studies, computer-modeled studies, and human cadaver studies. However, the effects of the surgical release of the costovertebral joints have not been previously investigated in intact torsos without disectomy or disruption of other anterior elements. Thus, the goal of the present study was to investigate the biomechanical effects of sequential costovertebral joint resection on lateral bending, axial rotation, and vertebral body displacement in a human cadaver model.

Materials and methods

Specimen preparation

Four female human (C7-L1) cadaver upper torsos were prepared for testing. The donors' heights ranged from 5'2" to 5'4" and their ages ranged from 71 to 84 years old. All specimens were examined under fluoroscopy to rule out any existing spinal deformities, prior instrumentation, or severe degeneration. Degeneration, which was defined as the presence of narrowed disk space with spurring or osteophytes, was ruled out using X-rays from a C-arm. The surrounding skin and subcutaneous tissues were dissected fully to preserve the spinal column, intact rib cage, and sternum. C7 and L1 were potted with hard-setting urethane foam (Kindt Collins, Cleveland, OH) to fit into Instron specimen mounts (Fig. 1). Aurora electromagnetic trackers (NDI, Inc. Waterloo, Ontario, Canada) were attached to the spinous processes of T7, T8, T9, and T10 with plastic screws, as opposed to metal screws, in order to minimize the interference with the electro-magnetic field [12].

Fig. 1 Photograph of specimen mounted in the Instron machine

Testing procedure

The specimens were mounted in an Instron Model 1321 servo-hydraulic bi-axial test machine (Instron Corp., Canton, MA). A sinusoidal axial rotation of $\pm 30^\circ$ at a rate of $1.0^\circ/\text{s}$ was then applied to the spine for four cycles. The axial rotational stiffness was calculated from the torque and rotation output from the Instron. Vertebral body mobility (displacement) was measured with the output from the Aurora electromagnetic trackers. The entire thoracic spine was rotated 30° , so displacement was measured in millimeters translated from neutral position. Since we were unable to measure the 3-dimensional angular rotation of each rib segment, we measured the linear displacement during rotation for each rib segment using the optical trackers. This effectively showed how much of the 30° axial rotation was distributed among each of the vertebrae. The first three cycles were preconditioning cycles and calculations were made from data collected on the fourth cycle. After axial torsion, bilateral side bending of the spine to 50 mm was tested by applying a translation from the Instron at a rate of 1 mm/s to a lever arm that was attached to the potted vertebrae through a frictionless bearing (Fig. 2). For this test, a 5 kg vertical distraction load was applied to the spine from the Instron. Again, the specimens were put through three preconditioning cycles and data were collected on the fourth cycle.

The above testing protocol was performed on intact torsos (before any surgical removal of the costo-transverse and costo-vertebral ligaments) and then again after each

Fig. 2 Mechanical addition to Instron machine. A is where the apparatus attaches to the Instron. The force was applied vertically from the Instron (blue arrow) where it articulates with the bearing at B. The lever arm (light green) connects with E the top of the potted thoracic spine. Both right and left lateral motion can be tested with the moveable bearing located at B and D. The Instron attaches to the potted vertebrae for rotational movement at C. This apparatus is made of aluminum

subsequent surgical release. The surgical procedures took place in the Instron test machine to minimize disruption of torso placement in the machine.

Rib head release protocol

After the specimens were tested intact (serving as the control), the rib head releases were performed sequentially in four regions of the spine: right-side T7–T10, right-side T6, right-side T5, and then finally left-side T5–T10. We chose to isolate T5–T10 because the T5–T10 region correlates with the apical vertebra in approximately 70% of idiopathic scoliosis cases. Thus, we decided to focus on the levels which are most commonly adversely affected by the progression of idiopathic scoliosis. Within each region, three sequential releases were performed (Fig. 3). First, the costo-transverse ligaments were completely cut, followed by a 50% cut of the costo-vertebral ligaments. Finally, the costo-vertebral ligaments were resected completely. After each release, both displacement and torque were measured. Linear displacement was measured using the optical trackers, and the torque was measured as an output of the Instron machine. The complete sequence of releases is outlined in Table 1.

Statistical analysis

Rotation torques, bilateral bending forces and vertebral displacement data for each surgical release were statistically analyzed using dependent (paired) *t*-tests. *P* values ≤ 0.05 were considered statistically significant.

Fig. 3 Surgical release of ligaments during study protocol. 1 Complete cut of right-sided costo-transverse ligaments. 2 50% cut of right-sided costo-vertebral ligaments. 3 Complete cut of right-sided costo-vertebral ligaments. These releases were performed sequentially in four regions of the spine: right side T7–T10, right side T6, right side T5, left side T5–T10

Table 1 Sequence of release procedures prior to each mechanical test

Right-side T7–T10	
1.	Complete cut costo-transverse ligaments
2.	50% cut costo-vertebral ligaments
3.	Complete cut costo-vertebral ligaments
Right-side T6	
4.	Complete cut costo-transverse ligaments
5.	50% cut costo-vertebral ligaments
6.	Complete cut costo-vertebral ligaments
Right-side T5	
7.	Complete cut costo-transverse ligaments
8.	50% cut costo-vertebral ligaments
9.	Complete cut costo-vertebral ligaments
Left-side T5–T10	
10.	Complete cut costo-transverse ligaments
11.	50% cut costo-vertebral ligaments
12.	Complete cut costo-vertebral ligaments

Results

Axial rotation

The mean torque values for each successive release are shown in Fig. 4. All torque values were negative, as the

Fig. 4 Change in torque after each successive ligament release. Values show the mean of the four specimens. All torque values were negative, as the measures reflected a change in torque from the intact spine. Data points statistically significant for $p \leq 0.05$ are marked with an asterisk

measures reflected a change in torque from the intact spine. Data points which were found to be significantly different ($p \leq 0.05$) from intact spines are marked with asterisks. Note that for both right and left axial rotation, the torque was significantly lower than that of the intact spine after release of the left-side T5–T10 ligaments, with the exception of after the third cut. There was a large difference in torque between left and right axial rotation at this point.

Displacement is plotted as mean displacement in millimeters relative to displacement of an intact rib cage. Although most of the data points for vertebral body displacement were not significant, a general trend showed an initial increase in displacement as sequential right-side releases were performed, followed by a decrease as the left-side ribs were released from the spine (Figs. 5, 6).

Distraction of the spine with 5 kg load

When a 5 kg vertical distraction load was applied from the Instron to the spine, displacements of the vertebrae (T7–T10) increased slightly as each consecutive rib was

released from the spine. However, there were no significant differences in displacement as compared to the intact spine (Fig. 7).

Lateral bending of the spine to 30°

Figure 7 shows the mean load values required to bend the spine laterally to 30° after each successive release. After right sided T7–T10 release, each subsequent release resulted in a significantly lower load for lateral bending ($p \leq 0.05$). The data were similar for both left and right bending, the major difference being that the left bending caused greater decreases in displacement on average.

Discussion

The present study investigated the biomechanical effects of sequential costovertebral and costotransverse ligament resection in an intact torso cadaveric model. We found that rib displacement during axial rotation was significantly increased by unilateral rib head release, and torque was

Fig. 5 Right axial rotation linear displacement (mm) from neutral for T7, T8, T9, and T10 measured by electromagnetic trackers. Data points show displacement relative to the mean displacement of an intact cadaver

Fig. 6 Left axial rotation linear displacement (mm) from neutral for T7, T8, T9, and T10 measured by electromagnetic trackers. Data points show displacement relative to the mean displacement of an intact cadaver

decreased with each successive cut. The decrease in rotational torque with each successive cut was expected, given that the ribs became less connected to the spine. Although not all of the data points for each release were found to be statistically significant, it is clear that there was a trend for decreased torque with each sequential release. The torque was not significantly different after the third cut; this is likely due to the fact that after the third cut, T7–T10 were completely cut on the right side. Intuitively we would expect left rotation torque to decrease more than right rotation torque after this cut. This is because after three cuts, the right side was effectively disarticulated from the axial spine, so the stress of left rotation could not be absorbed by the ligaments on the right side. However, the stress applied by right axial rotation was absorbed by the

still-intact ligaments on the left side of the spine. The discrepancy diminished as additional cuts were made.

We also found increased vertebral displacement with sequential rib head release. With unilateral release, the ribs remained connected to the spine, so they were displaced with the spine as the torso itself rotated. When bilateral release was completed, the spine became largely disconnected from the rest of the torso, so the vertebrae essentially rotated about the axis of the spine itself without displacement. When a distraction load was applied, we saw an additional increase in vertebral displacement, presumably due to the compromise of the structural integrity of the torso in general. Although these results are largely intuitive, to our knowledge they have not previously been shown in an intact torso cadaveric model.

Fig. 7 Mean load values required to bend spine laterally to 30°. Data points significant for $p \leq 0.05$ are marked with an asterisk and points significant for $p \leq 0.01$ are marked with a hash

Our present biomechanical results provide support for the potential clinical benefit of using sequential rib head release to facilitate mobilization and thoracic derotation during surgical correction of scoliotic thoracic spine deformities. In fact, Suzuki and Kono [11] recently presented the results of their “super hybrid method” in which the costovertebral and costotransverse ligaments from T5 to T10 are released and then followed by rod and hook derotation maneuvers. In their prospective study of 44 patients, they found consistent improvements in rib hump prominence and Cobb angle. The average Cobb angle for all patients decreased from 56.7° pre-operatively to 13.3° immediately postoperative and 18.1° at 2 years postoperative. In addition, rib hump prominence improved from 23.2 mm pre-operatively to 12.4 mm at 2 year postoperative. Of the 26 patients with a pre-operative rib hump greater than 20 mm, 69% showed a decrease of at least 10 mm using this method. While these results are encouraging, more clinical testing is needed before any conclusions can be reached. However, our present biomechanical findings together with Suzuki’s preliminary clinical data suggest that sequential rib head release may be an alternative method for achieving rib hump deformity correction in scoliotic patients.

Our present results are consistent with previous animal [5, 6], human cadaveric [3, 4, 7], and computer modeling [1] studies. For example, Oda et al. and Takeuchi et al. [5, 6] have investigated the stability of the thoracic spine in canine rib head-thoracic spine complexes. Oda et al. [5] found increases in range of motion during flexion/extension after resection of the posterior elements of T6–7 and during lateral bending and axial rotation after resection of the T7 costovertebral joint. Similarly, Takeuchi et al. [6] found significant increases in range of motion with flexion/extension, lateral bending, and axial rotation after sequential resection

of the T6–7 intervertebral disk, T7 rib head joint, and T7 costotransverse joint, indicating that these structures play an important role in the stability of the thoracic spine during these movements.

Oda et al. [4] extended the principles from their canine study to a human cadaver model that examined the effects of intervertebral disk resection and costo-vertebral joint release in various combinations. They showed that rib head resection further increased range of motion after a disectomy; however, this study was limited in that it only investigated functional spine units, rather than full, intact torsos such as in the present study. Horton et al. [3] later used full cadaver torsos in their biomechanical study on the effects of releasing the intervertebral disk, the costosternal joint, the sternum, and the facet joints. They found that a radical disectomy had the greatest influence on range of motion, followed by a combination of sternal osteotomy plus costosternal release, and radical disectomy plus sternal release. Our present results add to these studies and provide new evidence for the role of sequential costo-vertebral release in the correction of thoracic deformities. Furthermore, our study builds upon previous finding as it was performed on intact torsos with the posterior elements undisrupted.

There are several limitations to the present study, most of which are typical of any cadaver study, such as age of the specimens. However, we did examine the specimens under fluoroscopy prior to the study methods to exclude any specimens with spinal deformities. Given the advanced age of our specimens (71–84 years), we were limited in the amount of force we could exert on the old bone. Even so, the magnitude of the decreases in torque we witnessed in the cadavers is strong evidence that the forces needed for a scoliosis spine correction in vivo would likely not be as great as even the maximum forces applied to the specimens. Another limitation of this study was that the abdominal musculature unit was stripped and the intra-abdominal pressure was not simulated. Lam [13] found hypokyphotic deformity in a rare case of prune-belly syndrome, and it is hypothesized that the abdominal musculature plays an important role in preserving thoracic physiologic kyphosis and providing overall strength and mechanical stability to the spine. It is not clear to what extent the abdominal musculature and intra-abdominal pressure, if included in this study, would have decreased the proportion of overall stability and stiffness provided by the costo-vertebral joints and their surrounding ligaments. Our findings are also limited to the effects of releases in the thoracic region and did not include any releases in the thoraco-lumbar region; future studies should consider testing these regions as well. Lastly, the small sample size of four cadavers is also a limitation of this study. Unfortunately, we did not have funding to purchase additional

full cadaveric torsos. However, even with our smaller sample size we did find statistically significant results and non-significant trends that we believe provide evidence regarding the biomechanical effects of costo-vertebral joint releases.

Conclusions

This study specifically examined the biomechanical properties of the rib heads in a cadaver model. Our results show that sequential costo-vertebral joint releases result in a decrease in the force required for axial rotation and lateral bending, coupled with an increase in the displacement of vertebral bodies. These findings suggest that surgical release of the costo-transverse and costo-vertebral ligaments can facilitate segmental correction in scoliosis by decreasing the torso's natural biomechanical resistance to this correction.

Conflict of interest None.

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