

Biomechanics

Strength of Thoracic Spine Under Simulated Direct Vertebral Rotation: A Biomechanical Study

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Abstract

Background: Direct vertebral rotation (DVR) has gained increasing popularity for deformity correction surgery. Despite large moments applied intraoperatively during deformity correction and failure reports including screw pullout, aortic abutment, and pedicle fracture, to our knowledge, the strength of thoracic spines has been unknown. Moreover, the rotational response of thoracic spines under such large torques has been unknown.

Purpose: Simulate DVR surgical conditions to measure torsion to failure on thoracic spines and assess surgical forces.

Study Design: Biomechanical simulation using cadaver spines.

Methods: Fresh-frozen thoracic spines ($n = 11$) were evaluated using radiographs, magnetic resonance imaging (MRI) and dual-energy x-ray absorptiometry. An apparatus simulating DVR was attached to pedicle screws at T7–T10 and transmitted torsion to the spine. T11–T12 were potted and rigidly attached to the frame. Strain gages measured the simulated surgical forces to rotate spines. Torsional load was increased incrementally till failure at T10–T11. Torsion to failure at T10–T11 and corresponding forces were obtained.

Results: The T10–T11 moment at failure was 33.3 ± 12.1 Nm (range = 13.7–54.7 Nm). The mean applied force to produce failure was 151.7 ± 33.1 N (range = 109.6–202.7 N), at a distance of approximately 22 cm where surgeons would typically apply direct vertebral rotation forces. Mean right rotation at T10–T11 was $11.6^\circ \pm 5.6^\circ$. The failure moment was significantly correlated with bone mineral density (Pearson coefficient 0.61, $p = .047$). Failure moment also positively correlated with radiographic degeneration grade (Spearman $\rho > 0.662$, $p < .04$) and MRI degeneration grade (Spearman $\rho = 0.742$, $p = .01$).

Conclusion: The present study indicated that with the advantage of lever arms provided with DVR techniques, relatively small surgical forces, < 200 N, can produce large moments that cause irreversible injury. Although further studies are required to establish the safety of surgical deformity correction surgeries, the present study provides a first step in the quantification of thoracic spine strength.

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Keywords: Thoracic spine; Biomechanics; Strength; Torsion; Direct vertebral rotation

Introduction

The increase in popularity of pedicle screw-based instrumentation systems for deformity correction has led to developments in correction maneuvers employed during surgery. With the high bone–screw interface strength provided by pedicle screws [1,2], substantial forces and torques can be applied to the spine intraoperatively to achieve necessary sagittal plane and rotational deformity corrections. For example, using direct vertebral rotation (DVR) [3,4], axial torsion is applied directly to the spine through a device with large lever arms attached bilaterally to pedicle

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screws at multiple levels along the length of the deformity. With such techniques, torques purportedly in excess of 100 Nm have been applied to the thoracic spine intraoperatively [3], and satisfactory curve corrections have been reported.

Notwithstanding studies that have reported satisfactory curvature corrections and low complication rates using DVR [4–8], others have reported intraoperative complications with DVR and other rotational correction maneuvers [9–12]. Wagner et al. [9] reported seven cases (2.6%) of lateral pedicle screw plow following DVR. This is a potentially debilitating complication, particularly in patients with right thoracic scoliosis whose aorta is positioned more laterally and posteriorly [13], where lateral screw plow could cause aortic abutment and injury. Unfortunately, the true frequency of vascular injury is unknown and likely underreported [14,15], especially since the majority of DVR reports in the literature have not obtained postoperative CT scans which are important in evaluating pedicle screw placement [6–8,16–27]. Although the large intraoperative torques afforded by these new maneuvers may indeed achieve curve correction effectively in most cases, they may approach or even cross the strength limits of the spine in some cases.

Despite the potential risk involved with using DVR, the magnitude of torsional loads that can be safely applied to the thoracic spine has not been established. Bone–screw interface strengths under torsional loading in the thoracic spine have been reported at torques of less than 50 Nm [28,29]; however, unlike intraoperative conditions, for these measurements, the bone–screw interface was isolated, allowing no motion of the spine or transfer of load to the intervertebral discs. Previous biomechanical studies have not measured the torsional structural strength of the thoracic spine, that is, the strength of the intact thoracic spine under axial rotational torque. In the lumbar spine, torsional failures have been reported to be in the range of 50 Nm [30,31]. The thoracic spine, because of its smaller dimensions, is likely weaker. Facetectomies may reduce the torsional strength further still. Clearly, it is necessary to establish torsional strength of the spine as a first step toward reducing the risk of injury or failure during deformity correction surgery.

The purpose of the present study was to measure and establish the axial torsional strength of the thoracic spine under simulated DVR loading using an in vitro cadaveric thoracic spine model.

Methods

Specimen Preparation

Eleven fresh-frozen human cadaveric thoracic spines (T1–T12) were obtained from Science Care (Science Care, Phoenix, AZ). Specimens were wrapped in saline-soaked gauze, and frozen at -20° until testing [32]. Before experimentation, the specimens were dissected to remove all skin, muscle, and fat tissue, while maintaining the

integrity of the discs, bony structures, and stabilizing ligaments. Additionally, the posterior 5 cm of the ribs were preserved, with the costovertebral joints intact. The dissection was performed according to methods established previously in the literature [33,34].

Each specimen's T11 and T12 vertebrae were potted together in a low-temperature setting epoxy resin. Transverse screws were inserted partway into both T11 and T12 to provide additional fixation within the pot. The potted vertebrae were then placed in a custom-designed 15-cm-diameter aluminum ring for mounting onto the load frame. Two tri-planar laser levels (Stanley Crossline Level Max-CL2; Stanley Tools Product Group, CT) were used to align the pot within this ring such that, once mounted, the anatomical planes of the T10–T11 disc would align with the axes of the load frame [35].

Specimen Imaging and Health Evaluation

The bone mineral density (BMD) of each thoracic spine specimen was determined by dual-energy x-ray absorptiometry (DEXA) using a Hologic 2000 bone densitometer (Hologic Inc., Waltham, MA). Although t- and z-scores could not be assessed for the thoracic spine, the raw BMD score was used as a measure of bone health. Localized BMD measurements were obtained for each vertebra along the length of the thoracic spine.

Two other measures of bone health were included. First, standard high-resolution, 15% magnification anterior-posterior and lateral radiographs were taken using an HP Faxitron Series high-resolution radiography system (43805N, Hewlett Packard Company, Palo Alto, CA). The T10–T11 disc level of each specimen was then graded according to the grading systems established by Mimura et al. (1–4 grading system) [36] and Lane et al. (0–3 grading system) [37].

Finally, T1- and T2-weighted sagittal MRI images were taken before testing, and the T10–T11 disc levels were graded according to the degeneration grading system established by Pfirrmann et al. (I–V grading system) [38,39].

Instrumentation

Bilateral facetectomies were performed from T7 to T10 to allow for pedicle screw insertion. Polyaxial pedicle screws (Medtronic, Memphis, TN) were then inserted by trained pediatric spine surgeons bilaterally from T7 to T10 using the free hand technique. Standard high-resolution, 15% magnification anterior-posterior and lateral radiographs were taken using an HP Faxitron Series radiography system (43805N, Hewlett Packard Company) to assess pedicle screw placement. Although the radiographs could not definitively rule out misplacement of the pedicle screws, they were used to ensure that the screws were placed parallel to the endplates and directed along the pedicle axes, and that the screw tips converged toward but did not cross the midline.

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