Published in final edited form as:

J Biomech. 2018 March 21; 70: 262–266. doi:10.1016/j.jbiomech.2017.10.005.

THE RIB CAGE REDUCES INTERVERTEBRAL DISC PRESSURES IN CADAVERIC THORACIC SPINES BY SHARING LOADING UNDER APPLIED DYNAMIC MOMENTS

Dennis E. Anderson^{1,2}, Erin M. Mannen^{3,4}, Rebecca Tromp¹, Benjamin M. Wong³, Hadley L. Sis³, Eileen S. Cadel³, Elizabeth A. Friis³, and Mary L. Bouxsein^{1,2}

¹Beth Israel Deaconess Medical Center, Boston, MA, USA

²Harvard Medical School, Boston, MA, USA

³The University of Kansas, Lawrence, KS, USA

⁴University of Arkansas for Medical Sciences, Little Rock, AR, USA

Abstract

The effects of the rib cage on thoracic spine loading are not well studied, but the rib cage may provide stability or share loads with the spine. Intervertebral disc pressure provides insight into spinal loading, but such measurements are lacking in the thoracic spine. Thus, our objective was to examine thoracic intradiscal pressures under applied pure moments, and to determine the effect of the rib cage on these pressures. Human cadaveric thoracic spine specimens were positioned upright in a testing machine, and Dynamic pure moments (0 to ± 5 N·m) with a compressive follower load of 400 N were applied in axial rotation, flexion - extension, and lateral bending. Disc pressures were measured at T4-T5 and T8-T9 using needle-mounted pressure transducers, first with the rib cage intact, and again after the rib cage was removed. Changes in pressure vs. moment slopes with rib cage removal were examined. Pressure generally increased with applied moments, and pressure-moment slope increased with rib cage removal at T4-T5 for axial rotation, extension, and lateral bending, and at T8-T9 for axial rotation. The results suggest the intact rib cage carried about 62% and 56% of axial rotation moments about T4-T5 and T8-T9, respectively, as well as 42% of extension moment and 36–43% of lateral bending moment about T4-T5 only. The rib cage likely plays a larger role in supporting moments than compressive loads, and may also play a larger role in the upper thorax than the lower thorax.

Please address all correspondence to: Dennis E. Anderson, Beth Israel Deaconess Medical Center, 330 Brookline Ave, RN115, Boston, MA 02215, Phone: 617-667-5380, Fax: 617-667-7175, danders7@bidmc.harvard.edu.

CONFLICT OF INTEREST STATEMENT

The authors state they have no conflict of interest to disclose.

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Keywords

Thoracic spine; Mechanical Testing; Follower load; Pure Moment; Rib cage; Intervertebral Disc Pressure

INTRODUCTION

The rib cage is integral to the thoracic spine anatomically and believed to add stability or share loads with the thoracic spine. Supporting this view, removal of the rib cage increases ranges of motion and reduces stiffness during mechanical testing of cadaveric thoracic spines under applied moments (Mannen et al., 2015b; Watkins et al., 2005). However, the effects of the rib cage on thoracic spine loading are not well studied, and the contribution of the rib cage to spinal support cannot be easily measured in part due to the difficulty in measuring spinal loading within an intact spine-rib cage construct. Because of this, information remains limited on the amount of load sharing the rib cage may provide, and whether this is similar or varies across levels of the spine.

Intervertebral disc pressures have been measured both *in vivo* and in cadaveric spine tests to provide insight into spinal loading, as disc pressure is strongly correlated to compressive loading in cadaveric spine tests (Anderson et al., 2016; Nachemson, 1960; Pollintine et al., 2004). Applied moments also increase intradiscal pressures in lumbar cadaveric specimens (Rohlmann et al., 2001; Wilke et al., 1996), and finite element modeling suggests lumbar disc pressure increases with intervertebral flexion angle as well as compression (Ghezlbash et al., 2016). However, few studies have examined disc pressure in thoracic discs, whether *in vivo* (Polga et al., 2004) or in cadaveric specimens (Anderson et al., 2016; Dolan et al., 2013), and none have yet examined thoracic disc pressures under applied moments.

Examination of thoracic disc pressures could provide insight into how the rib cage shares loading with the thoracic spine. We have previously reported that the rib cage appears to have a limited effect on thoracic intervertebral disc pressures under static compressive follower loads (Anderson et al., 2016). However, examination of thoracic stiffness suggests that the rib cage has more effect on the thoracic spine under applied moments than compressive loads (Watkins et al., 2005). Thus, our objective was to measure thoracic spine intradiscal pressures under applied dynamic moments, to determine the effect of the rib cage on these pressures, and to use these measurements to evaluate the amount of moment supported by the spine vs. the rib cage at different locations in the spine. We hypothesize that disc pressure will increase with applied moments, that this increase will be higher with removal of the rib cage, and that the rib cage will support a significant fraction of the overall moment applied to the spine.

METHODS

Specimens and testing

Eight fresh-frozen human cadaveric thoracic spines (T1-T12) with the rib cage intact were obtained (4 female, 4 male, age range 61–71). Data from experimental testing of these specimens has been previously reported (Anderson et al., 2016; Galvis et al., 2017; Sis et al.,

2016), but the disc pressures that are the focus of the current analysis have not been previously examined. Specimens were potted at T1 and T12, and positioned upright in a testing machine (Applied Test Systems, Butler, PA) that can apply pure unconstrained moments at the T1 level. A compressive follower load of 400 N, a reasonable magnitude to represent thoracic loading in upright standing (Anderson et al., 2016), was applied by means of cables running lateral to the spine, connected to the spine by a rod inserted through each vertebral body with an eye nut at each end. Five cycles of dynamic pure moments (0 to ± 5 N·m) were applied in displacement control at 1°/s in three test directions: axial rotation (AR), flexion - extension (FE), and lateral bending (LB). Trials were repeated under three rib cage conditions as described previously (Anderson et al., 2016), first with the rib cage intact, second with the rib cage stiffened artificially by steel plates bridging the sternocostal joints at ribs 2 – 5, and third after the rib cage was removed by cutting the ribs about 2 cm lateral to the costo-transverse joints.

Disc pressures during trials were measured at T4-T5 and T8-T9 using needle-mounted pressure transducers (Gaeltec, Isle of Skye, Scotland) placed in the center of the intervertebral discs. Vertebral motion was tracked with motion analysis pins placed in the left pedicles of T4, T5, T8 and T9 (Optotrak, Northern Digital Inc., Waterloo, ON, CAN), and intervertebral rotations were calculated by Euler decomposition with the first Euler rotation corresponding to the direction of the applied moment (Mannen et al., 2015a; Sis et al., 2016). Additional pins at T1, T2, and T11 were not utilized in the current analysis. Pressure data, applied moments, and intervertebral motions were collected throughout each test.

Data processing and analysis

The data were synchronized, and the third cycle of each test was extracted for analysis. The primary outcomes were changes of disc pressure with applied moment (slopes), and fraction of moment supported by the rib cage (calculated from slopes). For each test, the slopes of pressure vs. moment magnitude were calculated via linear regressions in positive moment and negative moment regions separately. The effect of rib cage on pressure-moment slopes were examined with mixed effects regression models by spinal level and test direction, adjusting for specimen as a random variable. In the case of significant relationships (slopes) between disc pressure and applied moment, the amount of moment supported by the spine and rib cage was estimated by comparing the slopes obtained with and without the rib cage intact. The slopes represent change in disc pressure (ΔP) vs. change in applied moment (ΔM), and in the intact case, the total moment (M_{total}) is the sum of the moment supported by the rib cage (M_{ribs}) and the spine (M_{spine}). Thus, the slope in the intact case is:

$$\beta_{intact} = \frac{\Delta P}{\Delta M_{total}} = \frac{\Delta P}{\Delta (M_{spine} + M_{ribs})} \quad \text{Equation 1.}$$

However, with the rib cage removed, the moment is only supported by the spine, thus the slope with the rib cage removed is:

$$\beta_{\text{noribs}} = \frac{\Delta P}{\Delta M_{\text{spine}}} \quad \text{Equation 2.}$$

The fraction of total moment supported by the spine can thus be calculated from the slopes by:

$$\frac{\Delta M_{\text{spine}}}{\Delta M_{\text{total}}} = \frac{\beta_{\text{intact}}}{\beta_{\text{noribs}}} \quad \text{Equation 3.}$$

And the fraction of moment supported by the rib cage is:

$$\frac{\Delta M_{\text{ribs}}}{\Delta M_{\text{total}}} = 1 - \frac{\beta_{\text{intact}}}{\beta_{\text{noribs}}} \quad \text{Equation 4.}$$

Point estimates and 95% confidence intervals for the fraction of moment supported by the rib cage were estimated by Equation 4 using nonlinear combinations of the pressure-moment slopes. Secondary outcomes were changes of disc pressure with intervertebral angle and angular ranges of motion, which were examined to provide context to the primary analysis and check for confounding, as intervertebral motion was expected to increase without the rib cage present. For each applied moment direction, ranges of motion for the corresponding intervertebral angles were determined, and slopes of pressure vs. angle were calculated via linear regressions for positive and negative moment regions separately, similar to the analysis for pressure vs. moment. The effect of rib cage on ranges of motion and pressure-angle slopes were examined with mixed effects regression models by spinal level and test direction, adjusting for specimen as a random variable. Statistical analyses were performed with Stata/IC 13.1 (StataCorp LP, College Station, TX).

RESULTS

Data from one specimen was excluded entirely due to incomplete pressure data or irregularities in applied moments affecting the majority of tests. Thus, analyses were conducted with data from seven specimens (3 female and 4 male, height 1.71 ± 0.11 m, weight 75.8 ± 20.5 kg, age 66 ± 4 years, age range 61–71).

Pressure typically increased with applied moment, whether positive or negative (Figure 2). Flexion (positive moment) and extension (negative moment) pressure-moment slopes differed ($p < 0.05$), as did left LB (positive) and right LB (negative) at T4-T5, so these were analyzed separately; directions were combined for AR at both levels, and for LB at T8-T9. Pressure-moment slopes were significant at T4-T5 ($p < 0.05$), except for extension with the rib cage intact which did not reach significance ($p = 0.074$). Pressure-moment slopes were significant at T8-T9 for AR, Flexion, and LB with no ribs ($p < 0.05$). The pressure-moment

slope increased with rib cage removal at T4-T5, by 165% (AR), 74% (extension), 55% (left LB) and 76% (right LB), and at T8-T9 by 126% for AR ($p < 0.05$, Figure 2).

The estimated percentage (95% confidence interval) of moment supported by the rib cage at T4-T5 was 62% (46 – 78%) for AR, 43% (2 – 83%) for extension, 43% (10 – 77%) for right LB, and 36% (19 – 52%) for left LB ($p < 0.05$), but not significant for flexion. The percentage of moment supported by the rib cage at T8-T9 was 56% (32 – 80%) for AR ($p < 0.05$), but not significant for flexion, extension or LB.

Intervertebral range of motion increased with removal of the rib cage ($p < 0.05$, Figure 3), at T4-T5 by 152% (AR), 57% (Flexion), 68% (Extension), 48% (Left LB) and 76% (Right LB), and at T8-T9 by 27% (AR) and 72% (LB). Increases at T8-T9 of 25% for flexion ($p = 0.535$) and 47% for extension ($p = 0.247$) were not significant.

Pressure increased with intervertebral angle in AR at both T4-T5 and T8-T9, and in flexion and extension (with ribcage only) at T4-T5, but other pressure-angle slopes were not significant (Figure 4). Pressure-angle slopes did not differ with rib cage conditions ($p > 0.05$), except for a 59% increase in slope in AR at T8-T9 ($p = 0.025$).

The pressure-moment slopes, ranges of motion, and pressure-angle slopes in the stiffened rib cage condition were not different than intact ($p > 0.05$); these data are presented in Supplemental Table 1.

DISCUSSION

Overall, disc pressure increased with applied moments in the thoracic spine, and removing the rib cage increased the pressure-moment slope for most applied moment conditions at T4-T5, but only for AR at T8-T9. Furthermore, removal of the rib cage had the largest impact in AR, increasing the pressure-moment slope about 2.5-fold, while other significant increases were about 1.5-fold. Pressure-moment slopes were smaller in extension than flexion (and not significant at T8-T9) perhaps due to a shift of loading from the disc to the posterior elements as the spine moves into extension (Adams et al., 1994). Surprisingly, pressure-moment slopes were smaller in right LB than left LB at T4-T5. The reason for this difference is unclear, but highlights that left-right symmetry of the spine is not assured. For example, osteophytes were observed in the majority of the specimens tested, and anatomical review has shown that osteophytes in the thoracic spine occur predominantly on the right side (Nathan, 1962). In total, the significant effects show that the rib cage limits disc pressures in the intact thoracic spine-rib cage construct, particularly in axial rotations, likely by limiting the moment supported by the spine.

To our knowledge, this is the first report of thoracic disc pressure under applied moments, although increases in disc pressure with applied pure moments have been previously reported in lumbar cadaveric specimens (Rohmann et al., 2001; Wilke et al., 1996). While pressure-moment slopes were not reported directly in those studies, they appear to fall in the range of approximately 5 – 20 kPa / N·m, smaller than the current study. Furthermore, these studies reported that under compressive loading, pressure increase with applied moment was reduced or eliminated. In addition, the only report of *in vivo* thoracic disc pressure

measurements, Polga et al. (Polga et al., 2004) reported no significant changes with extension, flexion, LB or AR motions, but loading would not be directly comparable to the cadaveric tests conducted here. Overall, the pressure-moment response found here is larger than other studies, but there is limited relevant data for comparison. Additional studies of thoracic spine mechanics and disc pressures under applied moments are warranted to confirm and extend the current findings.

With the current analysis, we show that the rib cage supports a large proportion of the overall moment applied to the thoracic spine. This appears different from compressive loading, for which a previous analysis of the same specimens found unclear and likely minimal effects of the ribcage on disc pressure (Anderson et al., 2016). The moment sharing by the rib cage is generally consistent with previous studies suggesting that the rib cage contributes about 31–44% of AR stiffness, 16–40% of flexion-extension stiffness, and 27–35% of LB stiffness in the thorax (Mannen et al., 2015b; Watkins et al., 2005). Interestingly, while the findings for AR were similar at both levels examined, significant effects in other directions were only found at T4-T5. This may reflect actual regional differences in the effects of the rib cage, due to the anatomical differences between the true ribs (T1-T7), wherein the costal cartilage attaches directly to the sternum, and the false ribs (T8 – T10), wherein the costal cartilage merely connects to the costal cartilage of the superior rib.

Increases in the intervertebral ROM with rib cage removal were generally consistent with previous reports of increased ROM for the entire thoracic spine (Mannen et al., 2015a; Watkins et al., 2005). However, the 152% increase in AR ROM at T4-T5 was much larger than previous reports and the other motions examined here. This provides additional support for the idea that the effects of the rib cage differ regionally, with a greater effect in the upper thorax in the region of the true ribs. In addition to changes in ROM showing that the rib cage resists spinal motion under applied moments, the general lack of effect on pressure-angle slopes supports the conclusion that the rib cage supports moments in parallel with the spine. The only difference found was an increase in pressure-angle slope in AR at T8-T9 which does not preclude this conclusion, although it may raise an unanswered question about what other factors may cause pressure to vary with angle.

This study had several limitations common to such investigations in cadaveric specimens. The sample size was relatively small, and as all specimens were from older donors, it is likely that there was some disc degeneration present, which is known to reduce disc pressure (Buttermann and Beaubien, 2008). It is also known that long term compressive testing can cause a decline in disc pressure (Adams et al., 1996), which likely affected pressures in this study, and as testing intact necessarily preceded rib cage removal, there was likely an order effect in pressure measurements as well (Anderson et al., 2016). Finally, the follower load application technique and/or hardware could have produced unintended effects on disc pressure or intervertebral kinematics. The implication of most of these limitations is greater variance in pressure among the various discs measured and tests performed, and indeed disc pressure and pressure-moment slopes varied widely between specimens. Nonetheless, the repeated measures design with mixed-model regression analysis allowed significant effects to be revealed even with limited numbers of specimens.

Removing the rib cage increased the pressure-moment slope in most conditions, indicating that the rib cage supports moments in parallel with the thoracic spine, with the largest effect for moments in AR. There is also evidence of differing effects in the upper thoracic spine than the lower thoracic spine, perhaps reflecting anatomical differences between the upper and lower ribs. This suggests the *in vivo* thoracic spine may have mechanically distinct regions due to the rib cage, a possibility which deserves additional exploration through future experimental and modeling studies. The unique data produced in this study will be helpful in such future studies and modeling efforts to better understand thoracic mechanics and spinal loading *in vivo*. Overall, this study suggests the rib cage plays an important role in limiting thoracic spine loading and disc pressure *in vivo*, acting primarily by supporting moments rather than compressive loads, with important implications for assessing thoracic spine loading for research and clinical purposes.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

ACKNOWLEDGMENTS

This study was supported by the National Institute on Aging (K99/R00AG042458) and by a Mentored Career Development Award from the American Society for Bone and Mineral Research. The study sponsors had no role in the study design, data collection, analysis, manuscript preparation, or the decision to submit the manuscript for publication.

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Figure 1:
Example pressure-moment plot (left) and pressure-angle plot (right) from the T4-T5 disc of one specimen in axial rotation, showing data with the rib cage intact (gray) and removed (black). Linear fits to determine pressure-moment and pressure-angle slopes are also shown.

Figure 2: Estimates of pressure-moment slopes from mixed-effects regressions, by level and direction of applied moment, with error bars showing 95% confidence intervals. *Significant difference between intact and no ribs conditions ($p < 0.05$).

Figure 3:

Estimates of intervertebral ranges of motion from mixed-effects regressions, by level and direction of applied moment, with error bars showing 95% confidence intervals. Range of motion is the maximum angular motion with applied moment from 0 N·m to 5 N·m magnitude applied moment, in the direction of the applied moment. *Significant difference between intact and no ribs conditions ($p < 0.05$).

Figure 4: Estimates of pressure-angle slopes from mixed-effects regressions, by level and direction of applied moment, with error bars showing 95% confidence intervals. *Significant difference between intact and no ribs conditions ($p < 0.05$).