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Effect of follower load on motion and stiffness of the human thoracic spine with intact rib cage

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ABSTRACT

Researchers have reported on the importance of the rib cage in maintaining mechanical stability in the thoracic spine and on the validity of a compressive follower preload. However, dynamic mechanical testing using both the rib cage and follower load has never been studied. An *in vitro* biomechanical study of human cadaveric thoracic specimens with rib cage intact in lateral bending, flexion/extension, and axial rotation under varying compressive follower preloads was performed. The objective was to characterize the motion and stiffness of the thoracic spine with intact rib cage and follower preload. The hypotheses tested for all modes of bending were (i) range of motion, elastic zone, and neutral zone will be reduced with a follower load, and (ii) neutral and elastic zone stiffness will be increased with a follower load. Eight human cadaveric thoracic spine specimen (T1–T12) with intact rib cage were subjected to 5 Nm pure moments in lateral bending, flexion/extension, and axial rotation under follower loads of 0–400 N. Range of motion, elastic and neutral zones, and elastic and neutral zone stiffness values were calculated for functional spinal units and segments within the entire thoracic section. Combined segmental range of motion decreased by an average of 34% with follower load for every mode. Application of a follower load with intact rib cage impacts the motion and stiffness of the human cadaveric thoracic spine. Researchers should consider including both aspects to better represent the physiologic implications of human motion and improve clinically relevant biomechanical thoracic spine testing.

1. Introduction

The kyphotic nature of the thoracic spine and the presence of the rib cage create a mechanical phenomenon in the thoracic spinal section that is unlike the lumbar and cervical sections, and is not fully understood. Biomechanical testing of the thoracic spine provides necessary information for comprehension of instability in the spine and for creation of new treatment methods and improved device design. Previous research has reported the importance of the rib cage in providing stiffness to the thoracic spine (Watkins et al., 2005; Brasiliense et al., 2011; Mannen et al., 2015a,b,c). These findings provide unanimous agreement that rib cage removal when performing mechanical testing of the thoracic spine is not indicative of the physiological stability present in the thoracic skeleton, and as such, the rib cage should remain intact during mechanical testing. However, these studies did not use a compressive follower preload with the rib cage attached.

Because the spine operates under compressive conditions *in vivo*, researchers have reported on the use of a follower load to simulate this condition during mechanical testing in other sections of the spine. As defined by Patwardhan, a follower load applies the compressive preload approximately tangential to the curve of the spine, passing through the centers of rotation of the spinal segments (Patwardhan et al., 1999). Conversely, direct compressive loading does not follow the curvature of the spine and can cause buckling in multilevel spine segments. A compressive follower preload allows each individual vertebra to be loaded in nearly pure compression. Patwardhan et al. initially found a high-increase in load-carrying capacity of the lumbar spine under compressive follower loads relative to direct loading, and proved this finding for the cervical and thoracolumbar spine in subsequent studies (Patwardhan et al., 2000; Stanley et al., 2004). Shirazi-Adl et al. has also successfully applied the follower load method using finite element models in the thoracolumbar spine (Shirazi-Adl and Parnianpour, 2000). This increase in load-carrying capacity corresponds to the

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ability of these spinal segments to support *in vivo* muscle forces and the weight of the upper body with engagement of ligaments and other essential tissues. The muscle forces present in the thoracic spine are mainly created by the erector spinae muscle group, which provides a major part of the stability to the thoracic spine (Kurtz and Edidin, 2005).

The purpose of this study was to implement a compressive follower load on the thoracic spine with an intact rib cage, and examine the effects of the follower load on the *in vitro* range of motion and stiffness of the thoracic spine with rib cage intact. Motions of both individual functional spinal units (FSUs) and spinal segments within the entire thoracic spine were examined. FSUs consist of two adjacent vertebrae, all interconnecting soft tissues, and the associated articulations of the ribs. The spinal segments were defined as upper (T1–T4), middle (T4–T8), and lower (T8–T12). The following hypotheses were tested through the course of this experiment: for individual FSUs and segments in all modes of bending, (i) range of motion (ROM), elastic zone (EZ), and neutral zone (NZ) will be significantly reduced with an increase in applied follower load, and (ii) neutral and elastic zone stiffness (NZS and EZS) will be significantly larger with an increase in applied follower load.

2. Methods

2.1. Experimental design

Eight fresh-frozen adult human thoracic cadaveric spines (T1–T12) were used in this study, four male and four female. Average age was 66.9 ± 4.4 years. The specimens were dissected to include the rib cage, spinal column, and stabilizing ligamentous structures. Muscular and fatty tissues were removed. Specimens were thawed prior to testing and experiments were performed at room temperature. Hydration of the specimens was maintained with saline solution.

T1 and T12 were potted parallel to their vertebral endplates with screws inserted into the vertebral bodies and auto body filler (Bondo, 3M, St. Paul, MN). Bolts were rigidly fixed to the inferior potting and mounted on a FS20 Biomechanical Spine Test System (Applied Test Systems, Butler, PA) that allows 6 degrees of freedom with a pure continuous moment applied to the unconstrained, superior end (T1) (Mannen et al., 2015a,b,c). The pure moment was applied at a 1 degree/second rate to a displacement control of ± 5 Nm in three modes of bending: lateral bending, flexion/extension, and axial rotation. Five cycles were run for each test, with the third cycle used for data analysis, in accordance with previous literature (Wilke et al., 1998). The motion of T1, T2, T4, T5, T8, T9, and T11 vertebrae were tracked using orthopedic research pins (Optotrak, Northern Digital Inc., Waterloo, Ontario, Canada) rigidly fixed into the left pedicles. The FSU and segment levels chosen were reasonably spaced throughout the thoracic spine, producing representative motions of the top, middle, and bottom of the spine. Motion data from all seven pins and load data from the test machine were recorded.

2.2. Follower load implementation

Follower load instrumentation was based on the methods reported by Patwardhan et al. (1999). Modifications were made to account for the space-limiting presence of the rib cage. Instead of the use of U-shaped mounts around each individual vertebra, fully-threaded steel rods were inserted into the approximate center of rotation of the vertebral bodies of T3 through T11. The center of rotation was determined by use of lateral radiographs with the specimen in a neutral kyphotic position. Female ball joint rod ends were screwed onto both ends of all threaded rods, as shown in Fig. 1. A steel wire cable was guided through the ball joint rod ends bilaterally, with the ball joint rod ends allowing the cable to remain tangential to the curvature of the spine as deformation took place under loading. The top of the cable was threaded through the superior end of the potting, distributing the weight of the follower load from T1 to T11. The two bottom ends of the cable passed through pulleys to maintain the curve of the spine. Weights were hung from the knotted ends of the cable, with half the weight on each side, creating total load levels of 0 N, 200 N, and 400 N. Fig. 2 shows the experimental setup with the specimen mounted on the machine. Reaction forces and moments were measured at the base of the specimen using a six degree-of-freedom load cell, in order to ensure that the force acting on the spine was occurring in the proper direction. Anderson et al. reports application of follower loads on the same specimens as used in the present study, but in static loading only. Anderson et al. presented no significant difference seen in sagittal tilt with the addition of each of the load levels, providing further validation of the path of the follower load (Anderson et al., 2016).

Fig. 1. Inferior view of the interior of the rib cage, displaying the ball joint rod ends and rods threaded through the approximate centers of each vertebrae, T3–T11. The wire cable, not pictured, was then threaded superior to inferior through all of the ball joint rod ends seen.

2.3. Data analysis and statistics

Data analysis and statistics were performed in Matlab (Mathworks, Natick, MA). Rotations were calculated using Euler decomposition techniques. The order of rotation used in the decomposition was, for (1) lateral bending: lateral, axial, sagittal; (2) axial rotation: axial, lateral, sagittal; (3) flexion/extension: sagittal, axial, lateral. For all three modes of bending, ROM, EZ, NZ, EZS, and NZS were computed (Wilke et al., 1998). NZ was defined as the difference in angulation at zero load between the two phases of motion, and EZ was defined as the angular displacement from the end of the NZ to the point of maximal loading (Wilke et al., 1998). These parameters are depicted in Fig. 3. Comparisons were drawn between the baseline case (0 N) and each level of follower load applied (200 N and 400 N), as well as between the two levels of load applied. With specimen data being normally distributed, a one-way repeated measures analysis of variance (ANOVA) was completed with a significance level of $\alpha = 0.05$. No correction factor was used in the statistical analysis because the need for adjustment remains controversial, and some researchers have found that the use of corrections can increase the chance of Type II error when small sample sizes are used, as in this study (Perneger, 1998; Nakagawa, 2004).

3. Results

The combined segmental absolute value of ROM for all modes of bending is shown in Fig. 4. This figure demonstrates the trend in ROM as the follower load increases. Not all specific segment or FSU changes, however, were found to be statistically significant. Segment and FSU data for lateral bending ROM are shown in detail in Figs. 5 and 6 because of the large number of significant differences seen ($p < 0.05$). Compared to the 0 N load, segmental lateral bending ROM decreased by an average of 62.4% for a 200 N follower load, and by an average of 75.9% for a 400 N follower load. Compared to the 0 N load, FSU lateral bending ROM decreased by an average of 61.7% for a 200 N follower load, and by an average of 72.3% for a 400 N follower load. Significant decreases in EZ measurements were seen at every FSU level for lateral bending, except for T1/T2 ($p < 0.05$). Compared to the 0 N load, the EZ in lateral bending for all FSU levels decreased by an average of 64.5% for a 200 N follower load, and by an average of 75.6% for a 400 N