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Effects of follower load and rib cage on intervertebral disc pressure and sagittal plane curvature in static tests of cadaveric thoracic spines

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ABSTRACT

The clinical relevance of mechanical testing studies of cadaveric human thoracic spines could be enhanced by using follower preload techniques, by including the intact rib cage, and by measuring thoracic intervertebral disc pressures, but studies to date have not incorporated all of these components simultaneously. Thus, this study aimed to implement a follower preload in the thoracic spine with intact rib cage, and examine the effects of follower load, rib cage stiffening and rib cage removal on intervertebral disc pressures and sagittal plane curvatures in unconstrained static conditions. Intervertebral disc pressures increased linearly with follower load magnitude. The effect of the rib cage on disc pressures in static conditions remains unclear because testing order likely confounded the results. Disc pressures compared well with previous reports *in vitro*, and comparison with *in vivo* values suggests the use of a follower load of about 400 N to approximate loading in upright standing. Follower load had no effect on sagittal plane spine curvature overall, suggesting successful application of the technique, although increased flexion in the upper spine and reduced flexion in the lower spine suggest that the follower load path was not optimized. Rib cage stiffening and removal both increased overall spine flexion slightly, although with differing effects at specific spinal locations. Overall, the approaches demonstrated here will support the use of follower preloads, intact rib cage, and disc pressure measurements to enhance the clinical relevance of future studies of the thoracic spine.

1. Introduction

Better understanding of thoracic spine biomechanics is needed to improve treatments for common clinical conditions affecting the thoracic spine, which include scoliosis (Asher and Burton, 2006), hyperkyphosis (Kado et al., 2007), vertebral fractures (Van der Klift et al., 2002), and thoracic spinal pain (Briggs et al., 2009). The presence of the rib cage is a distinguishing feature of the thoracic spine, and mechanical testing studies indicate that the rib cage adds significantly to overall thoracic stiffness, (Brasiliense et al., 2011; Mannen et al., 2015b; Watkins et al., 2005). In addition, some treatments for thoracic and spinal deformity utilize implants that attach to the ribs (Campbell, 2013), making the interaction between thoracic spine and rib cage of direct clinical importance in these situations. Furthermore, age-related increases in costal cartilage calcification (Teale et al., 1989) or sternocostal joint osteophytes (Schils et al., 1989) could act to locally stiffen the rib cage, altering the interaction between spine and rib cage. Thus, studies of thoracic spine biomechanics should include the rib cage to enhance anatomical and clinical relevance.

Because of the importance of the rib cage, several recent studies examining basic and clinical biomechanics in the human cadaveric thoracic spine have left the rib cage intact during testing (Healy et al., 2015; Mannen et al., 2015a; Perry et al., 2014). However, these studies did not include a physiological level of spinal compressive loading. A follower preload technique increases the compressive load that a cadaveric spine specimen can carry (Patwardhan et al., 1999), allowing physiologically realistic levels of loading during mechanical testing studies. A few studies including the thoracic spine have implemented a follower load technique (Auerbach et al., 2012; Buttermann and Beaubien, 2008; Stanley et al., 2004), but these studies were performed without the

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rib cage intact. Because including both rib cage and follower load would increase the clinical relevance of biomechanical testing in cadaveric thoracic spines, there is a need to develop methods to incorporate both into mechanical testing protocols.

While the loading of a particular vertebral level within an intact spine cannot be measured directly, pressure within intervertebral discs is known to correlate strongly with directly applied compressive loading in cadaveric tests (Nachemson, 1960; Pollintine et al., 2004). Disc pressures have frequently been measured in cadaveric tests of lumbar spine segments (Dolan et al., 2013; Nachemson, 1960; Pollintine et al., 2004), and less often in thoracic specimens (Dolan et al., 2013). Several studies have measured lumbar disc pressures while applying follower loads to lumbar or thoracolumbar spine specimens (Auerbach et al., 2012; Buttermann and Beaubien, 2008; Rohlmann et al., 2001; Wilke et al., 2003). Disc pressure measurements have been also used in *in vivo* experiments as indicators of both lumbar (Nachemson and Morris, 1964; Sato et al., 1999; Schultz et al., 1982; Wilke et al., 2001) and thoracic (Polga et al., 2004) spinal loading. Thus, thoracic disc pressures may prove to be useful measurements in tests of cadaveric thoracic spines, but these have not been previously measured under follower load or with the rib cage intact.

As follower load implementation within the confines of an intact rib cage requires adaptation of previous approaches, the purpose of this study was to determine the effects of follower load and rib cage conditions on intervertebral disc pressures and sagittal plane curvature in static, upright, unconstrained loading conditions, providing a baseline to support future studies using these techniques. We hypothesized that disc pressure would increase with increasing follower load, would decrease by artificially stiffening the rib cage, and would increase by the removal of the rib cage from the spine. We also assessed differences in disc pressure between two vertebral levels (T4-T5 vs. T8-T9). We also hypothesized that spine curvature would vary between rib cage conditions, but not with follower load, when examined overall, regionally, or at specific levels.

2. Methods

2.1. Specimens

Eight fresh-frozen full human cadaveric thoracic spines (T1-T12) with the rib cage intact (4 female and 4 male, mean age 67 years, range 61–71) were obtained from an anatomic tissue bank. Specimens had no reported history of moderate-severe vertebral fracture, severe scoliosis or kyphosis, or spinal surgery. Muscles and soft tissues were removed, except the intercostal muscles which were left intact. Several rib fractures were fixed by plating in one specimen prior to testing, which has been done previously in mechanical testing of cadaveric full thoracic spines with rib cage (Watkins et al., 2005). The ends of each specimen (T1 and T12) were potted in auto-body filler (Bondo, 3M, St. Paul, MN, USA) parallel to their vertebral end plates.

2.2. Follower load application

The follower load approach of previous studies (Patwardhan et al., 1999; Stanley et al., 2004) was adapted to insert the follower load hardware within the confines of the intact rib cage. In this study a fully threaded rod was inserted laterally through vertebral bodies at levels T3 – T11. Steel cable was attached to the potting at T1 and fed through a series of rod ends with ball joints attached to the ends of the threaded rods on each side of the spine (Fig. 1). The potting at the inferior end of each specimen (T12) was bolted to a horizontal surface for testing. Below T11, the cables were fed through pulleys positioned to continue the curvature of the follower load cable. To apply a follower load, weights equaling half of the total load were hung from the end of each cable.

2.3. Testing conditions

Testing was performed on fully thawed specimens at room temperature, and specimens were frequently sprayed with saline solution to help maintain hydration. Measurements were performed under three testing conditions, first with normal intact rib cage, then with an artificially stiffened rib cage, and finally with the entire rib cage removed by cutting the ribs just lateral to the costotransverse joints as done in prior studies (Mannen et al., 2015b; Watkins et al., 2005) (Fig. 2). The stiffened rib cage condition used metal plates to bridge the costal cartilage and sternocostal joints bilaterally for ribs 2–5, with the goal of simulating potential effects of cartilage calcification or sternocostal joint osteophytes by reducing motion across these connections. Within each testing condition, four follower load levels were applied: 0 N, 200 N, 400 N, and 600 N.

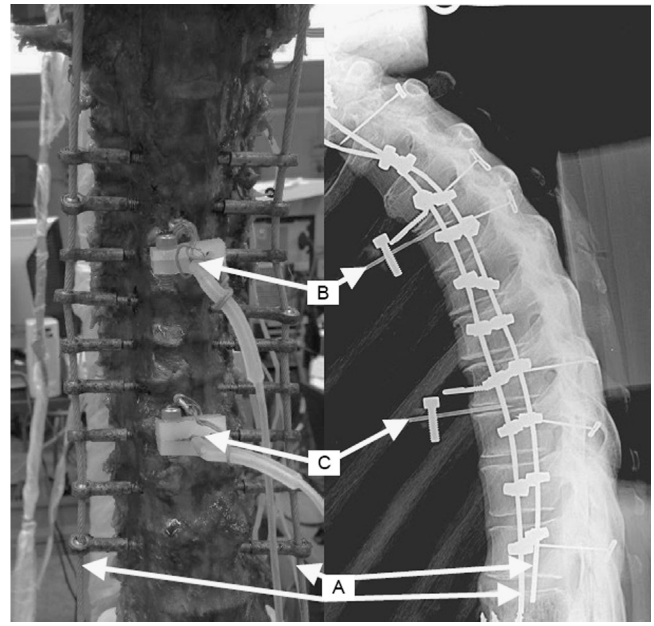

Fig. 1. Anterior view of a specimen with ribcage removed (left), and lateral x-ray view of a specimen with ribcage intact (right). Follower load application was via bilateral cables (A) attached to T1 and threaded through eye nuts attached to rods through vertebral bodies T3 – T11. Pressure transducer needles were inserted in the T4-T5 (B) and T8-T9 (C) intervertebral discs.

2.4. Measurements

Disc pressures were measured using pressure transducers side mounted on 1.3 mm diameter needles (Gaeltec, Isle of Skye, Scotland) inserted in the T4-T5 and the T8-T9 discs (Fig. 1). The pressure transducers were positioned to record pressure in the center of the nucleus pulposus, with locations confirmed by radiography. Disc pressures were recorded at 10 Hz, and an average value taken to represent the static pressure under each testing condition.

Motion-capture pins (Optotrak, Northern Digital Inc., Waterloo, ON, Canada) were inserted into the potting material at T1, and the left pedicles of T2, T4, T5, T8, T9 and T11, and vertebral position and orientation were recorded under each test condition. Local coordinate systems were developed (Wilke et al., 1998), and segmental sagittal curvatures were found overall (T1-T12), regionally (T1-T4, T4-T8, T8-T12) and at specific individual levels (T1-T2, T4-T5, T8-T9, T11-T12).

2.5. Statistical analysis

The effects of follower load and rib cage condition (Intact, Stiffened, No Ribs) on disc pressure and spine sagittal curvature were examined with mixed effects regression models, including follower load magnitude as a continuous fixed effect, rib cage condition as a categorical fixed effect with Intact as the baseline condition, and adjusting for specimen as a random variable to account for potential variation between specimens. A separate model was constructed for each disc pressure measured (T4-T5 and T8-T9), as well as for overall curvature (T1-T12), regional curvatures (T1-T4, T4-T8 and T8-T12), and individual curvatures (T1-T2, T4-T5, T8-T9 and T11-T12). Linear combinations of coefficients from the primary regression were used to estimate the intercept (outcome at 0 follower load) and slope (change with follower load) for Stiffened and No Ribs conditions, and significance of slope and differences of slope and intercept from Intact condition were examined. Useful pressure measures were not obtained in a few discs (recorded pressure remained at or near 0), and these were excluded from analyses. The difference in pressure between levels (T4-T5 vs. T8-T9) was also examined for effects of load and testing condition. Significance was set at $\alpha = 0.05$, and analyses were performed in Stata/IC 13.1 (StataCorp LP, College Station, TX).