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How do anterior/posterior translations of the thoracic cage affect the sagittal lumbar spine, pelvic tilt, and thoracic kyphosis?

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Abstract Anterior and posterior thoracic cage translations in the sagittal plane have not been reported for their range of motion and effects on the lumbar spine and pelvis. Twenty subjects volunteered for full-spine radiography in neutral, anterior, and posterior thoracic cage translation postures in a standing position. While grasping an anterior vertical pole, with hands at elbow level, subjects were instructed on how to translate their thoracic cage without any flexion/extension, utilizing a full-length mirror. On the radiographs, all four vertebral body corners of T1 through S1 and the superior margin of the acetabulum were digitized. Segmental and global angles of thoracic kyphosis, sagittal lumbar curvature, and pelvic flexion/extension in translation postures were compared to alignment in the neutral posture. Using the femur heads as an origin, the mean range of thoracic cage translation, measured as horizontal movement of T12 from neutral posture, was found to be 85.1 mm anterior and 73 mm posterior. In anterior translation, the thoracic kyphosis is hypokyphotic (Cobb T1–T12 reduced by 16°). In posterior translation, the segmental angles at T12–L1 and L1–L2 flexed, creating an “S” shape in the sagittal lumbar spine, while the thoracic kyphosis increased by 10°. Using posterior tangents from L1 to L5 and T12 to S1, and Cobb angles at T12–S1, the lumbar curve reduced slightly (by less than 3.3° for all global angle measurements) in anterior translation and reduced by 7.4°, 5.7°, and 8.1° respectively in posterior thoracic translation. The angle of pelvic tilt (measured as the angle of intersection of a line through posterior-inferior S1 to the superior acetabulum and the horizontal) reduced by a mean of 15.9°, and Ferguson’s sacral base angle to horizontal reduced by a mean of 13.1° in posterior translation. In anterior translation, pelvic tilt and Ferguson’s sacral base angle increased by 15.1° and 12.8°, respectively. The findings of this study show that thoracic cage anterior/posterior translations cause significant changes in thoracic kyphosis (26°), lumbar curve, and pelvic tilt. An understanding of this main motion and consequent coupled movements might aid the understanding of spinal injury kinematics and spinal displacement analysis on full spine lateral radiographs of low back pain and spinal disorder populations.

Keywords Lordosis · Kyphosis · Spinal coupling · Translation · Posture

Introduction

Recently, there has been renewed interest, with regard to both surgical and conservative care, in the sagittal plane alignment of the human thoracic, lumbar, and pelvic regions of the spine. Alterations in the sagittal plane alignment of the human spine have been implicated in the development of a variety of spinal disorders or diseases including: acute and chronic back pain [7], disc degeneration [33], spondylosis [23, 33], ossification of the spinal ligaments [6], adolescent idiopathic scoliosis (AIS) [4, 5], Scheuermann's kyphosis [38], impaired ribcage expansion during respiration [3, 24], osteoporosis and vertebral compression fractures [24], and spondylolisthesis [1]. Before surgical or conservative rehabilitative treatment is initiated, factors affecting the sagittal plane alignment of the spine must be identified and understood. Advanced age, weight, pelvic morphology, and body posture have all been shown to affect sagittal plane alignment of the human spine [7, 13, 16].

Concerning upright human posture, there are six degrees of freedom of posture of the head and thoracic cage. Only the rotational movements, termed "traditional planes of motion" by White and Panjabi [39], have been widely studied for their two-dimensional (2-D) and three-dimensional (3-D) spinal displacement (coupling) patterns [2, 26, 27, 28, 39, 40]. As there is a renewed interest in reducing sagittal plane deformities of the thoracic, lumbar, and pelvic regions, all postural movements in the sagittal plane need to be evaluated for their vertebral coupling patterns.

Currently, pelvic morphology and the angle of pelvic flexion/extension are thought to be the primary factors that affect changes in lumbar lordosis [13, 18, 19]. Likewise, thoracic cage flexion and extension are the primary movements thought to increase or decrease the thoracic kyphosis [32, 34, 39]. As such, pelvic tilt and/or thoracic cage flexion/extension are the primary movements utilized in today's clinical and surgical management for the correction/reduction of sagittal plane deformities [13, 18, 19, 32, 34, 39]. However, "fixed" sagittal plane translations of the thoracic cage have been overlooked as main motions in range of motion, spinal coupling, and in X-ray projection studies [8, 9, 29, 30, 31]. Using the 3-D Cartesian coordinate system suggested by Panjabi et al. [25], the anterior and posterior postural translations of the thoracic cage are *z*-axis translations (±Tz).

Penning studied cervical coupling during *z*-axis (sagittal) translations of the head, now known as protrusion and retraction [29, 30, 31]. He reported "S" shapes in the sagittal cervical spine during these head translation movements, and related these movements to whiplash injuries [30].

We hypothesized that changes in thoracic kyphosis, pelvic tilt, and lumbar curvature (similar to Penning's cervical findings) would occur during these rib cage postural translation movements. The present study seeks to quantify the range of motion of the thoracic cage in anterior/posterior translations and the associated thoracic, lumbar, and pelvic 2-D radiographic coupling patterns.

Materials and methods

In the standing position, three lateral full-spine radiographs of 15 men and five women volunteers, who were students at Life University in Marietta, Georgia, were obtained in 1999 in the following postures: neutral, anterior thoracic *z*-axis translation, and posterior thoracic *z*-axis translation (Fig. 1). All aspects of this study were approved by our internal review board (IRB). The subjects were without a history of back pain and/or prior spinal surgery. On a visual analog scale (VAS: 0="perfect health", 1="slight discomfort, only intermittently, annoyance",...,10="bedridden with unbearable pain") the volunteers had an average score of 0.5, indicating that they were pain free on the day of study participation. Subjects had an average age of 28.0 years (SD 6.6 years), an average height

Fig. 1 Full-spine radiographs of 20 normal subjects were obtained in neutral and anterior/posterior translational main motions of the thoracic cage (±Tz), (known as protrusion/retraction for head movements). These thoracic cage movements have been neglected in the literature for lumbar/pelvic coupling research. In the *middle photograph*, a neutral posture is depicted. The subject is holding onto a vertical pole to keep the upper extremities from projecting over the spine. In the *left photograph*, anterior (horizontal) translation of the thoracic cage is illustrated. In the *right photograph*, posterior (horizontal) translation of the thoracic cage is shown

of 176.7 cm (SD 10.0 cm), and an average weight of 76.6 kg (SD 15.3 kg).

A supervising instructor taught each subject, utilizing a full-length mirror, how to translate their thoracic cage with respect to their pelvis. The subjects were instructed to keep T1 approximately over the level of T12. Because this is not a common range of motion, specific attention was taken to avoid any thoracic cage flexion and extension. During all radiographs, the subjects grasped an anteriorly placed vertical pole at waist level to keep the humerus from overlapping the thoracic spine. After obtaining a neutral lateral full-spine radiograph, radiographs were obtained in the two thoracic cage translated positions.

Full-spine radiographs were obtained in each of these translated postures at a tube-film distance of 182.9 cm. To ensure the radiographic visibility of the T1–T4 area on the full-spine radiographs, special split/variable cassette screens were purchased from X-ray Cassette Repair Company (Crystal Lake, Illinois).

The radiographic images were digitized with a sonic digitizer (GP-9, purchased from GTCO CalComp, Columbia, Maryland). All four vertebral body corners of T1–S1 and the superior margin of the acetabulum were digitized. Digitized points were processed with our own code developed with Trent Computer Systems (Harvest, Alabama).

Adjacent segmental angles or relative rotation angles (RRAs) and global angles or absolute rotation angles (ARAs) of thoracic kyphosis and lumbar lordosis were determined with the posterior tangent method (Fig. 2). Also, Cobb angles were computed at T1–T12, T2–T11, and T12–S1. Ferguson's sacral base angle to horizontal was calculated. An angle of pelvic tilt was calculated by the intersection of a line through posterior-inferior S1 to the superior acetabulum and a horizontal line. To ensure that the subjects were not adding excessive flexion/extension of the thoracic cage to the desired anterior/posterior translations, lines connecting the centroids of T1 and T12 and T2 and T11 were compared to the true vertical. The range of thoracic cage anterior/posterior translation was measured as a horizontal translational movement of the T12 vertebral body compared to a vertical line through the superior margin of the femur heads. The reliability of the digitizing system in calculating the above rotation angles and translation distances has been found to have high inter- and intraclass correlation coefficients and low standard errors of measurement [10, 11].

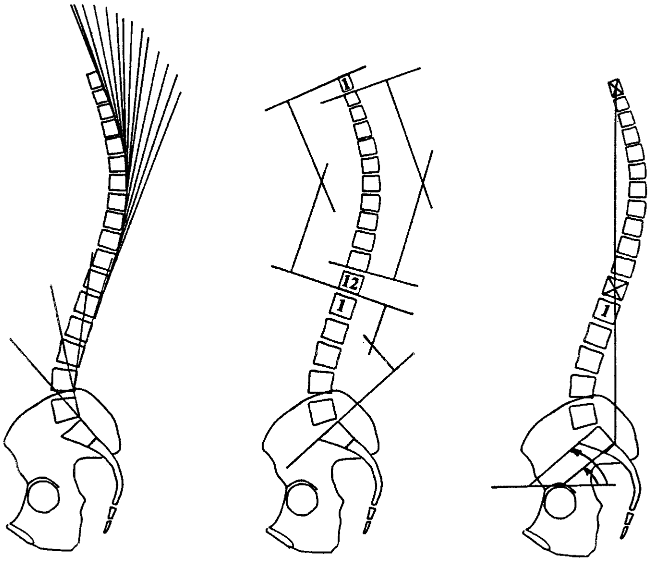

Fig. 2A–C Posterior tangents and Cobb angles were used to analyze vertebral positions on the full-spine radiographs. **A** Tangents at the posterior body margins of each segment can be intersected to create relative rotation angles (RRAs – segmental angles). Absolute rotation angles (ARAs – global angles) are the combined sum of the RRAs between the posterior tangents. **B** Cobb angles were drawn at T1–T12, T2–T11, and T12–S1. **C** The sagittal alignment of T1 above T12 was measured with a vertical line compared to a line through the centroids of T1 and T12. The range of translation motion was measured as a horizontal distance of posterior-inferior T12 from a vertical line through the superior margin of the femur heads. Ferguson's sacral base angle to the horizontal was computed. Also an angle of pelvic tilt to the horizontal was determined from inferior-posterior S1 to the superior margin of the femur head

Since the mean absolute differences of observers' measurements of the computed angles and distance have been reported as small (between 0.6° and 2° for angles) [10, 11], only means and plus/minus one standard deviation were required to analyze our results.

Results

Subjects could translate their rib cages forward 85.1 mm (+Tz) and backward 73.0 mm (–Tz), measured as horizontal movement from neutral alignment of T12 compared to a vertical line through the femur head (Table 1). After accounting for magnification, these distances were estimated to be anterior 76.7 mm and posterior 65.0 mm in vivo. Subjects who started in a posterior translated posture (mean of –69.4 mm) were able to translate a greater distance forward (101.8 mm) and less backwards (56.2 mm). Subjects whose neutral posture was an anterior translation of T12 relative to the femur head (mean of –36.9 mm) were able to translate less distance forward (79 mm) and more backward (77.7 mm). During these translational movements, subjects were able to minimize thoracic cage flexion/extension to a mean of less than 4.2° (Table 1).

Means and standard deviations are provided for all movements in all of the tables. There were changes in pelvic tilt, measured as the angle between a line from the posterior-inferior S1 to the superior acetabulum and the horizontal, during anterior/posterior translations of the tho-

Table 1 Displacement of the thoracic cage and rotations of the pelvis for 20 normal subjects during anterior translations (±Tz) and posterior translations (–Tz) of the thoracic cage. (These values are radiographic measurements, not corrected for magnification, and are presented as mean±SD)

Measure	+Tz	Neutral	–Tz
$Tz_{T12–S1}$ (mm)[a]	76.9±16.9	11.8±20.8	–43.1±21.6
$Tz_{T12–femur\ head}$ (mm)[a]	39.0±16.8	–46.1±15.9	–119.1±23.5
T1–T12 to vertical[b] (°)	–4.2± 6.0	0.5± 4.0	–0.5± 6.8
Sacral base to horizontal (°)	54.1± 8.5	41.3±10.0	28.2± 9.8
Pelvic tilt[c] (°)	81.2±11.7	66.1± 7.9	50.2± 9.5

[a] Anterior/posterior translational (horizontal) displacement of T12 above S1 or T12 above the superior margin of the femur head

[b] Line through the centroids of T1 and T12, used to check for any flexion/extension during thoracic cage anterior/posterior translation. Negative angle values indicate extension

[c] Posterior-inferior S1 to superior margin of acetabulum to horizontal

Table 2 Rotational changes of lumbar lordosis for 20 normal subjects during anterior and posterior translations (±Tz) of the thoracic cage. (These values are radiographic measurements, not corrected for magnification, and are presented as mean±SD)

Measure	+Tz	Neutral	–Tz
Cobb$_{T12-S1}$ (°)	–60.4±14.1	–62.0±12.0	–53.9±15.7
RRA$_{T12-L1}$[a] (°)	–4.0± 4.9	–0.4± 4.2	4.3± 3.9
RRA$_{L1-L2}$ (°)	–4.6± 4.1	–3.3± 6.2	2.5± 5.9
RRA$_{L2-L3}$ (°)	–7.1± 4.5	–7.5± 3.9	–5.3± 5.3
RRA$_{L3-L4}$ (°)	–10.3± 5.3	–10.6± 3.8	–10.6± 5.3
RRA$_{L4-L5}$ (°)	–14.8± 7.2	–17.2± 5.6	–17.8± 5.9
RRA$_{L5-S1}$ (°)	–26.6±10.3	–31.7±10.7	–38.1± 8.8
ARA$_{L1-L5}$[b] (°)	–36.8±13.8	–38.6±12.3	–31.2±15.4
ARA$_{T12-S1}$ (°)	–67.4±15.5	–70.7±14.0	–65.0±15.0

[a] Relative rotation angle formed by posterior tangents (segmental angle)

[b] Absolute rotation angle (sum of RRAs). Negative values indicate extension

Table 3 Rotational changes of the thoracic kyphosis for 20 normal subjects during anterior and posterior translations (±Tz) of the thoracic cage (mean±SD)

Measure	+Tz	Neutral	–Tz
H/L[a] of T1–T12	0.970	0.953	0.940
Cobb$_{T1-T12}$ (°)	31.5±14.2	47.5±10.4	57.5±12.3
Cobb$_{T2-T11}$ (°)	29.7±14.5	43.0±10.9	50.2±14.4
RRA$_{T1-T2}$ (°)	0.8± 7.8	–0.1± 4.8	1.0± 6.7
RRA$_{T2-T3}$ (°)	4.5± 5.5	3.6± 4.5	5.3± 5.5
RRA$_{T3-T4}$ (°)	2.7± 6.2	5.5± 5.2	4.4± 3.7
RRA$_{T4-T5}$ (°)	5.2± 5.3	6.2± 4.2	6.5± 5.2
RRA$_{T5-T6}$ (°)	4.6± 4.3	6.3± 4.1	5.5± 5.1
RRA$_{T6-T7}$ (°)	5.8± 4.3	6.9± 3.1	7.8± 3.6
RRA$_{T7-T8}$ (°)	3.6± 3.6	5.9± 4.4	6.4± 4.0
RRA$_{T8-T9}$ (°)	3.3± 3.6	4.3± 3.5	5.7± 3.9
RRA$_{T9-T10}$ (°)	2.1± 3.7	2.5± 3.3	3.4± 3.8
RRA$_{T10-T11}$ (°)	0.7± 4.9	3.1± 3.4	6.4± 3.3
RRA$_{T11-T12}$ (°)	–0.7± 4.0	2.2± 4.2	3.5± 3.3
ARA$_{T1-T12}$ (°)	32.7±14.8	46.3±11.6	55.7±12.9
ARA$_{T2-T11}$ (°)	32.6±13.6	44.1±11.5	51.2±12.4
ARA$_{T3-T10}$ (°)	27.4±11.4	37.4±12.2	39.6±11.3

[a] Height/length ratio; length along the posterior longitudinal ligament from T1 to T12

racic cage. In anterior translation, the pelvis rotated forward (+Rx) on the femur heads by a mean of 81.2°–66.1°=15.1°. During posterior translation, the pelvis extended (–Rx) by a mean of 66.1°–50.2°=15.9° (Table 1).

In the sagittal lumbar spine, posterior translation created an "S" configuration as the segmental angles at T12–L1, L1–L2, and L2–L3 flexed, on average, by a combined total of 12.7° compared to the neutral position, while L4–L5 and L5–S1 extended by a combined total of 7°.

In anterior translation, T12–L1 and L1–L2 extended, on average, by a combined total of 5° from the neutral position, while L4–L5 and L5–S1 flexed by a combined total of 6°. The global angles, Cobb$_{T12-S1}$, ARA$_{L1-L5}$, and ARA$_{T12-S1}$, slightly reduced (by less than 3.5° in all cases) in anterior translation, and reduced more (by 8.1°, 7.4°, and 5.7° respectively) in posterior translation (Table 2).

In posterior translation, the thoracic kyphosis increased in all global angles; the mean increase in ARA$_{T1-T12}$ was 9.4°, in ARA$_{T2-T11}$ 7.1°, in Cobb$_{T1-T12}$ 10°, and in Cobb$_{T2-T11}$ 7.2°. Anterior translation of the thoracic cage caused hypokyphosis of the thoracic curve with mean angle decreases between posterior tangents at ARA$_{T1-T12}$ of 13.6° and at ARA$_{T2-T11}$ of 11.5°, with Cobb$_{T1-T12}$ decreasing by 16° and Cobb$_{T2-T11}$ by 13.3° (Table 3).

Discussion

This paper is the first to report ranges of motion and spinal coupling patterns in the thoracic and lumbo-pelvic spines for anterior/posterior translation postures of the thoracic cage. As hypothesized, large changes in lumbar curvature and pelvic movements occur during anterior/posterior translations of the thoracic cage. Additionally, unexpectedly large changes in thoracic kyphosis occurred. Figure 3 and Fig. 4 illustrate the changes in the thoracic kyphosis, lumbar lordosis, and pelvic tilt caused by anterior/posterior translation of the thoracic cage.

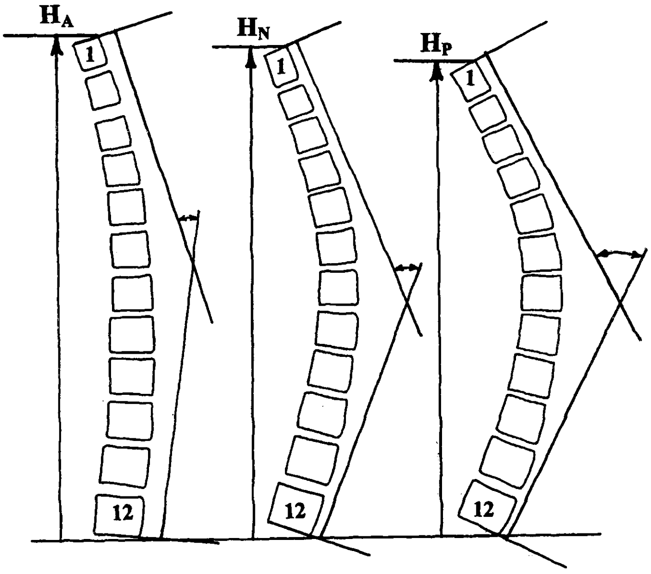

Fig. 3A–C Anterior/posterior translations of the thoracic cage created changes in thoracic kyphosis. Hypokyphosis (**A**) was found in anterior translation. Hyperkyphosis was observed in subjects in posterior translated posture (**C**) as compared with a neutral posture (**B**). The average total change in the Cobb angle at T1–T12 was 26° from the posterior to anterior translated positions. The length of the spine (L) is the arc length along the posterior longitudinal ligament from T1 to T12. The height-to-length index increased in anterior translation posture (mean H_A/L=0.97), indicating straightening in the anterior translated posture. The height-to-length index decreased in posterior translation (mean H_P/L=0.94)

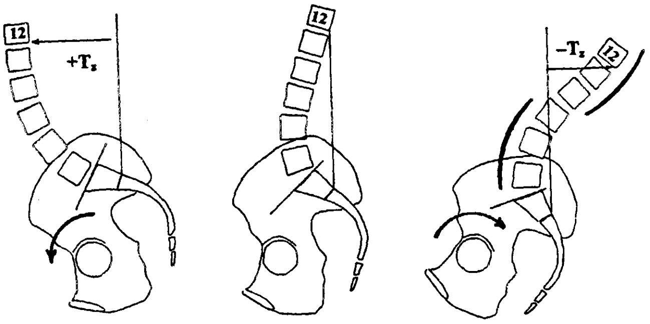

Fig. 4 Three configurations of the lumbar curvature and pelvic tilt are illustrated: **A** anterior thoracic translation (+Tz), **B** neutral posture, and **C** posterior thoracic translation (–Tz). In anterior translation (**A**), the pelvis flexes on the femur heads, the Ferguson's sacral base angle increases, while the upper lumbars extend and the lower lumbars flex compared to the neutral posture. In posterior translation (**C**), the pelvis extends on the femur heads, the sacral base becomes more horizontal, and the lumbar curve becomes an "S" shape as the upper lumbars flex (T12–L2), while the lower lumbars extend

Comparing horizontal displacement of T12 to the femur head, the range of motion was approximately 85 mm forward and 73 mm backward translational movement on the radiographs, but this was dependent on the initial starting posture. Using similar triangles to eliminate projection distortion, we estimated these distances to be anterior 77 mm and posterior 66 mm in the live subjects.

Concerning the change in thoracic kyphosis, in Table 3, the findings indicate that the lower thoracic region (T8–T12) accounts for 13.6° of this change, or 60%; this is probably related to the floating or incomplete rib arrangement in this region. This finding is unique, as these values are unlike those reported for thoracic coupling during flexion/extension (±R*x*) of the rib cage [39].

In regard to the lumbar lordosis, the opposite extension/flexion movements above and below the lumbar curve apex (L4) during anterior/posterior translations of the thoracic cage (Table 2) are similar to Penning's cervical findings in head protrusion/retraction [29, 30]. An "S" shape was noted in the sagittal lumbar spine during posterior thoracic cage translation (Fig. 4). However, even though the opposite extension/flexion coupling was observed in the lumbar segments, the opposite "S" shape was not observed during anterior translation of the thoracic cage. This is because of the deeper lordosis at L4-L5-S1 in the normal elliptical shape [7, 14].

Recently, Kiefer et al. [15] reported the importance of keeping T1, T12 and S1 vertically aligned in the sagittal plane to minimize muscle forces and moments in upright neutral posture. For these reasons, we measured thoracic cage translations as horizontal displacements of T12 to S1, while keeping T1 vertically aligned with T12. During thoracic Tz translations, subjects had a mean flexion/extension of less than 4.2° at T1–T12, indicating that these endpoints remained vertically aligned (Table 1). However, Kiefer et al. [15] modeled T1–T12 as one rigid body and the large changes in thoracic kyphosis reported here, especially in the lower thoracic region (total change in Cobb angle of 26° at T1–T12 in Table 3) indicate that the rigidity of the thoracic cage needs to be re-evaluated. Perhaps only the thoracic kyphosis from T1 to T10 should be modeled as a rigid body.

There are limitations inherent in the present study. First, we utilized only 20 normal subjects; however, the majority of range of motion and spinal coupling pattern reports have utilized a similar number of subjects [8, 9, 28]. Secondly, our subjects were healthy, pain-free volunteers; therefore, it is unknown how spinal disorders will affect or change the results of the present study. Third, and most important, there are different ways in which the anterior/posterior thoracic translation could have been carried out. Because we desired to simulate (as close as possible) a real life situation in upright stance, we did not constrain the pelvis. We wished to see any compensatory pelvic movements. Lastly, some of our subjects needed feedback to keep this sagittal plane translation a pure movement, and a supervisor was therefore used to give subjects visual feedback about the verticality of the thoracic cage. This could have influenced the movements in the ribcage in an unknown way. However, since the subjects' muscles were actively controlling the movement (no external loads were used), we feel that the movement is as close to a real life situation as possible.

The decreased range of movement or flexibility in posterior thoracic cage translation in our subjects is consistent with findings in cadavers subjected to anterior and posterior shear loads [20, 35]. This is probably related to the reduced range of motion of the thoraco-lumbar spine in extension compared to flexion.

Recently, there have been a multitude of studies describing the normal ranges and segmental contributions of the thoracic kyphosis, lumbar lordosis, and pelvic tilt angle [13, 36, 37]. According to the findings of the present study, differences in the magnitude and direction of thoracic *z*-axis translation postures in different individuals may be one of the causes of the variances in sagittal plane thoracic and lumbar curvatures. Many studies utilizing a type of a sagittal plane plumb line analysis to measure spinal balance of the thorax relative to the pelvis have described a wide range of values [13, 36, 37]. However, these vertical plumb lines cannot distinguish between thoracic cage flexion, extension, anterior translation, posterior translation, pelvic flexion and extension nor combinations of the above postures. To ensure that the subjects in the current study were not adding excessive flexion/extension of the thoracic cage to the desired anterior/posterior translations, lines through the centroids of T1 and T12 and T2 and T11 were compared to the true vertical.

Additionally, several surgical outcome studies have identified loss of the distal lumbar lordosis and decreased sacral tilt (extension) as risk factors for post-surgical low back pain [17, 18, 22]. As our present study demonstrates that posterior translations of the thorax reduces lumbar lordosis (6°–8°) and pelvic and sacral tilt (16°–13°), thoracic sagittal plane translations merit clinical evaluation as one of the corrective procedures in combating thoracolumbar spinal pain, impairment, and deformity.

It is interesting to speculate about the relevance of anterior translated thoracic postures to spinal disorders such as thoracic scoliosis, Scheuermann's kyphosis, and lumbar spondylolisthesis. Concerning scoliosis of the thoracic region, several studies indicate that the thoracic kyphosis must decrease or become lordotic in order for the coronal plane curvature to progress [4, 5, 12]. In a few of our subjects, the thoracic kyphosis dramatically straightened during anterior thoracic translation. In this anterior translated position, the application of compressive loads or lateral moment loads to the thoracic spine may be a risk factor for the development of or increase in the magnitude of curvature.

Conversely, posterior translation increased the thoracic kyphosis by 10° and could be one of the mechanical factors associated with the onset or progression of syndromes associated with an increased thoracic cage kyphosis (Scheuermann's kyphosis, osteoporosis, compression fractures, and decreased rib mobility). In support of this idea, Lowe and Kasten [21] reported that 31 out of 32 of their patients with Scheuermann's disease had an average increased posterior translation of 7.3 cm compared to normal sagittal balance.

Diagnostic thoracic sagittal plane translation studies could be made a part of the clinical evaluation and rehabilitative exercises in the management of increased or decreased lumbar lordosis and thoracic kyphosis. In such cases, no emphasis would need to be placed on pelvic tilting or thoracic cage flexion/extension movements. Currently, this idea is not in the armamentarium of teaching or clinical practice.

Conclusions

This study is the first to report ranges of motion and spinal coupling for anterior/posterior translations of the thoracic cage. Large changes (26°) in kyphosis occur in anterior/posterior translation of the thoracic cage (60% of this being at T8–T12); the thoracic kyphosis straightens in anterior translation and increases in posterior translation. The pelvis tilts forward in anterior thoracic cage translations, while the lower lumbars flex and the upper lumbars extend. The pelvis extends backwards in posterior thoracic cage translations, the lower lumbars extend and the upper lumbars flex, creating an "S" configuration. In the future, thoracic cage sagittal plane translations may lead to an increased understanding of physical medicine and rehabilitation for sagittal plane deformities of these regions.

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