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Unilaterally Rotating Vertebrae: A Unique Movement Behaviour Arising from Wedged Intervertebral Discs in Scoliosis Condition

Soheil Arastehfar, Athena Jalalian, Ian Gibson
University of Twente
Drienerlolaan 5, 7522 NB, Enschede, Netherlands
s.arastehfar@utwente.nl; a.jalalian@utwente.nl; i.gibson@utwente.nl

Abstract **-** Scoliosis condition wedges the intervertebral discs. Once wedged, the core (nucleus pulposus) of a disc migrates permanently off the centre of the annulus fibrosus. In severely wedged discs, the core is pushed all the way towards a limit of its range of motion. As such, these discs hypothetically may lose their capability of wedging further as they cannot surpass the limit. However, this is yet to be studied. On a dataset of X-rays of 9 scoliotic patients, we studied the rotations of 126 vertebrae with respect to their inferior vertebrae. The rotations were measured for lateral movements towards four different positions in the coronal plane. We found that almost half of the vertebrae, irrespective of the spine movement direction, always rotate in the same direction. For example, in both left and right bending spine movements, these vertebrae rotate only towards one side (either left or right), while the rest can rotate both leftwards and rightwards following the spine movement direction. Such unilateral rotational behaviour can have significant indications for scoliosis surgery simulations. In surgery, the spine is subject to high forces to be straightened and a scoliosis model that does not support this unique behaviour may overestimate the spine straightness and produce misleading predictive information, negatively affecting the surgery planning.

***Keywords*:** scoliosis, spinal movement, rotational displacements

1. Introduction

Scoliosis is a 3D structural deformity of the human spine (Fig. 1a). Scoliosis condition causes S- or C-shape spine in the coronal plane [1]. To correct severe cases of scoliosis, surgical instrumentation is often required (Fig. 1b) [2]. To help with surgical planning, several biomechanical models, e.g. [3], have been developed to simulate the surgery and provide predictive information regarding the surgical outcome, such as the straightness of instrumented spine.

Existing biomechanical models are heavily reliant on the intact spine models [4, 5]. For example, they are basically intact spine models, but their model parameters are adjusted for scoliosis to simulate the asymmetrical shape [6, 7]. However, scoliotic spines exhibit unique behaviours significantly deviating from their intact counterparts [8]. For example, in the coronal plane, some parts of scoliotic spines close to their inflection vertebrae (where the spine curvatures changes direction, transitioning from a convex curve to a concave one, or vice versa) can only negligibly bend [9]. Arastehfar et al. [8] extracted four of these behaviours through a study on the movement of scoliotic spine curvatures. As such, the scoliosis condition might not be accurately represented by the scoliosis models adapted from intact spines unless they show such behaviours.

One of the unique behaviours found by [8] is called “unilateral rotations”. Arastehfar et al. [8] split the spine curvatures of their patient cohort into micro-scale motion segments and measured their rotations during the spine movement in the coronal plane. They found that big fractions of these segments rotate only in one direction irrespective of the spine movement. However, this is yet to be studied for the functional spinal units (FSU), comprising two adjacent vertebrae and their intervertebral disc. On the vertebral level, it is not known if the vertebrae follow the same movement behaviour or the “unilateral rotations” only applies to the segments of curvatures. Given that most of the multibody biomechanical models of scoliosis are comprised of FSUs, it is essential to study applicability of the “unilateral rotations” to the vertebral bodies.

In this paper, we aim to study whether the “unilateral rotations” behaviour extends to the vertebrae. For this we measure the rotations of the vertebral bodies during scoliosis movements on the X-rays taken in the coronal plane. In section 2, we introduce the study design. Section 3 presents the results following a discussion. We conclude the paper in section 4.

(a) (b)

Fig. 1: X-rays of example of (a) scoliosis, and (b) instrumented scoliotic spine.

2. Study Design

2.1. Patient Cohort

X-rays of nine patients with adolescent idiopathic scoliosis [10] with no neurological deterioration were used for this study. These scoliotic patients undergone surgical treatments to correct the scoliosis condition. We properly consulted these patients after obtaining approval form from the domain-specific review board. We obtained the patients' approval and written informed consents.

The descriptive data of our patient cohort is presented in Table 1. There were seven female patients with ages ranging from 13 to 16 years and two male patients of 14 and 19 years old. The average age was 15 years. The patients' Cobb angles ranged from 46 to 59 degrees. The average of the main curves was 53°.

Table 1: Descriptive data of the subjects.

No.	**Gender**	**Age (years)**	**Lenke Classification** [11]	**Cobb Angle (degrees)**
1	Female	13	1A	49
2	Female	16	1C	46
3	Female	13	2A	53
4	Female	16	2B	53
5	Female	14	2C	55
6	Female	15	3A	59
7	Female	14	6C	59
8	Male	14	2A	59
9	Male	19	2B	48

2.2. Data Collection

There were six X-rays available per patient in this study. Five of the X-rays were taken pre-surgery in the coronal plane in the erect, left bending, right bending, neutral, and traction positions. One X-ray was post-surgery in the erect position.

We measured the location and orientation of the vertebrae on these X-rays according to the SRS guidelines [12]. The location is defined as the midpoint (Fig. 2) of the vertebral body: it the intersection of two lines, one from the upper left corner to the lower right one, and the other from the upper right corner to the lower left one [12]. The rotation is defined as the angle of the line passing through the centres of the upper and lower endplates of the vertebral body (Fig. 2) [12]. Vertebrae L4 to T2 were included in the data collection. Vertebrae L5 and T1 were excluded because at these vertebrae the images were often suboptimal for the measurement.

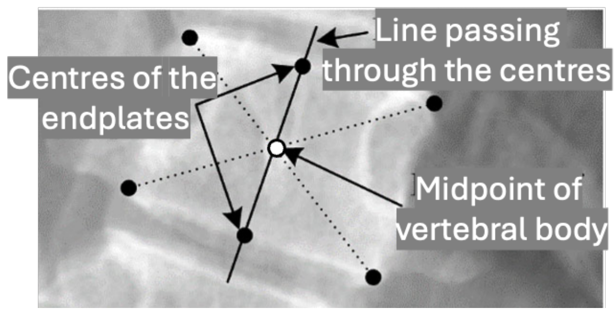

Fig. 2: The midpoints and centres of the endplates of a vertebral body marked on the X-ray.

The measurements were done by two experts. Each expert repeated each measurement three times. The average of the measurements was used. Pearson correlation analysis was done to test the intra and inter observer reliabilities of the measurements. The intra observer reliabilities for experts 1 and 2 were 0.95±0.04 and 0.92±0.03 respectively. The inter observer reliability was 0.90. According to [13], these excellent agreements demonstrate the repeatability and reliability of the measurements.

3. Results and Discussion

The intervertebral discs of a spine with scoliosis condition are wedged. An intervertebral disc can be defined as a cushion (annulus fibrosus) with a core (nucleus pulposus) inside [14]. The core moves inside the cushion and this movement results in a wedged disc [15]. For an individual wedged disc, the core might move all the way to one side, and thus, further wedging towards that side might not be possible. As a consequence, the intervertebral disc might lose its capability to wedge further towards that side.

In an erect scoliotic spine, some intervertebral discs are already wedged maximally towards left or right, and thus, they may not wedge further or only wedge minimally during left or right bending movements respectively. Hence, the vertebrae superior to these discs in an FSU may not bend further.

The rotational displacements of a vertebra were computed in their respective FSU, i.e. the rotation of the vertebra was subtracted by the rotation of its inferior vertebra. We identified the direction (clockwise / counterclockwise) of the displacements during the spine movement from the erect position towards the other four positions: left bending, right bending, neutral, and traction.

By using the direction information, we investigated if a vertebra during this spine movements could rotate in both directions, i.e. bilateral rotation, or could only rotate in one direction, i.e. unilateral rotation, irrespective of the direction of the spine movement. A bilaterally rotating vertebra rotates clockwise during right bending movement and rotates counterclockwise during left bending position in our measurements. However, for example, a unilateral vertebra that rotates clockwise only, rotates in the same direction during both left and right bending movements.

In our cohort, the rotational displacements of 126 (= 9 patients x 14 vertebrae) vertebrae were computed. Note that the rotation of L4 was the reference. Out of these vertebrae, 66 made unilateral rotations. This is almost 52% of the total vertebrae, showing that the unilateral rotation occurs very frequently in scoliotic spines. The same can be said per spine (Fig. 3) with standard deviation of 14%.

Fig. 4 shows the number of times that a vertebra rotated unilaterally or bilaterally. As can be seen, L1, T12, T7, T6, T3 and T2 are the vertebrae with a high frequency of unilateral rotations. This can be explained on the spine curvatures as these vertebrae are either an apex vertebra or adjacent to it.

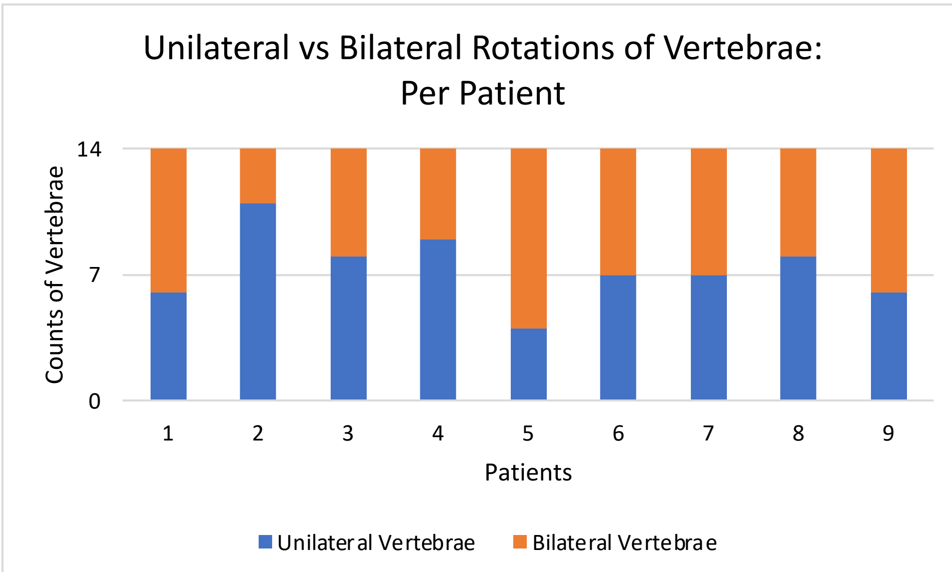

Fig. 3: The number of vertebrae rotated unilateral or bilateral per spine.

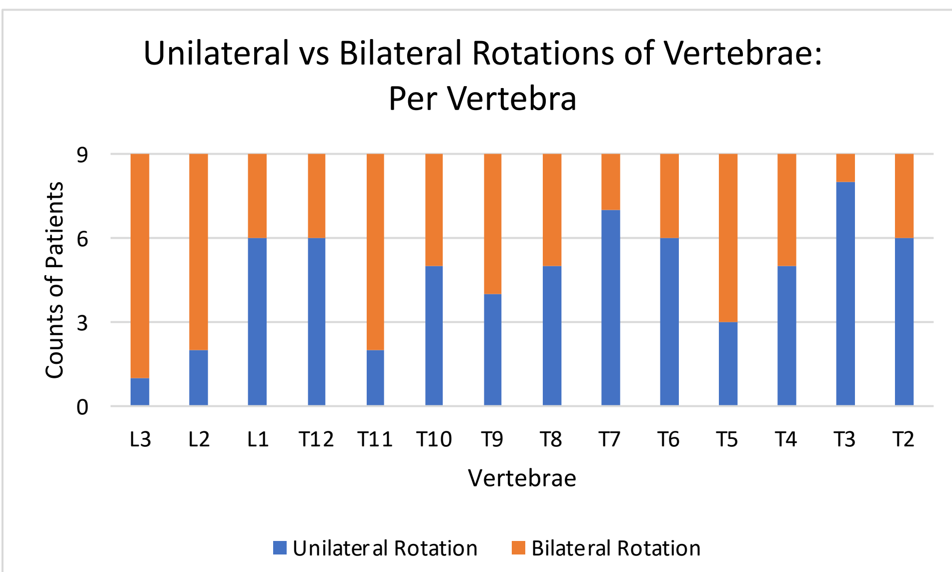

Fig. 4: The number of times a vertebra rotated unilateral or bilateral.

Fig. 5 shows an example of rotational displacements of a patient's spine. As can be seen, in the lumbar region the rotations were made both clockwise and counterclockwise. In the middle thoracic, from T10 to T7, around the apex of T8, the rotations were unilateral, and the vertebrae only rotated clockwise. The same can be observed for T3 and T2.

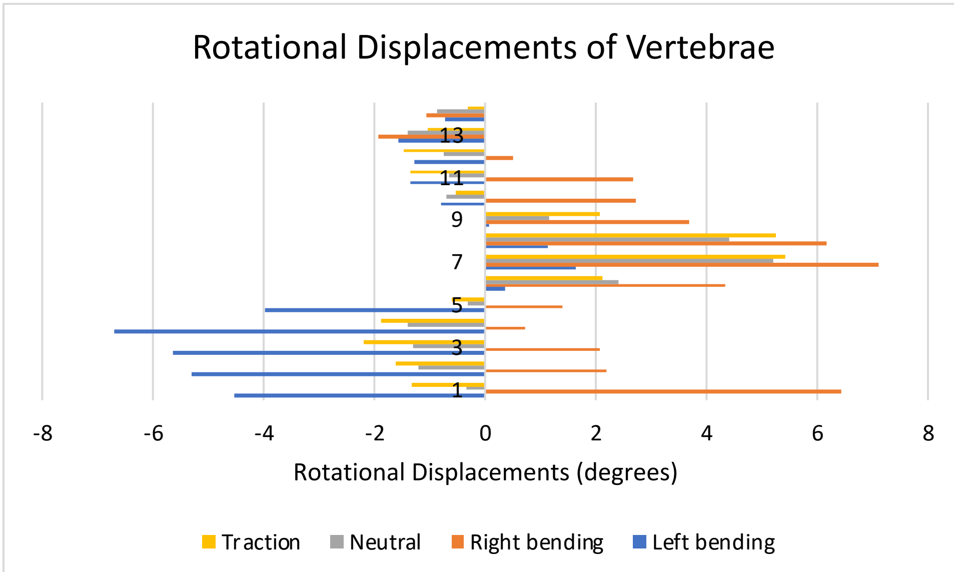

Fig. 5: An example of the rotational displacements of a patient's vertebrae during movements from the erect to the other four positions.

4. Conclusion

With the data extracted from X-rays of spines of nine patients in five positions, we showed that almost half of the vertebrae rotate unilaterally with respect to their inferior vertebra. This was complying well with the anatomical analysis of intervertebral discs wedged due to the scoliosis condition. Imposing unilateral rotational displacements on vertebrae in FSUs might be essential for proper surgical simulation of scoliosis, which is extremely important for reliability of the predictive information. We will study the effects of exclusion and inclusion of the unilateral rotational displacements on the accuracy of the simulation results in our future work.

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