In vivo three-dimensional segmental analysis of adolescent idiopathic scoliosis

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Abstract

Introduction An accurate assessment of three-dimensional (3D) intervertebral deviation is crucial to the better surgical correction of adolescent idiopathic scoliosis (AIS). However, a precise 3D study of intervertebral deviation has not been previously reported.

Objective The purpose of the present study is to evaluate the intervertebral coronal inclination, axial rotation and sagittal angulation of AIS using 3D bone models and a local coordinate system.

Materials and methods 3D bone models of the thoracic and lumbar spine of ten AIS patients were constructed using computed tomography. The local coordinate axis was determined semi-automatically for each vertebra. By using these local coordinates, the intervertebral deviation angles were calculated in the coronal, axial and sagittal planes and projected to subjacent local coordinates.

Result The intervertebral deformity in the coronal plane was larger near the apical region and smaller near the junctional region. Conversely, the intervertebral rotation in the axial plane was smaller near the apical region, and larger near the junctional region. Concerning the sagittal plane deformity, the constant tendency was not recognized.

Conclusion Using a local coordinate system for the vertebra of AIS, we measured the 3D intervertebral coronal, axial and sagittal deviation of the thoracolumbar spine and

found that the change in the intervertebral inclination angle in the coronal plane increased toward the apical region and decreased toward the junctional region, and that the converse tendency was noted for the axial intervertebral rotational angle. This analysis provides an improved 3D guide for the surgical correction of AIS.

Keywords Idiopathic scoliosis · Three-dimensional · Intervertebral deviation · Local coordinate system

Introduction

Adolescent idiopathic scoliosis (AIS) is a three-dimensional (3D) deformity associated with lateral deviation in the coronal plane, thoracic hypokyphosis in the sagittal plane and rotation in the axial plane [3, 4, 25]. However, two-dimensional evaluation of AIS remains the mainstay of most studies of AIS [10, 18]. In 2008, Modi et al. [18] reported the wedging angle of both the vertebral body and intervertebral disc and correlated the apical wedging angle and the severity of the curve in 150 AIS patients using only anteroposterior radiographs in the standing position. For evaluation in the transverse plane, Kotwicki et al. [10] used only a single axial slice from a computed tomography (CT) scan at the apex to measure the rotational angle and the intravertebral deformation. The asymmetry in the shape of the vertebral body and spinal canal and rotational deformity in the axial plane in AIS patients further contribute to the inaccuracy of such assessments of the vertebral axis in the two-dimensional plane.

3D evaluation of AIS is also gaining popularity. The in vitro 3D reconstruction of cadaveric vertebrae using 3D morphometric analysis [21–23], such as vertebral wedging, pedicle width, pedicle length, pedicle height, pedicle

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inclination and facet surface, is a recent example. In addition, several studies concerning 3D reconstruction of the spine using biplane radiographic images have been reported [2, 8, 9]. The method proposed by Kadoury et al. enabled 3D reconstruction from biplane radiographs. Although their studies involve 3D analysis of an in vivo model, their reconstructed bone models used anthropometric data and not patients' bones.

An accurate assessment of 3D intervertebral deviation is crucial to the better surgical correction of the deformity. Although there have been some studies regarding intervertebral deviation of AIS [5, 7, 24], no detailed 3D study using an in vivo model of AIS has been reported. Therefore, the present study aimed to develop a local coordinate system for the AIS vertebra and to evaluate the in vivo 3D intervertebral deviation in the coronal, axial and sagittal planes in order to provide guidance for its surgical correction.

Materials and methods

Patients

We examined spinal CT images from consecutive ten patients with AIS who were scheduled for corrective surgery. The patients included two males and eight females, with an age range of 12 to 19 years (mean 14.7 years) at the time of operation. Before CT imaging, anteroposterior (AP) plain radiographs were taken in the upright position. On AP radiographs, the measured mean Cobb's angles were 62.5° (range 29°–77°) at the thoracic curvature and 50.3° (range 30°–73°) at the lumbar curvature. According to King's classification [11], the curves were type I in two patients, type II in one, type III in six and type IV in one. Risser sign [15] showed grade 0 in two, grade 3 in four, and grade 4 in four patients. Nash and Moe's vertebral rotation [19] of the apex showed grade + in one, grade ++ in seven, and grade +++ in two patients.

The protocol was approved by the institutional boards of the hospital and fully informed consent was obtained from all participants.

CT image acquisition

Prior to surgery, all ten patients underwent CT scans of the entire deformed spine in the supine position. Scans were performed using a helical CT scanner (Light Speed VCT, General Electric, Maukesha, WI). The slice thickness was 0.625 mm, the tube voltage was 120 kV and the amperage was 90 mA. The data were saved in a standard DICOM (Digital Imaging and Communications in Medicine) format. The estimated radiation dose for the patients using this scanning protocol was 5.2 mSv.

Construction of 3D surface bone models

To construct the 3D bone models, we performed a segmentation procedure. Segmentation extracts bone regions and associates each region with individual bones. The anatomic structure or region of interest must be delineated and separated so that it can be viewed individually. Regions of individual bones were segmented semiautomatically using a software program for image analysis (Virtual Place-M; AZE Ltd, Tokyo, Japan). We then obtained the surface models of the vertebrae by applying 3D surface generation of the bone cortex [18, 20].

Axis configuration of local anatomic coordinate system

In order to measure the deviation in three dimensions between adjacent vertebrae, we first established the axis of the local coordinate system for each vertebra by first calculating the centroid of the vertebra automatically and designating it as the origin of the coordinate axis (Fig. 1a). Next, the planar approximation of the superior endplate was calculated using the least-squares method and we estimated a plane parallel to the superior endplate via the origin (Fig. 1b). On that plane, a line from both the centroid and the point which divided the front part of the vertebral body into half (using the least-squares method) formed the z axis (Fig. 1c), with 'anterior' as the 'positive' direction. A line perpendicular to the z axis pointing to the left formed the x axis. Finally, the y axis was defined as a line perpendicular z - x plane (Fig. 1d).

Measurement of intervertebral coronal plane deformity

The intervertebral coronal inclination between adjacent vertebrae was defined as the angle between adjacent x axes projected on the subjacent local coordinate x - y plane. From T1–T2 to L4–L5, each intervertebral coronal inclination was measured. For example, the adjacent inclination in the coronal plane of T8–T9 represented the angle between x axes of T8 and T9 projected to the x - y plane of T9 (Fig. 2). All adjacent intervertebral angles were measured automatically.

Measurement of intervertebral axial plane deformity

The intervertebral rotation in the axial plane between adjacent vertebrae was defined as the angle between adjacent z axes projected on the subjacent local coordinate z - x plane. From T1–T2 to L4–L5, each intervertebral axial rotation angle was measured. For example, the adjacent rotation in the axial plane of T8–T9 represented the angle between z axes of T8 and T9 projected to the z - x plane of

Fig. 1 The method used to establish the local coordinate system. **a** The *black sphere* is a centroid of the vertebra that is defined as the origin of the coordinate axis. **b** The cross-sectional surface of the vertebra; the planar approximation of the superior endplate was calculated using the least-squares method, and we estimated a plane parallel to the superior endplate via the origin. **c** In the cross-sectional plane, the *z* axis is defined as a line between the centroid and the point that divides the front portion of the vertebral body in half. **d** A line perpendicular to the *z* axis and pointing to the left on the plane forms the *x* axis. Finally, the *y* axis pointing cranial is defined as a line perpendicular to the *z*-*x* plane

Fig. 2 The T8 and T9 bone models and each local coordinate axis. The *solid lines* present the axis of T8, and the *broken lines* present the axis of T9. *Left* the intervertebral coronal inclination. The figure faces the subjacent vertebral *x*-*y* plane; the intervertebral coronal inclination angle (*arrow*) is defined as the angle between two adjacent *x* axes projected on the subjacent *x*-*y* plane. *Middle* the intervertebral axial

rotation. The figure faces the subjacent *z*-*x* plane; the intervertebral axial rotational angle (*arrow*) is defined as the angle between adjacent *z* axes projected on the subjacent *z*-*x* plane. *Right* the intervertebral sagittal angulation. The figure faces the subjacent *y*-*z* plane; the sagittal intervertebral angulation (*arrow*) is defined as the angle between adjacent *y* axes projected on the subjacent *y*-*z* plane

T9 (Fig. 2). All adjacent intervertebral angles were also measured automatically.

Measurement of intervertebral sagittal plane deformity

The intervertebral angulation in the sagittal plane between adjacent vertebrae was defined as the angle between adjacent *y* axes projected on the subjacent local coordinate *y*-*z* plane. From T1–T2 to L4–L5, each intervertebral sagittal angulation was measured. For example, the adjacent angulation in the sagittal plane of T8–T9 represented the angle between *y* axes of T8 and T9 projected to the

y-*z* plane of T9 (Fig. 2). All adjacent intervertebral angles were also measured automatically.

Results

Intervertebral coronal plane deformity

The left side of Fig. 3 shows the amount of change between each intervertebral coronal inclination for all ten patients. These results indicate that the intervertebral deformity in the coronal plane was larger near the apical region and

smaller near the junctional region. The maximum intervertebral change at apical region was 20.2° (absolute value), the minimum change at junctional region was 0° . Figure 4 shows two representative cases (Case 3 and Case 10). The 3D models of both the thoracic and lumbar spine and the intervertebral angle in the coronal and axial planes are shown in Fig. 4. The x axis of the graph to the left of the bone model represents the intervertebral inclination angle in the coronal plane. The 'plus' direction of the graph means that the x axis of the suprajacent vertebra is directed in the 'plus' direction in relation to the subjacent vertebral y axis. Similarly, the minus direction of the graph means that the adjacent vertebral x axis is directed in the minus direction in relation to the y axis of the subjacent vertebra (Fig. 2).

Intervertebral axial plane deformity

The middle of Fig. 3 shows the amount of change between each intervertebral axial rotation for all patients. As the converse to the intervertebral coronal deformity, the intervertebral rotation in the axial plane was smaller near the apical region and larger near the junctional region. The maximum intervertebral change at junctional region was 12.6° (absolute value), the minimum change at apical region was 0° . The angle to the plus direction represents the amount of axial rotational change in the clockwise

rotation of the suprajacent vertebra to subjacent z - x plane. On the other hand, when the suprajacent vertebral body rotates to the counterclockwise for the subjacent vertebral body, the change in the angle of the adjacent vertebral body is directed in the minus direction (Fig. 2). The amount of changes between adjacent vertebral axial rotation of two representative cases (Case 3 and Case 10) are shown in the graphs to the right of the bone models (Fig. 4).

Intervertebral sagittal plane deformity

The right side of Fig. 3 shows the amount of change between each intervertebral sagittal angulation for all the patients. Concerning the sagittal plane deformity, the constant tendency was not recognized. The 'plus' represents that the y axis of the suprajacent vertebra is directed in the minus direction in relation to the subjacent vertebral z axis. It means that the suprajacent vertebral bodies located in extension to subjacent vertebral bodies on subjacent y - z planes (Fig. 2).

Discussion

Idiopathic scoliosis is a complex spinal deformity characterized by lateral curvature of the spine associated with axial vertebral rotation. Recent 3D evaluations of the spine

Fig. 3 The intervertebral deviation of the each adjacent vertebrae of all ten patients. The x axes show the each intervertebral deviation angles of all patients in coronal, axial and sagittal plane. The intervertebral deformity in the coronal plane was larger near the

apical region and smaller near the junctional region. Conversely, the intervertebral rotation in the axial plane was smaller near the apical region, and larger near the junctional region. Concerning the sagittal plane deformity, the constant tendency was not recognized

Fig. 4 Two representative cases. The bone models of both the thoracic and lumbar spine are shown in the center, and the left sided graph represents the intervertebral inclination angle in the coronal plane; the right sided graph represents the intervertebral rotational angle in the axial plane. Left case 3, Right case 10

in patients with AIS have been performed [8, 9, 21–23]. As morphometric studies, Parents et al. [21–23] created a 3D reconstruction of a large number of cadaveric bones, and compared normal vertebrae with the vertebrae of AIS. For example, vertebral wedging increased progressively toward the apex and pedicles located on the concavity were found to be significantly thinner than normal specimens [21–23]. In addition, the evaluation of global 3D correction between pre- and post-operative spinal 3D shape was also reported by Kadoury et al. [8, 9]. They reconstructed 3D models using bi-planar radiographs, and examined the difference among four operative methods. Steib et al. also performed 3D studies about the 3D change before and after surgical correction by in situ contouring technique using the reconstructed 3D models from bi-planar radiographs [6, 7, 16, 27]. However, these methods lacked accuracy since their method required only about 6–20 landmarks when reconstructing the bone models. Although an accurate assessment of 3D intervertebral deviation is crucial to the better surgical correction of the deformity, no detailed 3D study using an in vivo model of AIS has been reported.

Our results indicate the different deviation patterns between the intervertebral coronal plane deformity and intervertebral axial plane rotation. The intervertebral deformity in the coronal plane was larger near the apical region and smaller near the junctional region. Conversely, the intervertebral rotation in the axial plane was smaller near the apical region and larger near the junctional region. In 1994, Dubousset also showed that the intervertebral axial rotation reached its maximum at the extremities and its minimum at the apex [5]. However, the simple finite element models of only one case were used in the study and it is not known how to measure the intervertebral deviation [5]. Therefore, using the precise 3D evaluation method, we can show that the change in the intervertebral inclination

angle in the coronal plane increased toward the apical region and decreased toward the junctional region, and that the converse tendency was noted for the axial intervertebral rotational angle in AIS patients for the first time.

There is a limitation in our method. The bone models were constructed from CT images taken in the supine position. Troell et al. [28] examined the radiographs of 287 girls with AIS and found that their mean Cobb angle, measured at standing position, was approximately 9° larger than that in the supine position, and the difference was 45° in the maximum. Yazici et al. [29] also showed that the average Cobb angle on a standing radiograph was approximately 16° larger than that in the supine position and they found that a rotational angle of 22.75° on the standing radiograph and 16.78° in the supine position. However, our results compared coronal with axial deviation under the same condition as supine. Though it is conceivable that the degree of the spinal deformity may be small in the supine position, it would appear that the features obtained from our study are not different from those obtained in the standing position.

The results in the present study can be applied to the surgical correction of AIS. The concave rod rotation maneuver, introduced by Cotrel and Dubousset, is generally concluded with derotation vertebral procedures. It's well accepted that rotation of precontoured concave rod (counter-clockwise) by alone has poor rotation improvement [1, 12–14, 17, 26]. Moreover, Kadoury et al. concluded that scoliosis also involves transverse plane rotation of the vertebrae in the opposite direction. In order to derotate the vertebrae, moments in the opposite sense should also be applied to the vertebrae [9]. According to our result, it might be easier to correct the rotation of each vertebra from the end vertebra to the apex using direct vertebral rotation technique.

Conclusion

We propose a new local coordinate system for deformed vertebrae of AIS. By using this coordinate system, the 3D intervertebral deviation in the coronal, axial and sagittal planes were measured. We found that the intervertebral deformity in the coronal plane was larger near the apical region and smaller near the junctional region. Conversely, the intervertebral rotation in the axial plane was smaller near the apical region and larger near the junctional region.

Conflict of interest None.

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