行政院國家科學委員會專題研究計畫　成果報告

長短腿對脊柱變形之生物力學效應及關係性研究

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行政院國家科學委員會專題研究計畫成果報告

長短腿對脊柱變形之生物力學效應及關係性研究(1/2)

Study on the Biomechanical Effect and Relationship between Leg Length Discrepancy and Spinal Deformity(1/2)

計畫編號：NSC93-2213-E-040-004-

執行期限：93 年 8 月 1 日至 94 年 7 月 31 日

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中文摘要

本研究係一兩年期之計畫。第一年已經完成脊柱變形中有關椎體軸向旋轉之測量方法，並於 94 年 10 月 4 日獲得國際期刊 Computer Methods and Programs in Biomedicine (SCI)接受發表。

本研究先識別 X 光片中椎體之特徵標誌，利用適當之幾何關係、椎體形狀參數、電腦疊代程式，可以快速計算出椎體軸向旋轉角度。藉由一自行設計之脊椎旋轉固定裝置,以 CT 影像之旋轉角為比較標準，證實此方法非常準確且方便。

關鍵詞：軸向旋轉、脊椎、椎弓投影

Abstract

This study presents a new method for measuring axial rotation of vertebra. Anatomical landmarks of the vertebral body were first recognized in X-ray film. By employing appropriate geometrical relationships, vertebral body shape parameters, and a computer iteration method, the rotation angle of vertebra on the transverse plane can rapidly be obtained. A cadaver lumbar spine axial rotation-fixation device was designed to confirm the accuracy of the proposed methodology. Rotation angles on CT images were adopted as the golden standard and compared with analytical results based on X-ray films. Analytical results demonstrated that the proposed method obtained more accurate and reliable results than previous methods.

Keywords: Axial rotation, spine, pedicle shadow

1. Introduction

Scoliosis is a three-dimensional deformity of spinal column, generally meaning displacement and/or rotation of spinal segments from normal positions. Measuring the degree of deformity is important to observing the progress of scoliosis, operative planning and correcting these spinal columns [1,2,3]. To determine the degree of scoliosis, deformation is typically using anteroposterior view (AP-view) and lateral view X-rays. However, assessing the extent of rotation of a spinal segment on the transverse plane is difficult. Although computed tomography (CT) technology is currently widely applied to measure spinal deformity, and can obtain accurate measurements [4,5], the subject must have a supine position. However, this position reduces mechanical effects as the gravitational force and asymmetry of both lower limbs, such as leg length inequality.

Another significant disadvantage of CT, apart from its high cost, is patient exposure to radiation. Therefore, a methodology is required that utilizes 1 X-ray film obtained in a standing position for estimating the rotation angle of the spinal column on the transverse plane.

In 1948, Cobb [6] first proposed a method for assessing the rotation angle of a vertebra based on the linear offset of the spinous process in relation to position of the vertebral body on X-ray film. The degree of rotation from normal to the maximal position was expressed by ‘0’ to ‘++++’; however, the relationship between the number of ‘+’ and actual degree of rotation was not reported.

Nash and Moe (1969) [7] proposed that the relative position of the pedicle in relation to the vertebral body on X-ray film should represent the degree of rotation of a spinal segment. Fait and Janovec (1970) [8] estimated a segment’s rotation angle based on trigonometric relationships. In this method, the distance between the pedicle at the convex side and the edge of the vertebral body is a, and the full width of the vertebral body is b. An approximate rotation angle was then obtained based on the ratio of a/b. However, Benson (1976) [9] explained why calculating rotation angle based on the pedicle position in X-ray images likely resulted in errors: (1) significant changes in the shape of all vertebrae; (2) differences between actual pedicle and pedicle images; and (3) inclination of vertebra on the sagittal plane. With an increasing vertebral rotation angle, the projected contour of the vertebral body results in some offset of the borders. Neither of these methods is completely satisfactory; however, they effectively describe the relationship between vertebral rotation and displacement of the pedicle or spinous process.

Coetsier et al. (1977) [10] utilized the position of the two pedicles and width of the vertebral body to calculate the rotation angle. However, Gunzburg questioned the accuracy of this method [1]. Perdriolle and Vidal (1981) [11] created a 'Torsionmeter' that can read vertebral rotation angles using the lateral edge of a vertebral body and the position of pedicle shadow on the convex side. However, this method produced errors that increased with the rotation angle [12].

In 1986, Stokes et al. [13] developed a procedure that separately marked six landmarks on both an AP-view and oblique X-ray to calculate vertebral rotation angles. Russell et al. [14] reported that the method proposed by Stokes was the least accurate of all methods and had a very complex analytical system.

In analyzing various techniques, Gunzburg [1] indicated that the methods developed by Perdriolle and Vida [11] and Coetsier et al. [10] had the best results. Furthermore, these two methods have other beneficial features, namely, pedicle shadows and the narrowest parts of the vertebral body on both lateral sides are considered to be anatomical landmarks.

2. Design considerations

As inclination angles of a spinal segment on coronal and sagittal planes are easily obtained using AP and lateral radiographs, respectively; they are not within the scope of this study. Furthermore, only AP radiographs are utilized.

The upper part of Fig. 1 presents images of a spinal segment before and after rotation. Point H at the middle of the vertebral foramen near the vertebral body was previously considered by some as the rotation center [8,15,16]. When a spinal segment rotates, the pedicle position is displaced relative to the vertebral body (lower part of Fig. 1). Each pedicle is roughly represented by an oval shadow. The oval's border close to the vertebral body center is considered as the inner side, and the border close to the lateral side edge of the vertebral body is considered as the outer side.

The two images (Figs. 1(a) and Fig. 1(b)) are then combined, and the center points, O, of vertebral body are superimposed. The projected relationship is illustrated in Fig. 2. The pedicle position is the midpoint of the connection between the cranial and caudal parts of the oval shadow [1]. Letters A and B indicate the positions of the left and right pedicles before vertebral rotation, respectively (Fig.2). The positions of these pedicles after rotation are marked as A' and B'. The rotation angle θ can be recognized as $\theta = \angle AOA'$.

Furthermore, let the projections of two pedicles (before and after rotation) and center of the vertebral body on the film be denoted by a, b, a', b' and o, respectively. Additionally, D is set at the midpoint of $\overline{AB}$, a straight line, $\overline{A'F}$, is draw perpendicular to $\overline{Oo}$ with point F located at the intersection of the two lines.

Based on trigonometric relationships, the following equations are obtained:

$$\theta = \angle AOD - \angle A'OF \tag{1}$$

$$\angle A'OF = \sin^{-1}\frac{\overline{A'F}}{\overline{OA'}} \tag{2}$$

Moreover, the distance between the vertebral body center and the pedicle at the convex side is

$$\overline{OA'} = \overline{OA} = \frac{\overline{AD}}{\sin\angle AOD} \tag{3}$$

Since $\overline{AD} = \frac{1}{2}\overline{AB}$, let the actual distance between the two pedicles be $\overline{AB} = \overline{ab} = w$, then Eq. (3) can be rewritten as

$$\overline{OA'} = \overline{OA} = \frac{\overline{AB}}{2\sin\angle AOD} = \frac{w}{2\sin\angle AOD} \tag{4}$$

In Eq. (4), $\angle AOD$ is correlated with the vertebral body shape, which is determined by $\overline{AD}$ and $\overline{OD}$. Additionally, $\frac{\overline{AD}}{\overline{OD}} = \eta$ is the shape parameter of the vertebral body. Notably, an AP radiograph taken in a standing position only obtains a coronal plane image (lower part of Fig. 2). Consequently, without other clues in a film, the shape parameter η for every vertebral body should be obtained from statistical data. Stokes et al. [13] obtained average width-to-depth values for vertebral bodies L1-L4 (Table 1); half of the width-to-depth value is the shape parameter η in this study. Thus, $\angle AOD = \tan^{-1}\eta$ is derived.

3. System description

3.1. Measurement and Computational Flowchart

Both $\overline{a'o}$ and $\overline{a'b'}$ are measured on X-ray film (Fig. 2). Actual distance w between the two pedicles is first assumed as the projected length $\overline{a'b'} = w'$ (that is, in initial state, the θ is assumed to be 0°), which is substituted into Eq. (4) to derive an approximate $\overline{OA'}$. Then this approximate $\overline{OA'}$ and measured $\overline{a'o} = \overline{A'F}$ is substituted into Eq. (2) to generate an approximate $\angle A'OF$. Using Eq. (1), the approximate rotation angle θ is derived. As

$$\overline{A'B'}\cos\theta = \overline{a'b'} \tag{5}$$

and

$$\overline{AB} = \overline{A'B'} = w \tag{6}$$

the assumed value w can be modified. This modified w is then input into Eq. (4) repeating the above process until θ converges. The criterion for terminating the iteration process is when the percentage change of θ between two iterations is less than a threshold value, such as 0.1 %.

3.2 Theoretical Validation

3.2.1 Human spine rotation-fixation device

Figure 3 shows the cadaver spine rotation-fixation device, which has a rectangular polyethylene (PE) base sized 28.5 cm × 6 cm × 20 cm on each side. The base has an open hole and a protractor attached to its center.

A PE rod was inserted through the vertebral foramen, such that the lumbar spine was strung in series. Vertebrae were fixed to the rod with adhesive to permit coaxial rotation. A pointer was placed at the end of the rod. Therefore, when the lumbar segments rotate simultaneously, the pointer can indicate the protractor scale.

3.2.2. Image acquiring procedure

Before taking an image, set the spinous process facing upward, and align the pointer with 0 on the protractor. Rotate the lumbar spine gradually from 0° to 30° at an increments of 5°, to achieve a total of 7 rotational states. At each state, take 1 X-ray and CT image. The spinal rotation-fixation device was placed on a wooden board, which supported the device and avoided any change in rotation state when transferring between X-rays and CT scans. For X-rays, standard AP radiographs were taken. The source film distance was set to 100cm, as in actual clinical work. The object film distance was roughly 10 cm; this distance only changed the magnification and did not affect the resulting rotation measurement (Drerup [17]).

3.2.3. Identification of rotation angle of lumbar segments

The protractor angle was only a reference for simulating the lumbar segments in various axial rotation states. Additionally, when segments were fixed on the PE axle, spinous processes may not be completely aligned. Consequently, actual initial angles of the segments were only very close to 0° when the pointer was aligned with 0 on the protractor. Thus, actual segment rotation angle was confirmed on CT scans. The rotation angle of segments on CT images was taken as a golden standard to validate the accuracy of the proposed computational method.

4. Status report

Based on partial damage of L5, the vertebral contour on the X-ray image was unidentifiable, and, therefore, the rotation angle was not obtained. Consequently, only four lumbar segments (L1–L4) were assessed.

After marking the necessary anatomical landmarks on the X-rays of four lumbar segments, a computer program based on the proposed equations was developed to determine the rotation angle. When the rotation angle of L2 measured on a CT scan is 15°, the angle, by the current method, rapidly converges to 15.7° after 10 iterations (Fig. 4).

Figure 5 shows the relationship between actual rotation angle θ_{CT}, measured from CT images, and the rotation angle θ_X, estimated based on X-ray films of the four vertebrae (L1–L4). For every vertebra, the calculated value θ_X and standard value θ_{CT} are stongly correlated, with R^2 of 0.988, 0.991, 0.961, and 0.970. Regression equations are provided.

The current methodology and four previous methods were used to assess vertebral rotation angles. The horizontal axis in Fig. 6 indicated the observed rotation angle θ_{CT} on CT images. The vertical axis represents angle θ_X, estimated using various methods, and a 45° straight line is a reference line produced when calculated and actual values are the same.

Fig. 6 demonstrates actual rotation angle is overestimated by these methods, for lumbar L1, and underestimated, for L4; whereas the actual rotation angle was estimated more accurately for L2 and L3. However, the proposed methodology obtains rotational angles closest to actual angles. This study uses root-mean-square (RMS) error (E_{rms}) (Table 2) to judge accuracy

$$E_{rms} = \sqrt{\frac{1}{7}\sum_{i=1}^{7}(\theta_X - \theta_{CT})^2} \tag{7}$$

The RMS error did not exceed 3° for all the four vertebrae using the proposed method (Table 2). The proposed method is more accurate than the other four methods. A significantly large RMS error (6.2°) for L4 was obtained by the method developed by Stokes et al. [13]. Conversely, it is worth to note the accuracy of the conventional torsionmeter with its ease-of-operation.

5. Lessons learned

All known methods of measuring length and angles on radiographs have marking and measuring error. Causes of marking errors include landmark labeling and the precision of rules. Some factors contributing to measurement error include the method employed, radiographic quality, inter-observer error and intra-observer error. A method's accuracy is mainly determined by its strategy. This study compared five measurement methods. The proposed methodology utilized the same marking and measuring tools as other methods, i.e., pen and ruler, but achieves better accuracy, and proved more reliable and reasonable than the other four methods. Image processing techniques, digitizers, and precision instruments can be utilized to improve accuracy; however, such an investigation is not the principle aim of this study.

Although the affects of translations on the projected image and the resulting rotation measurement perhaps may need to be addressed, Drerup [17] demonstrated that effects due to irradiation of the vertebra by divergent rays are ignored because of their small size.

Wall and Oppenheim studied the measurement error of spondylolisthesis [18] to identify the relationship between the measured vertebral slip and the radiographic beam angle from the true lateral, and concluded that a beam originating from anterosuperior to a true lateral consistently underestimates the slip, whereas a beam originating from anteroinferior tended to overestimate the slip. However, vertebral slip is a length measurement, whereas vertebral rotation is an angle measurement. Although the length measurement can be affected by different x-ray beam angles, Eq. (2) eliminates this effect since the measured lengths $\overline{A'F}$ (i.e. $\overline{a'o}$) and $\overline{OA'}$ (obtained by substituting $\overline{a'b'} = w$ into Eq. (4)) are the numerator and denominator in a division, respectively.

This study considered that the measurement accuracies of these methods differ, primarily owing to: (1) image landmarks utilized; (2) assumptions regarding the vertebral body shape [19].

Compared to the torsionmeter developed by Perdriolle and Vidal, the method proposed here obtains more accurate results. Although the landmark used in this work has a width w of two pedicles, it likely yields a projection offset. To correct this error, this work utilized an iteration procedure to obtain actual length (w). Analytical results demonstrated that the iteration method effectively corrects the rotation offset in a projection, obtaining a more accurate axial rotation angle for the vertebral body than that obtained using other methods.

Limitations of this proposed measurement method are as follows: the concave pedicle shadow on X-ray film should be clearly identifiable; and, the concave pedicle must not have shifted beyond the projection range of the vertebral body. The most appropriate measurement range of the angle obtained from lumbar AP radiograph is approximately 0–30°. Barsanti et al. [20] also estimated the rotation of a single vertebral body using Perdriolle's torsionmeter. Their study found that large errors exist when the vertebral rotation angle exceeds 35°. It was considered to be the fact that the difficulty of finding an accurate reference point on the vertebral body. When the rotation angle exceeds 35°, the analytical method based on the two pedicle shadows cannot achieve accurate axial rotation of the vertebral body.

6. Conclusion

The proposed method for measuring vertebral rotation angle achieved more accurate results than previous methods. For the analyzed spinal segments, this method was also reliable and accurate. Under 30°, measurement error did not increase with the rotation angle. In clinical applications, when patients stand with their shoulders parallel to the radiograph film, and the central ray is aimed at the level of the main target vertebra on the interlinked line of the cervical and sacral spinal processes, accurate measurement results can be obtained. When the spinal segment clearly deviates from the plumb line of a normal spinal column in clinical cases, the deviation distance can be measured, and the rotation angle can then be corrected.

7. Acknowledgments

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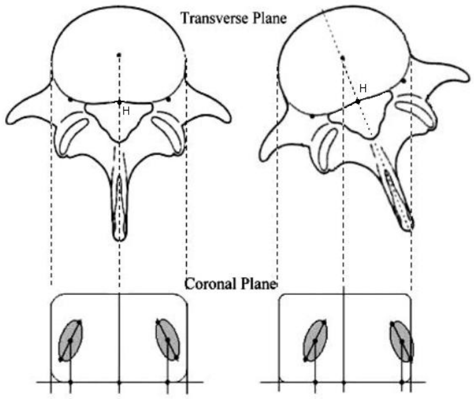
Table 1 Shape parameter of vertebrae

	Vertebra			
	L1	L2	L3	L4
Shape parameter η	0.97	0.92	1.04	1.25
∠AOD (degree)	44.1	42.6	46.1	51.3

Table 2 Root-mean-square errors of rotation angle

Method	E_{rms} (Deg.)			
	L1	L2	L3	L4
Nash&Moe-10°	3.0	1.9	3.3	9.7
Perdriolle	6.7	5.4	2.4	5.8
Drerup	3.6	3.3	3.5	3.9
Stokes	2.2	2.1	1.8	6.2
This work	2.9	1.0	1.9	2.8



(a) No rotation (b) Rotation
Fig. 1 Spinal segment rotates on the transverse plane

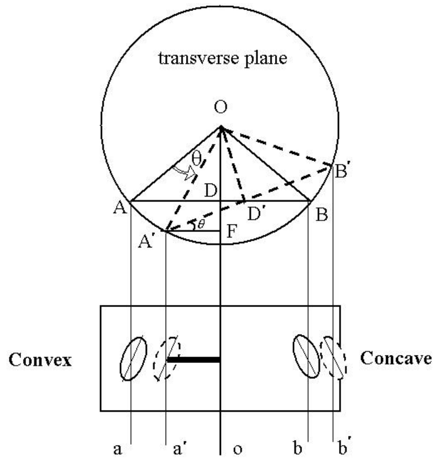


Fig. 2 Schematic drawing of vertebral rotation


Fig. 3 Human spine rotation-fixation device

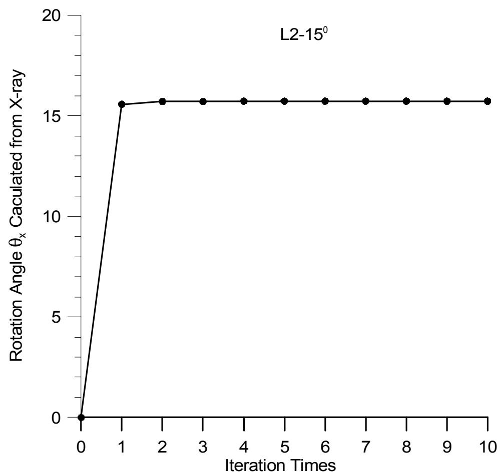


Fig. 4 Converging process of rotation angle

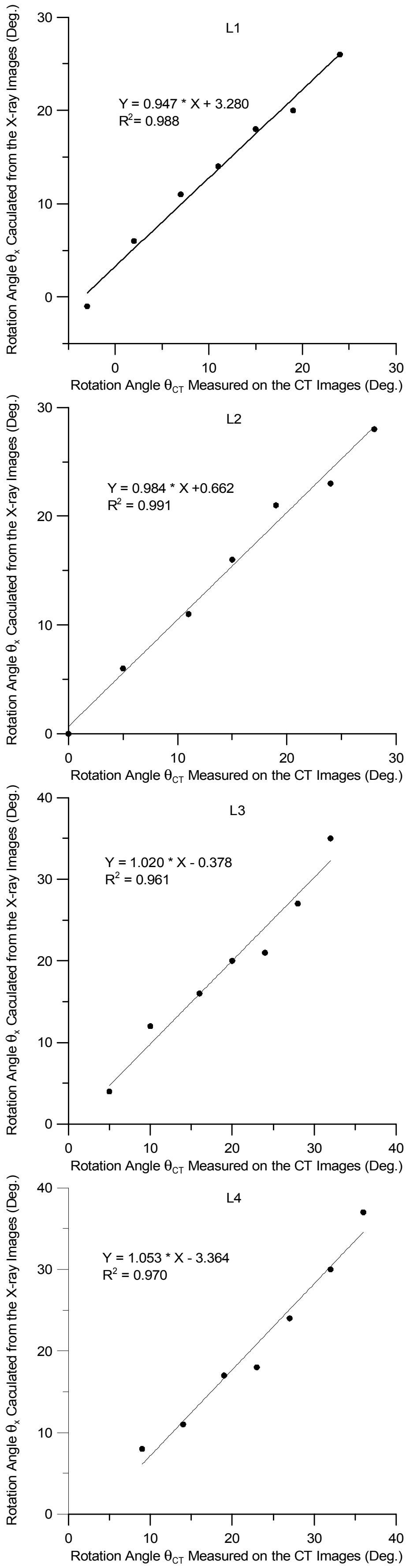


Fig. 5 Regression analysis of the calculated value θ_X and the standard value θ_{CT} for four lumbar vertebrae rotations.

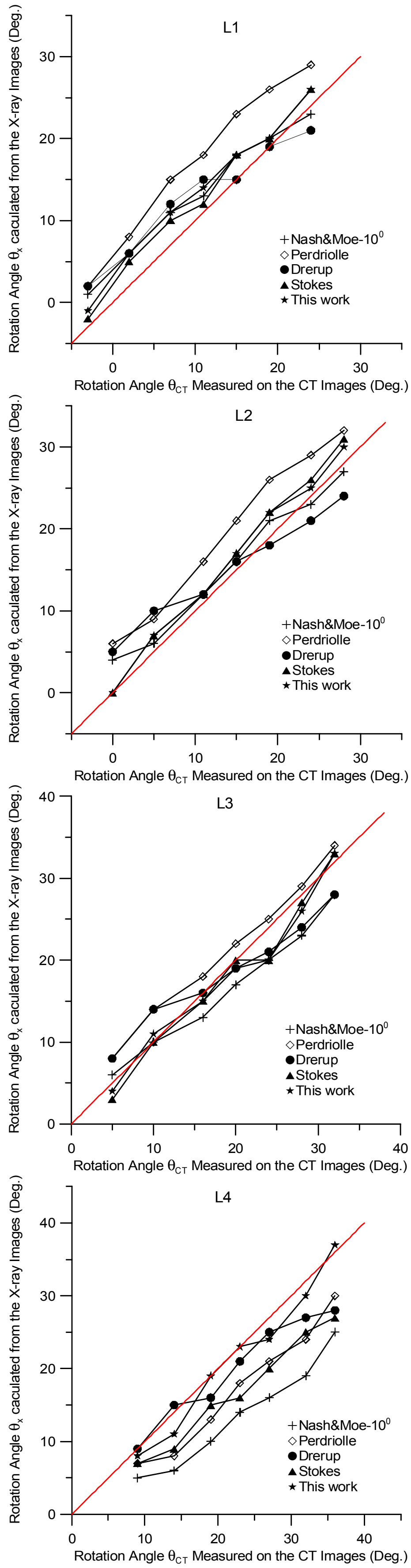


Fig. 6 Comparisons of rotation angles of L1 to L4 analyzed by five methods. The straight line with slope to be equal to 1 provides a reference of $\theta_X = \theta_{CT}$.