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Three-dimensional Curvature and Kinematic Analysis of the Human Spine

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Abstract

Three-dimensional Curvature and Kinematic Analysis of the Human Spine

by

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The purpose of this study was to develop a methodology to quantify spinal curvature and kinematics by using a video camera motion analysis technique. The space curvature and torsion, the projection figures and the three-dimensional angles provided the spinal curvature information. The kinematic analysis included the gross motion of thoracic spine, lumbar spine, and thoracic cage. One normal young male subject performing four static voluntary conditions for spinal curvature analysis and three dynamic voluntary conditions for spinal kinematic analysis. The angles of each point were reproducible and provided the pattern of curvature along the spine. The space curvature and torsion were not as reproducible due to the fact that these parameters combine the information from all three directions. Coupling of motion in thoracic and lumbar spine has been found for the axial rotation condition and also matched the range of motion with other studies. It was concluded that the methodology developed in this work is valuable since it is simple in testing, fast in data analysis, commercially available, noninvasive, and produced useful results.

Dedication

To my father Menyuan Cao, mother Dongkai He: Thank-you for your teaching throughout the past two and a half decades. Please frogive me for the years I stayed away from you for study.

To my wife Bing Deng: Thank-you for your love and patience, and the happiness you gave me throughout the period of studying in Michigan State University.

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Introduction

Spinal curvature and kinematics have long been treated as criteria in judging spinal deformity and treatment. The traditional quantifying method for static spinal curvature is either Cobb's method or Furguson's method. These methods are based on projections on planes or the tilting of vertebral end plates. However, the spinal curve is formed in a way that combines the sagittal plane deviation and frontal plane deviation, and also the coupled vertebrae rotation. This makes the spinal curve rather complicated, and distortion will occur no matter what directional plane is projected. Especially, for measuring scoliosis, a single frontal plane projection may include the curvature of a large amount in the sagittal plane. White and Panjabi (1978) have also noted that two different spinal curves might have the same Cobb's angle. Therefore, it has been realized that a three-dimensional spinal curve requires a three-dimensional quantification method.

This raises a real challenge to the traditional radiological measurements. Brown (1976) used a three-dimensional radiological technique taking two projections from different angles in quantifying spinal deformity. Even this method, providing the most accurate information, had shortcomings and was not popularly accepted. The difficulties were: 1. adding extra X-ray exposure which is not good for school screening, dynamic measuring, and long term treatments; 2. the identification of the space position of each point on the spinal curve is based on the two projections, thus is very time consuming and not suitable for computer automation.

Due to these challenges and a trend to reduce the usage of radiology, noninvasive techniques have been of common interest during the past years. Among all the new techniques, Moire fringe perhaps is the most successful. This technique is based on using the back surface contour to predict the actual spinal location. It has been proved that the

Moiré fringe can provide clinically useful information, and is commercially available. However, this method is also time consuming, as a large number of grids must be counted before analysis. This technique is not reproducible: slight changes of back contour will produce big differences in the results. Therefore, even though researchers have suggested that it could be used as an aid to radiology, these limits restrict its usage. Other techniques, such as eletrogoniometer, flexicurve, pantography etc., were less studied than the Moiré fringe method. However, they may be very useful in spinal deformity studies in the future, (Stokes 1984).

The increasing use of video-camera techniques in motion analysis raises the possibility that this could be also used in spinal curvature and kinematic analysis. Video-camera techniques are usually characteristized by three or four high speed cameras with computer data acquisition and processing systems. The targets made of reflective materials and the images are digitized by a pattern recognition method. If two cameras find the same target simultaneously, its three-dimensional location can be easily determined. Therefore, comparing this technique with either X-ray or Moiré fringe, it is possible that the spinal static curvature and dynamic movement can be quantified three-dimensionally, noninvasively, fast, and with any of the variety of video-camera systems.

By placing reflective targets on the skin over the spinal processes, a spinal process curve can be formed to represent the spinal column. Based on this curve, futher analysis can be done mathematically. Also, by placing reflective targets on appropriate positions of the trunk, the motions of either the lumbar or the thoracic spine can be measured. The purpose of this study is to provide the methodology and mathematics to use a video-camera motion analysis system in spinal curvature and mobility quantification and analysis.

Literature Survey

Part 1: Basic Anatomy, Normal and Abnormal Shape of Human Spinal Column

1.A. Basic Anatomy

The spinal column [Figure 1] consists of two parts: the vertebrae and the intervertebral discs. All the vertebrae are constructed similarly, with four parts: body, arch, articular processes and intervertebral formen, [Figure 2]. However, the vertebrae are different in different anatomical regions and they are separated into different groups. There are seven cervical, twelve thoracic, five lumbar vertebrae and the sacrum and coccyx, [Figure 1]. The size of each vertebrae increases from the first cervical to the last lumbar vertebrae, and is a "mechanical adaptation" to the increasing loads of the vertebrae, (White and Panjabi 1978).

The intervertebral discs make up about 20 to 33 percent of the length of the whole spinal column. Like the vertebrae, the size of the intervertebral disc increases from the cervical to the lumbar region, (White and Panjabi 1978). However, the ratio of disc thickness to the vertebral body height is greater in the cervical and lumbar regions and less in the thoracic region. The greater the ratio of disc to body thickness, the greater the mobility; the cervical and lumbar spine have larger mobility than the thoracic region, (Kapandji 1974).

It is always true that composition determines function and this is true with the intervertebral discs. "The intervertebral disc acts as a cushion between adjacent vertebral bodies". There are two predominate types of collagen in intervertebral discs that are responsible for this cushioning function. The first type, type 1, is mostly found in tissues that are designed to resist tensile forces, such as skin, tendon and bone, while type 2 is found in tissues that resist compression, (Ghosh 1988). The different distribution of the

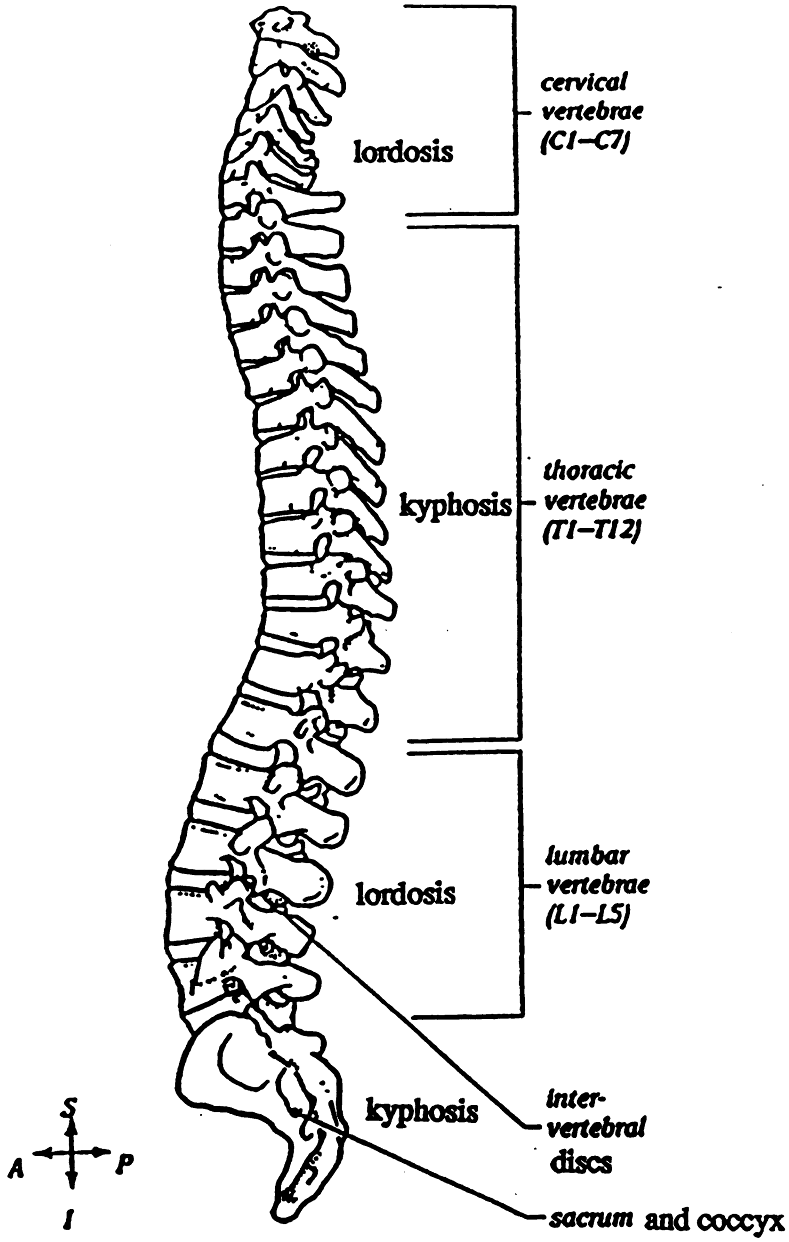


Fig. 1. Lateral View of the Spinal Column. A: anterior, S: Superior, P: Posterior, I: Inferior. (Gosling et al. 1985)

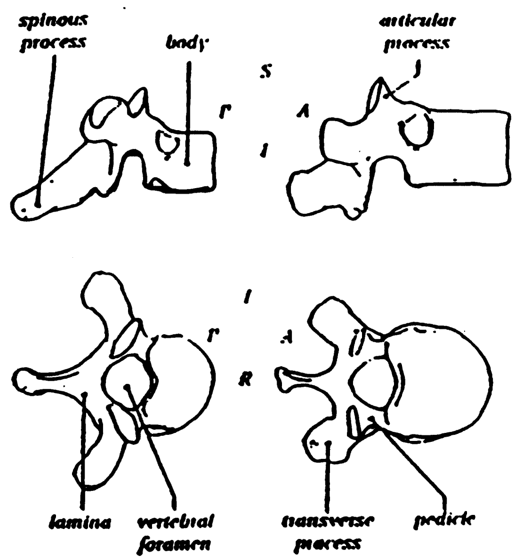


Fig. 2. Lateral and Superior Views of Typical Thoracic Vertebrae. (Gosling et al. 1985)

two types results from factors, such as aging, diseases and curvature of the spine. For example, there is more type 1 collagen on the concave side of the curve (which is subject to compression) than on the convex side (which is subject to tension), (Brickley-Parsons 1984, Ghosh 1988). Brickley-Parsons pointed out that the changes in the distribution of collagen preceded the development of a curvature and may have led to the formation of abnormal curvature.

For a standing erect condition of a normal subject, the spinal column is nearly a straight line in a anteroposterior view and curved in a lateral or sagittal aspect. The curves viewed laterally [Figure 1] are traditionally named lordosis when the concave side of the curve points backward and kyphosis when it points forward. For a normal person, the cervical and lumbar regions are lordotic and the thoracic and sacral regions are kyphotic.

1.B. Terminology of Spinal Curves

Spinal curves of normal and abnormal subjects are described by direction and location, and supplementary terms such as structural and non-structural, primary and secondary, compensatory, simple and compound, major and minor curve, (DeSmet 1985, Goldstein 1973).

Since most research work and clinical examinations of the spinal curve are based on projectional X-ray films, the terminologies of spinal curves are given as the sagittal and frontal plane projections, separately. For sagittal plane or lateral view curves, the terms indicating direction and location have been introduced. In the frontal plane, the directions is given by left when the concavity points to left, right when it points to right. Usually, the curve in the frontal plane is called scoliotic curve. Thus a frontal curve in thoracic region with its concavity pointing to right can be called right scoliosis in thoracic region.

The terms structural and non-structural refer to the flexibility of the curve. The structural curve generally is defined as "having a fixed rotation on forward bending and the presence of a permanent deformation of the vertebrae itself", (Lovett 1900). The non-structural or functional curve is a curve that has no structural component. More clearly, "a curve that is corrected by active or passive bending toward the side of convexity is considered a non-structural or functional curve while the curve remaining fixed is termed a structural curve", (DeSmet 1985).

If we consider the curve developing as a function of time, the terms primary and secondary curves can be easily defined. The primary curve is that curve which developed first while a secondary curve develops after the primary curve is established. The secondary curve is mostly a so called "compensatory curve", (Norkin 1992). For example, the vertebral column of a baby is a long kyphotic curve, maintaining the skeleton as a mostly upright posture, during growth two lordotic curves develop in the cervical and lumbar regions while the kyphotic shape is kept in the thoracic and sacral regions. Thus, cervical and lumbar lordosis can be called secondary curves while thoracic and sacral kyphosis are called primary curves since they exit at birth. This idea is also used for the abnormal curves. An abnormal curve that causes another abnormal curve due to equilibrium can be called the primary curve and the resultant curve is called the secondary curve.

The curves are interdependent, and if the head is to remain balanced over the sacrum, "the region between the head and the pelvis behaves as if it were part of a closed kinematic chain", (Norkin 1992). Changes in one segment will result in changes in adjacent superior or inferior segments. If there is a structural curve in the spinal column, usually there are two compensatory curves above and below developing to maintain the whole spinal column balance. If they are equal magnitude, the spine is in balance, [Figure 3a]. Spinal imbalance is commonly quantified by using the difference in magnitude between the upper and lower compensatory curves, (Leatherman 1988). When the spine lists to the side of the convexity of the single curve the term 'spinal decompensation' is used, [Figure 3b].

The complexity of spinal curvature can be described as a simple curve or compound curve. A simple curve is a single "C" curve. A compound curve consists of two or more curves. Thus, if there is one curve in the frontal plane, it can be called a simple frontal curve and if there is more than one curve, a compound frontal curve description should be used, such as an "S" curve.

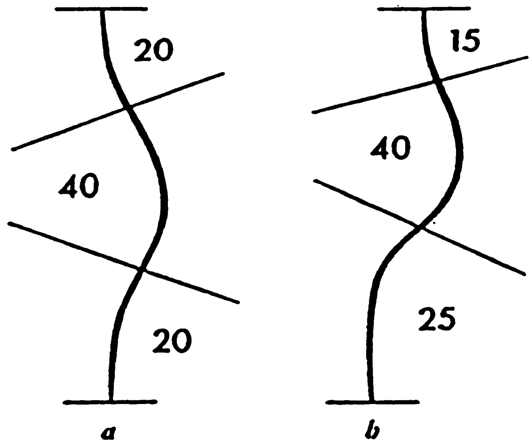


Fig. 3. Measuring spinal balance (compensation). The sum of the upper and lower compensatory curves is always equal to the size of the structural curve.
a. When the spine is in perfect balance then the upper and lower compensatory curves are of equal magnitude.
b. When the spine lists to the side of the convexity of the curve (decompensation) the lower compensatory curve is bigger than the upper. In this case the spine is decompensated by 10 degrees.

(Leatherman 1988)

According to "the degree of deviation from midline", the severity of spinal curvature can be described by terms like "major", "minor" or "smaller" curve, (Schafer 1987). The major curve is one of a compound curve which is the farthest away from the midline in contrast to the minor or smaller curves of the compound curve.

1.C. Spinal Deformity and Scoliosis

When a normal spine is viewed from the front or back, it will be shown as a "straight line or subtle, right physiologic curve", (White and Panjabi 1978). The term scoliosis originally meant any abnormal deviation of the spine from the midline, but for many years the term has been restricted to lateral deviation when viewed from anterior or posterior. In the sagittal plane, the cervical and lumbar curves are normally lordotic and the thoracic curve is normally kyphotic, the terms for "exaggeration of these curves" are referred to as "hyperlordorsis and hyperkyphosis", (Schafer 1987).

Scoliotic curves should be described by their direction and location and by the supplementary terms described above. Traditionally, scoliotic curves have been described as being either primary or secondary, or alternatively major or minor, but the terms of structural and compensatory curves are now used, (Schafer 1987).

According to the probable initial cause, scoliosis can be separated into three subgroups: idiopathic, neuromuscular and congenital. Idiopathic scoliosis means that a lateral curvature of the spine developed and we know of "no congenital spinal anomaly or associated musculoskeletal condition". Among all the different kinds of scoliosis, 80% to 90% of the cases are idiopathic, (DeSmet 1985). Congenital and neuromuscular scoliosis are also important because they are often "the most severe and intractable cases", (DeSmet 1985). Congenital scoliosis is lateral spinal curvature caused by anomalous asymmetric development of one or more vertebrae and neuromuscular scoliosis is defined as scoliosis due to a neurologic or muscular disorder.

Scoliosis is also frequently classified according to the skeletal age of the patient. Curves should be differentiated by patient age because of the different prognosis and treatment options in the different age groups, (DeSmet 1985). Infantile scoliosis refers to spinal curvature beginning during the first 3 years of life, juvenile scoliosis is defined as scoliosis which happened between 3 years of age and the beginning of puberty and adolescent scoliosis refers to those at or after the beginning of puberty but before "completion of skeletal maturity", (DeSmet 1985). Due to the rapid curve progression occurring during accelerated growth, "most patients with scoliosis present clinically during adolescence".

In order to know how common idiopathic scoliosis is and how many children will develop severe deformities or problems in adulthood, school screening program for the early detection of scoliosis have been widely used in the United States and abroad, (Ascani 1977, Asher et al. 1980, Lonstein et al. 1982, Segil 1974). In some countries and in more than 15 states in America, the program is legislated so that the screening is a mandated school program. In these states approximately three million children are screened annually, (Lonstein 1988). The Commission on Chronic Illness defined "screening" as "the presumptive identification of unrecognized disease or defect by application of tests, examination or other procedures which can be applied rapidly." Since scoliosis screening examines "well people with no disease, it is not diagnosis, and refers the positive findings for further evaluation", and this program meets the definition of screening, (Lonstein 1988).

"Scoliotic curves are always accompanied by axial rotation of the vertebrae", (Stokes 1984). It has been shown both on anatomic specimens (Roaf 1966) and with computer modeling (Schultz 1972, 1976) that the spine rotates when scoliosis develops. Because the anterior portion of the spine grows faster, if the total length of the trunk remains comparatively unchanged, the anterior part of the spine has to "deviate sideways and deviate more than the posterior part", (Roaf 1966). Rotation occurs and the greater the difference between the anterior and posterior components, the greater must be the rotation. This rotation permits "the posterior structures to remain the same length while the anterior elements elongate", (DeSmet 1985). This is also true for frontal plane curves, that is, to form a side direction curve one lateral side has to develop faster and rotation occurs as a result.

Spinal rotation brings one more term into the two-dimensional definitions (scoliosis, kyphosis and lordorsis) and three-dimensional deformities are better described using the inter-relationship of rotation to the two-dimensional definitions. Thus, none of the two-dimensional definitions accurately describe the condition and magnitude of the curve.

1.D. Treatment of Scoliosis

In the 18th century, physicians and surgeons tried to treat most adolescent idiopathic scoliosis with exercises. However, there was no difference between the results of exercise treatment in one group of patients and of a "simultaneous control group" of similar patients without any treatment, (Lonstein and Winter 1988). In 1945, Walter Blount and Al Schmidt (Blount and Moe 1973) first found a truly successful treatment orthosis for this disease, called the Milwaukee brace. However, the Milwaukee brace is used generally to "prevent progression of a mild-moderate curve until maturity or until a more appropriate age for surgery, or to prevent postoperative regression or for some cases of nonoperative scoliosis that do not exceed 40 degrees", (Turek 1977). After this first success, an enormous number of braces have been developed. There are basically two types: the higher braces used for thoracic curves, and the lower braces used for thoracolumbar and lumbar curves. The traditional Milwaukee brace is still the best choice for "the classic T5-T12 right thoracic curve", but thoracolumbar and lumbar curves are best treated by "the low-style underarm braces (TLSO)", (Lonstein and Winter 1988). Electrical stimulation treatment (surface stimulation) for reducing the progression of idiopathic scoliosis has become quite popular in recent years, (Brown et al. 1984, Axelgaard et al. 1983). During one study, when electrodes were placed over "the lateral trunk musculature rather than on the paraspinals", the scoliosis reduction improved threefold, (Shultz et al. 1981). This method can often be used as a good alliterative to bracing.

Part 2: Quantifying Methods of Spinal Curvature

2.A. Based on X-ray Films

2.A.1. Projectional Plane Curvature Analysis

The measurement of the magnitude of the deformity in scoliosis is usually performed by either the Cobb (1948) method or the Ferguson (1945) method. "The Cobb method is probably the most widely used and has been selected by the American Scoliosis Research Society as the standard method of measurement", (Kittleson 1970, McAlister 1975). Cobb(1948) suggested that "the angle of the scoliotic curvature be measured by drawing lines parallel to the superior surface of the proximal end vertebrae and the inferior surface of the distal end vertebrae of the curve". The angle between these lines, or the angle between perpendiculars of these lines (if the curve is of small magnitude and the two lines do not easily meet) is the angle of the scoliotic curvature according to Cobb, [Figure 4]. The top vertebrae is defined as "the highest one whose superior surface tilts maximally to the concavity of the curve" while the distal end vertebrae is defined as the lowest one whose "inferior surface tilts maximally to concavity of the curve", (Cobb 1948). Usually, the proximal and distal end vertebrae of the curve have the least vertebral rotation. On the condition that the superior or inferior surfaces of the end vertebrae are not clear, Cobb (1948) suggested "the superior or inferior pedicle surfaces" could be used instead. Thoracic kyphosis and lumbar lordosis can be measured in a similar fashion, (McAlister 1975) [Figure 5].

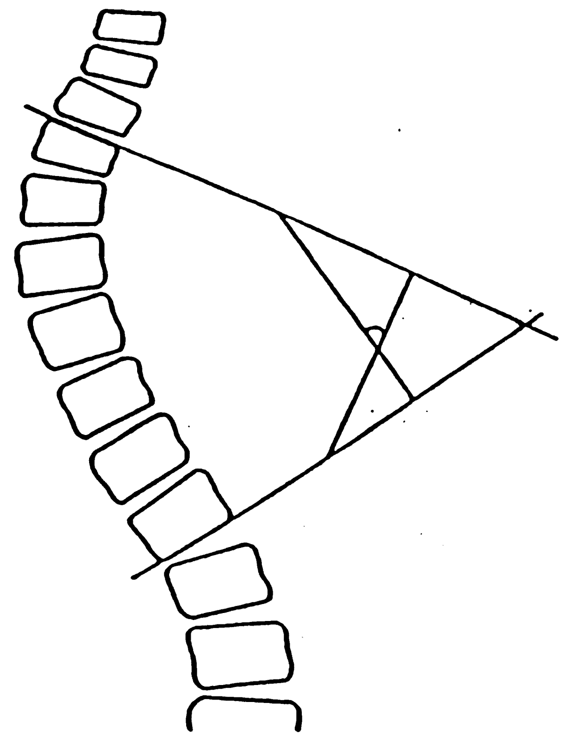


Fig. 4. Measuring spinal curve magnitude in frontal plane (scoliotic angle) by Cobb's method. (McAlister 1975)

Ferguson's method is "a more direct method of curve measurement not that dependent on the inclinations of the surfaces of the end vertebrae", but is more difficult to use especially in curves with Cobb angle greater than 50 to 60 degrees,(George 1961). Not the proximal or distal vertebrae, but the apex vertebrae of the curve usually has the greatest rotation. The center of this vertebrae is determined by "the intersection of the lines connecting each superior corner of one side of the vertebrae with the inferior corner on the opposite side", (Ferguson 1945) [Figure 6]. The centers of proximal and distal vertebrae are also marked in the same way. Lines are drawn from the apex to the centers of the end vertebrae and form the Furguson angle, [Figure 6]. If the vertebral body is wedged, convert the wedge into a rectangle and determine the center. It is sometimes difficult to select the apex and end vertebrae, or to determine the exact center of the apex vertebrae when it is wedged. Because of the considerable error in the measurement caused by identifying the exact center, the Ferguson's method is not recommended by some researchers, (Keim 1978, Kittleson 1970).

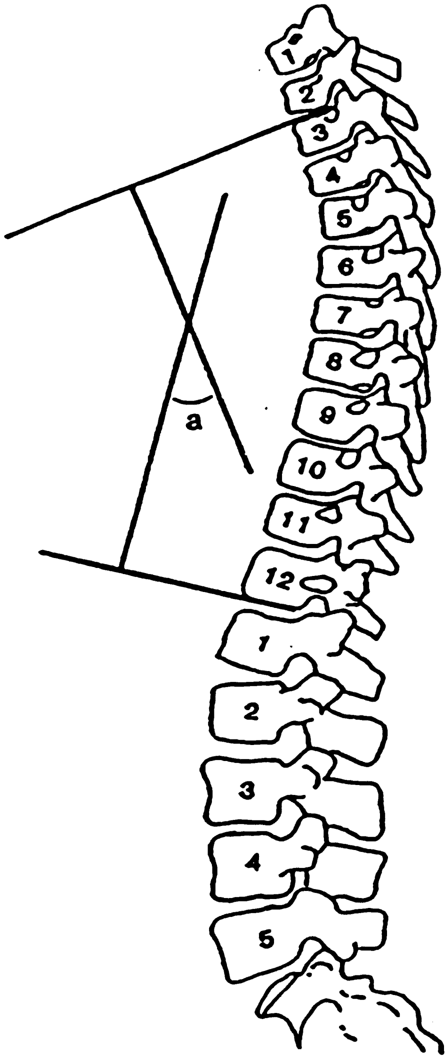


Fig. 5. Measuring spinal curve magnitude in sagittal plane (kyphotic and lordotic angles) by Cobb's method for scoliotic spine. (McAlister 1975)

Sevastikoglou and Bergquist (1969) did consecutive measurements on X-ray films of an unchanged scoliotic deformity of the spine by both Cobb's and Ferguson's methods. They found that measurements performed by Cobb's method gave "consistently higher values" than those performed by Ferguson's method, however, there was no appreciable difference between measurements performed by the two methods. Robinson et al. (1983) used both methods in measuring scoliotic curvature before treatment. They found a linear correlation between the two measurements but reported that "the Cobb angle was 1.38 times larger than the Ferguson angle for a given curve". However, the Cobb method is the preferred one because it is easier to use and more reproducible, and has been accepted as the standard method.

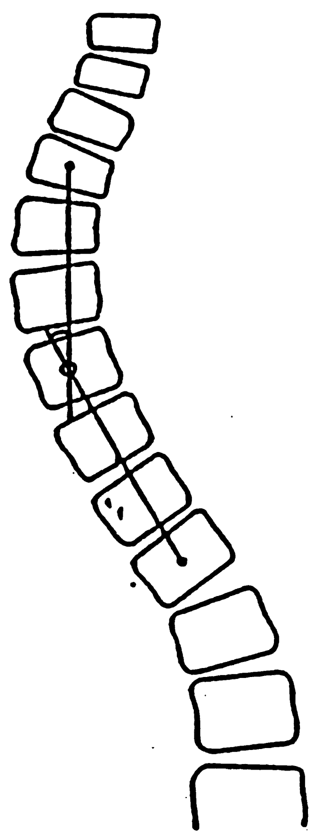


Fig. 6. Measuring spinal curve magnitude in frontal plane (scoliotic angle) by Ferguson's method. (McAlister 1975)

There is a standard error of measurement of 2.2 to 3.0 degrees with the Cobb method if the same end vertebrae are used for each measurement, (Beckman 1979, Jeffries 1980, Nordwall 1973, Wilson 1983). If several observers pick the end vertebral bodies independently, the standard deviation of curve measurement is increased to 4.5 degrees because of selection of different end vertebrae by various observers, (Oda, 1982).

White and Panjabi (1978) stated that Cobb's method could not give an accurate picture of the type of curvature present as "two scoiotic curves which were markedly different might have the same Cobb angle", [Figure 7a]. They suggested "a more precise and descriptive quantification of spinal deformity by also measuring the radius of curvature at the apex of the curves", [Figure 7b].

Voutsinas and MacEwen (1984) measured the sagittal profiles of the spine by using a new method called indices of kyphosis and lordosis and compared with the result measured by standard Cobb's method made by one investigator. The indices of kyphosis and lordosis were determined by ($W/L \times 100$), with L representing the inside length of the curve and W the maximum inside distance of the curve from the L line, [Figure 8]. This study showed that Cobb's method of measurement of kyphosis and lordosis matched well with the indices in the normal spine but not in pathologic conditions. They found that "the kyphosis and lordosis indices more accurately represent an arc, based on its length and width, and were easily reproducible".

Jeffries et al. (1980) used a computer measurement method to analyze scoliotic angle. They first reconstructed the spine mathematically by a computer program and then measured the scoliotic angle by both the computer method and manual Cobb's method. With the computer method, the end points on the curve to be measured were chosen as the inflection points (second derivative equal to zero) and the two tangential lines at the inflection points made up the scoliotic angle, [Figure 9]. A high degree of correlation (0.968) between the computer and the Cobb's methods was found.

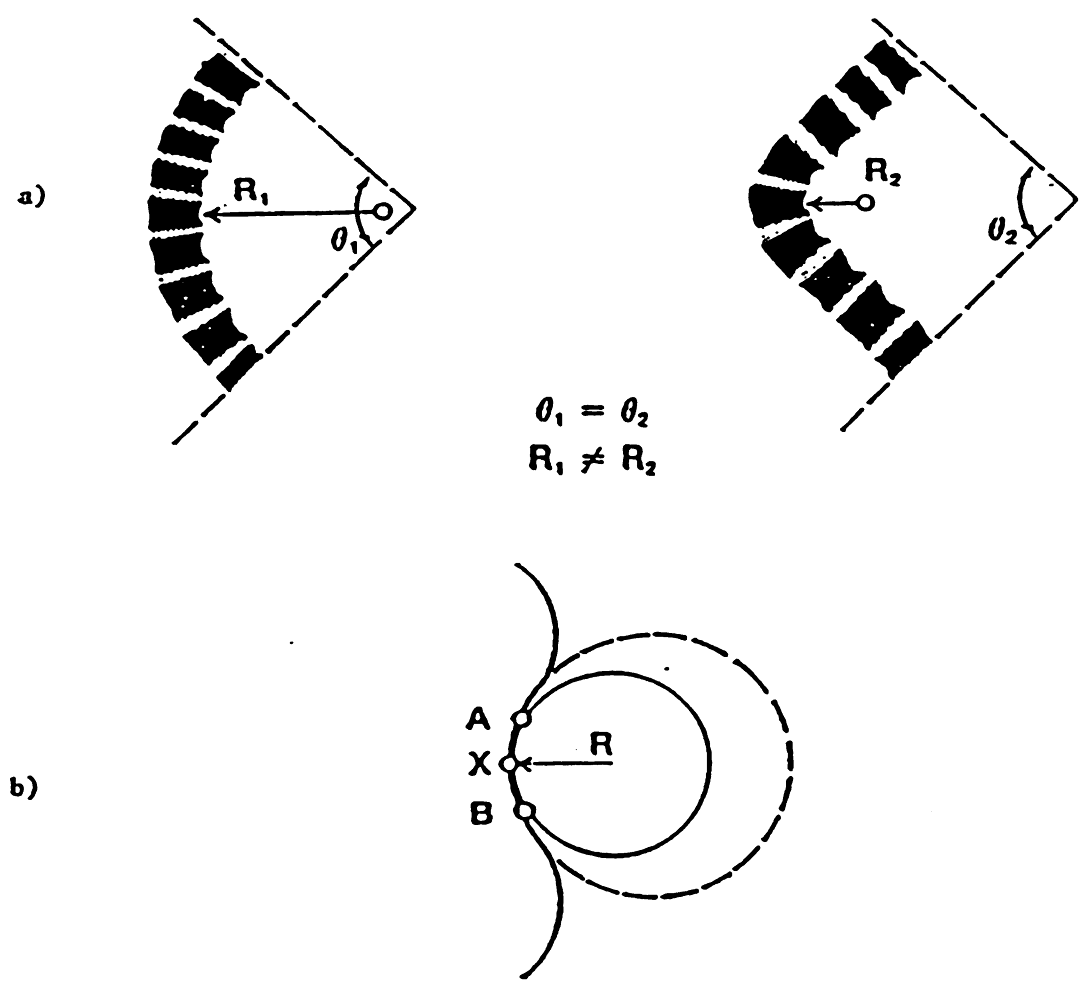


Fig. 7. Radius of curvature. a) Two scoliotic spines may have the same Cobb's angle but different shapes. The latter may be defined by the radius of curvature. b)Mathematical interpretation. (White and Panjabi 1978)

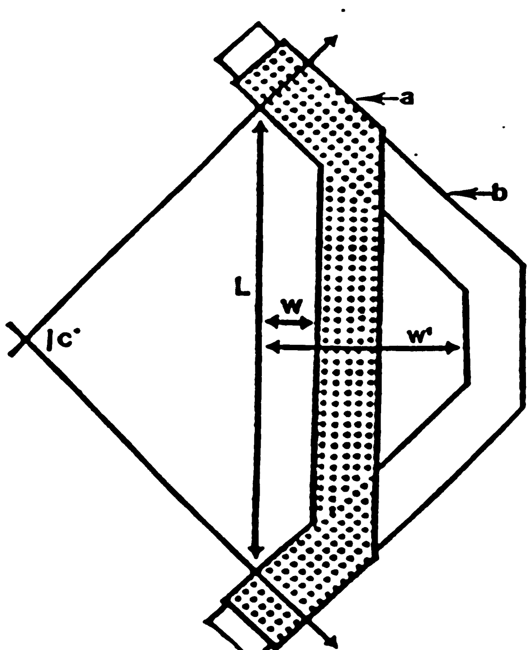


Fig. 8. The two spinal curvatures (a and b) represented by this schematic drawing are obviously quite different in magnitude. However, using Cobb's method to measure the deformities, the degrees of curvature are identical. The differences in the curves are more accurately reflected when the length of the curves (L) and their respective widths (W and W') are taken into consideration. (Voutsinas and MacEwen 1984)

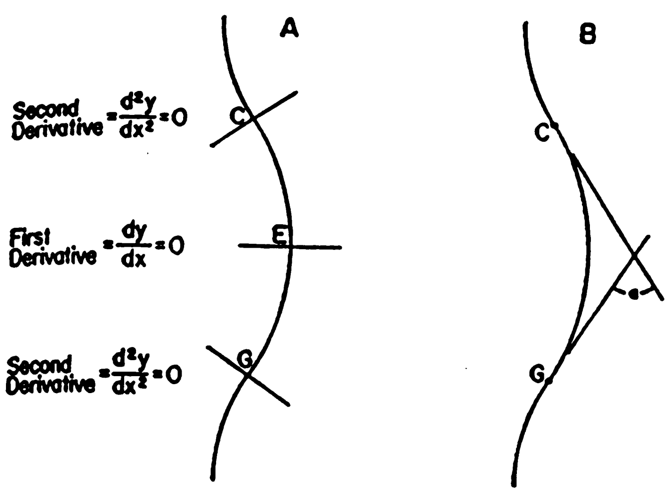


Fig.9. a) Mathematical derivation of the inflection points, C and G, and the apex of the curve, point E. b) Tangents to the curve at points C and G construct the scoliotic angle, a. (Jeffries et al. 1980)

Cobb's angle fails to describe the true severity of the curve because it reflects only the end vertebral bodies and not changes within the curve itself as stated by White and Panjabi (1978), but the computer method showed the true difference between the two curves with the same Cobb angle. Thus this computer method accurately identifies the actual slope of a curve at the inflection points rather than the tilt of a single vertebral body. Their study also showed that the computer method was more reproducible with a standard deviation of only 1.3 degrees.

Appelgren and Willner (1990) separated the standard Cobb angle into three angles, called the end vertebral angles, in a S-shaped scoliotic spine, [Figure 10]. The end vertebral angle were defined as the angle between each end vertebrae and the horizontal plane. The three angles were measured and called *A, B, C* where the middle end vertebral angle *B* is responsible for the improvement of the scoliosis in the brace and if end vertebral angles *A* and *B* are not equal, the thoracic curve is asymmetric. If *A* is greater than *B* [Figure 11a], the result of brace treatment was more successful than of the symmetric [Figure 11b] curves; if *B* is greater than *A* [Figure 11c], the result of brace treatment was not good. All theses could not be observed by using the Cobb method only.

2.A.2. Rotation Measurement

The determination of vertebral rotation is an important part of scoliosis evaluation, particularly in cases being considered for fusion, (Cobb 1948, Moe 1958, Nash 1969). Cobb (1948) described a standard technique for measurement of rotation based on "the position of the tip of the spinous process in relation to the underlying vertebral body". Values ranged from 0 to 4+; however, he did not correlate these grades with either the degree of rotation or the clinically deformity. Moe (1958) stated that the spinous

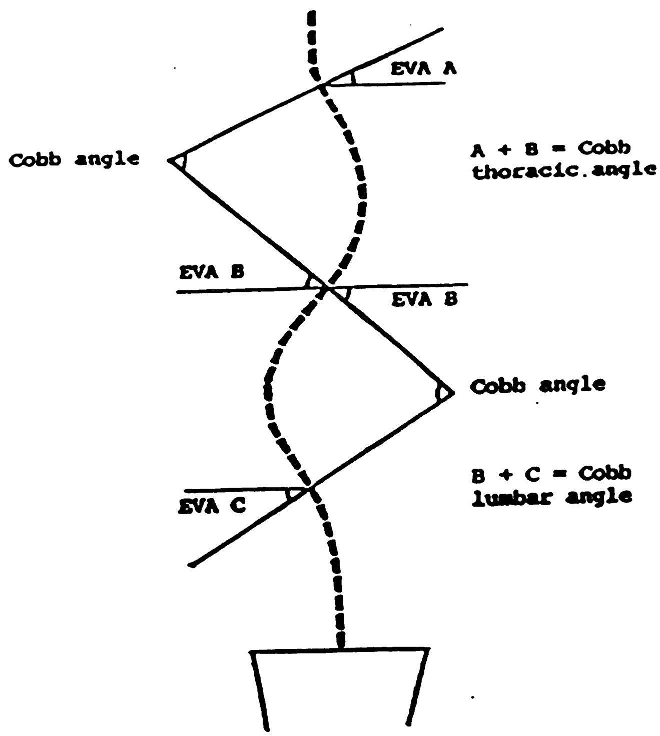


Fig.10. Description of the Cobb angle and the end vertebra angle. (Applegren and Willner 1990)

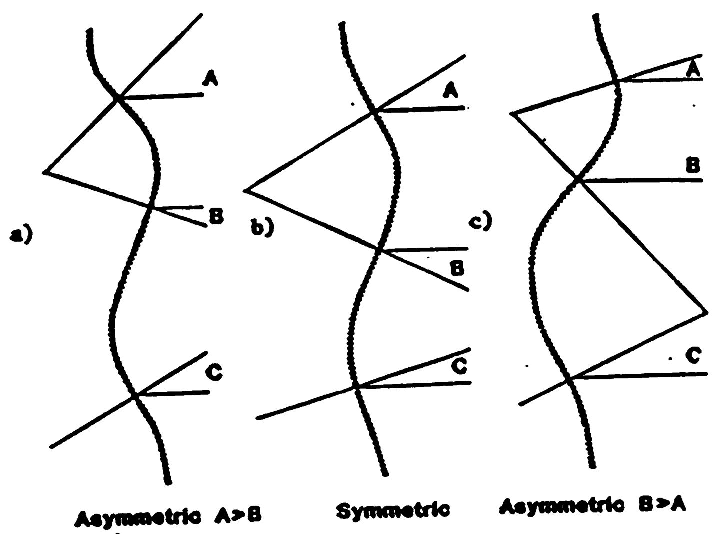


Fig.11. Symmetric and the two different types of asymmetric thoracic curves in S-shaped scolioses. (Applegren and Willner 1990)

processes were often difficult to visualize and suggested using the "pedicle shadows" instead, but no actual measurement system was proposed.

Nash and Moe (1969) compared the rotational measurements based on either spinous process or pedicle shadow displacement and found a method to determine rotation based on pedicle displacement. At the same time, they correlated the approximate range in degrees represented by each gradation of rotation. However, the apparent pedicle offset image depends on a number of factors, including the axial rotation of the vertebrae, the shape of the vertebral body, and the inherent symmetry of the body geometry of the vertebrae itself, (Stokes 1986). Although this pedicle displacement method cannot accurately and quantitatively determine the vertebral rotation, it has been long treated as a standard.

Stokes et al. (1986) reported a radiographic method for measuring the axial rotation of vertebrae in degrees by a simple mathematical formula based on the offset of the pedicle image from the vertebral body center and "a depth estimate". It was found that measurements of vertebral rotation could be made clinically from single-plane radiographs with a standard deviation of 3.6 degrees based on a study of known rotations of a radiographic phantom. They mentioned that measurement from clinical films were unlikely to be made more accurately than this because of inherent geometric constraint.

2.A.3. Three-dimensional Measurement

Simple single projectional film, such as radiographic film, or multiple single projectional films are not able to describe the three-dimensional geometric nature of spinal deformity, particularly with regard to rotation, even if kyphosis, lordosis or scoliosis are measured from the sagittal film or frontal film, or other directional films and the rotation is measured simultaneously. Three-dimensional deformity requires a true three-dimensional descriptive method.

Brown et al. (1976) first analyzed the three-dimensional configuration of spinal segments *in vivo* by bi-planar radiographic technique. They determined the coordinates of anatomical points in space by an anteroposterior and a lateral film, and then an orthogonal Cartesian coordinate system for each vertebrae based on its four anatomical points was reconstructed, with one axis directed superiorly along the longitudinal line of the vertebrae and with the center located at the vertebral mass center. Once each set of vertebral bodies had been assigned to its individual "mass center" coordinate system, the location and orientation of each vertebrae were uniquely described in terms of a translation vector and three Eulerian angles which describe the spatial orientation of the individual "mass center" coordinates with respect to the reference frame coordinate system. The three Eulerian angles provide the important information of spinal deformity with one angle responsible for kyphosis and lordosis, one angle for scoliosis and the remaining one for rotation of each vertebrae. They also described the spinal relationship between adjacent vertebrae by choosing the reference frame coordinate system as the inferior vertebral coordinate system.

Scholten and Veldghuizen (1987) summarized the error in using the conventional Cobb method to measure the magnitude of the deformity of a scoliotic spine. The system error is made when projecting the three-dimensional spinal shape into a two-dimensional image on a radiographic film. The experimental error is caused in measuring the Cobb angle in a frontal film. They used "a three-dimensional geometrical non-linear mechanical model to represent the spine as a collection of 17 rigid bodies", each corresponding to a thoracic or lumbar vertebrae, interconnected discs, the intervertebral joints and the ligaments. Each vertebrae was defined by local coordinates in a way similar to the study of Brown et al. (1976). In order to compare the deformity of a scoliotic spine described with two- and three-dimensional parameters, a space angle, a three-dimensional angle and the Cobb angle were calculated, with the space angle defined as "the smallest angle between the two local saggital planes of the end vertebrae of a curve", the three-dimensional angle defined as "the difference in rotation about the local anterior axes between the two end vertebrae of the curve "(Eulerian angles), and the Cobb angle as the angle "between the projections of the local upward axes of the upper and lower end vertebrae of the curve". The defined three-dimensional angle was always smaller than the defined space angle and the differences became larger by increasing the lateral deviation and axial rotation to the convex side of the curve. For the Cobb angle, the projection error of spatial angle in a plane in mild scoliosis (Cobb angle 20-30 degrees) was 1.5-2.0 degrees, the observation error for the recognition of the anatomical landmarks went up to 3-5 degrees, the total error of the Cobb method would be 4-7 degrees. They also found that the Cobb angle was mainly influenced by the lateral deviation and less by the axial rotation, so they suggested an accurate method to measure the axial rotation in addition to Cobb's angle measurement.

DeSilva and Yang (1991) suggested a new method different from Cobb's to precisely describe a scoliosis spine based on a differential geometry point of view. They modeled the spinal column as a space curve which connecting the centroids of the transverse vertebral sections. The mathematical curvature of the spine in the sagittal plane and the frontal plane were measured by projecting the curve into the two planes. The term "tortuosity' which describes the rotational asymmetry about the vertical axis, with axial rotation of the vertebrae, of the plane of maximum curvature of the spine. They stated that the curvature in the frontal plane was a more meaningful measure than Cobb's angle and the tortuosity described precisely "the phenomenon observed by surgeons in which there was asymmetric rotation of the vertebrae along the spine".

The three Eulerian angles describe each vertebrae's orientation and "influence the appearance of the projections of the vertebrae", (Drerup and Hierholjer 1992). Conversely, the angles should be able to be determined from the projections, if the space shape of the vertebrae is known. Based on this idea, Drerup and Hierholjer (1992) exploited the shape information as much as they could from only frontal radiographs of scoliotic patients under the assumption of "parallel projection and a circular cylinder model of each vertebrae". The lateral tilt angle was equal to "the tilt of the long axis of the elliptical projection of the end plates". The axial rotation angle was determined by added pedicle reference points of the vertebral model. From a single frontal plane film, they got the position parameters, lateral tilt angle and axial rotation, which were plotted as functions of the longitudinal coordinate separately. In addition, the length of the scoliotic curve and the location of the apex which are important parameters in describing scoliosis were also determined. In order to do that and obtain more information, the measurement points of the spinal column were fitted by a least-square harmonic approximation. They mentioned that the major advantage of using harmonic functions was that "a direct interpretation of the function parameters in term of clinical parameters" would be possible, and the least-square method improved the reliability of the data by smoothing them. The results were compared to conventional clinical results and a satisfactory agreement was found.

2.B. External Measurements to Describe Spinal Deformity

It is not possible to know the real condition of the spine from an external deformity measurement because of the muscles, fat, and ribs lying between the spine and the skin. Further, there is a difference in the appearance of a deformity in a thin and a obese person even if they have the same spinal condition. But, as the external surface deformity is actually caused by internal spinal deformity, it may be possible to detect the internal deformity by external surface parameters.

Shinoto et al. (1981) analyzed scoliosis and kyphosis deformity quantitatively by the Moiré method. They got several three-dimensional points on the back and fitted those points by a cubic function. When a peak existed on both the right and left sides of the curve, the distance from the each peak to the centerline and the height difference between the two peaks were calculated, [Figure 12]. The angle used to estimate the deformity of scoliosis was formed by the line linking two peaks (double tangent line) and a horizontal line and it was named "hump angle", [Figure 13]. Another parameter to describe scoliosis was the distance from the centerline to the point midway between the two peaks named "lateral deviation", [Figure 13]. In spite of some variation, there was a tendency for the maximum value of "hump angle" to increase with the increase of the rotation of the vertebrae measured from X-ray film by the method of Nash and Moe (1969). They concluded that the parameter "hump angle" could be said as "indicating the rotation of the spine to some extent". A linear relationship was found between "lateral deviation" and Cobb angle in degrees of the spine on X-ray film. The coefficient of correlation was 0.82 ($p<0.01$) and it seemed that "lateral deviation" was useful to estimate the Cobb angle of the frontal shape of the spine. A linear relationship was also found between "hump angle" and Cobb angle with the coefficient of correlation as 0.76 ($p<0.01$).

Willner (1981) compared the results between Moiré and X-ray in 216 cases with structural scoliosis. His study demonstrated that there was a coefficient relationship between a difference of Moiré fringe number on left and right side of the body, which mean hump height, and Cobb angle on X-ray film. He also reported that there was a higher coefficient relationship in the case of thoracolumbar or lumbar scoliosis than for

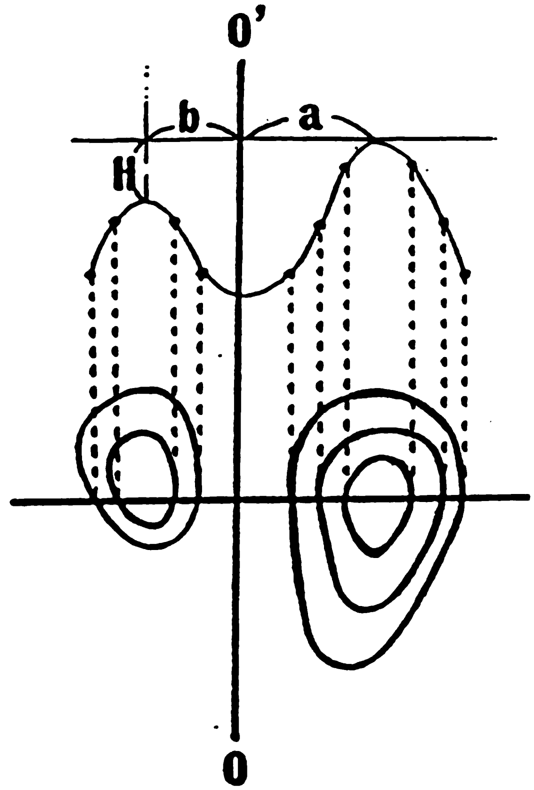


Fig.12. Cross-sectional contour line from Moiré fringe surface topography.(Shinoto et al. 1981)

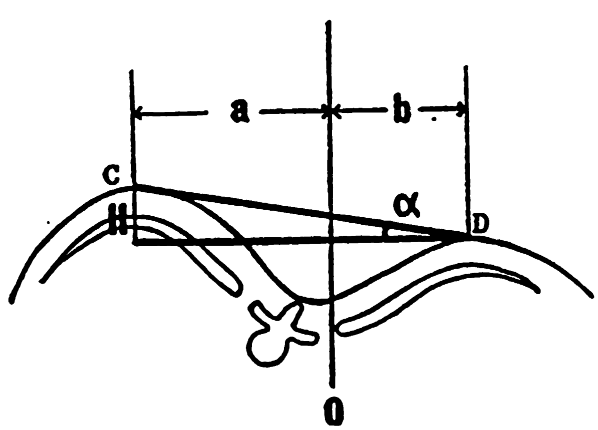


Fig. 13. Hump angle α: indicating the rotation of the spine, CD is the line of double tangent, lateral deviation is expressed by (a - b). (Shinoto et al. 1981)

thoracic scoliosis.

Moreland et al. (1981) summarized 558 examinations of 322 scoliotic patients by comparing the surface topography change to that of the Cobb angle and a good correlation was found. "Distance pattern shapes" seen on the Moiré topographies could be identified that correlated with "the anatomic regions of the scoliosis". By analyzing the components of the Moiré fringe topogram, it is possible to identify clearly the region of "spinal involvement".

Stokes et al. (1983) compared the back surface topography with three-dimensional spine shape in scoliosis. This study showed again that the back surface deformity in patients was a measure of idiopathic adolescent scoliosis and it was found that the back surface deformity tends to be considerably smaller than the actual deformities of the spine.

Hierholzer and Drerup (1986) reported a shape analysis study of the symmetry line of the back surface. The symmetry line [Figure 14] was constructed in "a point-wise manner" by analyzing the shape of the horizontal profile where "that point was searched to divide the profile into a left and a right half of minimum symmetry" and the serials of "symmetry points" of all horizontal profiles formed the symmetry line. The symmetry line is actually a three-dimensional curve on the back surface and its lateral view projection can provide the kyphosis and lordosis angles directly. The surface normal can be found along this line, which can be used to measure the surface rotation angle. Scoliosis produces not only a lateral deviation of the symmetry line, but also a rotation of the surface normal. They stated that "the symmetry line was in close relation to the line of the spinal processes even though this statement still required to be verified quantitatively". They concluded that back surface asymmetry could be described by the symmetry line, which is a generalization of the medial sagittal profile. Lateral deviation and surface rotation, which were calculated from surface curvature, might be used for an estimation of the three-dimensional shape of the spinal midline. The midline can be constructed from the line of the spinous processes and the vertebral rotation in the case of scoliosis according to Turner-smith (1983).

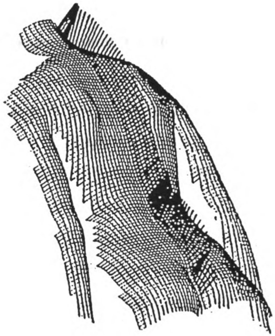


Fig. 14. Surface Normal along the Symmetry Line. (Heirholzer and Drerup 1986)

Frymoyer (1985) emphasized the importance of external measurements. "Curvatures which are at risk for rapid progression such as congenital scoliosis are best evaluated by radiography, however, the major problem of idiopathic scoliosis is cosmetic except in severe cases where cardiopulmonary function is compromised. As a result, the external shape measurements and their progression and change may be a more meaningful clinical measurement, particularly in the assessment of the rib hump deformity". He concluded that "the most intriguing possibility is that external shape changes may be a more important predictor of unfavorable cosmetic curve progression than the traditional measures of Cobb angle and Nash-Moe index of rotation".

Part 3: Measurement Techniques of Spinal Curvature and Mobility

3.A. Radiography Measurement Techniques

Plane radiography is the most used method for recording and quantifying spinal curvature. To measure curvature in the sagittal plane (kyphosis and lordosis angles), a lateral film is required and to measure curvature in frontal plane (scoliosis angles), anteroposterior or posteroanterior film is required and then either Cobb's or Ferguson's method is applied. However, if there are coupling conditions, sagittal plane curvature coupled with frontal plane curvature or rotation of vertebrae coupled with lateral tilt, the angles measured from those films will be erroneous. Movements in sagittal plane generally occurs without significant lateral tilt or axial rotation, (Pearcy 1985). Portek et al. (1983) showed that the plane radiographic technique and the three-dimensional technique in measuring intervertebral movements in sagittal plane correlated well with each other. Pearcy (1985) proved that lateral tilt is actually accompanied by axial rotation and sagittal plane movements. As a result, sagittal, anteroposterior or posteroanterior films can not correctly represent the true spinal curvature.

Measuring of axial rotation from single film is performed by Pedicle Shadow Offset technique (Nash and Moe 1969). However, because rotation is coupled with sagittal movements and lateral tilt, "this method will be liable to error unless careful consideration of the other planes is made", (Pearcy 1986).

Since X-ray tubes emit energy in a radial fashion just like any other kinds of points source, such as the Sun, to accurately represent the true shape by the shadows or images, it is required that the object be coplanar with the X-ray film plane, or a larger image will be produced than the object itself. As a result, a correct magnification factor should be taken into account depending on the tube position. However, since all of the geometric information is compressed into a single plane, the magnification actually varies with the position of the part of the skeleton being measured. This will produce a systematic error in single plane measurement. DeSmet et al. (1982) found differences in radiographic measurements between posteroanterior and anteroposterior films.

In order to document the change in the patient during treatment of spinal deformity, an accurate technique of observation is essential. Simple single plane or multiple single plane radiographs cannot meet this requirement from two respects. First, it cannot describe the true three-dimensional geometric nature of the spinal deformity, particularly with regard to rotation. Secondly, because X-ray tubes act as point sources emitting energy in a radial fashion, any object not coplanar with the X-ray film plane produces a nonlinear image larger than itself, as a result, single plane radiographs loses the accuracy required to detect the magnitude of change in spinal geometry needed.

Stereo-radiography provides a three-dimensional measurement of spinal curvature and requires a three-dimensional location of each landmark on the vertebral column. Lysell (1969) used a single X-ray source and film plate in a fixed relation to each other with the subject on a rotating table to produce a double exposure. More commonly, it is used with two X-ray source positions and a single X-ray film plate. While the X-ray film is changed between exposures. In each position, two oblique radiographs of subject are obtained. Brown et al. (1976) applied a biplanar technique with two X-ray source positions and two film plates for describing the three-dimensional configuration of the spinal segment from an anteroposterior and a lateral radiograph. DeSmet et al. (1976) determined the three-dimensional location and rotation of each vertebrae using a biplanar method but with posteroanterior and posterior oblique radiographs. They found that the frontal and lateral radiographs were not satisfactory projections for identifying the vertebral landmarks.

Once pairs of radiographic films are obtained, the analysis accuracy depends on the identifications of the locations of anatomical landmarks. This is the most inaccurate part of these techniques and several methods have been devised to reduce errors introduced by manual identification of landmarks. Selvik et al. (1976) placed metal marks on the vertebrae prior to examination in their study of measurement of the movement of spine. This method is only applicable for patients undergoing surgical procedures on their spines. Generally, more landmarks than the three required for three-dimensional analysis are used. Rab and Chao (1980) used nine landmarks on lumbar vertebrae and those landmarks have been shown to be repeatedly identifiable. To avoid this redundancy in landmarks, optimization procedures have been used by Stokes et al. (1980), considering the vertebrae as rigid bodies. The landmarks on a vertebrae, if it is a rigid body, should have the same spatial relationship to each other and their coordinates may be modified to satisfy this relationship. Drerup et al. (1978) described a geometrical reconstruction of the X-ray film position method to enable the manual positioning of the marks on the radiographs to be performed more accurately. Once the two-dimensional coordinates of each landmarks on each radiograph have been satisfactorily identified, they can be entered into a computer either manually or with a digitizer. The data can be rapidly processed utilizing previously obtained calibration data of the positions of the X-ray tubes relative to the film plates. However, due to the complexity of the identification of landmarks and the data entry procedures, a skilled operator is required.

Measurement of spinal mobility is very difficult using radiographic techniques. Most of the work done by radiography provided only the ranges of spinal movement and not the pattern of movement dynamically, (Portek et al. 1983, Burton 1986, Adams et al. 1986). Stereo-radiograph techniques have been the most accurate method in measuring static spinal curvature and should be for dynamic intersegmental vertebral motion. Overall, stereo-radiograph techniques have the following shortcomings: a) stereoradiographic techniques depend on the ability to identify landmarks on the vertebrae; b) use more exposure than conventional single plane techniques; c) require a complex marking and measuring procedure and a complicated theoretical development and d) are not suitable for spinal mobility examinations clinically. As a result, the stereo-radiograph techniques are mostly used in research laboratories.

Because patients undergoing long-term treatment for spinal deformity require periodic radiographic evaluations, the risks of radiation have been of increasingly concern. Regarding radiation risk to breast tissue, Nash et al. (1979) suggested a simple technique of taking posteroanterior rather than anterioposterior radiographs for simple single plane evaluation and the additional techniques, such as "higher speed film, more aggressive collimation, shielding, screens, and anthropomorphic filtering", can further reduce such risks, thereby keeping the long-term diagnostic radiographic follow-up of spinal deformity reasonably safe. For the increasing number of children undergoing periodic follow-up and treatment, they suggested "the number of different directional radiographic film should be used judiciously depending on the patients' condition". Their study has served as "a guide and a remainder to the practitioner and radiologist" concerning the risk of radiation to spinal deformity patients, (Nash et al. 1979). Ardan et al. (1980) used a low dose radiographic technique in assessment of scoliosis in children. Radiation exposure can be minimized by "using experienced technicians to minimize retakes, proper collimation and proper monitoring of X-ray tube performance and filtration".

More work has been done (Fabrikant 1982, Gregg 1977, Gross et al. 1983, Wagner 1983, Webster 1981) to reduce radiation risk in spinal deformity detection and treatment. However, risks exist for four conditions which have not been solved. The four conditions are: a) long-term treatment; b) school screening or radiographic examination and treatment of children; c) accurate quantification the three-dimensional magnitudes of spinal deformity by stereoradiographic techniques; d) spinal mobility examination or spinal deformity examination dynamically. The radiation risk, along with other disadvantages of using radiographic techniques for spinal deformity, forces researchers to investigate external or back surface noninvasive techniques to measure three-dimensional spinal deformity, as they are safe, easy, and economic to use.

3.B. External Measurement

3.B.1. Optical Techniques in Documentation Spinal Deformity

Due to the increasing interest in noninvasive methods to measure spinal deformity, many optical techniques have been developed in recent years. These methods include: Moiré Fringe Topography, Stereophotogrammetry, Rasterphotography, and television/computer systems.

Moiré fringe photography (meaning "water silk") technique was first described by Lord Rayleigh (1874) and involved "producing patterns on surfaces of objects by the optical interference of two separate grating patterns". Takasaki (1970) applied this method to the human body and was able to demonstrate accurate surface shape contours by "simple and elegant means". The interest in Moiré topography for spinal deformity examination has increased in the past years,(Adair et al. 1978, Ohtsuka et al. 1981, Willner 1979 and 1982).

Generally, there are two types of Moiré topography: shadow and projection. In shadow Moiré topography, standard gratings are arranged and the shadow of the grating is projected on the back of the human body using an illumination and a transformed grating according to the shape formed. By overlapping the standard gratings and the transformed gratings, Moiré fringes can be generated which indicate the contour line of the back. In projection Moiré topography, a grating image is projected on the back to form a transformed grating image. The transformed grating image will then be formed on the standard grating through lens so as to generate contour line Moiré fringes between the transformed grating and the standard grating. Both methods provide the necessary information, but the shadow type requires more equipment and is less accurate than the projection type. The projection Moiré fringe topography is the preferred type, (Stokes et al. 1984, Shinoto et al. 1981).

Moiré topography is a noninvasive and noncontacting method for recording the back shape and showing whether it is symmetrical. However, two particular problems are associated with the use of Moiré topography. First, the fringe contours of the Moiré topography are especially sensitive to the subject's posture. If the posture changes even slightly, the appearance of the fringe will change markedly. Therefore, for comparative studies, the subject must be rigidly constrained. Second, the contour itself does not provide numbers which can be used for further analysis. Various methods (Willner 1979, Moreland et al. 1981) have been proposed to assist in the analysis of Moiré topography quantitatively, but the measurement and analysis procedures tend to add time and complication to the Moiré technique.

In order to find the clinical value of Moiré topography in the management of spinal deformity, Sahlstrand (1985) used it as an adjunct to clinical assessment and roentgenographic examination in a consecutive series of 139 scoliosis observations. He concluded that even considering the disadvantages of Moiré topography measurement, it was "a valuable diagnostic tool and represents a practical way of recording the status of the back in children with scoliosis". When it was used to complete a clinical evaluation, one could gain better diagnostic accuracy and reduce the need for X-ray. More recently, Denton et al. (1992) used both radiography and "instant Moiré photography" to determine the degree of progression of spinal curvature. They found that in order to minimize errors, it required the clinician to interpret all three phases of scoliosis analyses - "physical examination, Moiré photography and Cobb angles" and at best, the accuracy of Moiré analysis is considerably less than that of radiography. Therefore they concluded that it should be intended only as an adjunctive technique to radiology.

Stereophotogrammetry has been widely used in analyzing object surface shape in biology and medicine. This method uses two cameras with known viewing angles to take different views of the object surface. Three-dimensional information is determined by optical triangulation from two separate two-dimensional pictures. This techniques takes hours for a skill operator to calculate, measure and analysis.

Based on the stereophotogrammetric method, Frobin and Hierholger (1981) suggested a rasterstereophotographic method for measurement of body shape to analyze spinal deformity. This method is similar to conventional stereophotogrammetry except that one of the two cameras is replaced by a projector with a raster diapositive. The projector and the camera may be considered as a rastereophotographic system with the raster diapositive and camera image forming the stereo image pair. Since the raster diapositive is a priori known, only the camera image need be evaluated. Identification of corresponding points in the image pair is carried uniquely by a determination of the row and column numbers of the raster intersection. In application, this method has a equivalent range to that of Moiré topography. However, the accuracy of the rasterstereographic system depends on the geometry of the objects to be measured.

Turner-Smith (1988a) described a television/computer three-dimensional surface shape measurement system which was designed primarily for human back shape. In this system, a projector and television camera were mounted together in a box which could rotate about a horizontal axis. The projector shone a horizontal plane of light, which was viewed at an angle from below by the television camera, linked directly to a minicomputer. Three-dimensional coordinates of points on the line of light formed by the plane as it fell on an object could be calculated with a knowledge of the geometry of the system. This system has been used by Turner-Smith et al. (1988b) to provide data for the assessment of scoliosis. They found the correlation of lateral asymmetry from the surface shape analysis with Cobb angle from X-ray measurement in 119 patients were in the range from $r=0.77$ to $r=0.94$. Comparing with structured light methods such as Moiré topography and rasterstereography, this television/computer system is more suitable for clinical use, eliminating the time required for chemical film processing and digitizing the image.

3.B.2. Other Techniques in Assessment of Spinal Deformity

In an order to measure spinal deformity with simple, easy and noninvasive tools, many new techniques have been developed and some have been used clinically. Among all the new techniques, inclinometer, goniometer, flexicurves, spondylometer, and pins in spinous processes are used most, (Pearcy 1986).

Asmussen and Heeboll-Nielsen (1959) described an inclinometric method of measuring the spine which allowed them to define numerically spinal posture and movement. However, they chose as points of reference the lowest lumbar lordosis and highest dorsal kyphosis, which have little anatomical functional significance. Lobel (1967) designed a special inclinometer that consisted of a dial divided into degrees and fixed to two plastic buttons. When the two buttons were held against the spine, the weighted needle remains vertical and indicated the angle of spinal incline. Adams et al. (1986) used an electronic inclinometer technique to measure lumbar curvature. These electronic inclinometers were small metal cylinders with a flat base which could be attached to the skin. Each contained a miniature pendulum as part of an optoelectric circuit that had a voltage output proportional to the angle between the flat base and the vertical. For measuring lumbar curvature, the inclinometers were attached to the skin overlying sacrum and L1 spinous processes and the summation of the output angles at the two landmarks made up the lumbar curvature. This technique requires frequent recalibration of the instruments and care to avoid skin wrinkling. The electronic inclinometer technique is suitable for research applications but is not good for routine clinical use.

Similar to electronic inclinometer, Paquet et al. (1990) developed a new electrogoniometer for the measurement of sagittal dorsolumbar mobility. The electrogoniomter consisted of a standard potentiometer fixed to a plate at the sacral level and connected by a flexible slat to the other plate at the thoracic level. This electromechanical device provided the amplitude, velocity, and acceleration of movements by means of a computer interface. A high correlation between this device and the inclinometer technique has been found. This new electrogoniometer can provide continuous measurements of sagittal dorsolumbar motions with an accuracy comparable to that of the inclinometer method. However, this device requires special consideration of the anthropomorphic features of patients and the selection of a flexible slat of appropriate length for the spinal segment to.

Burton (1986) used a draftsman's flexible curve (flexicurves or flexi-rule) to measure regional lumbar sagittal mobility. This flexicurve was capable of bending in one plane only and maintaining an adopted shape that could be transferred to paper. The measuring technique was performed by three steps: identification of bony landmarks, moulding of flexicurve to the spine, and measurement of the angle of the transferred curve on paper. This method provided an accuracy comparable to other methods, but it is cumbersome and laborious. All three methods, inclinometers, goniometers and flexicurves, are able to separate back movement from hip motion, and thus have a clinical advantage, (Pearcy 1986).

A spondylometer was developed by Dunham (1949) for the measurement of spinal movement in patients with ankylosing spondylitis. This device has a long linkage attached to a protractor pointer. The protractor is held against the base of the spine and the end of linkage is held against a point higher up the back. Movement of the trunk results in a displacement of the linkage and an angular reading on the protractor. Reynolds (1975) applied this device to measure spinal anterior flexion and extension from the erect position. A spondylometer was modified by fixing a protractor over the hinge joining the two arms of the instrument and was used to measure the change in the angle between the arms during flexion and extension. After a comparison of this techniques to goniometers, he found difficulties with technical feasibility and reproducibility of some of the measurements using the spondylometer.

In order to get more accurate information about spinal curvature and mobility, the complexity and inaccessibility of the spine has led to invasive techniques on groups of volunteers using pins in the spinous processes, (Gregerson and Lucas 1967, Lumsden and Morris 1968). The insertion of Steinnman pins into spinous processes of volunteers has been used to examine axial rotation of intervertebral joints, this method is obviously of limited applicability.

Mathematical Development

Part 1: Curve Representation and Curve Fitting

1.A. How to Represent a Space Curve

Generally, there are three ways to represent a space curve: implicit, explicit and in parametric form, (Eisenhart 1960).

In three-dimensional space, a single equation usually represents a surface, and at least two equations are needed to specify a curve. Thus the curve appears as the intersection of the two surfaces represented by the two equations in Cartesian coordinates (x, y, z) as:

(1-1) $F(x, y, z) = 0\,,\ G(x, y, z) = 0\,;$

The curve represented by (1-1) is expressed in implicit form.

If the implicit equations (1-1) is solved for two of the variables in terms of the third, say for y and z in terms of x, the result can be written in the form:

(1-2) $y = y(x)\,,\ z = z(x)\,;$

The curve represented by (1-2) is expessed in explicit form.

The Cartesian coordinates (x, y, z) of the point on the curve can be expressed as real-valued functions (f_1, f_2, f_3) of a parameter u:

(1-3) $x = f_1(u),\ y = f_2(u),\ z = f_3(u)\,;$

The curve represented by (1-3) is called in parametric form.

Alternatively, in vector notation the curve can be specified by a vector-valued function:

(1-4) $\vec{r} = \vec{R}(u)$;

where: $\vec{r} = x\hat{i} + y\hat{j} + z\hat{k}$;

$\vec{R}(u) = f_1(u)\hat{i} + f_2(u)\hat{j} + f_3(u)\hat{k}$;

$\hat{i}, \hat{j}, \hat{k}$ are coordinate unit vectors corresponding to x, y, z coordinates;

A parametric representation of a curve specifies not only the curve but also the particular manner in which the curve is described, (Willmore 1959). This is easily seen if parameter u is interpreted as time and the curve is considered as the locus of a moving point. In differential geometry, a parametric representation is not only a convenient way of description but it is also a useful tool for further study of the properties of the curve, (Willmore 1959). Theoretically and practically, the independent variable in curve equations would be chosen as <u>arc length</u> in parametric form than one of the coordinates.

Let us consider a point P(x,y,z) and a neighboring point Q(x+Δx, y+Δy,z+Δz) on a curve represented in parametric form, [Figure 15]. Draw the line PQ and let the segment of this line between P and Q be denoted by Δc, while the arc of the curve between P and Q is denoted by Δs, then

(1-5) $\Delta c^2 = \Delta x^2 + \Delta y^2 + \Delta z^2$;

As Q approachs P, we obtain

(1-6) $\Delta c \cong \Delta s$;

(1-7) $ds^2 = dx^2 + dy^2 + dz^2$;

i.e. $(\frac{dx}{ds})^2 + (\frac{dy}{ds})^2 + (\frac{dz}{ds})^2 = 1$;

i.e. $(x')^2 + (y')^2 + (z')^2 = 1$;

where $x' = \dfrac{dx}{ds}$, $y' = \dfrac{dy}{ds}$, $z' = \dfrac{dz}{ds}$;

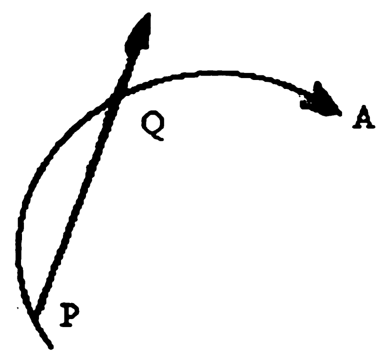


Fig. 15. Two points on a space curve A, as Q approaches to P, the length of line segment PQ approaches to that of curve segment PQ.

If we let the arc length s be time, $\sqrt{(x')^2 + (y')^2 + (z')^2}$ will be the "speed" of a point travelling along the curve. If we choose arc length as the independent variable, the curve will always have unit speed, i.e. $\sqrt{(x')^2 + (y')^2 + (z')^2} = 1$. This property simplifies the calculations and makes it easy to understand and track the mathematical inductions.

For the spine, if we choose the independent variable as one of the coordinates (x,y,z). For example:

(1-8) $x = x(z)$, $y = y(z)$, $z = z$;

where: positive x is anatomical anterior ,

positive y is anatomical left side ,

positive z is anatomical up;

We can successfully locate a point on the curve by the z value in the standing erect condition, but we will have trouble in large flexion or extension conditions. It may be found that different points have the same z value. On the other hand, if the arc length is chosen as the independent variable, starting at sacrum and increasing as we move a point along the curve directed to the T1 vertebrae. Any point can be located by their different arc length on the curve no matter what condition is chosen.

In our spinal curvature study, the spinal curve is represented in parametric form with arc length as the parameter:

(1-9) $x = f_1(s)$, $y = f_2(s)$, $z = f_3(s)$;

where: s is the arc length starting at sacrum and increasing along the curve to the T1 vertebrae.

1.B. Curve Fitting

"Curve fitting is the process of fitting particular classes of functions to discrete data in an exact or approximate manner", (Lindfield and Penny 1989). If the discrete data is accurate, exact curve fitting methods will produce one or several functions to join those discrete data into a continuous curve without losing the accuracy. In the case that the known data is inaccurate, it is important that the fitting function follows the trend of the data, rather than passing through each data point. This procedure is called approximate curve fitting. Among approximate curve fitting methods, the least squares criterion applied to polynomial or trigonometric functions is most frequently used. Other methods such as the minimax criterion may also be employed for some special cases.

In this spinal curvature study, discrete data points are collected with small error and an exact fitting method is the better choice. Usually, there are three methods for exact curve fitting: collocation, osculation and piece-wise curve fitting, (Lindfield and Penny 1989).

Collocation fitting means that "a function is chosen and its coefficients adjusted so that it passes through all the data points", (Lindfield and Penny 1989). In the collocation method, a system of equations is solved to determine the coefficients and ill-conditioning will cause trouble. Furthermore, the chosen function has its own properties and might not match the curve to be fitted. This can be seen in Figure 16.

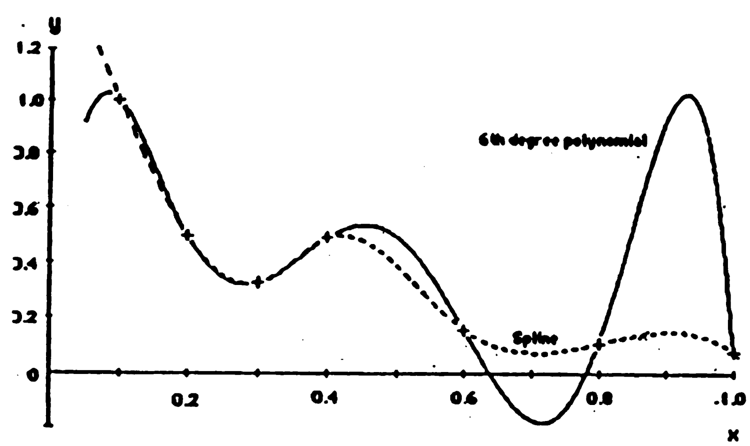


Fig. 16. Cubic spline and 6th degree polynomial passing through fitted the data points. (Lindfield and Penny 1989)

The osculation fitting method is defined such that "a function is chosen and its coefficients adjusted so that it both passes through all the data points and has given values for some of its derivatives", (Lindfield and Penny 1989). This method has advantages when one or more values of the derivatives are known at specific points. Obviously, it is not useful in our spinal curve fitting.

Piece-wise curve fitting means that "a function is chosen and its coefficients are adjusted so that forms of the function fit subgroups of the data", (Lindfield and Penny 1989). Thus the data is represented by a series of different forms of the function in a piece-wise manner rather than by a single function. The most used piece-wise method is the cubic spline. The term "spline" is derived from the name of a device traditionally used by a draftman to join points in drawing a smooth curve. It consists of a steel strip, held in position by weights. Since a steel strip is subject to the laws of elastic deflexion, its shape, between adjacent weights, is a cubic polynomial function. The polynomial functions are different in each interval but at each fixed point there is no discontinuity in slope or curvature. The cubic spline is mathematically generated to mimic this behaviour, (de Boor 1979). Between points (s_i, x_i) and (s_{i+1}, x_{i+1}), the function of cubic spline can be expressed as:

(1-10) $x = a_i + b_i(s-s_i) + c_i(s-s_i)^2 + d_i(s-s_i)^3$;

Let us derive a method to find the coefficients a_i, b_i, c_i, d_i as follows.

If (s_i, x_i) and (s_{i+1}, x_{i+1}) make up the interval, they should satisfy the function:

(1-11) $x_i = a_i$;

(1-12) $x_{i+1} = a_i + b_i h_i + c_i h_i^2 + d_i h_i^3$;

where $h_i = s_{i+1} - s_i$

Since we require the slope and the curvature at the end of each interval match that of its neighbor, we have

(1-13) at $s = s_i$, $\qquad c_i = \dfrac{r_i}{2}$

(1-14) at $s = s_{i+1}$, $\qquad d_i = \dfrac{(r_{i+1} - r_i)}{6h_i}$

where $r_i = \dfrac{d^2 x_i}{ds^2}$, or the curvature at s_i

substituting (1-11), (1-13) and (1-14) into (1-12) leads to

(1-15) $b_i = \frac{(x_{i+1} - x_i)}{h_i} - \frac{h_i(2r_i + r_{i+1})}{6}$;

Now, we have the expressions for the coefficients in terms of r_i, r_{i+1} which can be determined as following.

(1-16) at $s = s_i$ $\qquad x_i' = b_i$;

Considering the previous interval, the subscript i in (1-10) is replaced by (i-1), then

(1-17) $x_i' = b_{i-1} + 2c_{i-1}h_{i-1} + 3d_{i-1}h^2{}_{i-1}$;

where $h_{i-1} = x_i - x_{i-1}$

The requirement that the slopes of the two joining cubics at the point (s_i, x_i) be identical, leads to equating (1-16) and (1-17)

(1-18) $h_{i-1}r_{i-1} + 2(h_i + h_{i-1})r_i + h_i r_{i+1} = 6[\frac{(x_{i+1} - x_i)}{h_i} - \frac{(x_i - x_{i-1})}{h_{i-1}}]$;

where i = 2 , 3, ...,(n-1)

By (1-18), a set of (n-2) equations is formed with unknowns r_i . Two more equations are needed in order to solve it. Assumptions are made at the extreme points, $i = 1$ and $i = n$, that the curvature at these extreme points be zero. It is then only necessary to solve (n-2) equations with (n-2) unknowns. An alternative assumption is to make r_i a linear extrapolation from r_2 and r_3, and r_n a linear extrapolation from r_{n-2} and r_{n-1}. The latter assumption gives:

(1-19) $h_2 r_1 - (h_1 + h_2)r_2 + h_1 r_3 = 0$;

(1-20) $h_{n-1}r_{n-2} - (h_{n-2} + h_{n-1})r_{n-1} + h_{n-2}r_n = 0$;

(1-18), (1-19) and (1-20) make up n equations with n unknowns. The number of equations may be large, but the matrix of coefficients is diagonally dominant and banded, and an iterative method can be used since convergence is guaranteed for diagonally dominant systems, (de Boor 1978).

1.C. The Use of Quintic Spline in Spinal Curve Fitting

Let's differentiate the cubic spline functions (1-10) twice, yielding

(1-21) $x''_{i+1} = 2c_i + 6d_ih_i$;

Obviously, second derivatives of the cubic splines are linear functions. In differential geometry, we need the derivatives to evaluate curvature, principle normal and binormal vectors. These linear relationships give artificial information for the actual smooth changes of the second derivatives of the human spine curve. As a result, we need an exact curve fitting function with first and second order derivaive continuous and smooth. This requirement forces us to raise the order of the polynomial spline functions. "Usually, there is an essential difference between splines of even and odd degree, such as, polynomial splines of even degree interpolating to a prescribed function at mesh points need not exist and yield the expected extension of cubic spline properties must be modified for splines of even degree", (Schumacher 1969). It has been found in practice that there is an advantage in curve fitting using quintic spline instead of the simple cubic spline for smoothing first and second order derivatives, (Schumacher 1969). Quintic splines have been used also in cam design and kinematic design of a cam system, (MacCarthy at al. 1985 and MacCarthy 1988).

The quintic spline function is represented in the form

(1-22) $x(s) = a_i + b_ih + c_ih^2 + d_ih^3 + e_ih^4 + f_ih^5$;

with $h = s - s_i$ for $s_i \le s \le s_{i+1}$

The evaluation of the five coefficients in (1-22) is quite similar to that of cubic spline coefficients in (1-10). The following assumptions have been made:

i) x(s) and its derivatives $x'(s), x''(s), x'''(s), x^{IV}(s)$ are continuous in $s \in [s_1, s_n]$

ii) $x(s_i) = x_i$

iii) $x'''(s_1) = x'''(s_n) = x^{IV}(s_1) = x^{IV}(s_n) = 0$;

which makes the quintic spline to be natural spline.

The resultant system of equations of $r_i (r_i = x^{IV}(s_i))$ is also diagonal dominant and thus unique solutions to this system of equations are guranteed.

Part 2: Differential Geometrical Analysis

2.A. Tangent

A space curve may be specified by a vector-valued function in parametric form:

(2-1) $\vec{r} = \vec{R}(s)$; $s_1 \le s \le s_n$;

where s is the arc length and $\vec{r}$ is the position vector introduced in equation (1-4).

The positive direction along the curve at any point is taken as that corresponding to algebraic increase of s. If $\vec{R}(s)$ is twice differentiable, its derivatives with respect to s will be denoted by $\vec{r}'$, $\vec{r}''$. Let P, Q be the points on the curve whose position vectors are $\vec{r}$, $\vec{r} + \delta\vec{r}$ corresponding to the values s, $s + \delta s$; then $\delta\vec{r}$ is the vector $\overrightarrow{PQ}$, [Figure 17]. The quotient $\delta\vec{r}/\delta s$ is a vector in the same direction as $\delta\vec{r}$; and $\lim_{\delta s \to 0} \frac{\delta\vec{r}}{\delta s}$ becomes tangent at P. Moreover, as shown in previous section, $\lim_{\delta s \to 0} \frac{\delta\vec{r}}{\delta s}$ is a unit vector in the positive tangent direction at P. We denote this by $\hat{t}$ and call it the unit tangent at P. Thus

(2-2) $\hat{t} = \lim_{\delta s \to 0} \frac{\delta\vec{r}}{\delta s} = \frac{d\vec{r}}{ds} = \vec{r}'$

If x, y, z are the Cartesian coordinates with unit vectors $(\hat{i}, \hat{j}, \hat{k})$:

(2-3) $\vec{r} = x\hat{i} + y\hat{j} + z\hat{k}$

and $\hat{t} = \vec{r}' = x'\hat{i} + y'\hat{j} + z'\hat{k}$

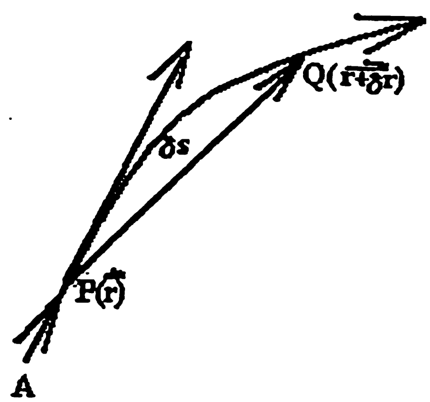


Fig. 17. Interpretation of tangent vector: when $Q \rightarrow P$, $\delta\vec{r}/\delta s \rightarrow \vec{t}$.

2.B. Principle Normal. Curvature. Radius of Curvature

The curvature of a curve at any point is generally defined by the change of the direction of tangent with respect to the changing of arc length, (Willmore 1959, Eisenhart 1960).

Suppose $\delta\theta$ is the angle between the tangents at P and Q (Figure 18), $\delta\theta/\delta s$ is the average curvature of the arc PQ; and its limiting value as δs tends to zero is the curvature at the point P. We shall denote it by k. Thus

$$(2\text{-}4) \quad k = \lim_{\delta s \to 0} \frac{\delta\theta}{\delta s} = \frac{d\theta}{ds} = \theta'$$

Let $\hat{t}$ be the tangent at P and $\hat{t} + \delta\hat{t}$ at Q (Figure 18), if the vectors $\vec{BE}$ and $\vec{BF}$ are respectively equal to these, then $\delta\hat{t}$ is the vector $\vec{EF}$ and $\delta\theta$ the angle EBF. The quotient

$\delta\bar{t}/_{\delta s}$ is a vector parallel to $\delta\hat{t}$, thus as δs tends to zero $\delta\bar{t}/_{\delta s}$ becomes $d\hat{t}/_{ds}$ and is perpendicular to $\hat{t}$ at P. Moreover, since $\vec{BE}$ and $\vec{BF}$ are unit length, then

(2-5) $$\lim_{\delta s\to 0}\frac{\delta\hat{t}}{\delta s}=\frac{d\hat{t}}{ds}=\lim_{\delta s\to 0}\frac{\delta\theta}{\delta s}\hat{n}=k\hat{n}$$

where $\hat{n}$ is a unit vector perpendicular to $\hat{t}$, and in the plane of the tangent at P and a consecutive point. This plane, containing two consecutive tangents and therefore three consecutive points at P is called the osculating plane at P. $\hat{n}$ is called the principle normal at P and always points to the concave side of the curve. From equation (2-5),

(2-6) $$\hat{n}=\frac{d\hat{t}}{ds}\frac{1}{k}=\left(\frac{(d\bar{r}/_{ds})}{ds}\right)\frac{1}{k}=\frac{\bar{r}''}{k}$$

where $\bar{r}''=\dfrac{d^2\bar{r}}{ds^2}$

and the curvature

(2-7) $$k=|\bar{r}''|=\sqrt{x''^2+y''^2+z''^2}$$

The osculating circle lies in the osculating plane and is tangent to the curve at P. Its radius ρ is called the radius of curvature, and its center C, the center of curvature.(Figure 19) Thus

(2-8) $$\frac{1}{\rho}=\frac{d\theta}{ds}=k$$

The center of curvature C lies on the principle normal and the vector $\vec{PC}$ is equal to $\rho\hat{n}$ or $\hat{n}$/k.

2.C. Binormal. Torsion. Frenet Frame

The binormal $\hat{b}$ is defined as the unit normal vector to the osculating plane and forms a right-handed frame with $\hat{t}$ and $\hat{n}$ in the order as $\hat{t}$, $\hat{n}$, $\hat{b}$. We have:

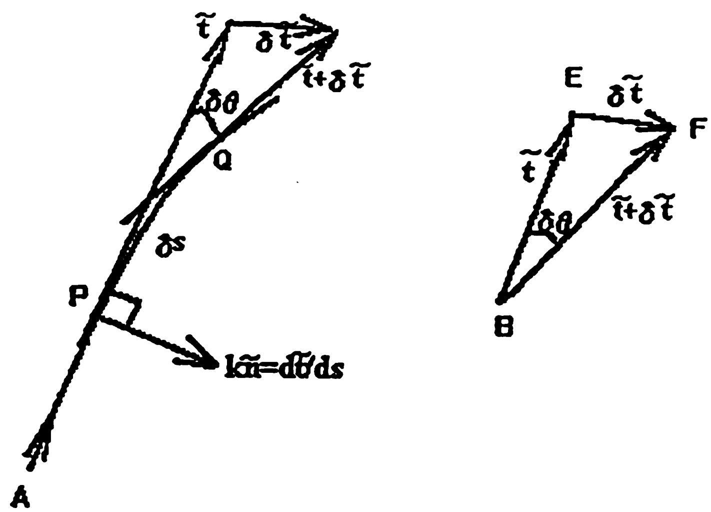


Fig. 18. Interpretation of principle normal vector n and curvature k.

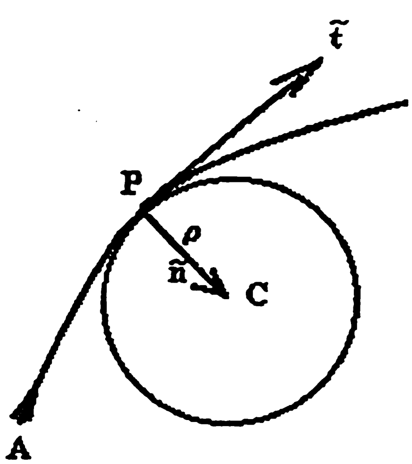


Fig. 19. Radius of Curvature.

(2-10) $\hat{t} \bullet \hat{n} = \hat{n} \bullet \hat{b} = \hat{b} \bullet \hat{t} = 0$

and $\hat{t} \times \hat{n} = \hat{b}$, $\hat{n} \times \hat{b} = \hat{t}$, $\hat{b} \times \hat{t} = \hat{n}$;

If we differentiate the relation $\hat{b} \bullet \hat{t} = 0$, we get:

$$\hat{t}' \bullet \hat{b} + \hat{t} \bullet \hat{b}' = 0$$

i.e. $k\hat{n} \bullet \hat{b} + \hat{t} \bullet \hat{b}' = 0$

i.e. $\hat{t} \bullet \hat{b}' = 0$

i.e. $\hat{b}'$ perpendicular to $\hat{t}$, and $\hat{b}'$ also perpendicular to $\hat{b}$, this means that $\hat{b}'$ should parallel to $\hat{n}$. Let's write this relation in a formulae:

(2-11) $$\frac{d\hat{b}}{ds} = -\tau\hat{n}$$

In equation (2-5), the scalar k measures the change of $\hat{t}$ with respect to the change of arc length, and here τ measures the change of $\hat{b}$ with respect to the change of arc length. τ is called the torsion of the curve at the point P measuring the rotation of the osculating plane. It is interesting to note that a curve lies in a single plane if $\tau = 0$. If we model a space curve as a circular helix, τ is positive when it is right-handed and negative for a left-handed helix. When τ is positve, the curve is also called "sinistrosum" and "dextrosum" if τ is negative, (Eisenhart 1969).

The orthonormal system formed by $\hat{t}$, $\hat{n}$, $\hat{b}$ is known as the Frenet frame at each point on the curve. This frame varies its orientation as s traces out the curve. The vectors $\hat{t}$ and $\hat{n}$ make up the osculating plane, $\hat{n}$ and $\hat{b}$ make up the normal plane and $\hat{b}$ and $\hat{t}$ the so-called rectifying plane. The orientation of each plane can be defined by its normal vector, for example, the orientation of the oscualting plane can be found from its normal vector $\hat{b}$.

When we move the Frenet frame along the curve, it is similar to moving a trihedron with its principle axes determined by $\hat{t}, \hat{n}, \hat{b}$. As the arc changes, the orientation of the trihedron changes with its principle axes keeping the alignment with $\hat{t}, \hat{n}, \hat{b}$.

Part 3: Kinematic Analysis

3.A. The Reference Coordinates

In order to describe the orientation of the spinal column kinematically, a referrence coordinate system is needed. Usually there are three choices of reference to describe the kinematics of spine (White 1979, Stokes 1984): lab or room coordinates, central coordinates and spinal coordinates, [Figure 20]. Lab or room coordinate system [Figure 20a] is the one fixed in space and independant of the subject. The central coordinate system [Figure 20b] is one with origin at the sacrum and the axes aligned with the principle axes of the pelvis. The spinal coordinate system [Figure 20c] also originates at sacrum but with the z direction axis aligned with the line connecting the ends of the spinal curve. In this spinal curvature study, all the raw position data relative to lab coordinates has been transformed into the data relative to the central or pelvis coordinates. The detailed steps are shown as follows:

To get the coordinate system of the pelvis or the reference, the following vector analysis is required, see Figure 21. Left and right ASIS form a vector, called $\vec{RL}$:

(3-1) $\vec{RL} = \vec{P}$(left asis) - $\vec{P}$(right asis) ;

where $\vec{P}$(x) indicates the position vector of target x.

Sacrum and right asis form another vector $\vec{SR}$:

(3-2) $\vec{SR} = \vec{P}$(right asis) - $\vec{P}$(sacrum);

The third vector $\vec{UP}$ is formed by:

(3-3) $\vec{UP} = \vec{SR} \times \vec{RL}$;

If $\vec{RL}$, $\vec{UP}$ are chosen as the two coordinate directions Y_p, Z_p of the pelvis, the unit vectors will be:

(3-4) $\hat{e}_y = \vec{RL}/|\vec{RL}|$;

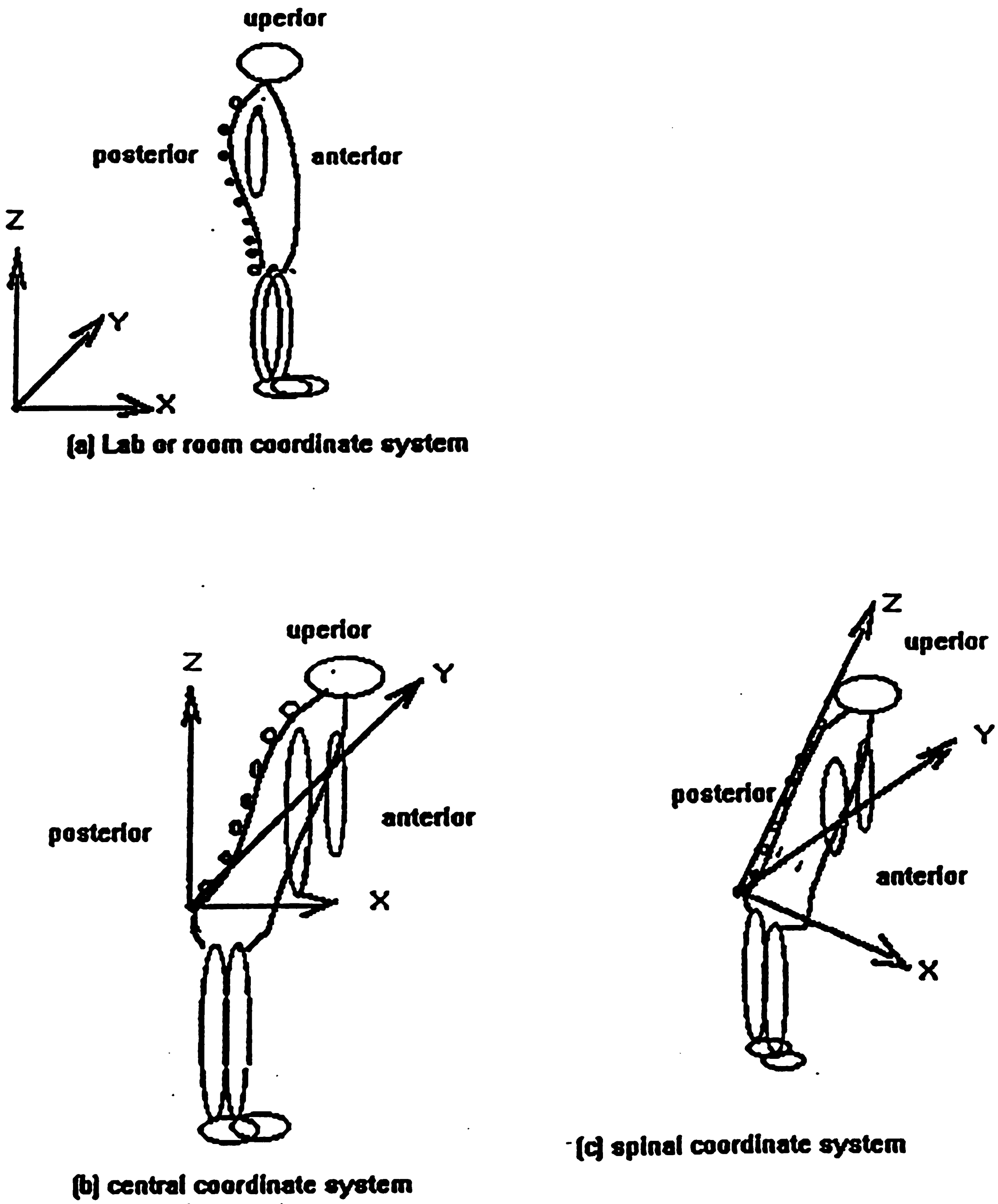


Fig. 20. The possible coordinate systems in describing three-dimensional spinal curvature and mobility.

(3-5) $\hat{e}_z = \vec{UP} / |\vec{UP}|$;

The third coordinate X_p is found by:

(3-6) $\hat{e}_x = \hat{e}_y \times \hat{e}_z$;

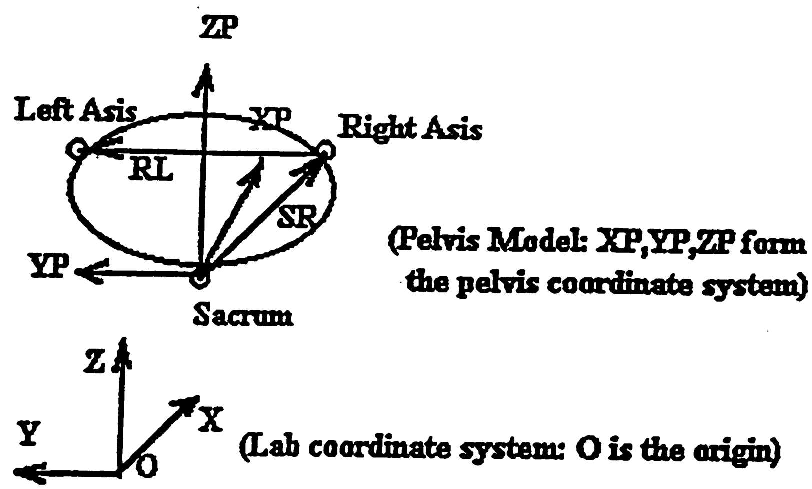


Fig. 21. The construction of pelvis coordinate system.

Thus, X_p, Y_p and Z_p construct a right-handed Cartesian coordinate system and point to the anatomical directions:

X_p: to anatomical anterior direction;

Y_p: to anatomical left side;

Z_p: to anatomical superior.

The sacrum has been chosen as the center of the reference coordinate system, thus a transformation of target position vectors is needed to move all the raw target positions from the lab coordinates to the pelvis system. Two steps accomplish the move:

Step 1: Translation.

(3-7) $\vec{P}_1(x) = \vec{P}(x) - \vec{P}(\text{sacrum})$;

where: $\vec{P}_1(x)$ stands for all the targets new position vector after translation.

Step 2: Rotations.

(3-8) $\vec{P}_2(x) = [A] \cdot \vec{P}_1(x);$

where:

(3-9) $$[A]=\begin{bmatrix} \hat{e}_x(x) & \hat{e}_x(y) & \hat{e}_x(z) \\ \hat{e}_y(x) & \hat{e}_y(y) & \hat{e}_y(z) \\ \hat{e}_z(x) & \hat{e}_z(z) & \hat{e}_z(z) \end{bmatrix}$$

and $e_x(x)$ indicates the x component of unit vector $\hat{e}_x$.

3.B. Kinematic Analysis of Rigid Body Motion

Kinematically, there are six degrees of freedom for a rigid body, three being translational and three rotational. The three translations can be decided by the change of a position vector. In Largrangian mechanics, the three degrees of freedom of rotation are three independent generalized coordinates, which are most common parametrized by Euler angles, (Greenwood 1989).

Euler's angles are the traditional way to analyze three-dimensional rigid body motion. However, it has been found that, for clinical usage, this description of human motion is not easily understood by clinicians. Grood and Suntay (1983) provided a way to describe three-dimensional knee joint motion in a manner which "faciliates the communication between biomechanician and physician". "Considering the angular position and the corresponding rotational motion between two arbitrary bodies, three spatial axes about which the corresponding rotational motions occur can be specified in order to decide the angular position in three dimensions". A "nonorthogonal joint coordinate system" is formed with unit base vectors of this coordinate system denoted as $\hat{e}_1$, $\hat{e}_2$, $\hat{e}_3$. Two of the axes are called body fixed axes since they are embedded seperately in the two bodies whose relative motion is to be described. Their direction is specified by unit base vector $\hat{e}_1$ in body A, and $\hat{e}_3$ in body B. The third axis $\hat{e}_2$ is the common perpendicular to the body fixed axes, its orientation is given by

$$\text{(3-10)} \quad \hat{e}_2 = \frac{\hat{e}_3 \times \hat{e}_1}{|\hat{e}_3 \times \hat{e}_1|}$$

Because of the different nature of $\hat{e}_2$ from body fixed axes $\hat{e}_1$ and $\hat{e}_3$, $\hat{e}_2$ is called the floating axis. This floating axis is equivalent to Euler's "line of nodes".

In this spinal curvature study, a "joint coordinate system" has been used in the description of several types of movements: the orientation of thoracic cage relative to pelvis, the gross motion of the cervical spine, the gross motion of the whole thoracic spine, the gross motion of the whole lumbar spine, the orientation of each point on the spinal curve relative to pelvis and other adjunct analysis. In each of these analyses the relative movement between two rigid bodies were calculated and a joint coordinate system was formed as follows:

In Figure 22, xyz is the coordinate system of rigid body A and XYZ is the coordinate system of rigid body B with:

$\hat{X}$, $\hat{x}$: positive to the anterior direction;

$\hat{Y}$, $\hat{y}$: positive to the left side;

$\hat{Z}$, $\hat{z}$: positive to the superior direction.

$\hat{X}$ is chosen from A as one of the two fixed axes and noted as $\hat{e}_1$, $\hat{z}$ is chosen from B as the other fixed axis and noted as $\hat{e}_3$. The floating axis $\hat{e}_2$ is found from a cross product:

(3-11) $\hat{e}_2 = \dfrac{\hat{z} \times \hat{X}}{\left|\hat{z} \times \hat{X}\right|}$

In this "joint" coordinate system, $\hat{e}_2$ is the axis about which flexion-extension occurs (we call $\hat{e}_2$ as the flexion/extension axis), $\hat{e}_3$ is the rotational axis and $\hat{e}_1$ is responsible for side bending. Let's define:

ϕ: flexion-extension angle (flexion +);

θ: rotaional angle (to right +);

φ: lateral side bending angle (to right +).

Then:

(3-12) $\hat{e}_2 \bullet \hat{Z} = \cos(90 + \varphi) \Rightarrow \varphi = -\operatorname{asin}(\hat{e}_2 \bullet \hat{Z})$;

(3-13) $\hat{e}_2 \bullet \hat{x} = \cos(90 + \theta) \Rightarrow \theta = -\operatorname{asin}(\hat{e}_2 \bullet \hat{x})$;

(3-14) $\hat{e}_3 \bullet \hat{e}_1 = \cos(90 - \phi) \Rightarrow \phi = \operatorname{asin}(\hat{e}_3 \bullet \hat{e}_1)$;

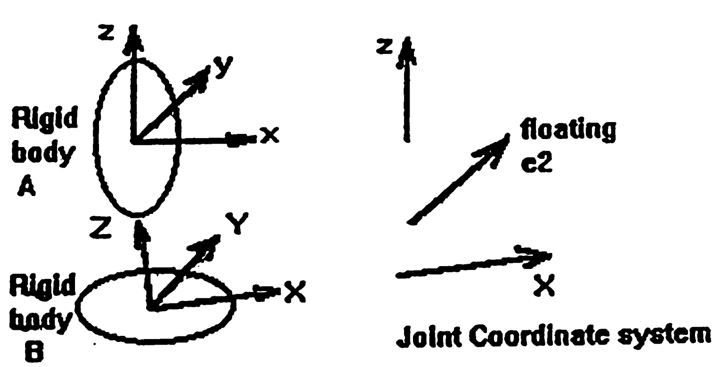


Fig.22 : Joint Coordinate System Formation

3.B.1) To calculate the movement of thoracic cage relative to pelvis. Three targets have been placed on the surface points over bony landmarks of the thoracic cage at sternal notch (D), xyphoid (E) and T1 spinal process (F), [Figure 23]. The position vectors of these points were used to form the thoracic coordinate system. Then:

(3-15) $\vec{DE} = \vec{P}(D) - \vec{P}(E)$

(3-16) $\vec{FD} = \vec{P}(F) - \vec{P}(D)$

The vectors $\vec{DE}$ and $\vec{FD}$ form the sagittal plane of the thoracic cage, and the normal vector points to the side:

(3-17) $\hat{Y}(T) = (\vec{FD} \times \vec{DE}) / | \vec{FD} \times \vec{DE} |$

and (3-18) $\hat{Z}(T) = \vec{DE} / | \vec{DE} |$

therefore (3-19) $\hat{X}(T) = \hat{Y}(T) \times \hat{Z}(T)$

$\hat{X}(T)$, $\hat{Y}(T)$ and $\hat{Z}(T)$ are the unit vectors of the coordinate system of the thoracic cage. To calculate the orientation, this system has been treated as that of rigid body A and the reference system (the pelvis) has been treated as that of rigid body B, a "joint coordinate system" has been formed as mentioned before.

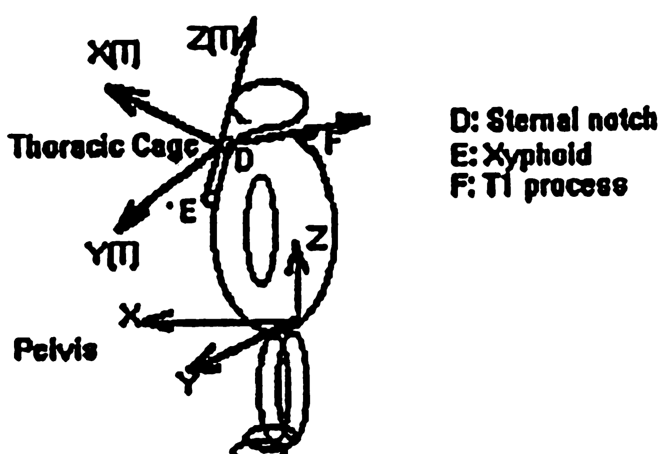


Fig.23 : Thoracic Cage Motion Calculation

3.B.2) To calculate the gross motion of the cervical spine[Figure 24], the gross motion of the cervical spine actually can be expressed by the relative orientation of head to thoracic cage, therefore head and thoracic cage were modeled as the rigid bodies A and B. Three targets were put on the head locating at the right and left temple and the forehead, such that the targets formed a anatomical transverse plane.

(3-20) $\hat{Y}(\mathrm{H}) = \vec{MN} / |\vec{MN}|$

(3-21) $\hat{Z}(\mathrm{H}) = (\vec{ON} \times \vec{MN}) / |\vec{ON} \times \vec{MN}|$

and (3-22) $\hat{X}(\mathrm{H}) = \hat{Y}(\mathrm{H}) \times \hat{Z}(\mathrm{H})$

$\hat{X}(\mathrm{H})$, $\hat{Y}(\mathrm{H})$ and $\hat{Z}(\mathrm{H})$ are the unit vectors of the coordinate system of head and $\hat{X}(\mathrm{T})$, $\hat{Y}(\mathrm{T})$ and $\hat{Z}(\mathrm{T})$ are those of the thoracic cage. A "joint coordinate system" has been formed between the two bodies and the gross motion of the cervical spine was calculated, (Soutas-Little and Cao 1993).

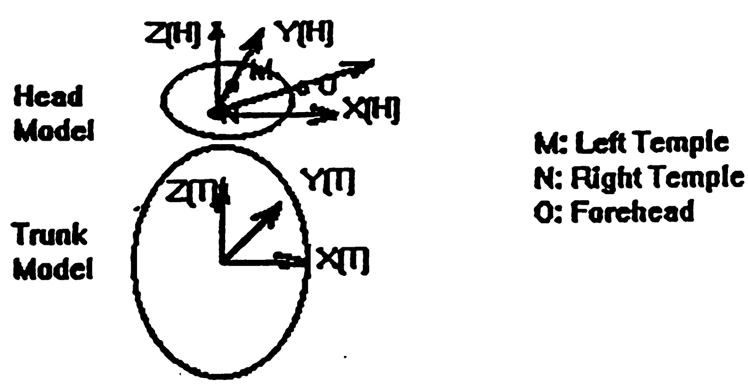


Figure 25 Cervical Spine Motion Measurement Targetting

3.B.3) To calculate the gross motion of the thoracic spine, the rigid body A was chosen as the thoracic cage formed by T1, sternal notch, and xyphoid process and B as the lower thoracic body formed by T10, T12, and xyphoid process. Targets were putted on these bony locations. [Figure 25]

(3-23) $\hat{Z}(BT) = \vec{HI} / |\vec{HI}|$

(3-24) $\hat{Y}(BT) = (\vec{HE} \times \vec{HI}) / |\vec{HE} \times \vec{HI}|$

and (3-25) $\hat{X}(BT) = \hat{Y}(BT) \times \hat{Z}(BT)$

where: $\hat{X}(BT)$, $\hat{Y}(BT)$ and $\hat{Z}(BT)$ are the unit vectors of lower thoracic rigid body B. A "joint coordinate system" has been constructed between the thoracic cage and lower thoracic body and the gross motion of the thoracic spine has been calculated.

3.B.4) To calculate the gross motion of the lumbar spine, similar to the procedures of 3.B.2), the upper body was chosen as the lower body of the thoracic spine and the lower body was chosen as the pelvis. Therefore, $\hat{X}(BT)$, $\hat{Y}(BT)$ and $\hat{Z}(BT)$ are the unit vectors of the rigid body A and $\hat{X}$, $\hat{Y}$ and $\hat{Z}$ are the unit vectors of rigid body B. A "joint coordinate system" has been constructed between the two bodies and the gross motion of the lumbar spine has been calculated.

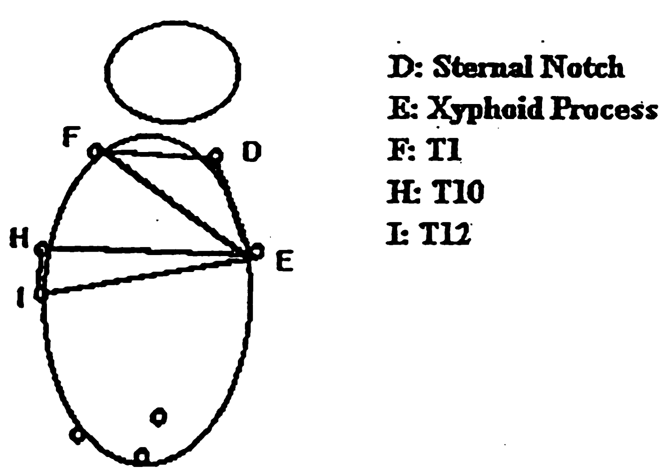


Figure 25: Thoracic Spine Movement Measurement Targetting

3.B.5) To calcualate the orientation of each point on the spinal curve, the spinal curve can be thought as the path of the movement of a trihedron. The orientation of this trihedron on the spinal curve has been related to the anatomical orientation of the trunk. As shown in Figure 26 , one more target has been placed on each of the spinal processes than was targetted originally. The upper targets and the base targets were fitted by quintic splines seperately, and two curves were constructed, [Figure 26a]. Between two adjacent targets on the same curve, ten small segments were made with equal length as shown by Figure 26b.

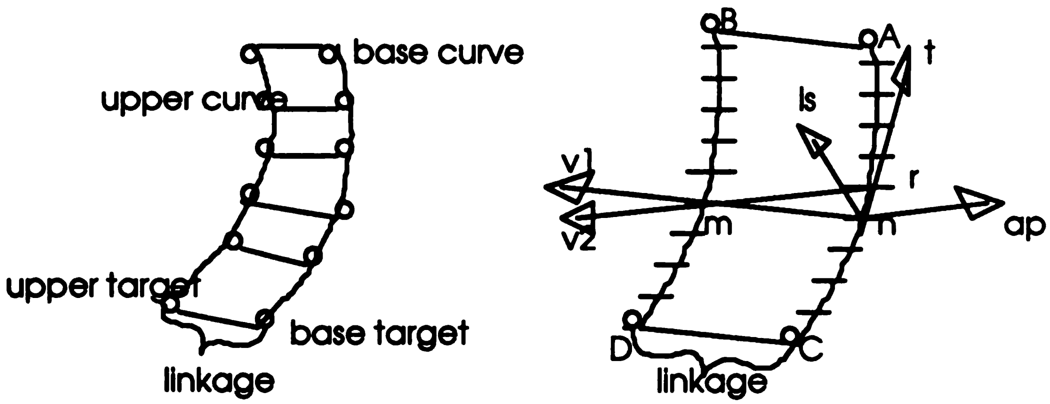


Fig. 26. The coordinate system ($\hat{ap}$, $\hat{ls}$, $\hat{t}$) of the trihedron construction based on points on the base and up curves.

Points r and n are adjacent on the base curve and m is the point on the upper curve with the same count from D as that of n from C. $\hat{t}$ is the tangential unit vector of the base curve at n, $\vec{v1}$ and $\vec{v2}$ are formed by m,n and r. A unit vector $\hat{ls}$ is formed as follows:

(3-26) $\hat{ls} = \vec{v1} \times \vec{v2} / |\vec{v1} \times \vec{v2}|$;

where $\hat{ls}$ points anatomical lateral side;

The $\hat{ap}$ unit vector is calculated by a cross product:

(3-27) $\hat{ap} = \hat{ls} \times \hat{t}$;

where $\hat{ap}$ points anatomical anterior;

The three unit vectors $\hat{ap}$, $\hat{ls}$, and $\hat{t}$ construct a right-handed coordinate system of the trihedron at each point on the spinal curve. The trihedron is treated as rigid body A and the pelvis as B, and a "joint coordinate system" is constructed between the two bodies and the orientation of each point on the spinal curve can be calculated.

Experimental Methods

1. Apparatus and Working Space Calibration

The spinal curvature study obtained position and motion data using a motion analysis system made by Motion Analysis Cooperation. Four video cameras with 60 Hz sampling frequency were used to take the images made up by pixels of reflective targets in a calibrated space. The three-dimensional centroid location of each target was determined based on at least two different camera images with more than 3 pixels of each by using the Expertvision Three-dimensional (EV3D) digitizing program. Each target's location was expressed in the lab coordinate system with its position vector:

$$\vec{P} = x\hat{i} + y\hat{j} + z\hat{k}$$

where $\hat{i}$, $\hat{j}$, $\hat{k}$ are the base unit vectors of the lab coordinates.

The calibrating of the working space was performed in the following procedures:

1) Choose the best space volume for the study. The smaller the space volume , the more accurate the position vectors will be. For this study, the volume was chosen as 1×1×0.8 m, where the last number indicates the height of the volume, [Figure 27].

2) Sixteen control points (targets), four on each standing structure, were place on the boundaries of the chosen volume. The positions of those points were decided for calibration, as shown in Figure 27.

3) Position the cameras such that each could see all the points and had the closest view.

5) Calibrate each control point position to match up the designed coordinates.

6) Run data acquization and calibration programs to get calibration results.

The residual number was reported for each camera and the closer the residuals for the cameras, the more accurate the calibration. For all the tests in this study, the residual values were within 0.13 apart and less than 0.35, which fitted the system requirements of residual values of less than 2.0.

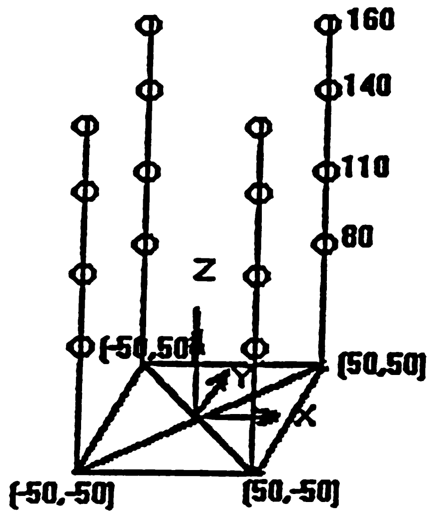


Figure 27 Calibration space and control points.

2. Experimental Preparation

In this study, the targets located on the spinal processes were target linkages. Two small targets were rigidly connected by a rigid light bar on the ends, see Figure 28a. To calibrate the linkage for our purpose, it was mounted on a level table surface and adjusted to make the bar perpendicular to the table, see Figure 28b. To calibrate the linkages to be used as a system, they were mounted on the table again and the bars were adjusted such that they were parallel to each other and perpendicular to the table, see Figure 28c.

The subject used for the test was a young male with normal spinal condition. The purpose of the research was explained and a signed informed consent obtained, (IRB #89-559)

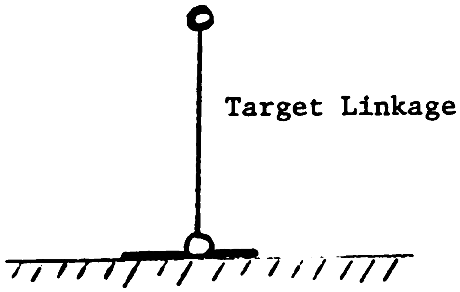


Figure 28 a)

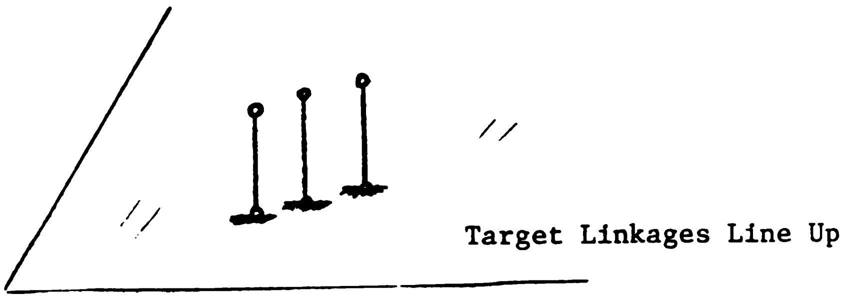


Figure 28 b)

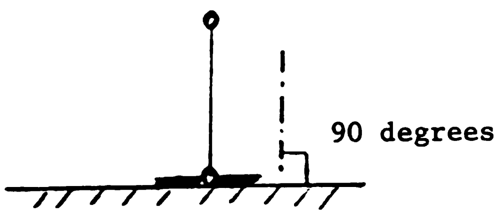


Figure 28 c)

Two targets were mounted at the left and right ASIS and another two at the sternal notch and the xyphoid. The linkages were mounted on the spinal processes such that the bars were perpendicular locally to the skin surface. The bony process levels chosen were S1, L5, L3, L1, T11, T9, T7, T5, T3, and T1.

3. Testing Procedures and Data Analysis

During testing, the subject was located in the calibrated space. Four static conditions were chosen for spinal curvature analysis: standing erect, standing with maximum right side bending and standing with forward flexion, and standing with right rotation. Four seconds of data were collected for each condition or each trial. Three dynamic conditions were chosen for spinal kinematics analysis: bending, flexing, and axial rotation. After tracking the target images, the position of each target was obtained in the lab coordinates. All the data was smoothed once by EV3D programs. The position data of each target of each frame was then combined in a position file.

The data analysis was performed using a SUN4/260C workstation. The program, created by this author, for spinal curvature analysis accomplishes these steps of analysis:

a) transforming all the position data from the lab coordinate system into the pelvis coordinate system;

b) curve fitting by quintic splines for the targets on the spinal processes and upper;

c) differential geometrical analysis for the base spinal curve;

d) calculating the orientation of each point on the spinal curve relative to pelvis.

Another program, created by this author, for spinal kinematics analysis, performs the followings analysis:

a) calculation of the movement of the thoracic cage relative to pelvis;

b) calculation of the gross motion of the thoracic spine;

c) calculation of the gross motion of the lumbar spine;

Results and Discussion

Spinal Kinematics Analysis

1. The Movement of Thoracic Cage Relative to Pelvis

Because of the structure of the thoracic cage, it can be easily modeled as a rigid body. Also because the thoracic spine is less mobile than lumbar spine, it is possible to use the movement of thoracic cage relative to pelvis to approximate the gross motion of the lumbar spine. Figure 29 shows the time history of the three-dimensional angles of the subject performing three different voluntary movements.

Figure 29a is three directional angle time historys for voluntary flexion/extension movement,. The flexion(+)/extension(-) angle started at -10 degrees, which indicates the thoracic cage tilted 10 degrees backward for the starting posture. The subject forward flexed first to about 55 degrees, then backward extension to about -35 degrees. Bending and rotating angles remained approximately unchanged throughout the movement.

Figure 29b is of voluntary side-to-side bending movement. The side-to-side bending angle started at almost 0 degree, bending to left first to about -45 degrees, then to right to about 45 degrees. It shows the symmetry for the subject in side-to-side bending movement. The remaining two angles, flexing and rotating, remained nearly unchanged throughout the movement.

Figure 29c is of voluntary axial rotation movement. The rotation angle started close to 0 degree, rotating to right first to about 40 degrees, then to left to about -40 degrees. It shows the symmetry for the subject in axial rotating movement. The flexing

Figure 29: Thoracic cage motion relative to pelvis: three different conditions

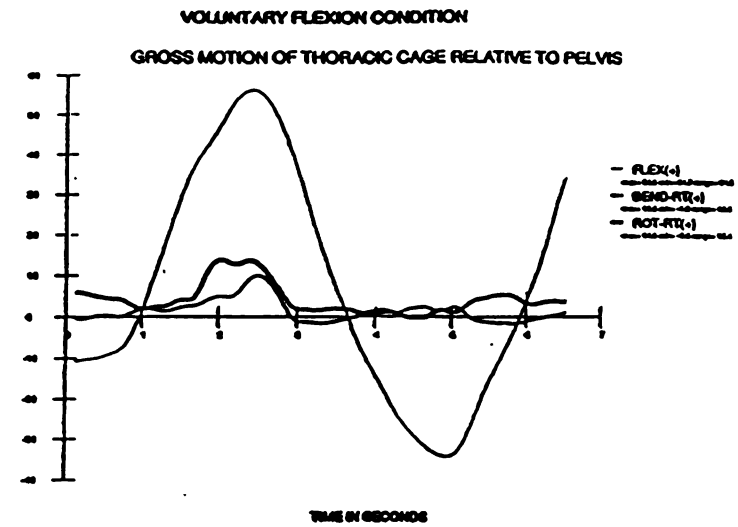


Figure29 a)

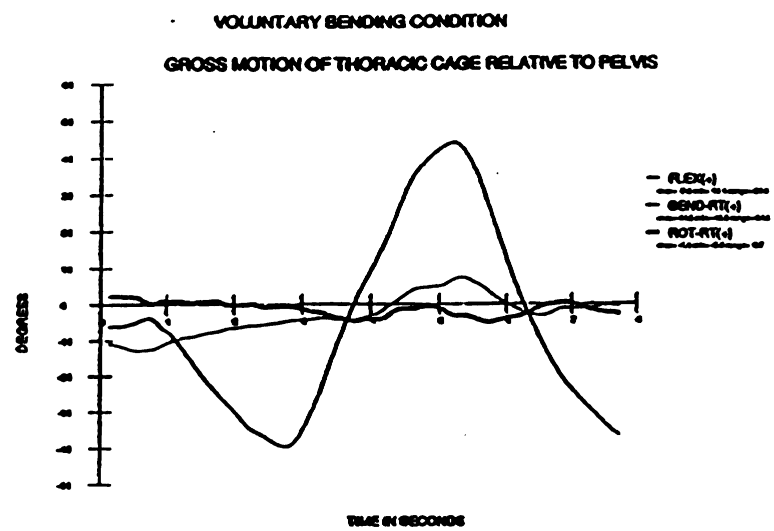


Figure29 b)

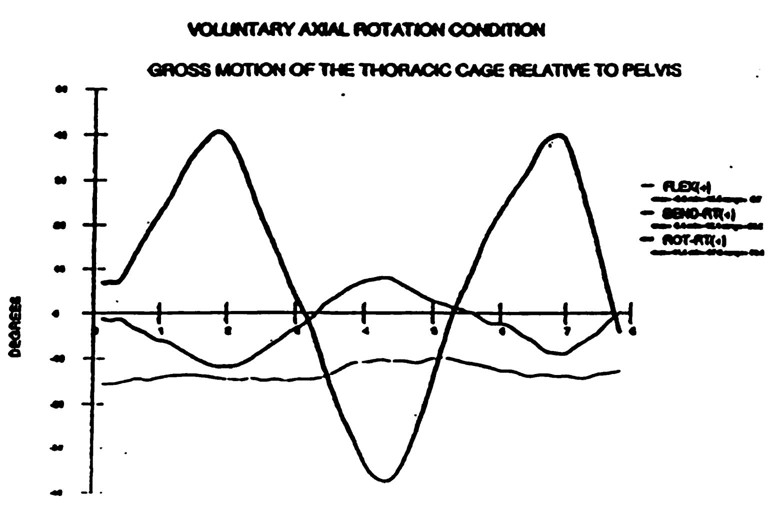


Figure29 c)

angle remained unchanged throughout the movement. However, the bending angle varied with the rotating angle in a way that always went to the opposite direction. This is the well known spinal movement coupling. The ratio of the two angles, primary movement and coupled movement (here is rotating and bending), is called the coupling ratio. Here the coupling ratio is about (4 degrees rotating) : (-1 degrees bending). The minus sign indicates the coupled movement goes to the opposite direction of the primary movement.

2. The Gross Motion of the Thoracic Spine and the Gross Motion of the Lumbar Spine

Even though the thoracic spine movement is restricted by ribs, the ribs themselves are deformable and the lower part of thoracic spine is free of these restriction. Therefore the movement of thoracic cage combines the movements from both lumbar and thoracic spine, with the thoracic spine contributing less. It is possible to separate these two parts by different rigid body modeling. Figure 30 and 31 show the time history of the three angles for the lumbar spine and thoracic spine during the three voluntary movements.

Figure 30a is the gross motion of the lumbar spine during voluntary flexion/extension movement. The flexing/extension angle started at -10 degrees, which meant the initial posture for lumbar spine was -10 degrees lordotic, forward flexing first to about 40 degrees, then backward extending to about -30 degrees. These numbers show a large mobility of the lumbar spine for the subject. The other two angles, bending and rotating, were nearly unchanged throughout the movement.

Figure 30b is the gross motion of the lumbar spine during side-to-side bending movement. The side-to-side bending angle started at about 0 degree, bending to left first to about -25 degrees,

Figure 30: Thoracic spine motion: three different conditions

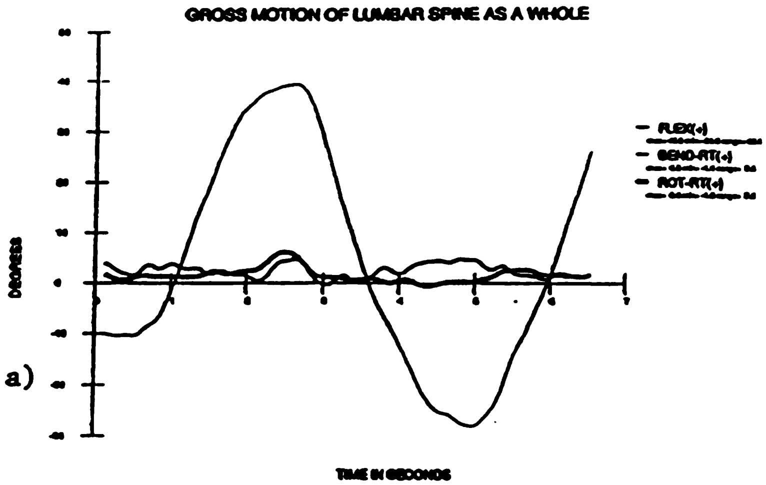


Figure30 a)

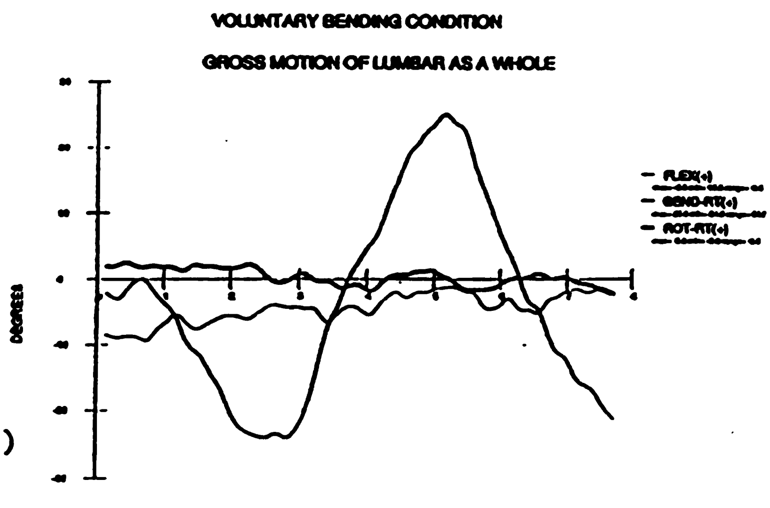


Figure30 b)

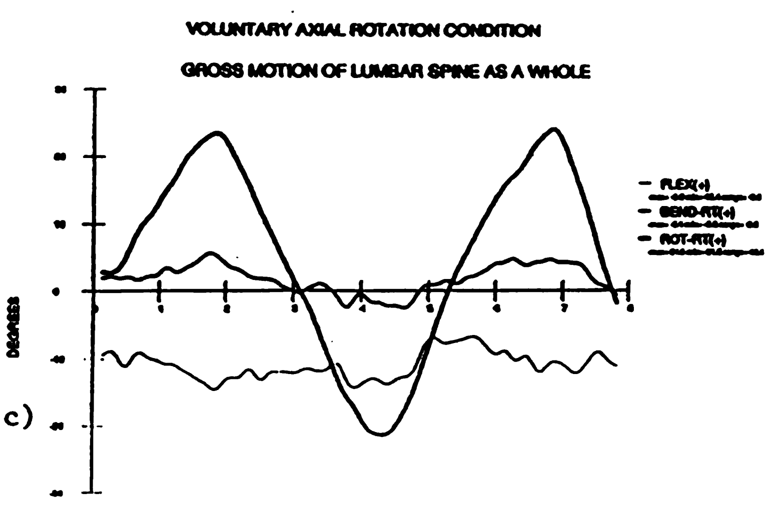


Figure 30 c)

then to right to about 25 degrees. It shows the symmetry of the subject performing side-to-to bending. The other two angles, flexing and rotating, remained almost unchanged.

Figure 30c is the gross motion of the lumbar spine during axial rotating movement. The rotating angle started at 0 degrees, rotating to right first to about 20 degrees, then to left to about -20 degrees. The flexing angle remained unchanged, but the bending angle showed a slight variation. When rotating to one side, the lumbar spine bent to the same direction. This is the coupling characteristics of lumbar spine which has been discussed by many researchers (White and Panjabi 1979). The coupling ratio here is about (6 degrees rotation) : (1 degrees bending), which also matches with other researcher's, (Pearcy 1985).

Figure 31a is the gross motion of the thoracic spine as a whole during flexing/extension movement. The flexing/extension angle started at 0 degrees, forward flexing first to about 18 degrees, then backward extension to about -8 degrees. Comparing this result with that of lumbar spine, the thoracic spine showed a more restricted mobility in the sagittal plane. The other two angles, bending and rotating, remained almost unchanged throughout the movement.

Figure 31b is the gross motion of the thoracic spine side-to-side bending movement. The bending angle started at 0 degree, bending to left first to about -20 degrees, then to right to about 20 degrees. These numbers showed a large mobility of thoracic spine in the side-to-side bending movement, and also a symmetry in the two directions. The other angles, flexing and rotating remained predominantly unchanged.

Figure 31c is the gross motion of the thoracic spine axial rotating movement. The rotating angle started at almost 0 degree, rotating to right first to about 18 degrees, then to left to about -18 degrees. The flexing angle again remained mostly unchanged. There

Figure 31: Lumbar spine motion: three different conditions

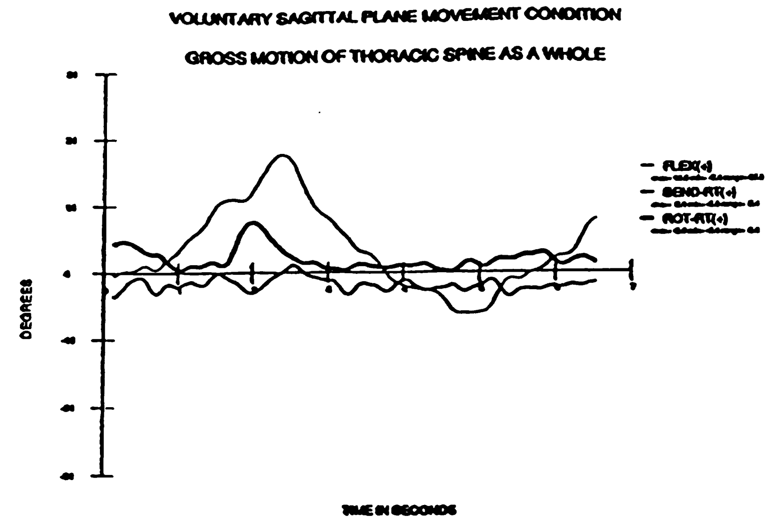


Figure31 a)

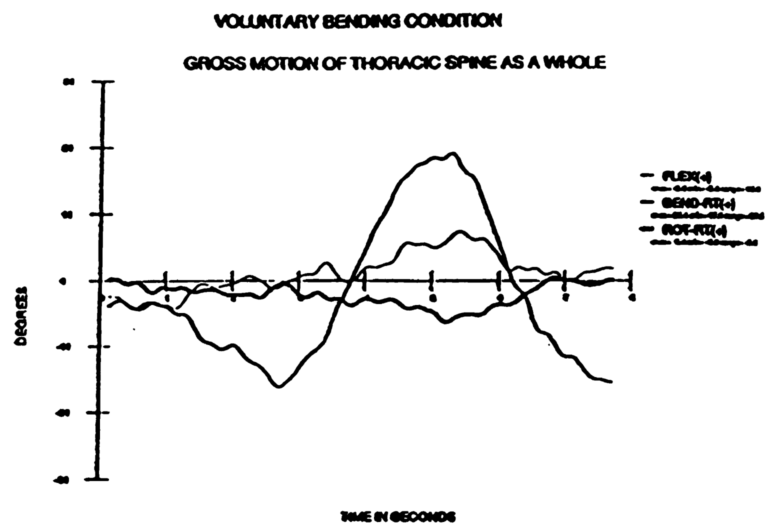


Figure31 b)

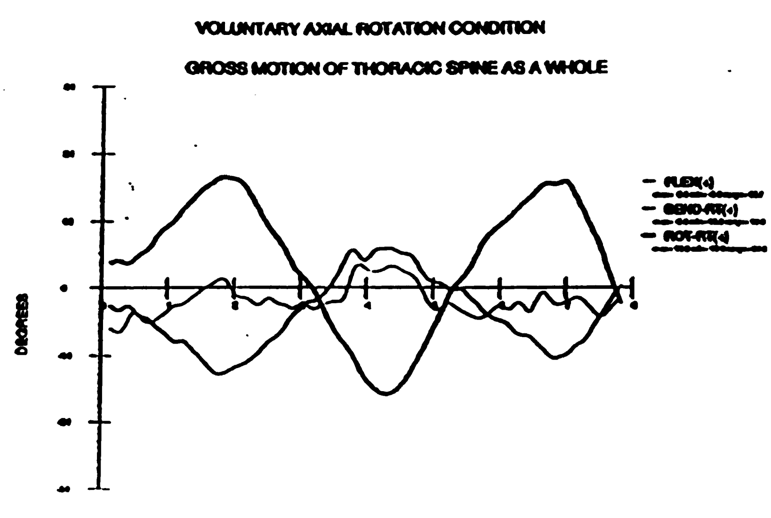


Figure31 c)

was a strong coupling between rotating and bending for this movement, the coupling ratio was (2 degrees rotating) : (-1 degree bending).

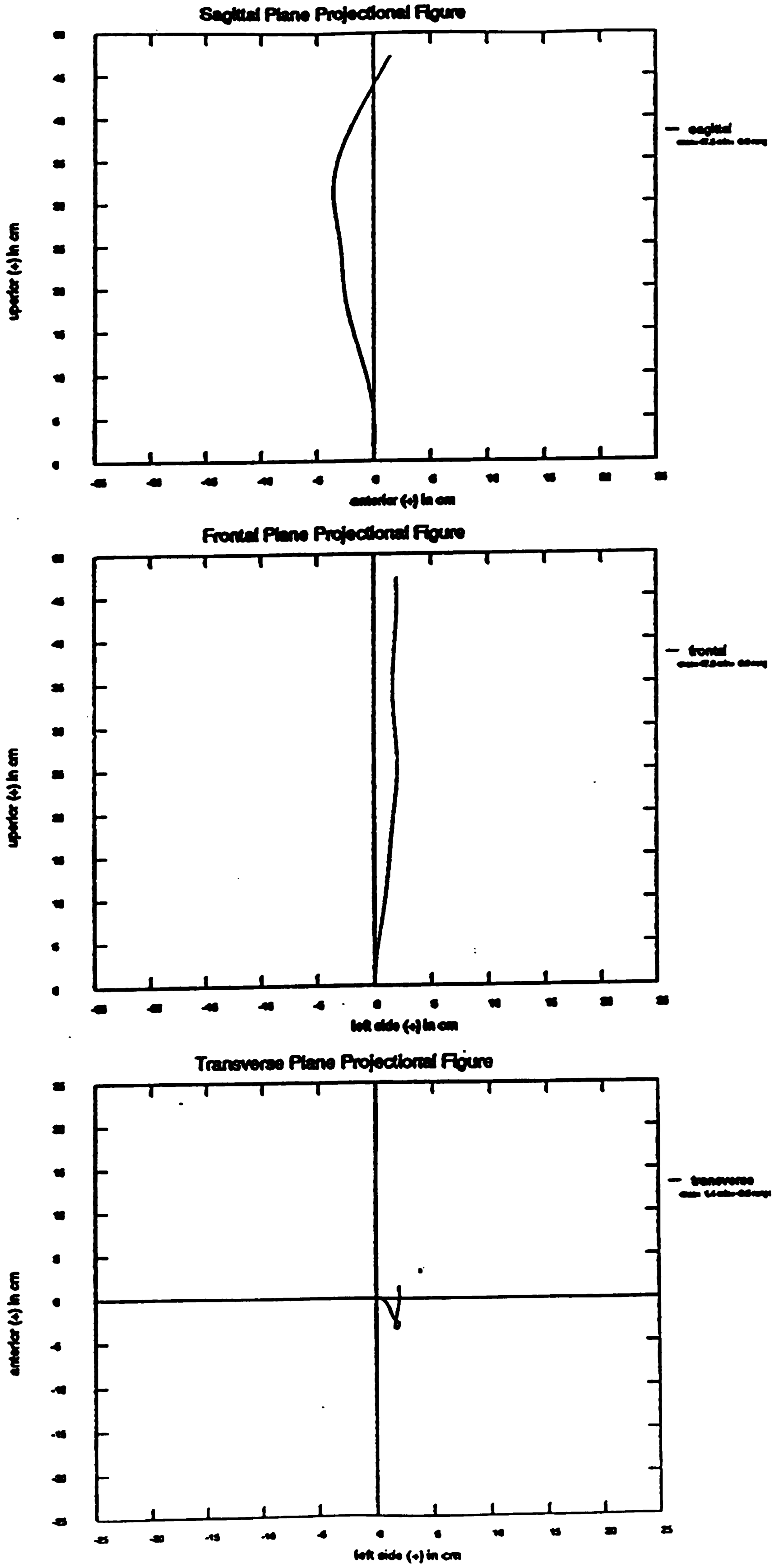
Spinal Curvature Analysis

1. The Projection Figures of the Spinal Curve

As mentioned previously, the targets on and above the spinal processes have been fitted by quintic spline functions to get a base curve and upper curve. The base curve was the actual spinal curve which joined the spinal processes. It is possible to view this curve from different view points. In this study, this spinal curve has been projected onto three orthogonal planes: sagittal, frontal and transverse which were formed by pelvis coordinates **X & Z, Y & Z** and **X & Y** respectively. Figure 32 to 35 are the projections for each of the three trials of the primary movement conditions.

Figure 32 is the projections of the curve of standing erect condition. Based on the sagittal plane view, the thoracic kyphosis and lumbar lordosis can be identified. Since the current measurement technique is a noninvasive, external measurement method, the thoracic kyphosis and lumbar lordosis can not be compared directly with either radiography or other noninvasive methods. For better use of these projections and other methods in this study, a normative standard data base should be set up. Based on the frontal plane view, it is possible to identify the testing subject's scoliotic condition. The transverse view provided us a clear impression of the excursions in side-to-side and anterior/posterior directions of the spinal curve. Also, the area occupied by the spinal curve in this projection can serve as another spinal deformity criterion, the larger the area, the more deformity of the whole spinal column.

Figure 32: Spinal column projected on pelvis coordinate planes: standing condition



The reason for plotting the three projections is that different possible spinal deformities can be represented. Figure 33 is the projections of the curve for rotating to right condition. Comparing these projection with those of standing condition, the sagittal plane and frontal plane views are very similar to those of standing condition, but they shows a little backward tilt of thoracic spine in the sagittal plane projection. The transverse view provided us clear information that a rotating of upper trunk occured by comparing it with that projection of standing condition. Figure 34 is the projections for bending to right. The sagittal plane view remains similar to that of standing condition, but the frontal and transverse views both show a large excursion of the spinal curve to the right side. Figure 35 is the projections for flexing forward. The frontal plane view remains similar to that of standing condition, but the sagittal and transverse views both show large excursions of the spinal curve to the anterior direction.

2. The Orientation of Each Point on the Spinal Curve Relative to Pelvis

The spinal curve can be treated as the path of moving trihedron whose principle axes align with the anatomical axes of the trunk, therefore each point on the spinal curve has a local orientational coordinates. A "joint coordinate system" has been formed between the coordinates of each point and the pelvis, and the orientation of the trunk was calculated everywhere on the curve relative with pelvis. To test the reproducibility of the experiment, all the trials of each condition have been plotted together in one plot for the angles, see Figure (36) to (39). To test the functions of different primary movements, one average trial of each condition has been chosen and plotted in Figure (40).

Throughout all the trials, there was good reproducibility for each condition. For the standing condition the thoracic kyphotic angle was 35 degrees and lumbar lordotic angle was only 15 degrees. This result is different from most of the X-ray results.

Figure 33: Spinal column projected on pelvis coordinate planes: rotation condition

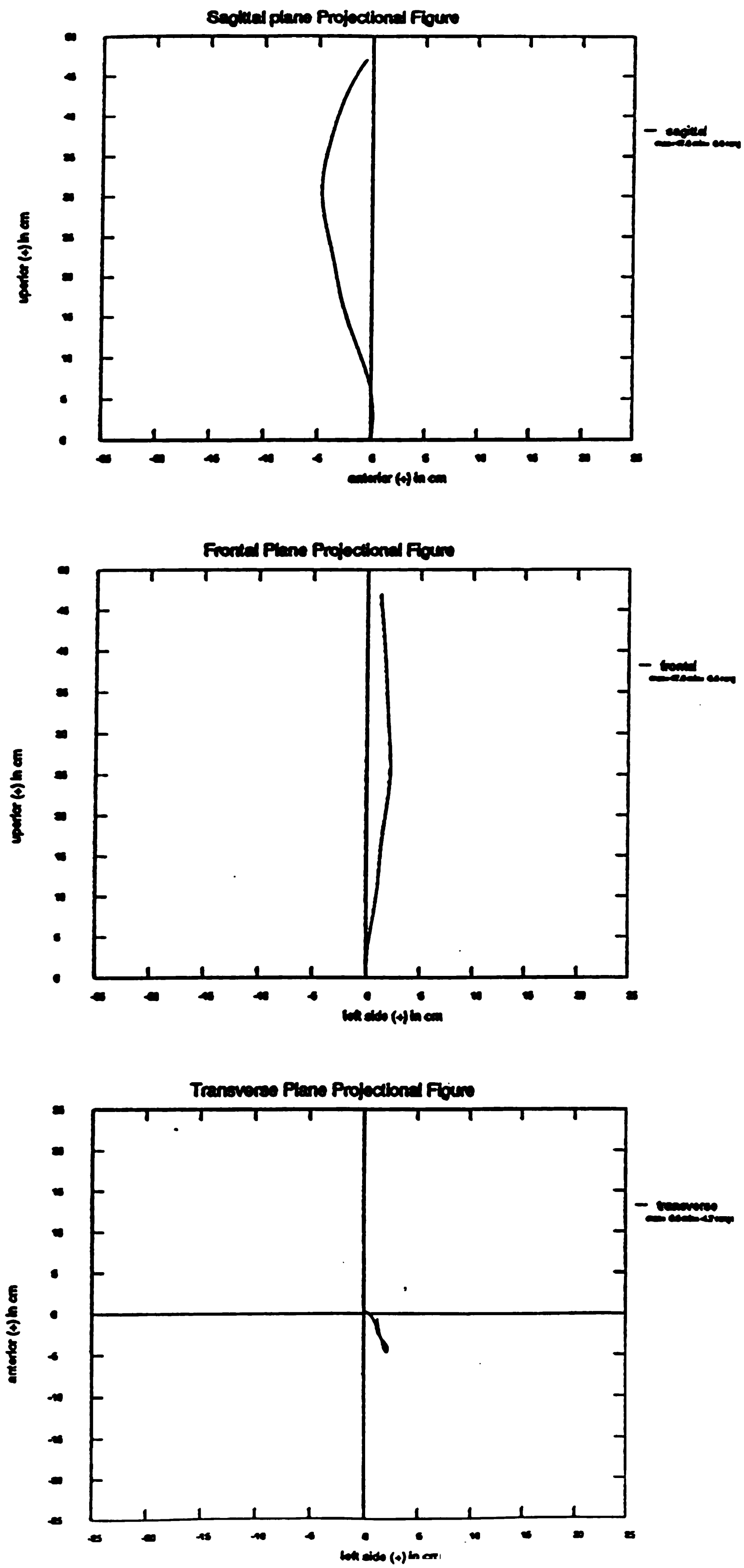


Figure 34: Spinal column projected on pelvis coordinate planes: bending condition

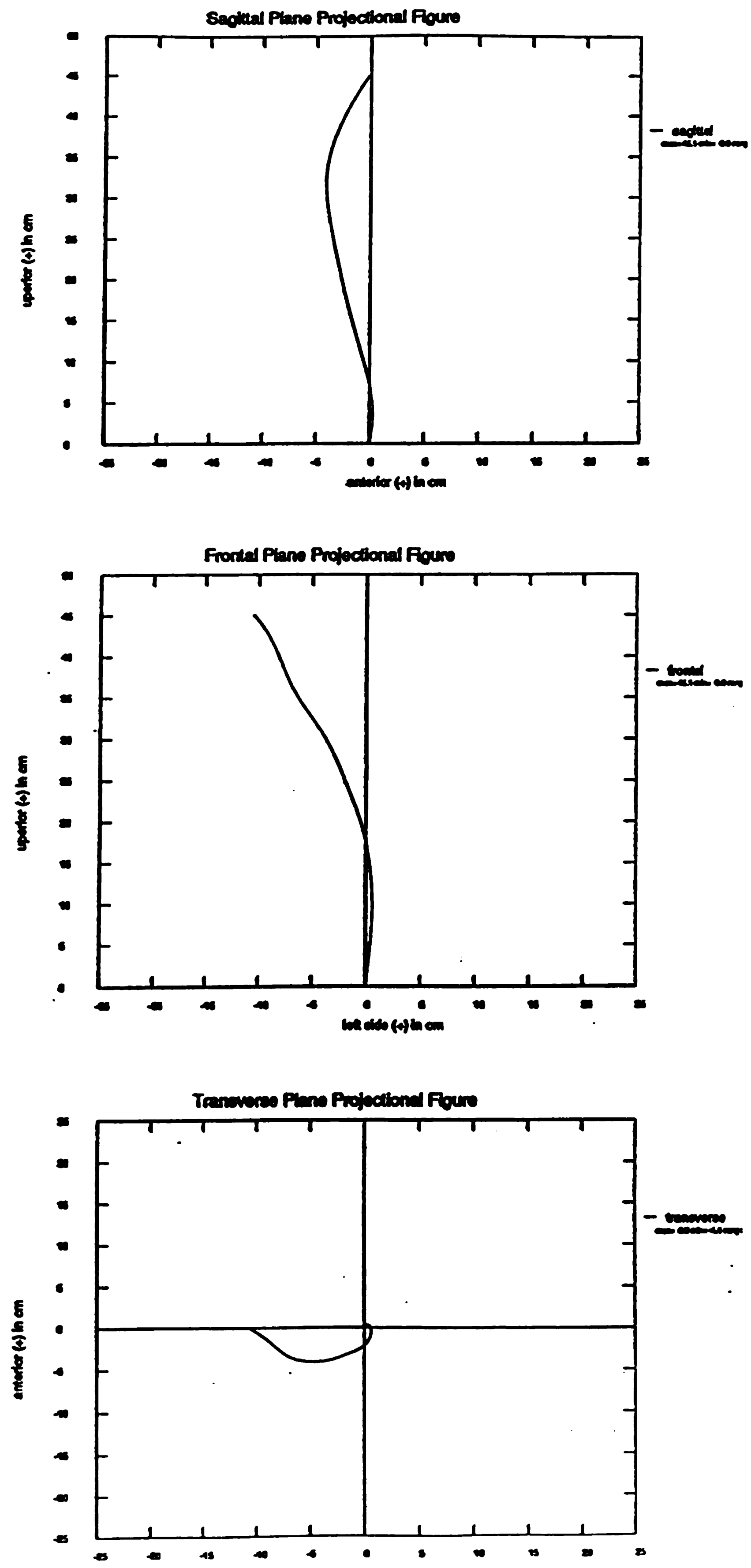


Figure 35: Spinal column projected on pelvis coordinate planes: flexing condition

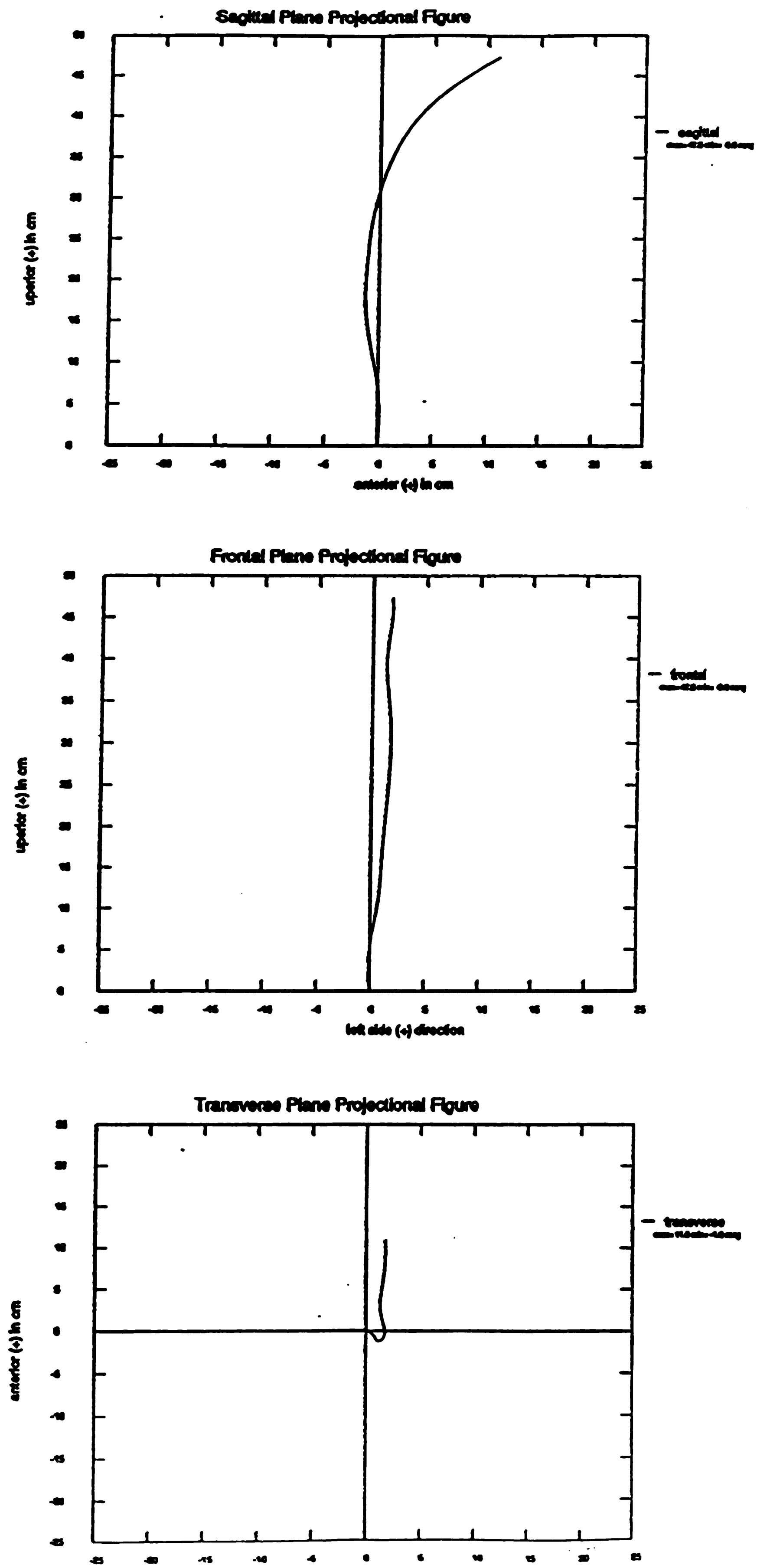


Figure 36: Three-dimensional orientation of each point relative to pelvis: standing

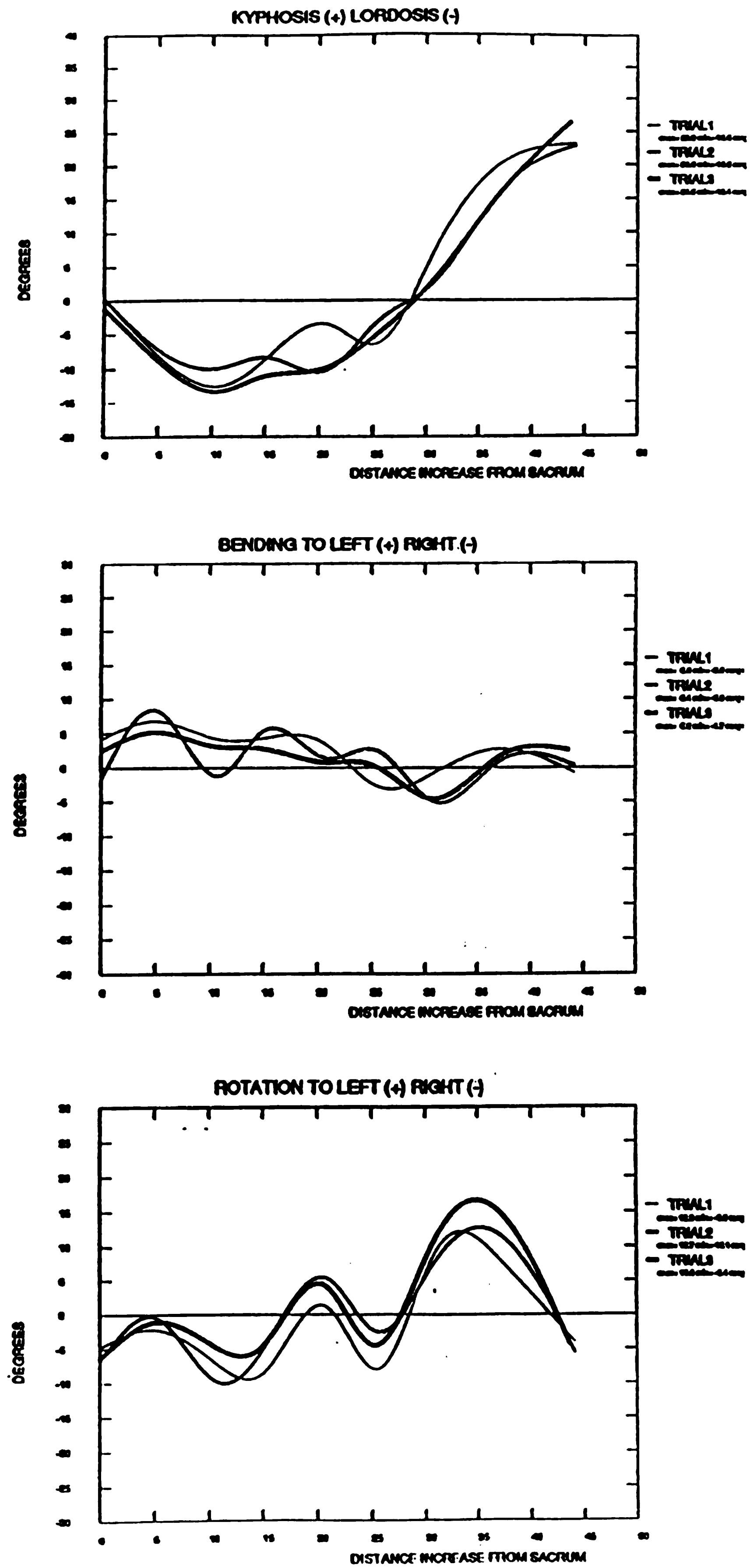


Figure 37: Three-dimensional orientation of each point relative to pelvis: rotation

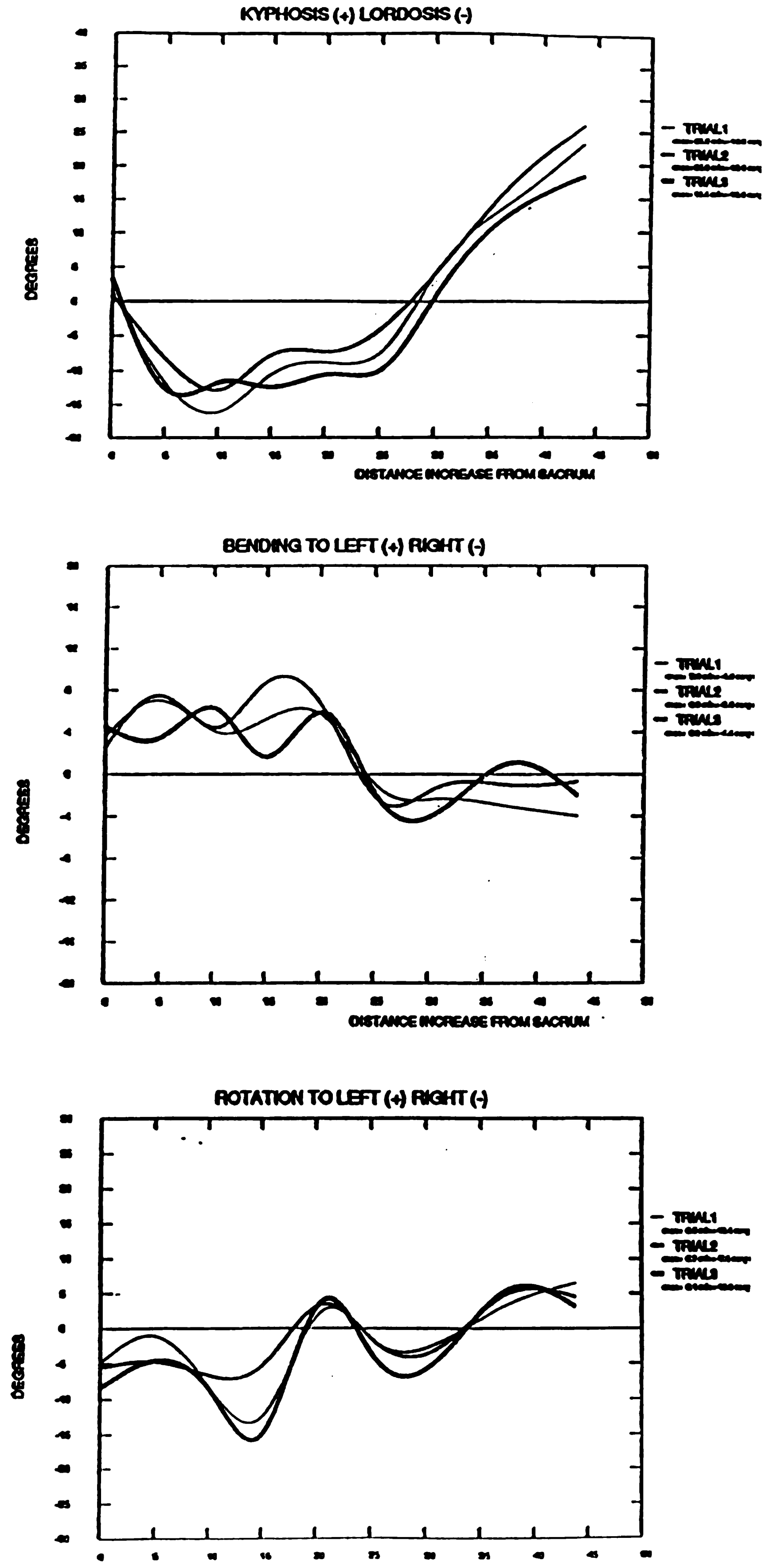


Figure 38: Three-dimensional orientation of each point relative to pelvis: bending

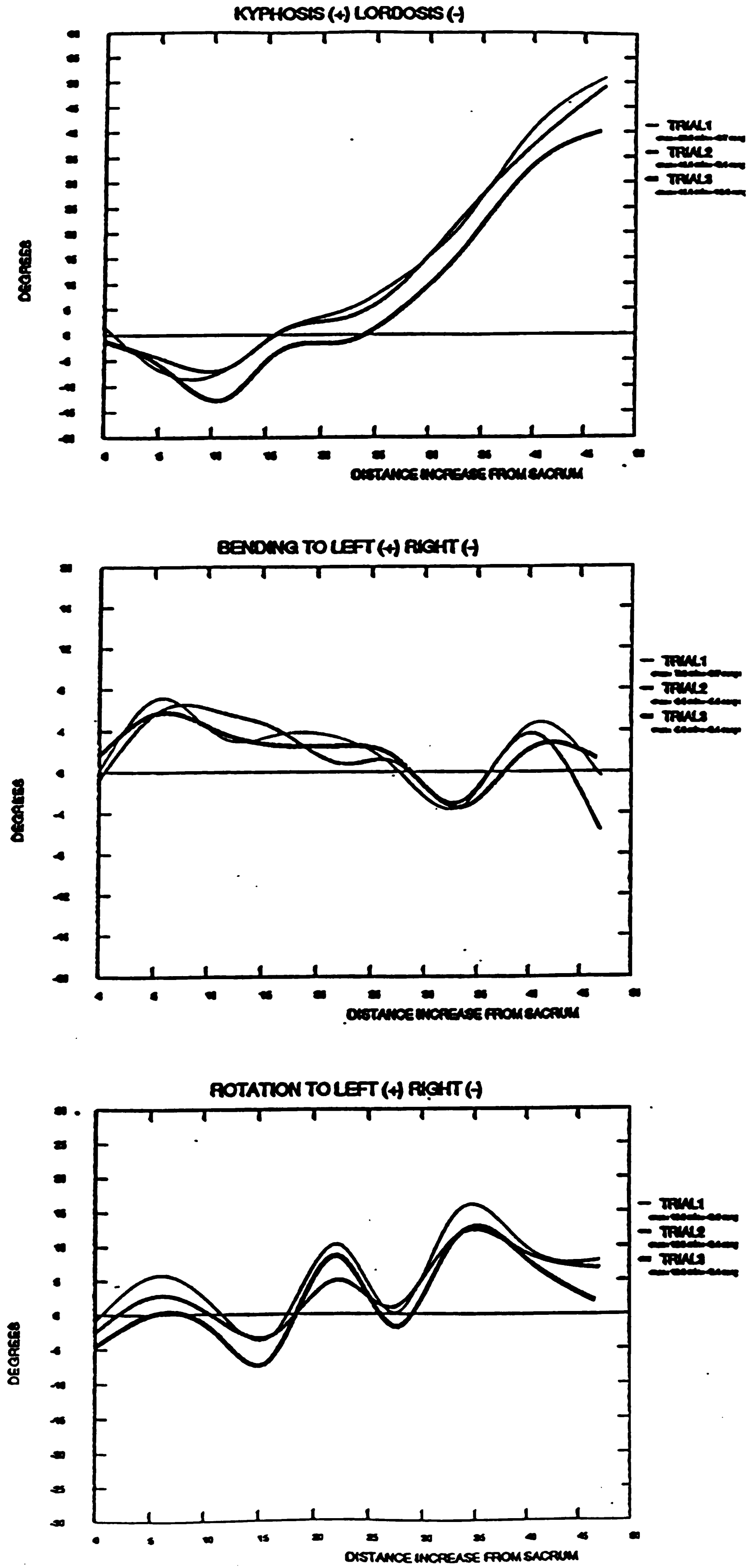


Figure 39: Three-dimensional orientation of each point relative to pelvis: flexing

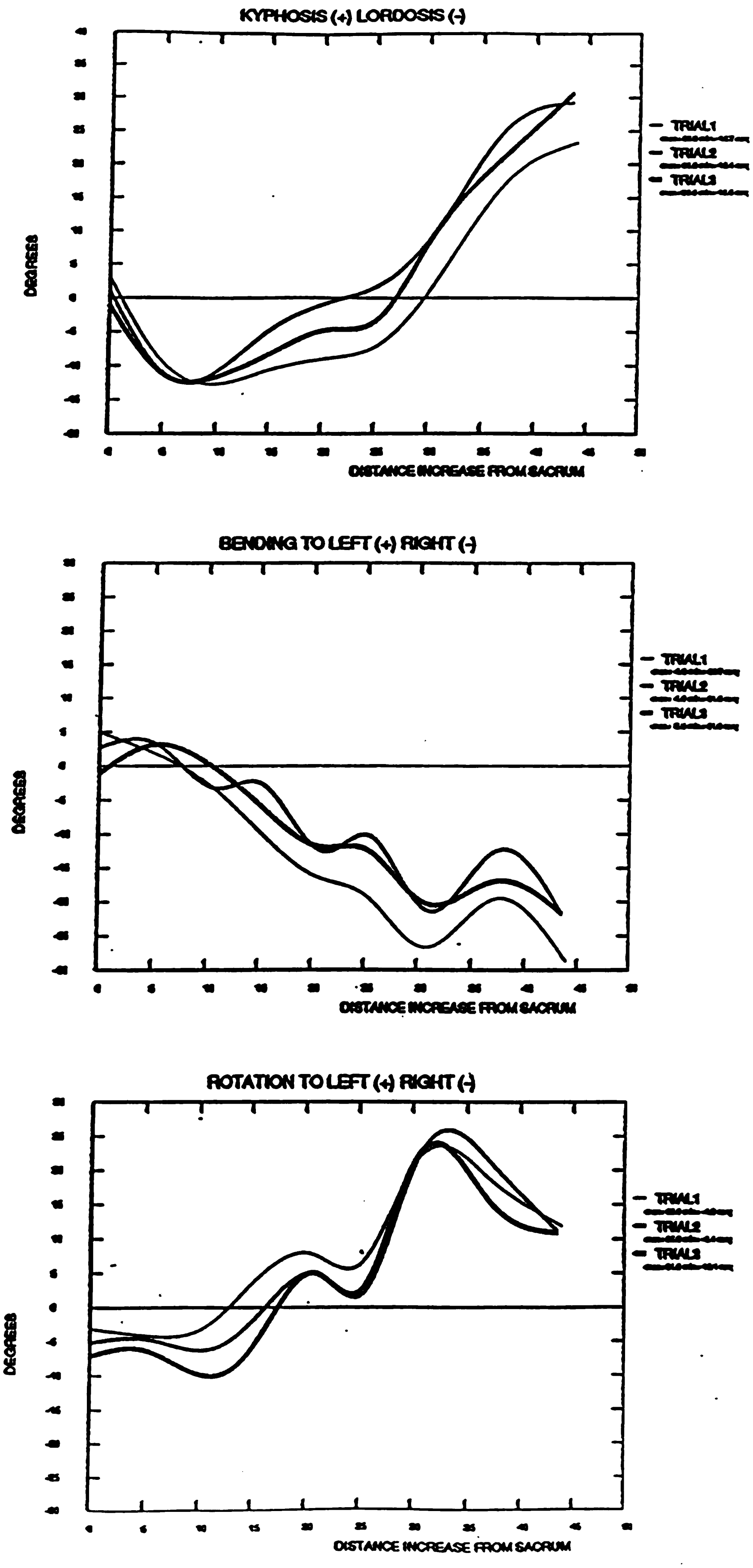
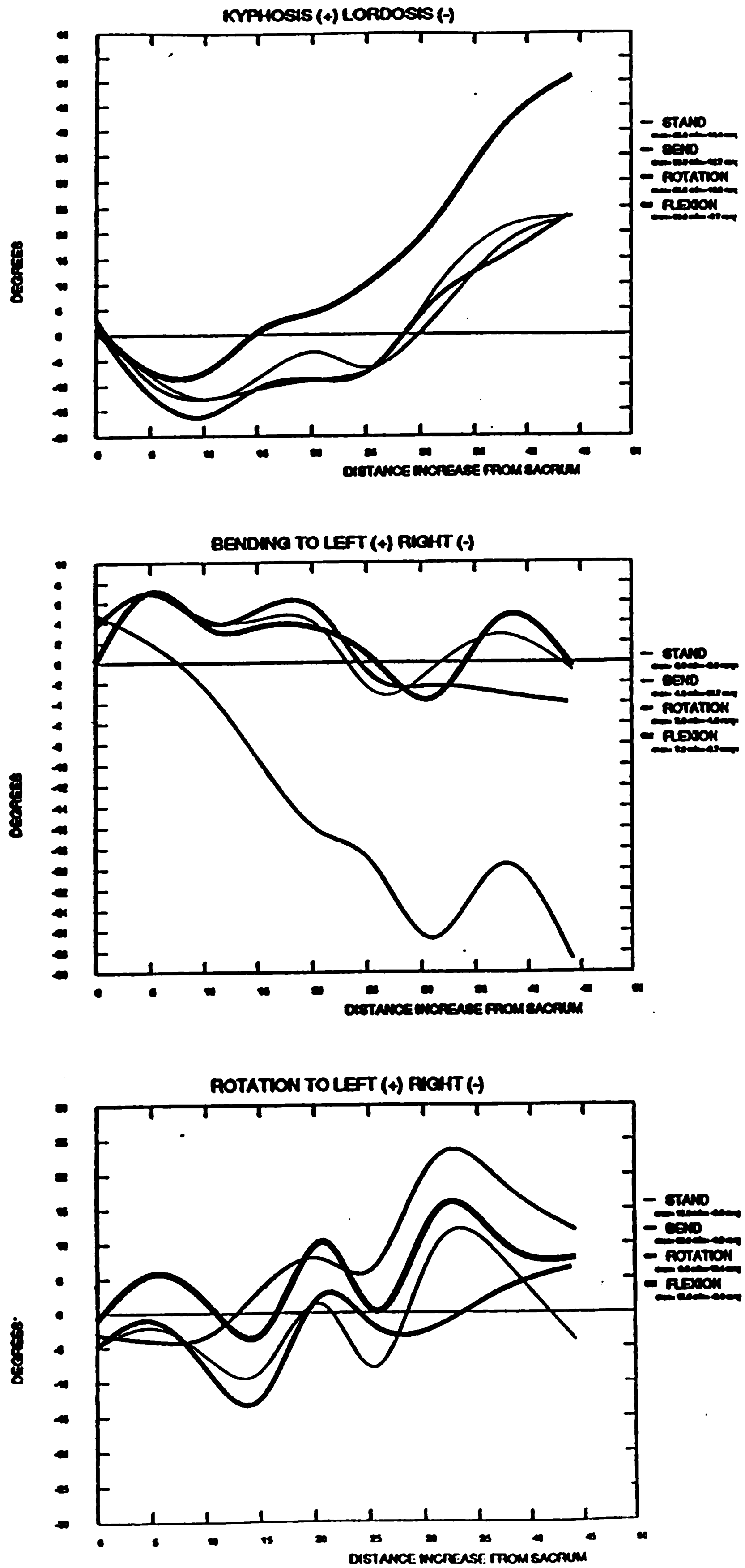


Figure 40: Three-dimensional orientation of each point relative to pelvis: four conditions



However, since the spinal vertebral surface measurement, and the space angle measurement are not based upon the traditional two-dimensional Cobb projectional measurement based on the end plates of proximal and distal vertebrae, the difference in results is understandable. Spinal side tilting angle was within -5 to 10 degrees normal range. Some differences might be produced by targeting error or tracking error. The rotational angle is not the actual spinal vertebrae torsion angle, but the orientation of the trunk relative to pelvis. The variation in results was obviously created by alignment of the bars connecting the two targets. Therefore they cannot be used as the value in quantifying spinal rotation. However, it is useful in judging the mobility of spinal rotation.

Comparing the results of bending, rotating and flexing with that of standing by Figure 40, it was obvious which were the primary movements shown by the plots. It is important to note here that the motion of the higher level of the spine is the accumulation of the lower region. Primary rotation of the trunk was coupled with side bending and the primary bending of the trunk was coupled with rotation.

3. Differential Geometrical Analysis of the Spinal Curve

Space curvature and torsion are the two parameters indicating the condition of a space curve from a differential geometrical point of view. The space curvature plots of the three trials of each condition were shown by Figure 41 to 44. Since space curvature indicates the curvature in every direction, it is a compound value of all the directions in space. As a result, it was not expected that this parameter would have the same reproducibility as that of the kinematic angles. However, since the human spinal shape is predominantly an "S" style, the space curvature can be modeled in a "non-zero, zero, non-zero" format. The non-zero indicate the lumbar lordosis curve and thoracic kyphosis

Figure 41:

CURVATURE ANALYSIS (DIFFERENTIAL GEOMETRY) OF SPINAL CURVE
THREE TRIALS OF FLEXION FORWARD CONDITION

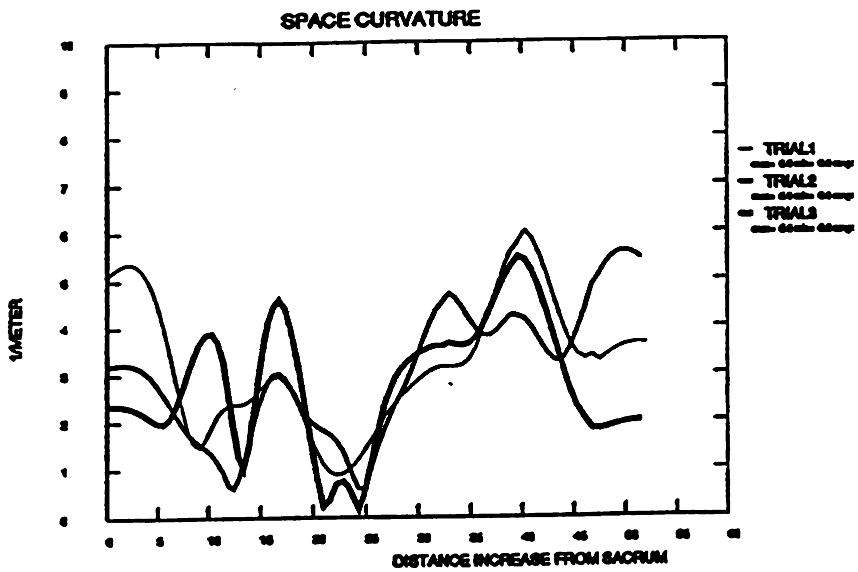


Figure 42:

CURVATURE ANALYSIS (DIFFERENTIAL GEOMETRY) OF SPINAL CURVE
THREE TRIALS OF ROTATION TO RIGHT CONDITION

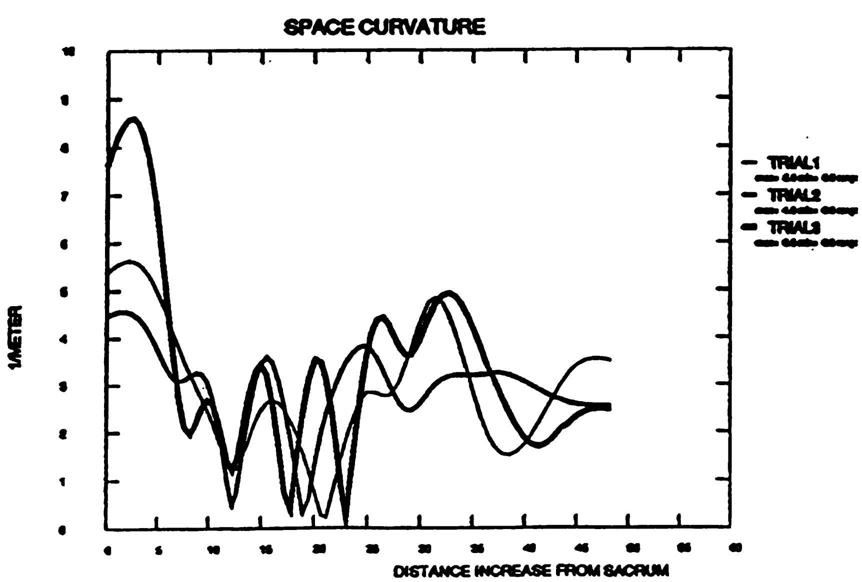


Figure 43:

CURVATURE ANALYSIS (DIFFERENTIAL GEOMETRY) OF SPINAL CURVE
THREE TRIALS OF STANDING CONDITION

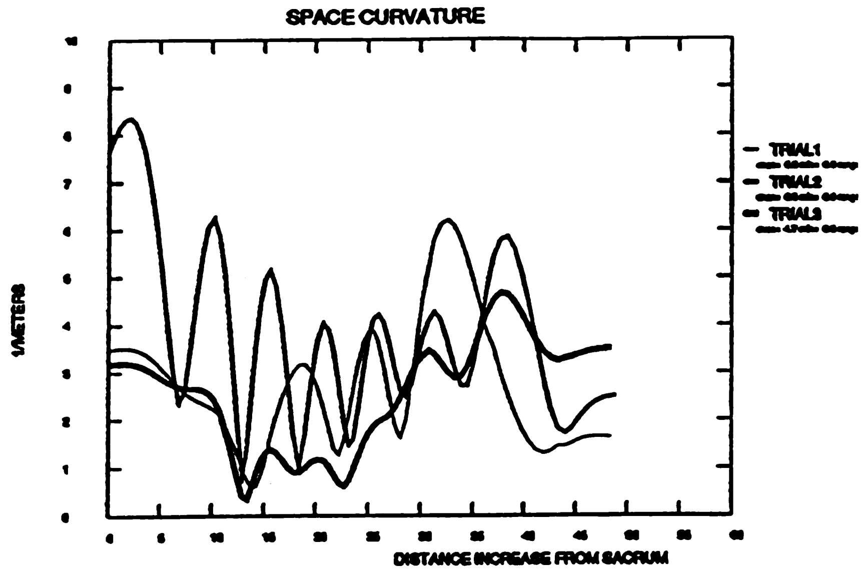
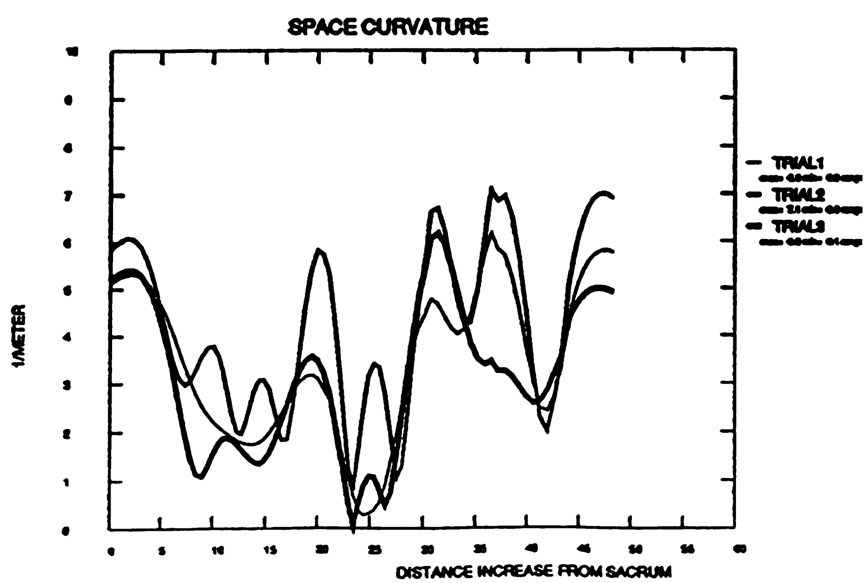


Figure 44:

CURVATURE ANALYSIS (DIFFERENTIAL GEOMETRY) OF SPINAL CURVE
THREE TRIALS OF BENDING TO RIGHT CONDITION



curve and the zero indicates a transitional point between the two curves. Throughout all the conditions, the peak values of the thoracic curve were unchanged which indicated the rigidity of thoracic spine and the large variation of lumbar curvatursshowslarge mobility of lumbar spine.

Since bending added a comparable curvature in the frontal plane with that in the sagittal plane, [Figure 44], the space curvature for this condition showed a consistently curvature increase of lumbar curve and consistent upward shift of transitional point. This means that frontal plane deviation or deformity can be qualitatively understood by the space curvature plot. The space curvature, as a differential geometrical parameter, is useful in judging scoliosis condition.

By comparing the curvature plots of standing with rotating, [Figure 42], it was found that there was an increase of lumbar curvature and a slightly decrease of thoracic curvature. This matched up well with the result from kinematic point of view. Even though there was a decrease of lumbar curvature of flexing from standing, a similar trend existed motion in sagittal plane.

The torsion of a space curve measures the twisting of the osculating plane. The results were very similar to that of the curvature, see Figure 45 and 48. The reproducibility throughout the trials of the conditions were not good due to the sensitivity of space curvature. However, it was found that the torsion values of the upper thoracic and lower lumbar region were always close to zero which meant that the curves at those regions were very close to planar curves. On the other hand, large variations existed in the thoracolumbar region which meant that there was not only large three-dimensional mobility but also curve directional changes.

Figure 45: THREE TRIALS OF FLEXING FORWARD CONDITION

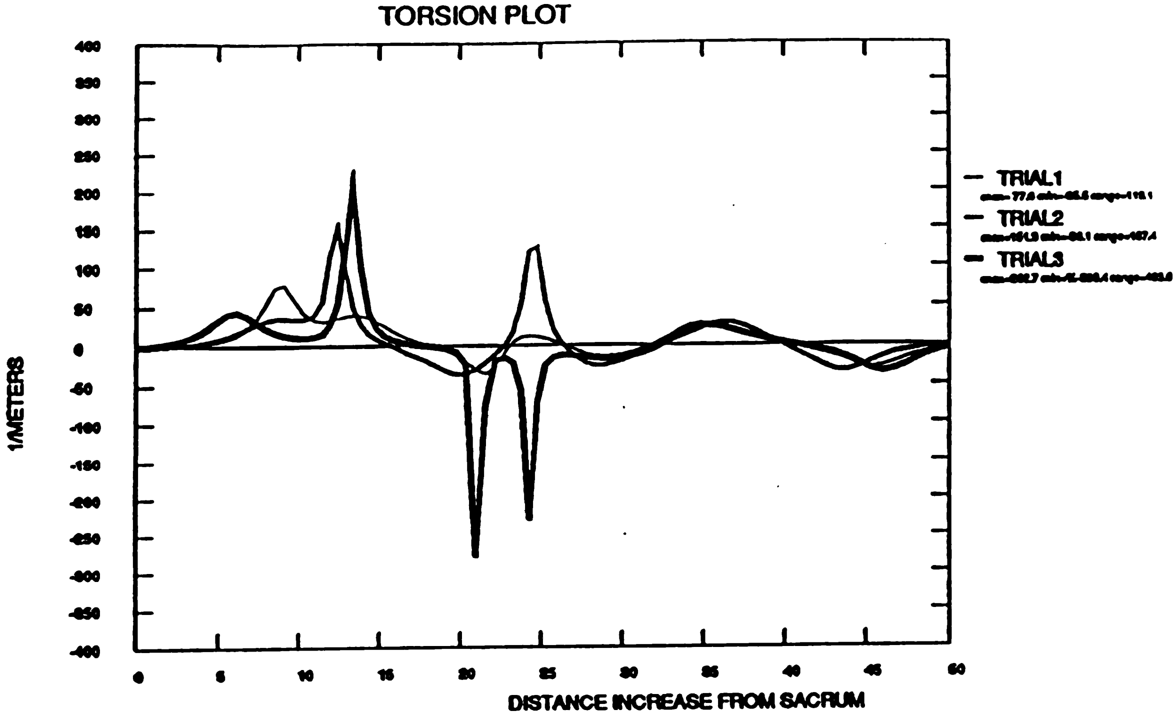


Figure 46: THREE TRIALS OF ROTATING RIGHT CONDITION

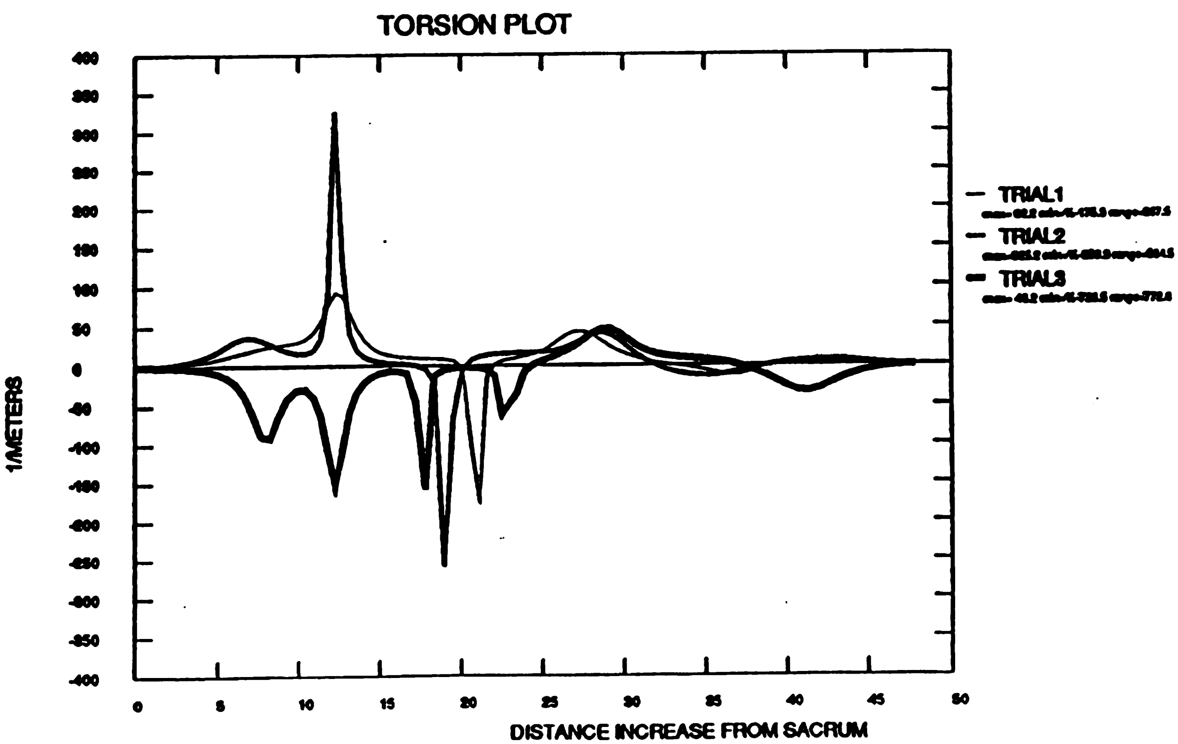


Figure 47: THREE TRIALS OF STANDING ERECT CONDITION

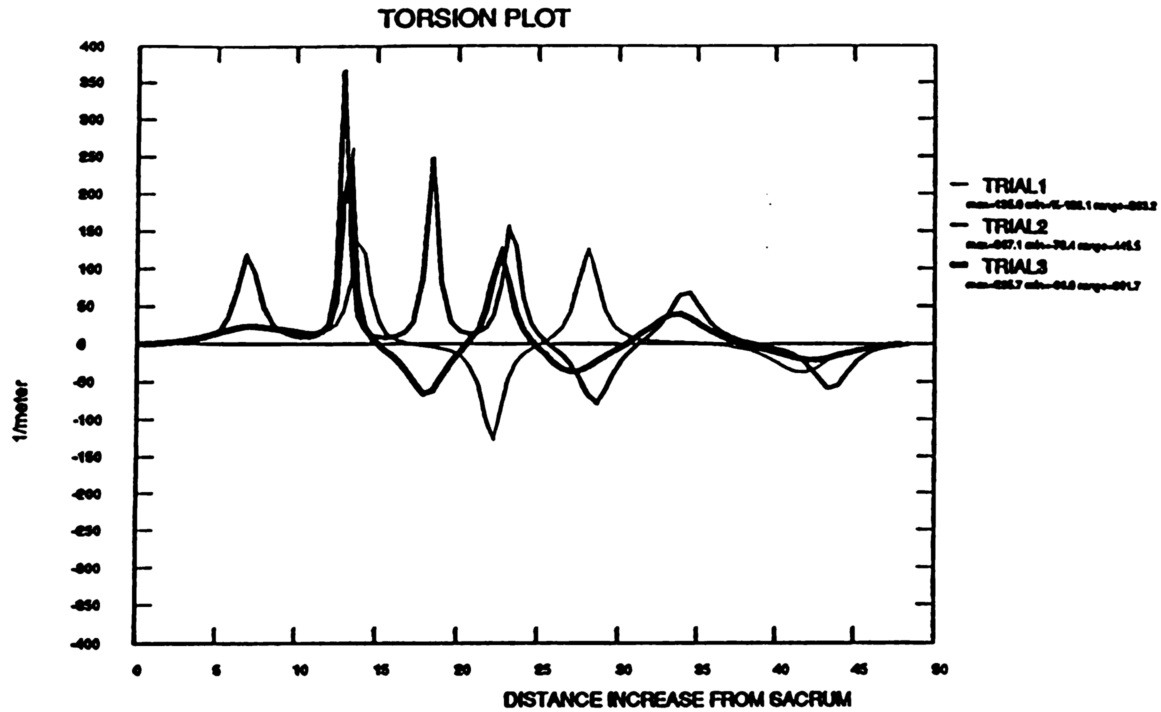
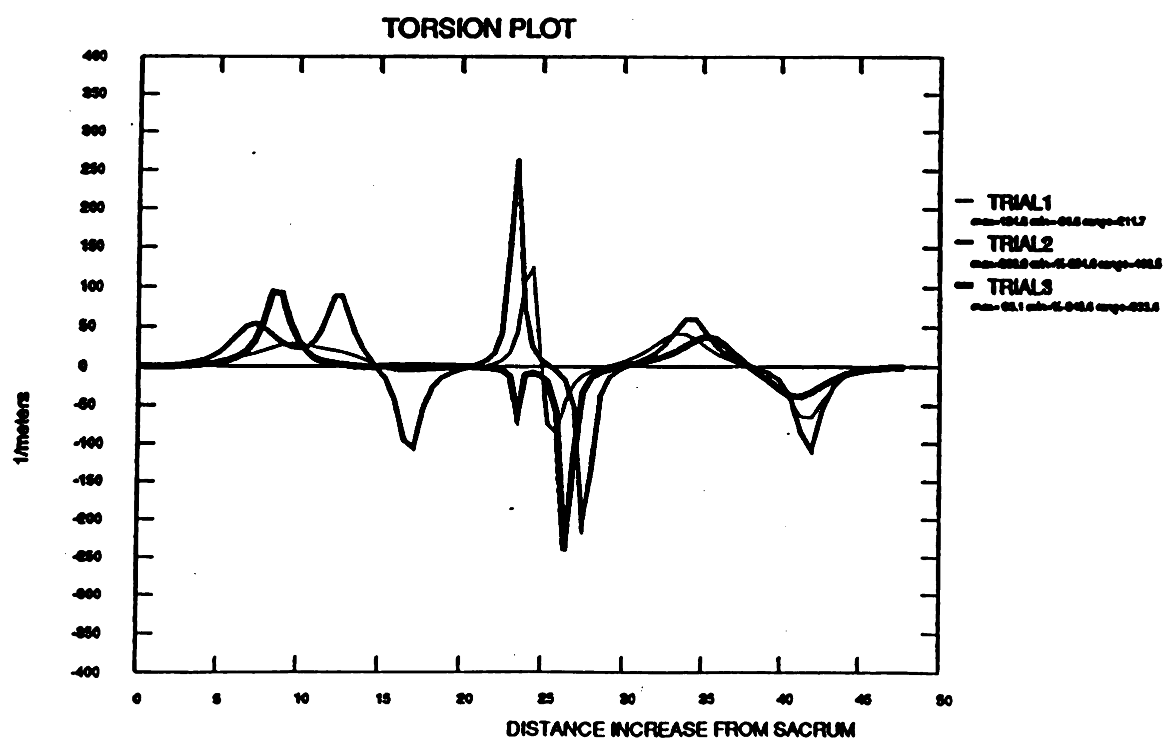


Figure 48: THREE TRIALS OF BENDING RIGHT CONDITION



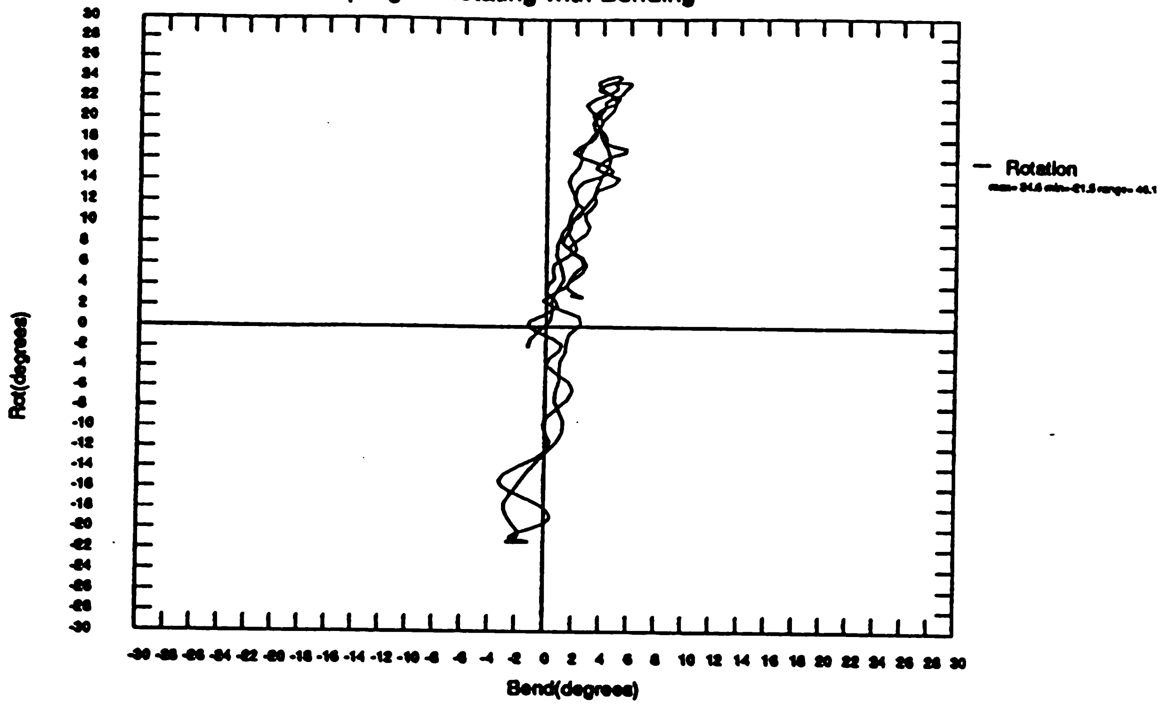
Overall, the differential geometrical information was not as reproducible as that of kinematic results and this was due to the combination of three-dimensional information into one value. Both the curvature and torsion provide us a more qualitative understanding of the spinal curve than a quantitative one.

4. Coupling Analysis of Lumbar and Thoracic Gross Movement by Cross Plot

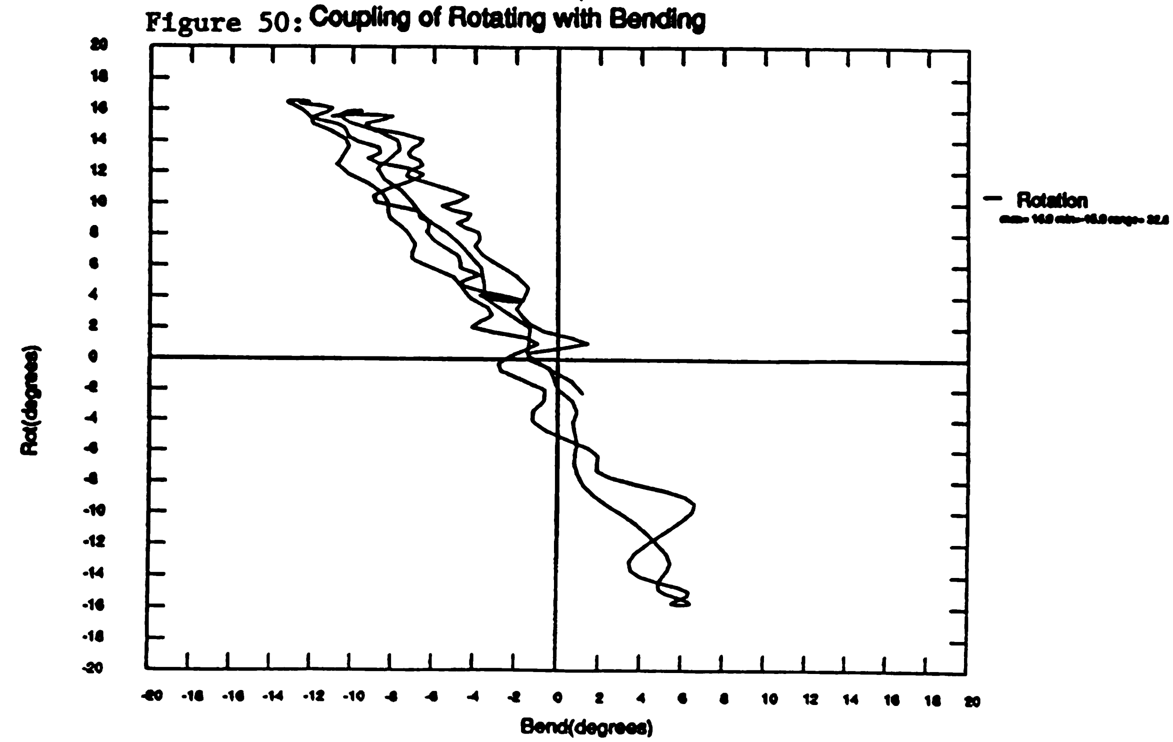
Figure 49 is the cross plot of rotating and bending angle of lumbar spine during the voluntary rotating movement. The resultant straight line proved that there was a coupling happened during that movement. The positive slope means the coupled movement went to the same side of primary movement. The straight line tilts more toward primary movement axis, which means the coupling is weak. All these results agreed very well with other researches, (White and Panjabi 1978, Pearcy 1985).

Figure 50 is the cross plot of rotating and bending angle of thoracic spine during the voluntary rotating movement. The resultant straight line proved that there was a coupling happened during that movement. The negative slope means that coupled movement went to the opposite side of primary movement. The straight line makes up almost an equal angle with both axes, which means the coupling is strong. Even there is not much work have been done previously on testing the gross motion of thoracic spine in vivo, the results developed here matched very well with the anatomical information, (White and Panjabi 1978).

Voluntary Rotating Condition
Gross Motion of Lumbar Spine as a Whole
Figure49: Coupling of Rotating with Bending



Voluntary Rotation Condition
Gross Motion of Thoracic Spine as a Whole
Figure 50: Coupling of Rotating with Bending



Conclusion

Spinal curvature and kinematics are important in spinal deformity analysis and ergonomic design. Most of the studies done in the past are either based on radiology projectional pictures or either too complicated or use grossly invasive techniques. An easy and reasonable accurate noninvasive measurement method would benifit current programs such as school scoliosis screening, long term spinal deformity treatment, and mobilty measurements. In this study, not only the static spinal curvature but also the dynamical movement have been quantified by a video camera system, and the data was easily processed by a computer.

Kinematic analysis has been used to quantify the gross motion of whole thoracic and lumbar spines, and the movement of the thoracic cage. The thoracic spine is anatomically retricted by the ribs. The gross motion results showed that the thoracic spine had a restricted mobility for flexing/extending, but as large a mobility as that of lumbar spine for side-to-side bending and axial rotating movements. Coupling has been found in both thoracic and lumbar regions for axial rotating movements, but not for side-to-side bending movements. The direction of coupling and approximate coupling ratio matched well with other studies. The movements of thoracic cage combined the motion from both thoracic and lumbar spine, and it is dangerous to use the movement of thoracic cage to approximate lumbar spine mobility.

The relative orientation of each point on the spinal curve with the pelvis has also been calculated. Good reporducibility was found among all the trials for each condition. The primary motions were easily recognized by the plots, and the accompanying motions could also be seen.

Differential geometrical analysis was based on a space curve fitted by quintic spline functions, and the curve was smooth in the second derivative. Space curvature and torsion are two parameters that provide the information for the curve condition.

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