

ACTA ORTHOPAEDICA SCANDINAVICA
SUPPLEMENTUM NO. 127

Department of Orthopaedic Surgery,
University of Gothenburg, Sweden

ANALYSIS OF THE MECHANICS
OF THE THORACIC SPINE IN MAN

AN EXPERIMENTAL STUDY OF AUTOPSY SPECIMENS

By

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MUNKSGAARD

Copenhagen 1969

GÖTEBORG 1969
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*To My Mother, My Late Father
and All Afro-Americans*

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FOREWORD

The background events that ultimately lead to the production of this work take their origin several years ago at Yale Medical Center where the author was a resident in orthopaedic surgery. Interest in biomechanics was expressed at that time to his chief and friend Professor *Wayne Southwick*. As a result of the endeavours and encouragement of Dr. Southwick arrangements were made for a fellowship to pursue this interest. Because of the outstanding work and reputation of Professor *Carl Hirsch* in the field of biomechanics he was approached regarding a position in his Department. Professor Hirsch has contributed generously to this project through his perspective, experience and stimulating discussions. This participation has been very much appreciated.

Acknowledgement is to be given for the valuable assistance of Docent *Svante Rolander* and Doctor *Erland Lysell*, both of whom discussed constructively principles and techniques related to the project. Mr. *Manohar Panjabi* has been a valuable and very essential consultant regarding engineering considerations and applied mathematics. The writer is grateful for the able participation of Mr. *Lennart Beckmann* and Mr. *Bengt Carlsson* in computer programming and Mr. *Bo Ericksson* in statistical analysis. Ing. *Hans Hellström* has assisted tremendously in innumerable aspects of the project, as has Miss *Lena Johnsson* and Mrs. *Inga-Lisa Elzer*. Their help is certainly appreciated. The author wishes also to express his gratitude to Professor *Jan Mellgren*, Docent *Bertil Stener*, Docent *Leif Lehman*, Docent *Alf Nachemson* and Assistant Professor *Mart Mägi*. Miss *Margareta Apelskog* is to be thanked for secretarial work and Miss *Anita Nordqvist* for photographic assistance.

This investigation was supported by grants from:

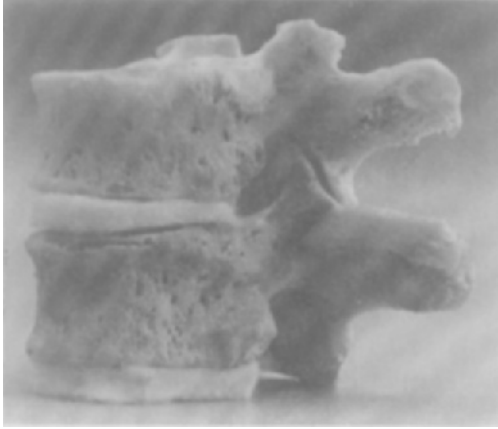
The Swedish Medical Research Council, Professor Hirsch: B70-17X-565-06, The University of Gothenburg, The Carin Trygger Memorial Fund, King Gustaf V Jubilee Fund, The Swedish Labour Insurance Society, Yale University School of Medicine and The National Institute of Health Bethesda, Maryland.

Gothenburg, September 1969

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INTRODUCTION



... It is as if one undertook, for example, to investigate a railroad accident solely from a study of the wrecked cars. Much could be learned as to the effect and direction of the destructive forces, the amount of force expended, and the kind of damage done, but more could be learned and future accidents could be better prevented by a study of the normal running time of the trains, their proper relation to each other at the time of the accident, and by an investigation of the signal system and the routine precautions adopted.

This quote from Lovett's classic work on *The mechanisms of the normal spine and its relation to scoliosis*, puts into perspective one of the most obvious clinical values of a study of the mechanics of the thoracic spine. It applies with equal relevance to the practical problem of the effects of trauma on the thoracic spine. Pain syndromes related to the thoracic spine, though not as frequent as in the cervical and lumbar spine, do present a significant clinical problem (Hult, 1954; Horal, 1969). Accurate reliable information about the normal is generally the basis if not the prerequisite for progress in the understanding and treatment of the abnormal.

In the mechanical modelling of the human system one must have access to the relevant biomechanical data before the modelling process can be meaningful. Frequently, however, such data is simply not available, or at least not in a form for direct use by the engineer or physical scientist interested in developing a mathematical model. With regard to the spine, more attention appears to have been given to the behavior of the cervical and lumbar regions than to the thoracic region although, as mentioned previously, vertebrae in the thoracic region fracture more frequently than other vertebrae.

This above quotation from a dissertation by Orne and Liu in 1969 on *A mathematical model of spinal response to impact*, points up quite nicely the more contemporary significance of a study of the mechanics of the thoracic spine.

The goals of this investigation are to provide information about the mechanics of the thoracic spine in man. A review of the literature will show that previous studies on the thoracic spine have defined the relevant problems and provided the background for current investigations. However, there are no studies which employ *precise modern* techniques, use *substantial* numbers of subjects and analyse *all* aspects of the movement of this important part of the vertebral column. It will be noted that there is considerable variance in the writings of previous authors as regards their description of some of the very basic factors involving the patterns and extent of movement in the thoracic spine. There are two precise and accurate methods which have been employed for analysis of motion of the spine. One has been used by *Rolander* (1966) on the lumbar spine. The other has been employed by *Lysell* (1969) on the cervical spine. As there are some differences in the information that can be derived from these two techniques, both methods are employed in this investigation. Basic concepts of engineering mechanics play a significant role in the presentation and interpretation of this material. This will most probably be the case for subsequent works. Consequently, an attempt is made to deal with the material in a manner meaningful to mechanical as well as biological interpretation.

There are several important questions the answers to which constitute a thorough descriptive analysis of the motion of the thoracic spine. These questions are:

1. What is the amount and the pattern of flexion and extension? What is the relative amount of each?
2. What is the amount and the pattern of lateral bending and rotation?
3. What are the cephalocaudal variations in the above mentioned patterns and quantities?
4. Is there coupling of axial rotation with lateral bending? What is the direction of the axial rotation?
5. Where are the "Centers of Motion" for the various movements?

6. Are there differences in the motion of the vertebrae when their posterior elements are removed?

The aim of the study is to provide, through two separate experimental investigations, information that will answer the preceding questions. The first part is a two dimensional analysis in which the motion of one vertebra in relation to the fixed subjacent one is observed under controlled loads. The second part is a truly three dimensional analysis of larger segments of the thoracic spine taken through their various ranges of motion.

ANATOMIC CONSIDERATIONS RELATED TO MECHANICS

To follow is a recapitulation of those aspects of the anatomy that appear to be pertinent to the mechanical behaviour of the spine. A more extensive review of the anatomy is possible by referring to *Fick* (1904), *Strasser* (1913), *Braus* (1921), *Frazier* (1940), *Hollingshead* (1965) and *Gray* (1967).

Normal Curves and Regional Variations

In the frontal plane the spine appears straight and symmetrical with the exception of a very slight right convex thoracic curve. This is said to be due to the position of the aorta (*Steindler*, 1955). Other writers suggest that it is due to increased use of the right hand (*Davis*, 1918; *Frazier*, 1940). The relation of handedness has been supported by the observation of left convex curvature in left handed individuals (*Gray*, 1936). There are four normal curves in the sagittal plane. The mechanical value of the curves are increased flexibility with stability and augmented shock absorbing capacity. These curves are convex forward in the cervical and lumbar regions and concave forward in the thoracic and sacral regions (Fig. 2). The lumbar curve, quite aesthetically, is slightly more accentuated in the female. The thoracic curve is primary and can be looked upon as the persisting curve of the embryonic axis (*Frazier*, 1940). The dorsal curve of the thoracic portion of the spine is due to the lesser vertical height of the anterior as opposed to the posterior border of the vertebral bodies (*Gray*, 1967). This is also true for the sacral curve (Fig. 2). The thoracic curvature has been observed to increase with age. Below the age of 40 the female thoracic spine is straighter than that of the male. This difference is not found after 40 when the female's dorsal spine becomes as bent as the male's. Such change may contribute to the so-called "dowager's hump" (*Loebl*, 1967). The convexity of the cervical and lumbar regions is largely contributed to by the relative ventral thickness of the discs. Therefore, when distracting forces are applied to the entire spine there is a flattening of the cervical and lumbar lordosis. This is probably due to the deformation of the discs. At the same time the thoracic kyphosis, based on osseous asymmetry, is almost unaltered (*Klausen*, 1965).

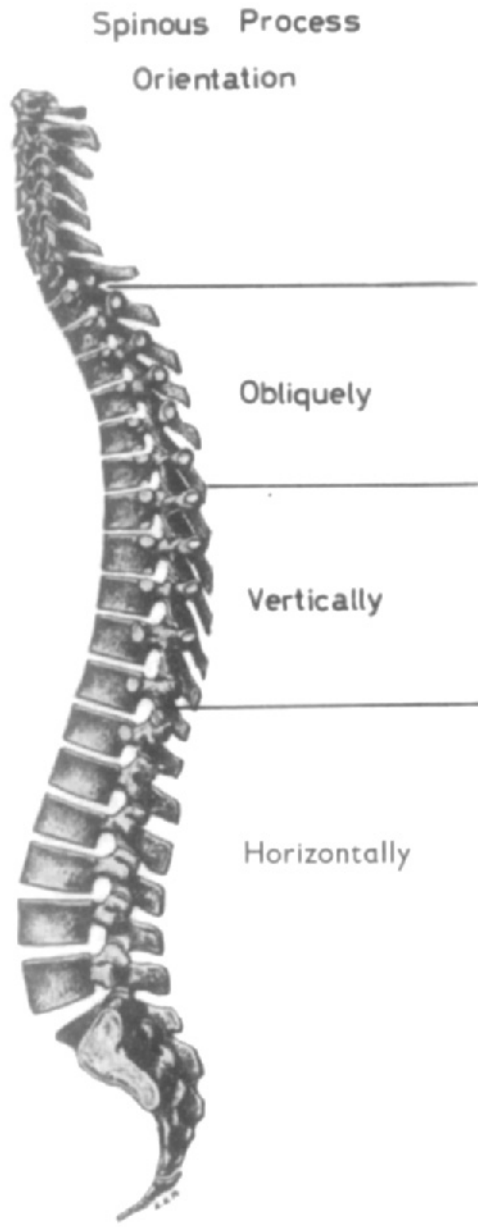


Fig. 2. This demonstrates the normal curves of the vertebral column in the sagittal plane. The orientation of the spinous processes is also pointed out. (The drawing is reproduced from Gray's Anatomy 34th Edition London 1967, with permission of the publisher.)

From the first cervical to the last lumbar vertebra the bodies increase consistently in mass (*Steindler, 1955; Gray, 1967*). In the frontal plane the width of the bodies of the vertebra increases from the second cervical to the third lumbar (*Gray, 1967*). In the thoracic spine the sagittal and frontal diameters are about equal (*Gray, 1967*) or slightly greater in the sagittal plane (*Strasser, 1913*). Measurements by *Frazier (1940)* of outlines of upper surfaces of thoracic vertebrae revealed consistently greater frontal diameters. In the upper three vertebrae this pattern of a greater frontal than sagittal diameter was more marked than in the lower vertebrae.

Articular Facets and Spinous Processes

Winslow (1732) published probably the earliest definite contribution to the subject of motion in the vertebral column. He included a meticulous description of the apophyseal facets and a discussion of their contact during movements of the spine. *Humphry (1858)* pointed out that movements permitted in the spine are mainly due to the shape and position of the articulating processes of the diarthrodial joints. It is the orientation of these joints in space that determine their mechanical importance. In the thoracic spine the superior facet is almost flat and directed backwards, a little laterally, and upwards. The inferior facet is directed forwards, slightly downwards, and medially (*Gray, 1967*). (See Figs. 2 and 3). This orientation more or less aligns the plane of the joints along the arch of a circle lying in the transverse plane, the center of which is in the vertebral body (*Rockwell, 1938*). *Strasser (1913)* emphasized the variation of the slopes of the facets in different regions of the spine. *Davis (1959)* studied nineteen vertebral columns, two of which were freshly macerated from young adult males. Using instruments with line markers at right angles to an edge, which could be fitted over the facet, he determined the

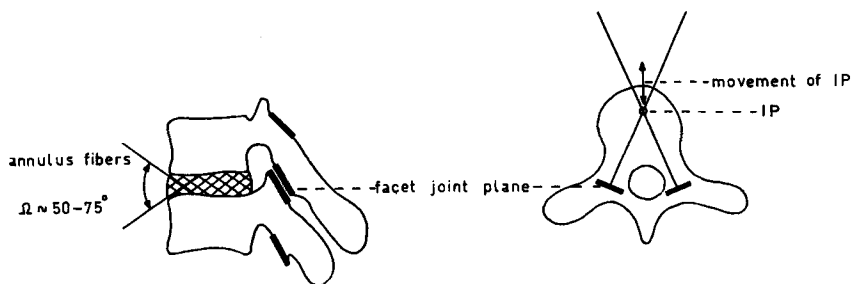


Fig. 3. This diagram demonstrates the orientation of the articular facets in the horizontal and sagittal planes. The intersection point (IP) of Davis and the geometrical arrangement of the annulus fibers are also shown.

intersection points (IP) of lines perpendicular to the plane of the facets (Fig. 3). In the upper two thoracic vertebrae this point was found to be well in front of the vertebral body. As observations are made more caudally, the point is found to approach and then enter the line of the vertebral bodies. Even lower in the thoracic region the point again leaves but may re-enter at the lowest thoracic joint. The freedom of rotation in the thoracic region is thought to be related to this particular orientation of the facets in space (Rockwell, 1938; Steindler, 1955; Lucas and Bressler, 1961). One witnesses an abrupt change in the orientation of the plane of the articular joints, when a comparison is made between the thoracic and the lumbar spine. This occurs most commonly at the inferior facet of Th 11 or Th 12 but can be as high as Th 10 (Gray, 1967). Such a vertebra with the plane of the facet joint lying more sagittally than frontally will behave in motion like a lumbar vertebra.

The spinous processes in the upper thoracic region are directed obliquely downwards; in the middle they are longer and almost vertical. In the lower thoracic and lumbar regions they are horizontal (Fig. 2). In the thoracolumbar region dorsiflexion is limited by the spinous processes (Åkerblom, 1948).

Intervertebral Discs

A number of writers have discussed the significance of the intervertebral disc in relation to the amount of movement between vertebrae (Keller, 1924; Beadle, 1931; Wiles, 1935; Steindler, 1955; Lucas and Bressler, 1961). This organ constitutes 1/3 of the length of the column (Klausen, 1965). Gray (1967) places this estimate at 1/5. The intervertebral disc is comprised of three parts, the nucleus pulposus, the annulus fibrosus and the cartilagenous end plate. The gelatinous nucleus pulposus contrary to popular opinion is *not a notocordal remnant*. It is described as an area of *degenerated notocord invaded by fibrocartilagenous cells derived from intervertebral mesenchymal cells* (Keyes and Compere, 1932; Hollingshead, 1965). Microscopically it is composed of a very loose and translucent network of fine fibrous strands. In this there are found a variety of connective tissue cells, some spindle shaped, others with clear vacuolar nuclei. The latter *have been* thought to be descendants of the special cells of the embryonic chorda tissue (Beadle, 1931). These connective tissue elements lie in a mucoprotein gel which contains various mucopolysaccharides (Hirsch, Paulson, Sylven and Snellman 1953; Happey, McRae and Naylor 1953; Naylor et al., 1955; Naylor, 1962). The nuclear water content ranges from approximately 70–90%. It is highest at birth and tends to decrease with age (Naylor et al., 1955). The lumbar nucleus fills 30–50% of the total disc area in cross section (Perey, 1957; Nachemson, 1960; Eie, 1966). In the low back the nucleus is usually more posterior than central and lies about at the juncture of

the middle and posterior thirds of the sagittal diameter. In general it is placed further forward in the thoracic region (*Beadle, 1931; Joplin, 1935*). The size of the nucleus as well as its capacity to swell is larger in the cervical and lumbar region and probably related to the greater flexibility there (*Beadle, 1931; Gray, 1967*).

The annulus fibrosus is a portion of the intervertebral disc, which gradually differentiates itself from the periphery of the nucleus. This structure is composed of fibrous tissue in concentric laminated bands, approximately six in the thoracic spine (*Joplin, 1935*). The collagen bands run obliquely from one vertebra to the next in a helicoidal arrangement with the fibers in contiguous laminae lying at angles of about 50–75° to each other (*Horton, 1958; Naylor, 1962; Galante, 1967*) (Fig. 3). The annulus fibers are attached to the cartilagenous end plates in the inner zone, while in the more peripheral zone they attach like Sharpeys' fibers directly into the osseous tissue of the vertebral body (*Hirsch and Schajowicz, 1952*). The third and final portion of the intervertebral disc is that of the cartilagenous end plate. Comparatively little is known about this structure. It is composed of hyaline cartilage and separates the other two components of the disc from the vertebral body (*Beadle, 1931; Hirsch and Schajowicz, 1952*).

The above considerations complete the anatomic description of the disc and bring into focus some relevant mechanical properties of the organ. The angular arrangement of the annulus fibers and their strong attachment to the vertebral end plates create mechanical conditions for strong resistance to horizontal translation (*Hirsch and Sonnerup, 1968*). The disc in various mannerisms behaves with visco elastic properties (*Virgin, 1951*). Loads lasting seconds give perfect elasticity curves of the same shape as those observed for hyaline cartilage. If a disc is kept loaded a certain amount of compression occurs until equilibrium is reached (*Hirsch and Nachemson, 1953*). When stress is applied to a normal or slightly degenerated disc, the pressure per unit area is about 50% higher in the nucleus. This is probably due to the elastic resistance of the fibers of the annulus. The nucleus can be considered to be subject to Pascal's laws of fluids and consequently is hypothetically incompressible (*Keyes and Compere, 1932; Joplin, 1935; Inman and Saunders, 1947; Nachemson and Elfström, 1969*). Forces applied to the lumbar nucleus have been explained. They are thought to be transmitted throughout the nuclear material with the forces exerted on the cartilagenous plate and the annulus being equalized. The complete unit of nucleus and annulus is consequently somewhat analogous to a rubber tire with relatively high internal pressure (*Nachemson and Elfström, 1969*). Compression of the disc thus results in a bulging of the annulus as observed by *Hirsch (1951)* and re-evaluated and interpreted by *Rolander (1966)* in the lumbar region of the spine. *Horton (1958)* maintained that this increase in the

radius of the disc with compression is achieved by the movement of adjacent uniaxial sheets with consequent decrease in Ω (Fig. 3). Loss of the elasticity of the disc is described by *Beadle* (1931) as the most conspicuous change differentiating the old or middle aged spine from the young. *Naylor et al.*, (1955) observed in the aged annulus a loss of gel properties of the nucleus along with increased crystalization of its collagen fibers. In the annulus crystalization changes, as well as alterations in fibrillar orientation, affected its biaxial structure. This complex of changes in the disc associated with ageing was interpreted as affecting particularly the function of mobility, which is thought to be decreased in the aged.

Ligaments

The major ligaments of the spine from anterior to posterior are as follows: the anterior longitudinal ligament, the posterior longitudinal ligament, the ligamentum flavum (yellow ligament, interarcuate ligament), the capsular ligaments, the intertransverse ligaments, the interspinous ligament and the supraspinous ligament. The radiate ligaments, anterior costotransverse, intertransverse, costae tubercle and posterior costotransverse ligaments are listed

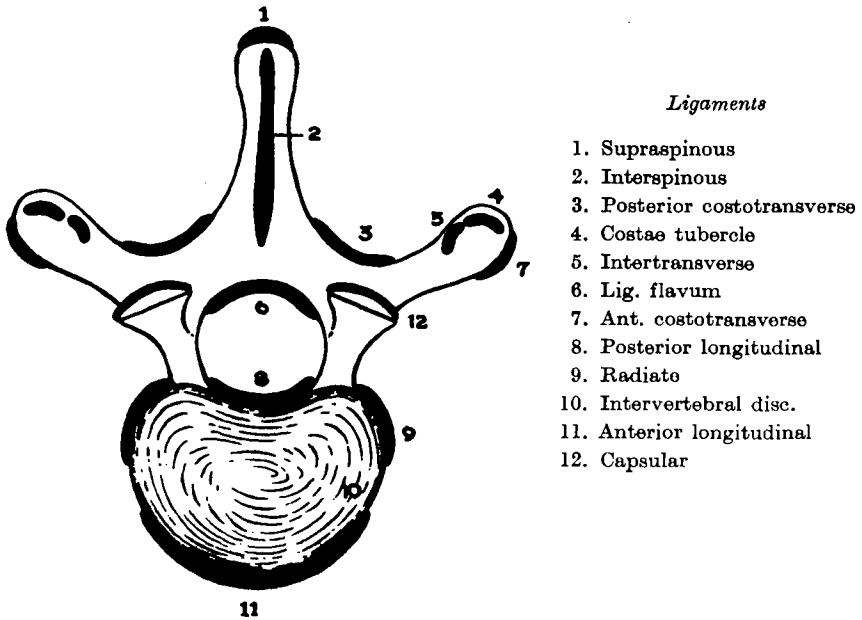


Fig. 4. Diagrammatic review of ligaments in thoracic spine. (From *Lucas and Bressler*, 1961.)

for the sake of completeness but will not be discussed further (Fig. 4). The anterior longitudinal ligament arises from the tubercle of the occiput and is attached to the atlas and the anterior surface of all vertebrae down to and including a part of the sacrum. It attaches firmly to the edges of the vertebral bodies but is not so firmly interwoven with the annulus fibers of the intervertebral disc (*Schmorl and Junghanns, 1932*). The width of the anterior longitudinal ligament is diminished at the level of the disc. It is more narrow and more thick in the thoracic region (*Gray, 1967*). The posterior longitudinal ligament arises from the basilar portion of the occiput and runs over the posterior aspect of all the vertebrae down to the coccyx. It too is interwoven with the intervertebral disc and thicker in the thoracic region. It is, however, the converse of the anterior longitudinal ligament in that it is wider at the disc and narrower at the vertebral body. *Tkaczuk (1968)* found both the anterior and the posterior longitudinal ligaments to be pre-stressed in the lumbar region.

The ligamenta flava extend from the anterior inferior border of the lamina above to the posterior superior border of the lamina below (*Gray, 1967*). They connect the borders of adjacent lamina from the second cervical vertebra to the first sacral vertebra (*Morris, 1879*). The yellow ligaments are thicker in the thoracic region. They are not paired structures with a midline cleavage as often described but rather like a single structure that extends from the roots of the articular process on one side to the corresponding process on the other (*Ramsey, 1966; Gray, 1967*). The ligament is composed of a large amount of elastic fibers (*Ramsey, 1966*) and represents the most pure elastic tissue in the human body (*Braus, 1921*). However, *Ramsey (1966)* states that with aging there is a type of fibrous substitution which increases the relative amount of fibrous tissue. *Åkerblom (1948)* demonstrated elastic qualities of the yellow ligament from his investigation of the thoracolumbar spine. He noted that the greatest degree of ventroflexion that could be achieved is that in which the interarcuate ligaments are stretched to a maximum. He found that the interarcuate ligaments were the chief factor limiting ventroflexion in the freely dissected lumbar spine. The ligament has been shown to have considerable active compressive force which pre-stresses the intervertebral disc (*Nachemson and Evans, 1968*). These ligaments are also said to protect the disc by slowing flexion. They are thought also to help restore the vertebral column to an erect attitude following flexion. *Rolander (1966)* concluded that, though the yellow ligament is probably the only ligament with restrictive activity, such restriction is not a significant factor in the movement of the spine.

The ligaments of the articular capsules are thin and loose. Their attachment is just beyond the margins of the adjacent articular processes. They are shorter and more taut in the thoracic and lumbar region than in the cervical region (*Gray, 1967*). These ligaments do not become taut in ventroflexion before the

affect of the interarcuate ligaments are operative (*Åkerblom*, 1948). The intertransverse ligaments pass between the transverse processes. In the thoracic region they are characterized as rounded cords intimately connected with the deep muscles of the back. The interspinous ligament takes its origin in the ligamentum nuchae and continues along the tips of the spinous processes, as a round slender strand, down to the sacrum. This ligament is not as thick in the thoracic as in the lumbar or cervical region. The supraspinous ligament has been observed to be taut on ventroflexion (*Åkerblom*, 1948; *Steindler*, 1955). The length of the supraspinous ligament in the lumbar region in maximal ventroflexion is the same as the maximum length obtained with tensile stresses applied directly to the ligament. This same phenomenon was noted in testing the interarcuate ligament (*Åkerblom*, 1948).

The ribs and the muscles are not involved in the scope of this investigation and consequently are not included in these anatomical considerations.

CONSIDERATIONS, TERMS AND DEFINITIONS

The following considerations are applicable to the remainder of this study. Related concepts, terms and definitions involving engineering mechanics are based on the texts of *Christie* (1952), *Timoshenko and Young* (1956) and *Shames* (1966).

The mechanics of the spine can be analysed, intersegmentally, as the motion of a rigid body (one vertebra) in relation to some reference (the subjacent vertebra). Precise description requires a coordinate system. The system to be employed is a righthand Cartesian coordinate system which is fixed in each vertebra. This reference system applies for the entirety of this work. See Fig. 5.

Motion of a rigid body is a combination of translation and rotation.

Translation—A body is said to be in translation when movement is such that all particles in the body have at a given time the same velocity relevant to some reference.

Rotation—A body is said to be in rotation when movement is such that all particles along some straight line in the body or a hypothetical extension of it have a zero velocity relative to some reference.

Axis of Rotation—This is the line of stationary particles whose velocity is zero at the time of rotation.

Coupling—This is applied to motion in which rotation about one axis is consistently associated with rotation about a second axis.

From Fig. 5 it can be seen that the planes can be defined as below.

Sagittal—This is the x, y plane.

Frontal (coronal)—This is the y, z plane.

Horizontal (transverse)—This is the x, z plane.

Flexion—This is movement predominantly in the sagittal plane ventrally directed (i.e. toward the negative direction of the x axis).

Extension—This is movement predominantly in the sagittal plane dorsally directed (i.e. toward the positive direction of the x axis).

Lateral bending (lateral flexion)—This is movement predominantly in the frontal plane to the right (toward the negative direction of the z axis) or to the left (toward the positive direction of the z axis).

Sagittal plane rotation—This is rotation about the z axis. (θ_z). Positive θ_z is tilting forward as in flexion. Negative θ_z is tilting backwards as in extension.

Frontal plane rotation—This is rotation about the x axis. (θ_x). Positive θ_x

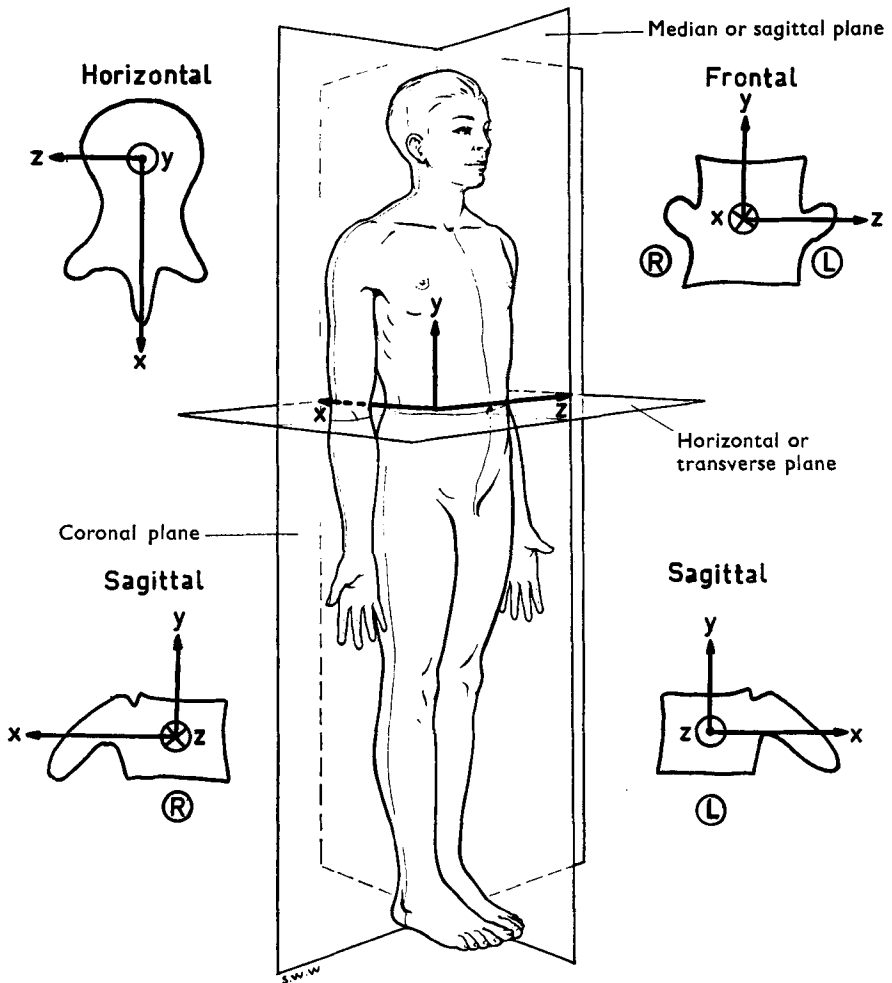


Fig. 5. This shows the righthand Cartesian coordinate system to be used throughout this investigation. The system is also indicated with views of a vertebra in the standard planes. (The man and the body planes are reproduced from Gray's Anatomy 34th Edition London 1967, with permission of the publisher.)

is tilting to the left as in left lateral bending and negative θ_x is tilting to the right in right lateral bending.

Axial rotation—This is rotation about the y axis (θ_y) positive to the left (counterclockwise). Negative θ_y is rotation to the right (clockwise). Clockwise and counterclockwise are as viewed from above. See horizontal view Fig. 5.

Thoracic (dorsal) vertebrae are numbered Th 1–Th 12.

Motion segment—This is constituted by two vertebrae and their adjoining soft tissue (Junghanns, 1931). The movement of a given vertebra unless otherwise stated is in relation to the subjacent vertebra.

MOTION IN THE THORACIC SPINE

The following section is a review of the literature. It will be organized in such a way as to point up the basic considerations of importance in describing the motion of the thoracic spine. The inconsistencies of previous authors are noted, not to detract from their work but to illuminate the problems at hand. These previous studies have laid the more difficult ground-work, and they provided the foundation on which this and subsequent investigations can be developed. This review does not emphasize historical sequences or development of techniques. The history is thoroughly reviewed by *Elward* (1939) and *Andersson* and *Ekström* (1940). The technical development is described in the works of *Rolander* (1966) and *Lysell* (1969). The major topics in a description of the motion of the thoracic spine can be expressed by the questions heading each section of this review. These questions will constitute the outline for the review of previous investigations as well as the frame work on which the presentation of the material of this study is developed.

What is the Extent and Pattern of Flexion and Extension?

Weber (1827) was probably the first to actually do measurements of the motion of the vertebral spine. From his work based on the analysis of three cadaver spines he concluded that the majority of the dorsal vertebra cannot be flexed but only rotated. *Lovett* (1907) and *Elward* (1939) stated that flexion is not great and that extension is very slight in the thoracic spine. *McKendrick* in 1916 studied photos and made measurements of the spine in various attitudes. He observed and emphasized that there is no flexion in the dorsal spine. (From *Keller* 1924). *Monro* (1965), based on roentgen studies in flexion and extension, stated that thoracic spine motion under normal conditions and from a practical aspect is almost nonexistent.

Keller (1924) studied motion of the spine in living subjects by roentgenograms, electrical stimulation of the muscles of the thoracic spine and by careful measurements of markings on the skin. He disagreed with the statement of immobility of the dorsal spine. The investigations were reported as showing segmental motion in flexion and extension beginning with the 9th dorsal vertebra and moving caudally. He stated that the upper portion has poor motion in the

anterior posterior plane. Bakke (1931) also published roentgen studies of vertebral motion. He reported findings which differed widely with those of previous investigations describing segmental motion. Bakke described an *equal amount of flexibility at the various levels.*

There is marked variation in reports regarding the total range of flexion and extension in the dorsal spine. Virchow (1911) reported intersegmental motion of the thoracic spine. When added they come to 108.0° total flexibility in the sagittal plane between C7 and Th12. Bakke (1931) found 45.9° extension and 22° flexion. This constitutes a total flexibility of 67.9° with a ratio of approximately 2:1, extension vs. flexion. It is of interest to note that Fick (1904) reported total flexibility of the dorsal spine of 135° . Novogrodsky (1911) studied four cadaver specimens and reported a total of 62° for the intersegmental motion of the dorsal spine in flexion and extension.

Loebl (1967) conducted in vivo measurements in 176 normal subjects, using a special inclinometer, and made recordings with the spine in various positions including full flexion and extension. This is not intersegmental motion of course. He reported his findings for total flexion and extension as "far greater than is generally described". He noted that the dorsal spine contributed about 25% of the total range of spinal movement in flexion and extension.

What is the Extent and the Pattern of Lateral Bending and Rotation?

According to Keller (1924) Mc Kendrick reported an *absence of lateral flexion* in the dorsal spine. Keller (1924) wrote that there is *poor motion in lateral flexion.* He also found the upper portion less mobile than the lower. Gray (1967) stated that *lateral movement is free in any part of the column.* Lovett (1905) stated that though the entire dorsal spine participates in lateral bending *the larger portion of such motion takes place below the 10th dorsal vertebra.* In side bending in all positions he states that the 12th dorsal vertebra behaves as a lumbar vertebra. Lucas and Bressler (1961) found *the most mobile elements to be between the 3rd and the 7th thoracic vertebra in lateral bending.*

Novogrodsky (1911) reported a total lateral flexibility of 76° . Bakke (1931) found about 2° - 3° at each level for a total of 30.6° . Steindler (1955) reported 30° - 40° on either side or approximately 70° total.

A number of previous investigators agree that there is axial rotation in the thoracic spine (Weber, 1827; Hughes, 1892; Keene, 1906; Lovett, 1907; Davis, 1918; Keller, 1924; Arkin, 1950; Steindler, 1955; Roaf, 1958; Lindahl, 1962; Gregersen and Lucas, 1967). Their statements disagree, however, on the amount of rotation, its regional variation and the presence or absence of coupling of this motion with lateral bending.

Hughes (1892) described *axial rotation* from the 2nd dorsal to the 1st lumbar

vertebra as totalling 52.25°. Lovett (1905) studied cadavers and a live model whom he both selected and photographed carefully, observing that *rotation in the dorsal spine gradually diminishes in a cephalocaudal direction*. He accounted the following degrees of rotation from Th 1–Th 12: 51°, 50°, 50°, 49°, 47°, 43°, 40°, 34°, 27°, 25°, 21°, 17°. Steindler (1955) wrote that rotation was 40° to either side *totalling 80°* for the dorsal spine. Lindahl (1962) reported about 3°–4° of axial rotation at each level of the dorsal spine. Gregersen and Lucas (1967) inserted Steinmann pins in the spinous processes and conducted an in vivo investigation with seven subjects. They too found a smaller quantity of motion than did Lovett (1905). They stated that there was a *total of 74° of rotation in the dorsal spine* with an average of about 6° at each level. These writers noted that the *amount of rotation in the upper portion of the thoracic spine increases gradually from Th7 upwards*. When their subjects were walking, however, the maximum rotation was observed at the middle portion of the thoracic spine.

Is Rotation Coupled with Lateral Bending?

The issue of the presence or absence of a coupling of axial rotation with lateral bending has received the attention of a number of investigators (Schultness, 1902; Lovett, 1905, 1907; Feiss, 1908; Arkin, 1950; Steindler, 1955; Roaf, 1958; Tideström, 1958; Gregersen and Lucas, 1967). Here too there are differences of opinion. Roaf (1958) studied the spines of stillborns and observed that *the two motions occurred independently* in the thoracic as well as in the lumbar regions. Lovett (1905) studied cadaver spines and found *rotation and side bending to be inseparable*. In the *erect* and the *hyper-extended* positions he stated that the rotation was coupled with lateral bending. He noted it to be *toward the concavity of the lateral curve*. In other words, when bending to the left the axial rotation of the vertebrae was also to the left. However, he reported that in the *flexed* position the axial rotation was *toward the convexity of the curve with lateral bending*. To state it differently, when the flexed thoracic spine was bent to the left the axial rotation of the vertebrae was to the right. Arkin (1950) made roentgen investigations in 5 subjects and reported a *tendency for convex side rotation with lateral bending* in both the flexed and the extended positions. Feiss (1908) and Novogrodsky (1911) also reported *rotation of the vertebral body to the convexity of the lateral curve*. Tideström (1958) used a mechanical model of the spine to show that based on Polhem coupling *rotation is a necessary component of side bending in the spine*. The direction of the rotation was not stated. Gregersen and Lucas (1967) studied living subjects and found the *rotation of the vertebral bodies with lateral bending to be toward the concavity of the curve*.

Table 1 gives an outline of previous descriptions of thoracic spine motion.

Table 1. Outline of Previous Descriptions of Thoracic Spine Mechanics

Author year	No. of Subjects investigated	Method	Flexion and Extension	Lateral bending	Rotation	Coupling
Weber, E. H. 1827	3 cadavers, 2 males 1 female, live males age 20-32	Direct measurements	The majority of dorsal vertebrae cannot be flexed		Majority of dorsal vertebrae can only be rotated	
Hughes, R. W. 1882	2 cadavers, M age 20 M age 40	Attached metal pins to vertebrae; studied movement in relation to subjacent vertebra			2nd thoracic to 1st lumbar 20 yr. old 52.25°, 40 yr. old 99.8°. Lower portion moved less than upper	
Schulthess, W. 1902	Studied mechanical models			Pure side bending without rotation is impossible		Yes
Fick, R. 1904	1 cadaver	Direct measurement	Total flexibility 135°		Total amplitude 80°	Yes; to concavity of lateral curve
Lovett, R. W. 1905	3 subjects, 2 cadavers, 1 live ages 20-26	Pins in spinous processes, also photographed live model	Not an extensive motion for this part of the spine	Greatest in the mid-dorsal region	The major motion of the spine is rotation	Yes; Rotation to concavity of lateral curve. In flexed position, however, rotation is to convexity
Kreene, C. W. 1906	2 cadavers, 1 infant 1 adult M	Pins in spinous processes and tracing rods,			Can be effectively achieved by pressure applied to the appropriate corresponding ribs	

Author year	No. of Subjects investigated	Method	Flexion and Extension	Lateral bending	Rotation	Coupling
Novogrodsky, M. 1911	4 M cadavers, 2 fresh 2 formalin preserved	Studied inter-segmental motion with vertebrae fitted to measuring apparatus which indicated motion when loaded.	1st thoracic to 1st lumbar 62°	1st thoracic to 1st lumbar totaled 76°		Yes; to concavity of lateral curve
Virehow, H. 1911	1 cadaver	Plaster casts made of spec. in 3 positions in the full range of motion in the sagittal plane. Positions in plaster casts were then measured.	Total flexibility 1st thoracic to 1st lumbar 108.0°			
Davis, G. G. 1918	Stated in textbook no experiment described				Free in upper portion of dorsal region and gradually diminishes to absent in the lumbar region	Yes; to the concavity of the lateral curve
Keller, H. A. 1924	1 male	X-ray studies in vivo with careful skin-markings and measurements; electrical stimulation of muscles with subjects prone	There is poor motion in the upper regions in the anterior and posterior directions	Poor motion also in lateral direction; there is motion from the 9th thoracic down	Noted more rotation in the upper portion of thoracic spine	Yes; to the concavity of the lateral curve

Author year	No. of Subjects investigated	Method	Flexion and Extension	Lateral bending	Rotation	Coupling
Bakke, S. N. 1931	44, 20 males 24 females ages 3-79	X-ray investigation living subjects	There is an even grading of flexibility. Total flexibility of thoracic spine 67.9°, 22° flexion and 45.9° extension	Equal amount of flexibility, about 2-3° at each level; total 30.6°		
Steindler, A. 1955	Not stated	In vivo		Noted 30-40° to either side; total approximately 70°	Described 40° to either side for a total of 80° rotation in thoracic spine	Yes; to the convexity of the lateral curve
Roaf, R. 1958	2 fresh autopsy 1 infant 1 age 8	X-ray studies; also with pins as markers in spinous processes			Axes of rotation in region of posterior longi- tudinal ligament	No
Tideström, F. 1958	Mechanical model	Constructed mechanical model of spine to describe mechanism of coupling			Based on same principal as Folhem coupling rotation is necessary	Yes
Lucas and Bressler, 1961	3 frozen autopsy spec. ages 22, 32, 44	Spine with ligaments loaded and multiple rapid exposure photographs taken		Most flexible ele- ments appear to be between the 3rd and 7th thor- acic vertebrae		

Author year	No. of Subjects investigated	Method	Flexion and Extension	Lateral bending	Rotation	Coupling
Davis and Troup, 1965	13, ages 18-29	In vivo chronocyclophotographic study, reflective strips over spinous processes	Very little thoracic spine motion with no definite pattern			
Gregersen and Lucas, 1967	7, ages 20-26	In vivo with Steinmann pins in the vertebrae			6° at each level rotating from one extreme to the other; 74° total from 1st thoracic to 12th thoracic. The amount increases gradually from the 7th to the 1st thoracic	Yes; to the concavity of the lateral curve
Loebel, W. Y. 1967	176, ages 15-84	In vivo using an inclinometer	35° total for thoracic spine (not intersegmental total). This amount was about 25% of total flexion and extension for entire spine			

Where are the "Centers of Motion" for the Various Movements?

The question of a "center of motion" or an axis of rotation has been discussed by various investigators in relation to movement of all regions of the vertebral column. *Novogrodsky* (1911) considered the center of motion for combined lateral flexion and axial rotation to be somewhere in the anterior portion of the disc. *Dittmar* (1930) demonstrated a *moving center of motion* in the lumbar spine. *Elward* (1939) stated that there is *no single center of motion*. *Gianturco* (1944) with roentgenologic studies of the lumbar spine observed *wide variation of the axis of motion*. *Åkerblom* (1948) stated that the *center of motion was in the center of the disc* in the middle of the nucleus pulposus. *Rockwell* (1938) suggested a theoretical center in axial rotation somewhere in the anterior portion of the vertebral body. *Roaf* (1958) suggested that the *axis of rotation is somewhere in the region of the posterior longitudinal ligament*. *Rolander* (1966) found a *large number of motion centers* with little or no regional clustering. *Lysell* (1969) reported in his analysis of cervical spine movement that the *axis of rotation for flexion and extension was situated in the subjacent vertebra*. It was not possible for him to state whether the axis of motion is fixed or is mobile. He noted that in the combined motion of lateral bending and rotation there was very little movement of a measuring point in the anterior central portion of the moving vertebra. From this observation he deduced that this point was very close to the center of motion.

The broad variations in the description of thoracic spine motion noted in the preceding paragraphs is probably based on several factors. The investigators employed different experimental methods. Few subjects were analysed in most instances and the techniques of observation were rather imprecise. There is variation of opinion on several points. The extent of motion in flexion and extension and lateral bending does not seem to be at all agreed up. The question of the presence or absence of coupling of lateral bending with axial rotation remains contraversial concerning both its existence and direction. The descriptions of the regional variations within the thoracic spine are not consistent as regards each of these movements. The questions of the existence and position of "centers of motion" and the possibility of their movement remain unsettled. There is a paucity of information on the actual pattern of intersegmental motion.

PART I

TWO DIMENSIONAL ANALYSIS WITH CONTROLLED LOADS

Method

Material

The material for these experiments was removed at the time of routine necropsy at one of the three following institutions: University Hospitals, Gothenburg, Vasa Hospital, Gothenburg and City Hospital, Mölndal. The entire thoracic spine or some major portion of same was removed with a small portion of the attached ribs and the adjoining musculature. Table 2 summarizes the relevant data on the subjects from which the material was removed. There were 10 specimens in this part of the investigation. The age range is 16 to 83 years. Specimens with tumors, fractures, from patients with scoliosis and from patients with metabolic diseases known to affect bone were not included.

Handling and Preparation of Test Material

A fresh specimen was received sealed in a plastic bag. A roentgenogram was taken while the material remained sealed. A motion segment for this part of the investigation was always made up of one of the following: Th 1-2, Th 3-4,

Table 2. Autopsy Material Part I

Subject	Years of Age	Sex	Cause of Death
IV	64	F	bronchopneumonia
V	71	F	respiratory and circulatory insufficiency
VI	83	F	arteriosclerosis with cerebral infarction
VII	33	F	rupture of basilar aneurysm
VIII	16	F	status epilepticus with tetanus encephalitis
IX	33	F	diabetes mellitus with neuropathy
X	49	F	respiratory insufficiency
XI	46	M	myocardial infarction
XII	50	M	pulmonary edema
XIII	64	F	myocardial infarction

Th 5-6, Th 7-8, Th 9-10 or Th 11-12. On the basis of the roentgenograph and direct anatomical evaluation by the author the specimen was cut so as to include as many of the above defined motion segments as the material would allow. (Due to damage or errors at the time of removal from the body the entire thoracic spine was not always usable.) The remaining portion of the ribs were dissected away. The muscles were removed and the ligaments preserved. All soft tissue was removed from the superior one third of the more cephalad vertebrae and the inferior one third of the more caudad vertebrae of each motion segment. This and all handling of the specimen, unless otherwise stated, was carried out in a specially constructed high humidity chamber. This chamber maintained a relative humidity of 95 % or greater. The importance of maintaining a high humidity to preserve the physical properties of the annulus and the longitudinal ligaments has been well demonstrated by *Hirsch and Galante* (1967), *Galante* (1967) and *Tkaczuk* (1968). Specimens that were not to be analysed immediately were labeled, sealed and preserved in a deep freeze at -25°C . There is evidence that freeze storing does not affect the physical properties of bone (*Evans*, 1957; *Sedlin and Hirsch*, 1966), the annulus fibers of the disc (*Hirsch and Galante*, 1967; *Galante*, 1967), nor the ligamenta flava (*Akerblom*, 1948).

The motion segment(s) (MS) was prepared for testing as described below. Those that had been stored by deep freeze were permitted to thaw overnight at $+6^{\circ}\text{C}$ while still sealed. The unfrozen MS was treated as follows in the high humidity chamber. The MS was balanced in a special metal tray so that the disc was horizontal with a flat level surface. This sometimes necessitated removal of a portion of the more caudal spinous process. The caudad member of the MS was fixed with a polyester cast (*Hirsch*, 1964). Due to the marked vertical direction of the spinous process in the middle portion of the thoracic spine (Fig. 2), it was sometimes necessary to remove the distal portion of the spinous process of the cephalad vertebra. This was done so that the upper vertebra would not be fixed by the polyester. A polyester cast was also constructed about the superior one third of the cephalad vertebra (Fig. 10, No. 5). This cast conformed to the general configuration of the vertebra and its top was horizontal and level (checked with spirit level). When the polyester had hardened the MS with the metal tray was sealed in a plastic bag and nails were affixed to the vertebra. Two nails were placed anteriorly at each end of an imaginary vertical line 20 mm long. The middle of this line was in the midline of the frontal plane of the vertebra and at approximately the middle of the height of the disc at that point. This would be nails AS and AI shown on the sagittal plane of Fig. 6. Nails PS and PI shown on the same diagram were placed in the spinous processes in the same sagittal plane as nails AS and AI and also vertical to each other. Nails RS and RI were placed on the right side

POSITION OF EXTENSOMETERS AND DISPLACEMENT GAUGES

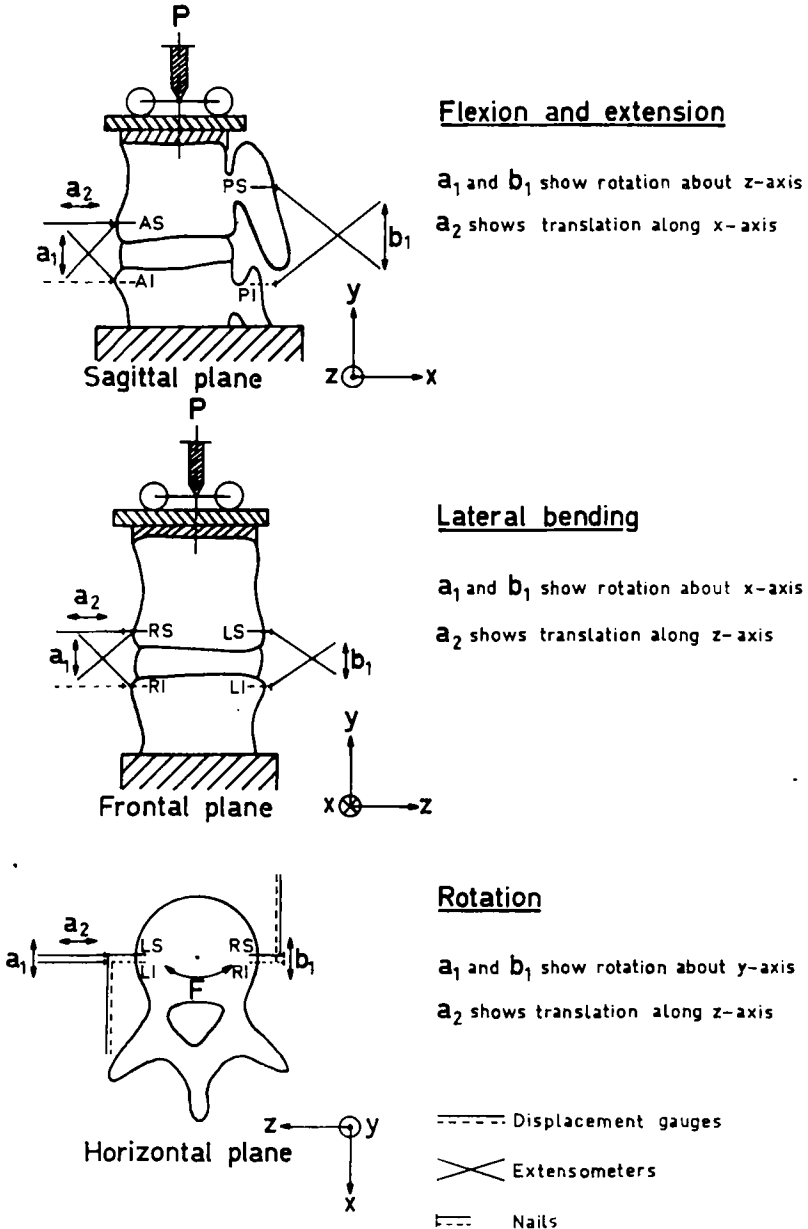


Fig. 6. Diagrammatic representation of planes, nails, and motion gauges, (P) is load, (F) is moment. The dashed lines represent nails and displacement gauges on the lower fixed vertebra. See text for detailed explanation.

of the vertebra midway the anterior posterior diameter of the body. The nails both lie in the frontal plane and vertical to each other. Their heights corresponded approximately to those of the anterior nails AS and AI respectively. Positions of nails LS and LI had the same specifications but were placed on the left side of the vertebra. Nails RS, RI, LS and LI are shown in the frontal and horizontal planes of Fig. 6. Due to vertebral asymmetry and measuring error the above defined positions of the nails represent accurate approximations and not precise relationships. All nails were affixed through the plastic seal. The MS at this point was ready for analysis.

Experimental Apparatus

The experimental apparatus used in this part of the present investigation is the same equipment as was employed by *Hirsch* (1951), then subsequently modified and used by *Rolander* (1966). The same methods of calibrations and the same errors of measurement apply. The reader is referred to the latter reference for detailed description of the equipment and its use. The salient features of the testing material are summarized below. The equipment is photographed and shown in block diagram (Figs. 7 and 8).

The *compression apparatus* is designed so that a loading force of a known quantity, position and direction can be applied to the MS. The load is powered by compressed air. The amount and rate of application of the load can be controlled by standard valves. The load can be varied from 0-200 Kp and is recorded through electro-dynamometers. A trolley resting on four ball-races resting on a steel plate is placed between the loading edge and the top of the MS. This arrangement permits the specimen to rotate about some axis parallel to the loading edge and to translate along some axis perpendicular to it. (Fig. 7, No. 2).

Movement of the specimens in the horizontal (x, z) plane was recorded by *displacement gauges* (Fig. 7, No. 4). *Extensometers* (Fig. 7, No. 5) were used to record motion in the vertical planes sagittal (y, x) and frontal (y, z). In both cases motion is transformed into an electrical impulse created by the displacement of the antimagnetic stainless steel tip of a brass shaft inside an electromagnetic coil. This arrangement is called a *differential transformer* (Fig. 7, No. 9). There is an error of measurement inherent in any such motion gauge. In the case of the horizontal gauge, when the specimen rotates about its z axis (as an example see sagittal plane Fig. 6), the new position of the measuring point lies on the arch of a circle having a radius equal to the length of the measuring arm (approximately 80 mm). As the vertical displacement is ± 2.5 mm the correction for the horizontal displacement is given by the sine of a very small angle. Consequently, it does not affect the recorded value. In

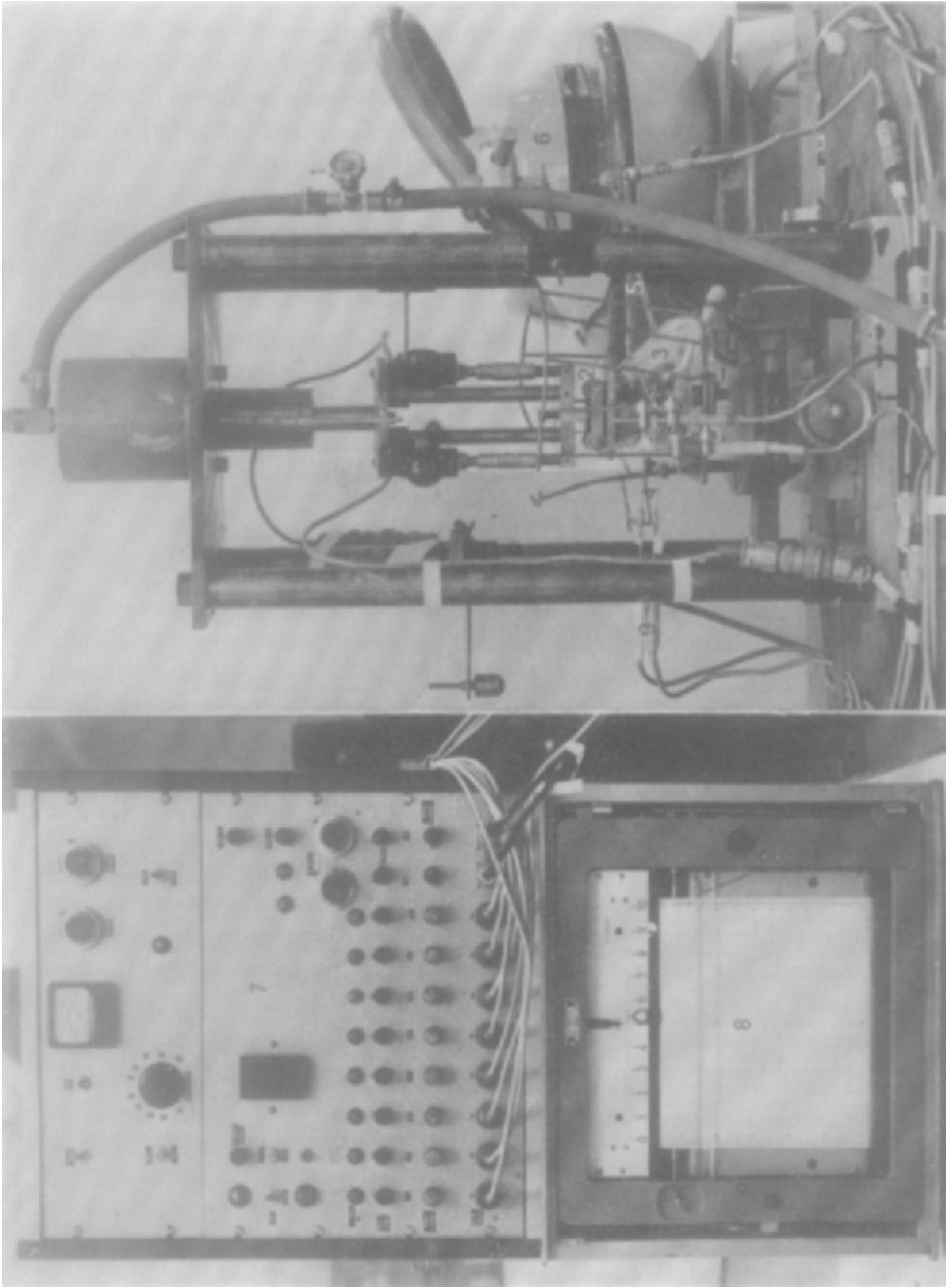


Fig. 7. Experimental Apparatus. To the right is the compression device; (1) valve and air hose, (2) loading edge, trolley and steel plate, (3) specimen in plastic seal, (4) displacement gauges, (5) extensometer, (6) humidifier and hose, and (9) differential transformers. To the left is the (7) amplifier and channel selector and the (8) recorder.

BLOCK DIAGRAM

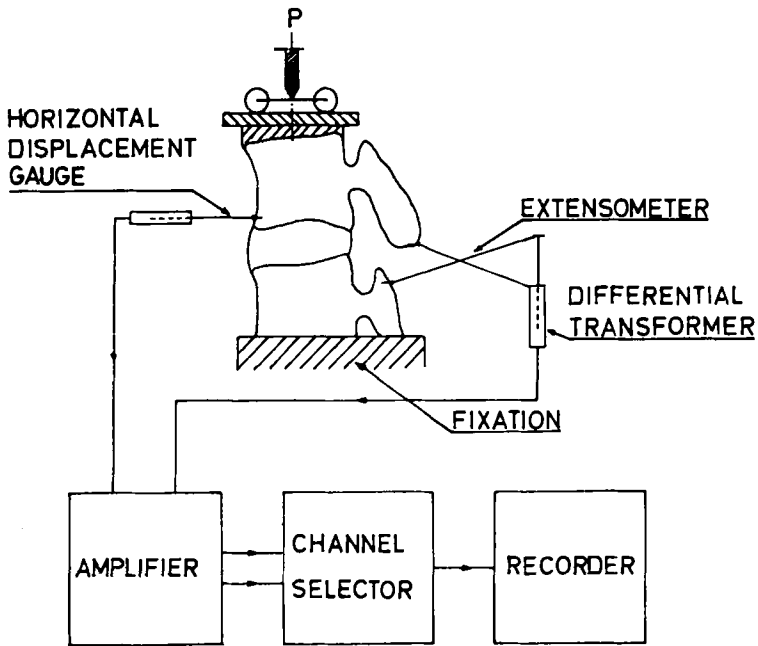


Fig. 8. Diagrammatic representation of equipment. (P) is load applied to motion segment.

the case of the vertical motion gauge, the horizontal displacement of the measuring point is along the arch of a circle with a radius equal to the distance between the tips of the gauges legs. This distance is $25 \text{ mm} \pm 5 \text{ mm}$. Because of the relatively short radius for the vertical gauge there could be a large percentage of error in the vertical displacement, if there was a large horizontal displacement. The fact is, however, that the horizontal displacement has been quite small both in relative and absolute terms (Rolander, 1966). Horizontal displacement was also very small in this investigation. The median horizontal displacement for any given increment of force is estimated at 0.01 mm for this series.

The information from the extensometers and displacement gauges was fed into a recording system. This system included an *amplifier*, a *channel selector* and a *recorder* (Figs. 7 and 8). The reading error on the recorder was $\pm 0.005 \text{ mm}$ and $\pm 0.1 \text{ Kp}$.

An electrically driven *humidifier* with hose and a fiber glass horn at the end was employed. Its purpose was to maintain a high humidity at that point in the procedure when it was necessary to disrupt the plastic seal.

Roentgenograms were taken employing a portable *Schönander* machine with a 2 mm focus. Those used for measuring were taken at a target to focus distance of 1 meter with about 10 cm between the center of the target and the film. Roentgenographs were taken of a notched radiopaque measuring instrument at five positions in the 5 mm focus to film range in which the measuring points (nails) would be found. The distance between the same two points represented on each of the five roentgen films was measured. The mean of these measurements was taken. The *actual* distance was then measured on the instrument. The measurement on the radiograph was found to represent an 8.8% enlargement of the actual distance. This information is employed in all calculations based on roentgenographic measurements under the above conditions.

An Amsler *planimeter* was employed to measure the area of a tracing of the horizontally sectioned disc of each motion segment after testing was completed. The accuracy of this instrument in the stated measurement was 0.10 cm².

Procedure for Analysis of Motion Segments

The sealed MS with its nails in place and the lower vertebra fixed in the metal tray was attached firmly to a loading platform in the compression devise. The MS was positioned so that its sagittal plane could be roentgenographed. The platform was then rotated 90° and its frontal plane similarly pictured. The horizontal displacement gauges and extensometers were then attached as indicated in Fig. 6 (sagittal plane). The calibrations were checked. By employing a scale on the compression devise (reading accuracy ± 0.25 mm) and a pointer it was possible to make an accurate approximation of the diameter of the vertebral body in the sagittal and the frontal planes. From these diameters the 25, 50 and 75% positions shown in Fig. 9 could be determined for the two planes. These positions are employed in order to apply loads to the MS in such a way as to simulate the different movements of the spine. They have the advantage of making comparisons of different motion segments more meaningful in that they have all been loaded at relatively the same points.

The extensometers and horizontal displacement gauges were put into place to prepare the MS for testing. The extensometers were held in position by rubber bands attached to an encircling brass cage. The brass cage is also affixed to the loading platform. By adjusting the tension and position of these rubber bands the extensometer could be balanced with its points positioned in shallow holes drilled in the previously described nails. The horizontal gauges were similarly affixed to their appropriate nail heads with rubber bands. All measuring points were derived from points on the specimen. The extensometer itself recorded all vertical motion in relation to the subjacent vertebrae.

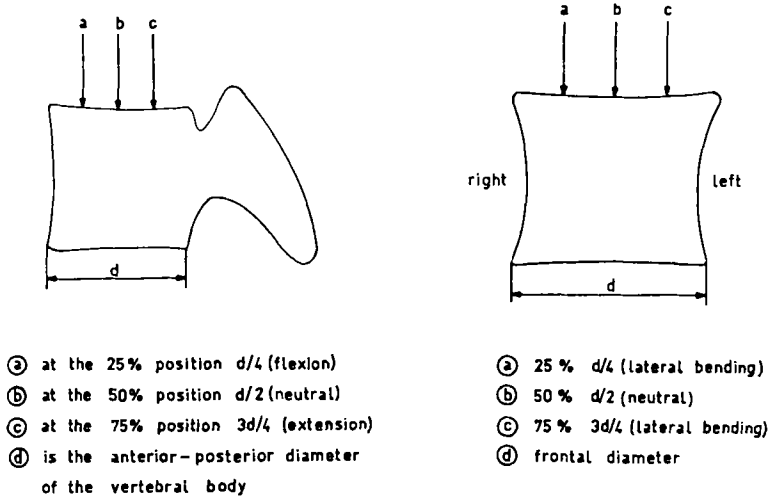


Fig. 9. Diagram to show determination of loading position in sagittal and frontal planes. See text for explanation.

The *paired* horizontal displacement gauges provided information about relative horizontal motion between the vertebrae. There were no external reference points. With these conditions prevailing any extraneous motion of the compression apparatus could not affect the recorded information which represented the movement between the two vertebrae.

The specimen was first pre-stressed. This variable was introduced to standardize the starting points and to minimise hysteresis. *Virgin* (1951) stressed human intervertebral discs with the same load one minute apart. He stated that it was conclusively demonstrated that the hysteresis during the second test was always appreciably less than during the first test. In this study the pre-stress load was applied at the 50% position of the sagittal plane. Its magnitude was 50 Kp for the upper two motion segments (i.e. Th 1-2 and Th 3-4), 60 Kp for the middle two and 70 Kp for the lower two. The load was applied five times. A 5 minute interval was observed before the testing series began. During preliminary experiments it was noted that most (>98%) of the residual deformation (hysteresis) passes in the first minute. After 5 minutes all or nearly all had passed away. Any remaining very small quantity could persist for several hours. Because of this problem any residual deformation lasting more than five minutes was handled by either of two maneuvers depending on the dictates of the experiment. It was either recorded and subtracted from subsequent deformation or taken away by a slight external force. These manipulations made all reading and consequently all motion comparable as far as the starting points were concerned.

The forces to be applied were between 10-40 Kp, 20-50 Kp and 30-70 Kp for the upper, middle and lower two motion segments respectively. These ranges were selected so as to effect gradations of movement. The intent was to apply enough of a load to assure significant motion but to avoid deformation of the bone. At the same time the design was to select a range that could reasonably be assumed to include and exceed that of the superincumbent weight of the body. This is discussed in more detail subsequently.

The loading tests were conducted in the following manner. The load was applied at the various positions 50, 25 and 75 %, first in the sagittal plane; then the MS was rotated 90° and the loads were applied in the three positions for the frontal plane. For example Th 12 would be loaded in the sagittal plane at the 50 % position with 10 Kp followed by serial additions of 10 Kp to 20- 30-, 40- and finally up to 50 Kp. These increments and ranges of load were not followed precisely but served as guidelines. However, the precise load for each recorded movement of the specimen was indicated by the recorder. After loading at the 50 % position the subject was then similarly loaded at the 25 and the 75 % positions. Each series of loads at a given position was followed by a 5 minute pause for the residual deformation to pass. The resultant position was then recorded. Between the 25 and the 75 % positions a very small external force (a light touch with a probe) was sometimes applied to move the specimen toward the initial starting position. This resultant position was recorded and subsequent motion taken in relation to it.

The rotation test was carried out as follows. A threaded steel bar 4 mm in diameter and 17 cm long was pointed at one end. This bar was drilled through the body of the superior (free) vertebra of the MS. The bar was placed horizontal to the loading platform and in the upper one third of the vertebral body at approximately the middle of its anterior posterior diameter (Fig. 10, No. 1). A metal ring was secured between two ordinary nuts at either end of the bar. The rings were positioned 4.5 cm from the respective entrance and exit of the bar into and out of the vertebra. This positioning caused the lever arm of the moment and thus the force to vary directly with the frontal diameters of the vertebrae. Each ring was wired to a cable which was fashioned to accommodate a series of measured weights at its distal end. A system of pulleys was constructed which could be adjusted to correspond to the height and horizontal position of the attached end of the cable. The cable was held perpendicular to the bar and in the same horizontal plane. The pulley system could be adjusted to maintain these same conditions with the directions of the cables reversed. Small grooves had been cut into the necks of the nails at positions LS, LI, RS and RI (Fig. 6 horizontal plane). Specially constructed plexiglass connectors were employed. They fit into the groove of the nail on one end and accepted the displacement gauge on the other. This arrangement made it

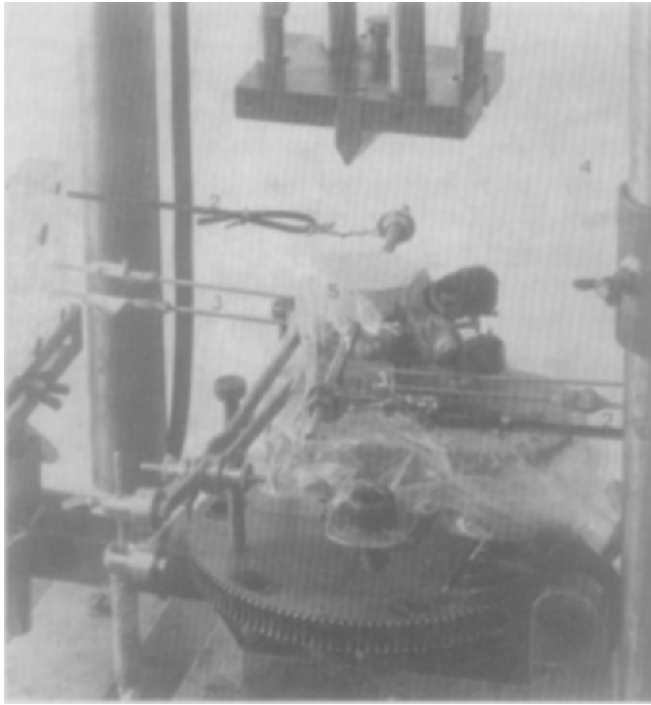


Fig. 10. Photograph shows motion segment set-up for testing *rotation*. (1) metal pin in vertebral body, (2) wires through which moment is applied, (3) horizontal displacement gauges, (4) horn from humidifier, (5) polyester cast. See text for explanation.

possible to record motion in the horizontal (xz) plane (Fig. 10, No. 3). The axial rotation was then tested by adding measured weights of equal quantity to each cable after the pulleys had been adjusted as described above. The initial load to each cable was 0.25 Kp. The load was then increased on each cable by 0.5 Kp increments up to 1.75 or 2.25 Kp. The cables were arranged to test the MS first in the counterclockwise direction ($+\theta_y$) then in the clockwise direction ($-\theta_y$).

An outline is provided to show the procedure as described above.

I. Schedule of Testing

- A. MS was pre-stressed at the 50 % position in the sagittal plane.
- B. Motion in the sagittal plane was tested.
 - 50 % position
 - 25 % position—flexion ($+\theta_z$)
 - 75 % position—extension ($-\theta_z$)

C. Motion in the frontal plane was tested.

50 % position

25 % position—bending to right ($-\theta x$)

75 % position—bending to left ($+\theta x$)

D. Motion in the horizontal plane was tested.

Counterclockwise vertebral body turns to left ($+\theta y$)

Clockwise vertebral body turns to right ($-\theta y$)

II. Loads employed

A. Loads for Sagittal and Frontal Testing

Pre-stress		Range for Testing
Th 1-2 & Th 3-4	50 Kp	10-50 Kp
Th 5-6 & Th 7-8	60 Kp	20-60 Kp
Th 9-10 & Th 11-12	70 Kp	30-70 Kp

B. Loads for Axial Rotation

2.75-30.05 Kp cm

Range varied directly with frontal diameter of superior vertebra.

In Fig. 10 one can see two nails positioned at the side of the upper vertebrae. The nails were placed along a vertical line perpendicular to the loading platform. They were used to check with an additional extensometer (not shown in photograph) for deformation of the vertebra. Several motion segments from different thoracic levels were arbitrarily selected and tested during the pre-stress. There was no indication of deformation. In some instances loads up to 100 Kp were applied without deformation. During the routine testing of motion loads of such great magnitude were not employed. Most probably for the range of stresses applied in this investigation the vertebrae behaved as rigid bodies.

Removal of Posterior Elements

An additional experimental variable was introduced into the described routine. The variable was introduced in order to compare, in the same specimen under the same conditions, the motion with and without the posterior elements. It was felt that such comparisons would give some insight into the question of the role, if any, that these elements play in the mechanics of the thoracic spine. For the purpose of this investigation the posterior elements (PE) shall be defined. This term will be used to designate the following structures between any two vertebrae: the facet joints, the intertransverse ligaments, the yellow ligament, the inferior $\frac{1}{2}$ of the laminae and the spinous process. This leaves only the intervertebral disc and the anterior and posterior longitudinal ligaments connecting the two vertebrae.

After the previously described manipulations were completed with the MS remaining in the apparatus the PE were removed. The plastic seal was cut and with ordinary surgical instruments the task was accomplished without having to remove or even change the position of the MS. Fig. 10 shows a MS with this operation completed. When the plastic seal is broken the humidifier (Fig. 10, No. 4) is directed on to the specimen in order to maintain a high humidity. The MS is then loaded again exactly as when it was intact. Thus, the MS is tested in the same planes with the same range of loads at identical points of application.

Data Processing, Description and Comments

Five discretely increasing loads were applied to each MS at three positions in the frontal and sagittal planes, first on the intact vertebra then with the PE removed. There were eight to ten observations of rotation about the y axis resulting from discretely increasing moments on each MS with and without the PE. As there were 50 motion segments, this constituted close to 4,000 angles to be calculated from the raw data. Computer analysis of the data was therefore employed using the following mathematical approach. The rotation of a body in a plane can be determined by the movement of two points of the body in that plane. The movement of the points in each of the three planes is represented by a_1 and b_1 in Figs. 11 and 6. Fig. 6 also explains how these values come from the measuring instruments. The distance B_2 shown in Fig. 11 is measured from a roentgenograph of the MS. The 8.8% magnification is corrected for during the computer analysis of the data. The angle of rotation θ in a given

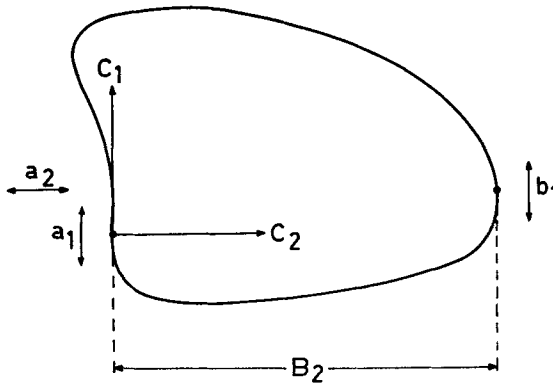


Fig. 11. Diagram shows information needed to calculate angle of rotation and instantaneous axis of rotation of a rigid body rotating in one plane. A point plotted on the coordinates C_1 and C_2 gives the location of the instantaneous axis of rotation for the body.

roentgenographic plane can be calculated by the formular:

$$\theta = [(b_1 - a_1) / B_2]$$

Information about horizontal movement is provided by a_2 . With these informations it is possible to calculate the position of the instantaneous axis of rotation, that is; the position on coordinates C_1 and C_2 .

$$C_1 = a_2 / \theta$$

$$C_2 = a_1 / \theta$$

Cumulative force was plotted against cumulative displacement in angles for all MS in all planes of motion as shown in Figs. 12 and 13. From the example given it can be readily observed that the points fit quite nicely to a straight line. This visual observation is supported by statistical evaluation which employed the "Method of least squares" to test the extent to which the points fit a straight line. Consequently, it was possible to extract from the slopes meaningful approximations of the cumulative load and cumulative displacement in angles *between* the actual experimentally determined points. A load of 6 Kp/cm² and a moment of 20 Kp cm were selected as the standard forces to be employed for extensive evaluation. For this load and moment the cumulative displacement in angles of all the MS in all conditions of testing was extracted. This additional analysis of the data was included to offer a meaningful comparison of the motion of a large number of MS from different subjects under conditions of a standardized force and constant relative point of application. These extracted quantities of angle shall subsequently be referred to as the standardized motion(s) (SM).

There are several sources of error operative in the results obtained in this part of the analysis. The errors can be divided into two groups: namely, those having to do with experimental factors and those related to the mathematical analysis. The mathematical errors arise from the assumption that, for the calculation of θ for small angles, the movement of the points a_1 and b_1 represent movement along the arch of a circle. This error was calculated for angles of the quantities listed in Table 3. One is reminded that angles presented in the results are *cumulative* values. The actual calculated angles that go to make up the cumulative values are usually less than 3°. Errors involved in the experimental method are difficult to generalize about, as their influence varies tremendously in quantity and direction. It is possible to be specific about such

Table 3. Percentage of Errors in Calculated Angles

Calculated angle	1°	3°	5°	8°	10°	15°
Percentage of error	0.02%	0.14%	0.38%	0.98%	1.54%	3.58%

errors only in a specific set of circumstances. Some of the errors have been discussed. Other errors are those having to do with the measurements of B_2 (± 0.5 mm) and the variations in the positions of the nails and extensometers. To provide some guideline to the experimental errors a geometrical analysis and a mathematical estimate of the errors of a representative case were carried out. The conditions were chosen so as to facilitate the effective operation of the errors. This analysis estimates the maximum error of θ to be in the range of 3–4 %.

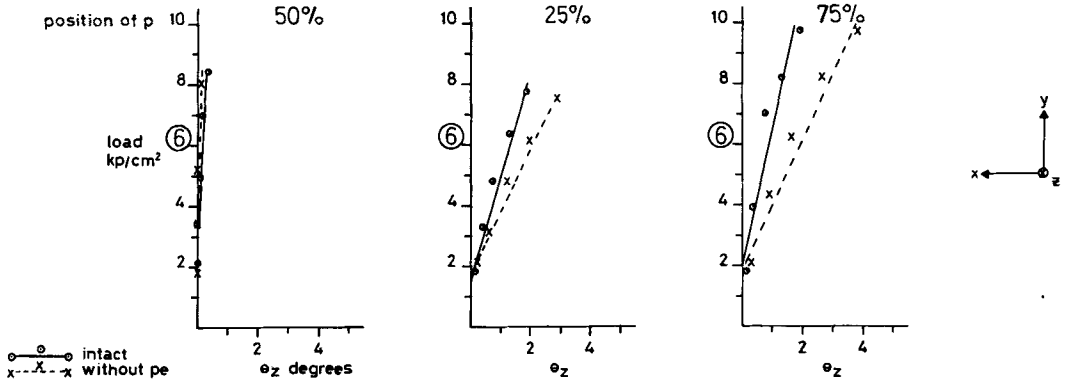
Results and Interpretation

The Effects of Various Loads and Moments on the Movement of the Motion Segments

The data for all fifty MS was plotted as shown in Figs. 12 and 13. This particular example is used because it is thoroughly representative. In this section the motion referred to is rotation in all instances. There was generally little or no motion when the MS was loaded at the 50 % position. This was the case for both the frontal and the horizontal planes. In the sagittal plane there was generally more motion when the load was applied to simulate flexion of the movable vertebra (25 % position) than when the load was applied to cause extension (75 % position). In the experiments on axial rotation (θ_y) there was a pattern for the slopes of the force deflection curves. They tended to increase as observations of the different MS were made in a cephalocaudal sequence. See Fig. 14. Table I in the Appendix gives the basis for statistical interpretation of differences in these slopes for all subjects. The standardized motion of the various levels for the different subjects is given in Appendix Table II, the means of the total motion in various experimental conditions is shown in Appendix Table III. It is apparent that when flexion is simulated the movement is almost always greater than when extension is simulated. If these two movements are combined the means of the combined sagittal motion can be seen to increase at the more caudal levels. See Fig. 15. Statistical evaluation of this trend gently supports this statement and its graphic representation at the 0.10 level of confidence. Appendix Table IV gives the information for this statistical interpretation. Similar evaluation of the SM in the frontal plane graphically and statistically implies more frontal motion at the lowest MS when compared with the intermediate levels. See Fig. 16 and Appendix Table IV. A comparison of the means of the SM in axial rotation at the different levels shows this motion to decrease as the observations move caudally. Here again statistical analysis lends corroborative support with a 10% level of emphasis (Fig. 17, Appendix Tables III and IV).

Based on this data, certain statements can be made about the behavior of thoracic spine MS when known forces are applied under controlled conditions. Graphical and statistical analyses of the material show greater motion in flexion

SAGITTAL PLANE



FRONTAL PLANE

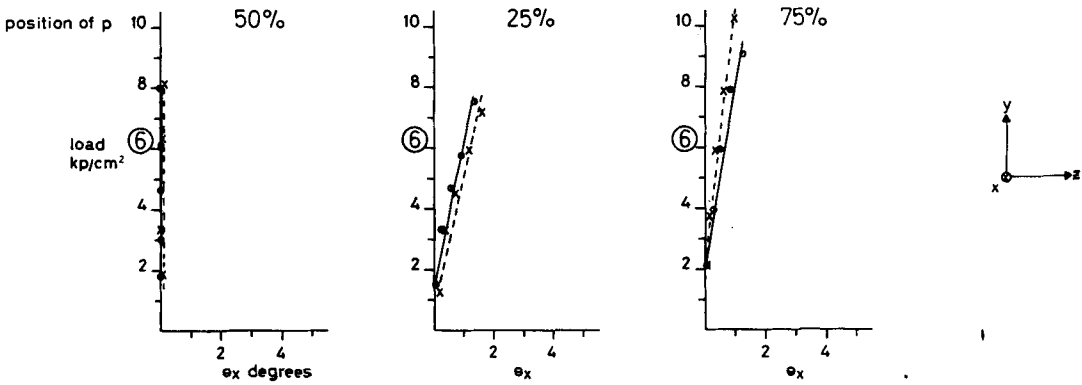


Fig. 12. Graphic representation of cumulative load and cumulative motion in angles. See text for explanation.

than extension. There is a definite tendency for greater flexion and extension at the lower levels as compared with the intermediate levels. Motion in the frontal plane (lateral bending) shows also a tendency for larger quantities of movement at the lower MS when compared with the intermediate levels. Axial rotation is greater in the upper levels and shows stepwise decrease as observations are made cephalocaudally.

Effects of the Removal of the Posterior Elements

The behavior of the MS with the posterior elements removed is also recorded on Figs. 12 and 13 and Appendix Tables II and III. In these two dimensional

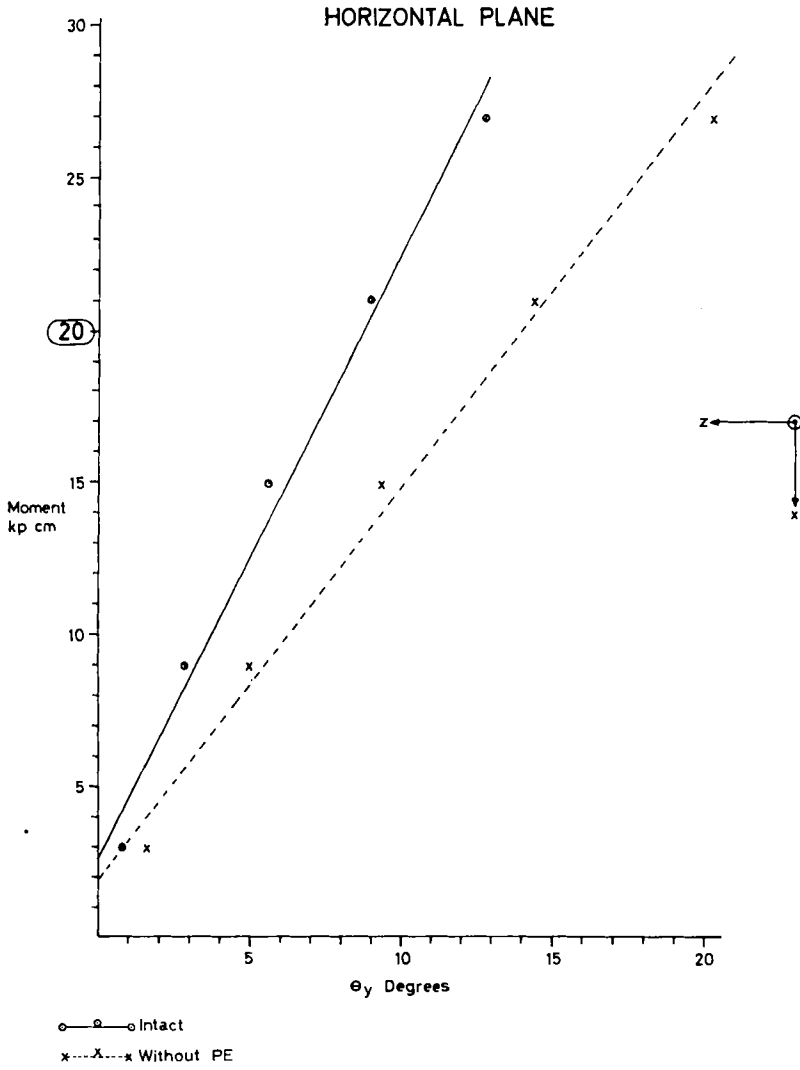


Fig. 13. Graphic representation of cumulative moment and cumulative angles. See text for explanation.

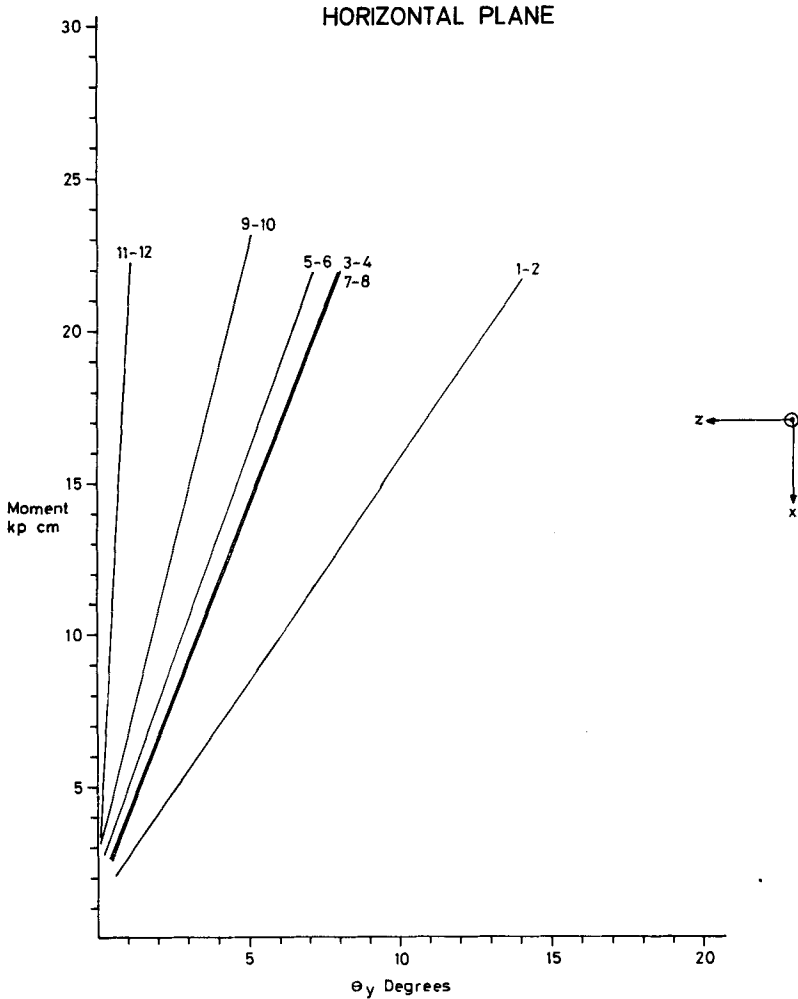


Fig. 14. Comparison of slopes for cumulative moment and cumulative motion in angles for different vertebral levels in one subject. See text for discussion.

studies it can be said that removal of the PE effected significantly the motion in several parameters. Visual evaluation of the slopes as seen in Fig. 12 reveals slopes of a more acute angle with the horizontal at the 25 % and 75 % positions in the sagittal plane after removal of the PE. Furthermore, the slopes were shifted toward a higher range of cumulative angle values. This general trend could be observed as an over all trend by inspection of the other 49 graphs like Fig. 12. The same generalization characterizes the change in axial rotation demonstrated in Fig. 13. Statistical analysis was carried out. The Sign test

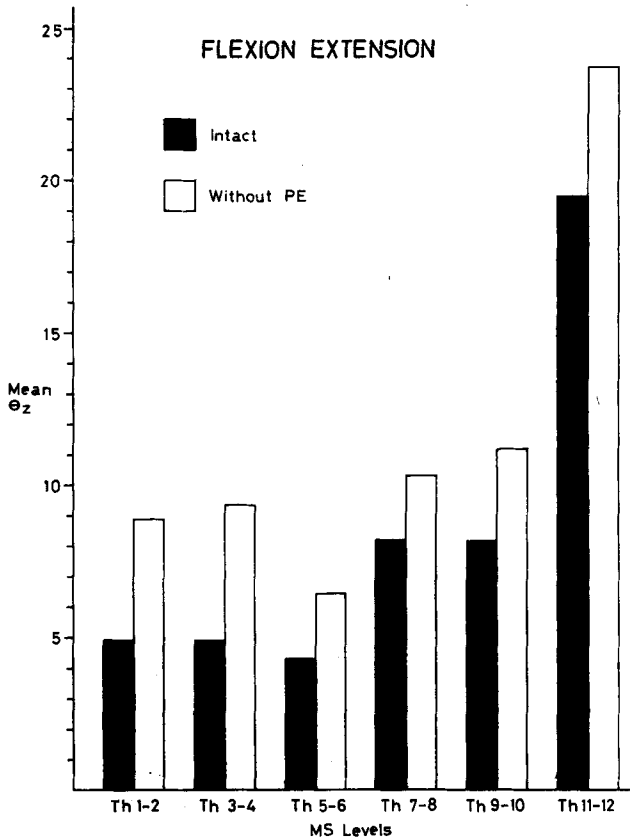


Fig. 15. Graphic representation of means of standardized motion of combined flexion and extension at the different vertebral levels, with and without the posterior elements. See text for description.

was employed on the hypothesis, that the mean difference with and without the PE is zero (*Brownlee, 1965*). This test was carried out for all the types of motion described except that at the 50 % position in the frontal and sagittal planes. Statistically significant differences were noted in the slopes after removal of the PE at the 75 % position in the sagittal plane and with the tests for axial rotation. These differences were significant at the 0.05 level of confidence and in the positive direction for the cumulative angle values. In other words graphic and statistical analysis of the data shows that with removal of the PE there is a greater motion per unit force when such force is applied to simulate extension and axial rotation.

The standardized motion (SM) was also studied to recognize any effects of the elimination of the PE. Here too the differences were evaluated by the

LATERAL BENDING

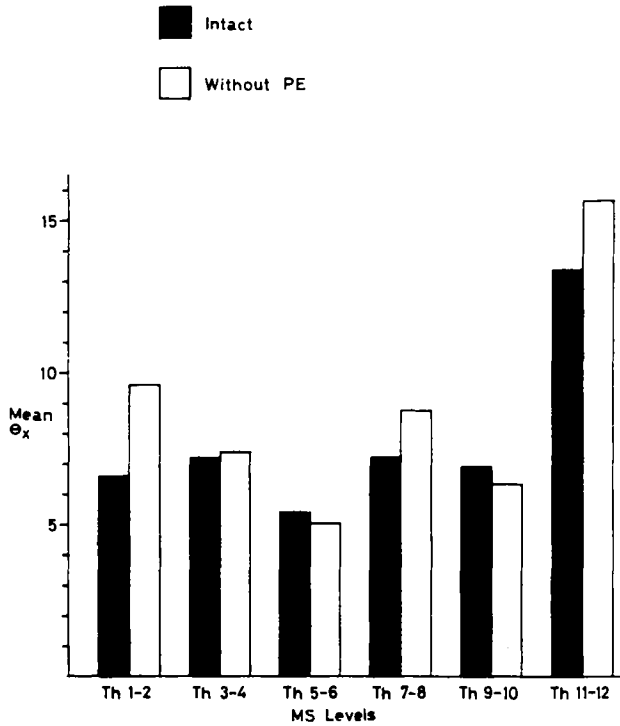


Fig. 16. Graphic representation of means of standardized motion of combined lateral bending at the different vertebral levels, with and without the posterior elements. See text for description.

Sign test. In these observations differences were noted at the 25% and 75% positions in the sagittal plane and with axial rotation. These differences again are in the direction of an increase of motion and they are significant at the 0.05 level of confidence. Figs. 15, 16 and 17 show graphically all the differences in the amount of motion in the various planes with and without the posterior elements.

Instantaneous Axes of Rotation

Calculations of the instantaneous axes of rotation (IAR) were carried out and plotted on tracings of the corresponding radiographic views of all the motion segments of the three youngest and one of the older subjects. Data

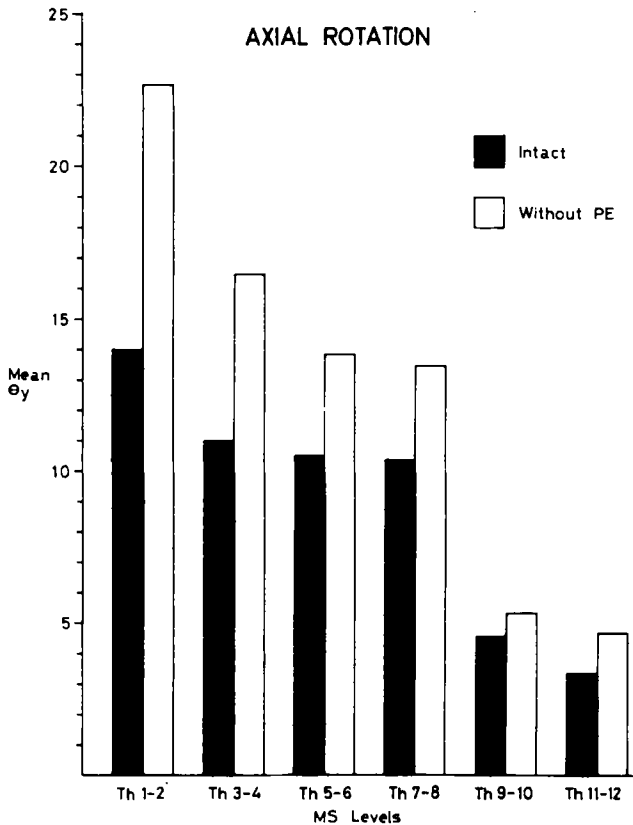


Fig. 17. Graphic representation of means of standardized motion of axial rotation at the different vertebral levels, with and without the posterior elements. See text for description.

processing took into account radiologic magnification and adjusted the C_1 & C_2 calculations to make the location of the IAR correspond accurately to the image on the film.

Fig. 18 shows representative examples of the IAR in the sagittal plane. The majority of the MS showed clustering of the points within a 5 mm diameter circle. In all instances the axes for extension were located above those for flexion. Those for extension were located above the disc and more anteriorly, while those for flexion were found below the disc and posterior to the extension axes. In a small minority of examples the axes for extension were above the body of the moving vertebrae. This can be seen in subject VIII Th 5-6, Fig. 18. When the posterior elements were removed, the IAR generally remained clustered and moved only a small distance away from the corresponding points for the intact vertebrae (subject IX Th 9-10, Fig. 18). The representa-

TWO DIMENSIONAL ANALYSIS
OF INSTANTANEOUS AXES OF ROTATION IN
SAGITTAL PLANE OF ROENTGENOGRAM

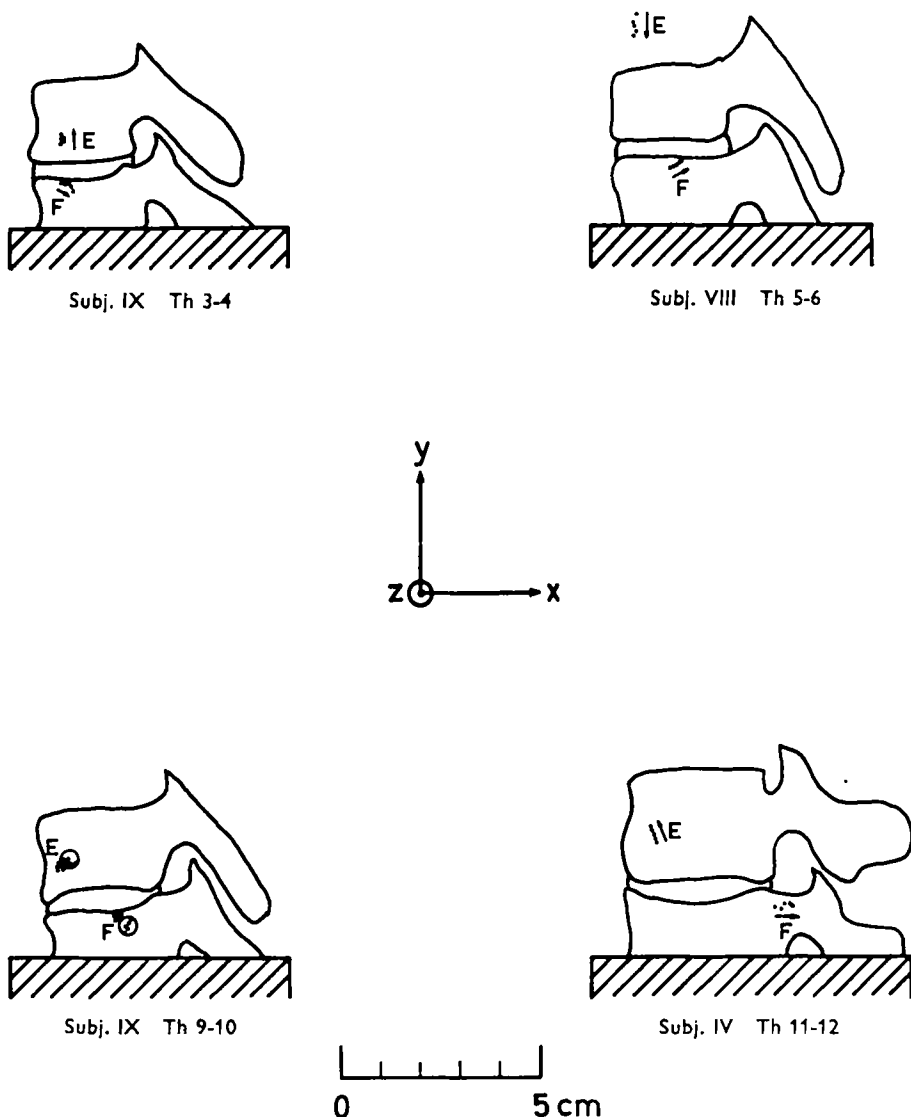


Fig. 18. Examples of instantaneous axes of rotation. (E) indicates the axes when vertebra was loaded at the 75% position (extension). (F) indicates the axes when vertebra was loaded at the 25% position (flexion). The circles show the corresponding IAR after the posterior elements were removed. The diagrams represent actual tracings from roentgenograms. See text for further description.

TWO DIMENSIONAL ANALYSIS
OF INSTANTANEOUS AXES OF ROTATION IN
FRONTAL PLANE OF ROENTGENOGRAM

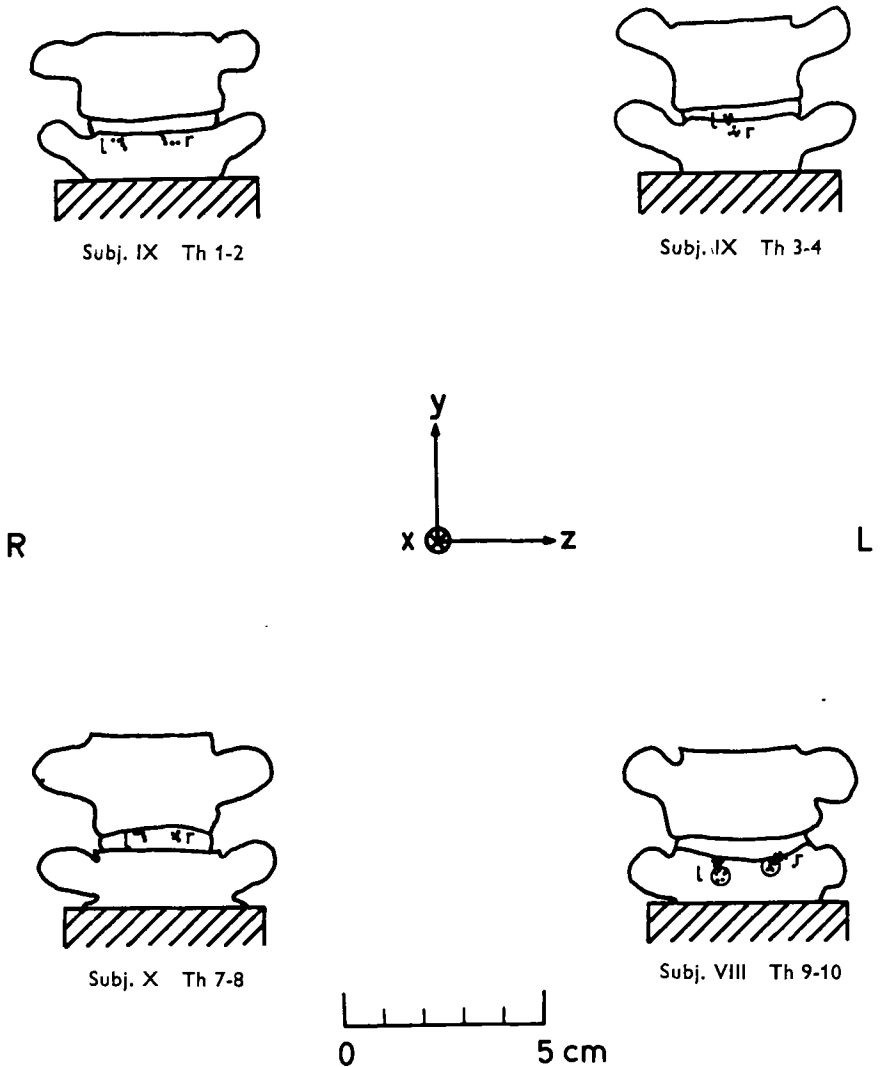
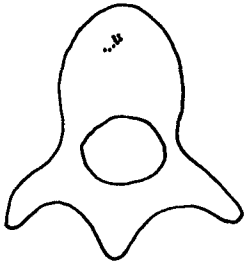
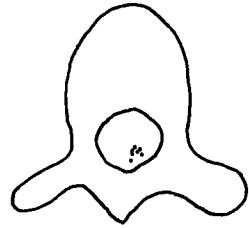


Fig. 19. Examples of instantaneous axes of rotation. (l) indicates the axes when vertebra was loaded at the 75% position (left lateral bending). (r) indicates the axes when the vertebra was loaded at the 25% position (right lateral bending). The circles show the corresponding IAR after the posterior elements were removed. The diagrams represent actual tracings from roentgenograms. See text for further description.

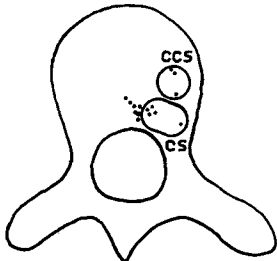
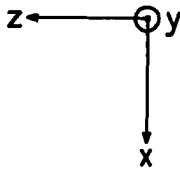
TWO DIMENSIONAL ANALYSIS
OF INSTANTANEOUS AXES OF ROTATION
IN HORIZONTAL PLANE OF ROENTGENOGRAM



Subj. XII Th 5-6



Subj. XIII Th 7-8



Subj. XII Th 9-10



Subj. XII Th 11-12

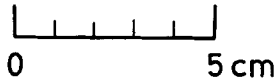


Fig. 20. Examples of instantaneous axes of rotation. (c) indicates those axes when rotation was clockwise. (cc) indicates those axes when rotation was counterclockwise. (cs and ccs) show the same without the posterior elements. The diagrams represent actual tracings from roentgenograms. See text for further description.

tive examples of IAR for the frontal plane are depicted in Fig. 19. Here as in the sagittal plane there was clustering of the points. On left lateral bending (positive rotation about the x axes) the IAR tended to cluster to the right of the midline. Conversely with right lateral bending (negative rotation about the x axes) the IAR were observed to be to the left of the midline. This pattern was evident in the data presented by *Rolander* (1966) with movement of the lumbar spine in the frontal plane. Again ablation of the posterior elements resulted in only minimal movement of the still clustered IAR (Fig. 19 subject VIII Th 9–10).

The IAR in the horizontal plane during axial rotation has been calculated and depicted in the same manner in Fig. 20. All motion segments for subjects XII and XIII were analysed. It should be mentioned that for technical reasons these points are not considered to be entirely as accurate as for the preceding two planes. Rotation was tested in two segments counterclockwise then clockwise, and generally the points were clustered. The groups of IAR tended to be in the midline at different points along the x axis. Removal of the posterior elements resulted in a somewhat greater shift here than was noted in the preceding two planes (Fig. 20 subject XII Th 11–12). These observations seem to fit with the movement of *Davis'* (1959) "intersection point" and the suggestions by other writers that the orientation of the plane of the facet joints influence the axis of axial rotation (*Rockwell*, 1938; *Gregerson & Lucas*, 1967). The IAR were not found as far anteriorly in the vertebral body as where *Lysell* (1969) suggested the possible center of axial rotation in the cervical spine might be located.

Age and Motion

The experimental control of applying loads at relatively the same positions (50, 25 and 75 % of the diameter in the plane in which motion was tested) allowed a comparison between different subjects. The total SM in the sagittal and frontal planes was combined for the Th 7–8 MS of each subject and plotted against age in years. Similarly total rotation at the same MS (Th 7–8) for each subject was plotted. Inspection of Figs. 21 and 22 shows that there is no evidence in this data of any relationship between amount of motion and age of subject. This was the case for axial rotation as well as for the total motion in the sagittal and frontal planes.

"Motion ratio" and Total Motion

It has been suggested that the amount of allowable motion at a given intervertebral segment may be related to the amount of disc material and the diameter of the vertebral body in the plane in which the predominant motion

AGE AND MOTION

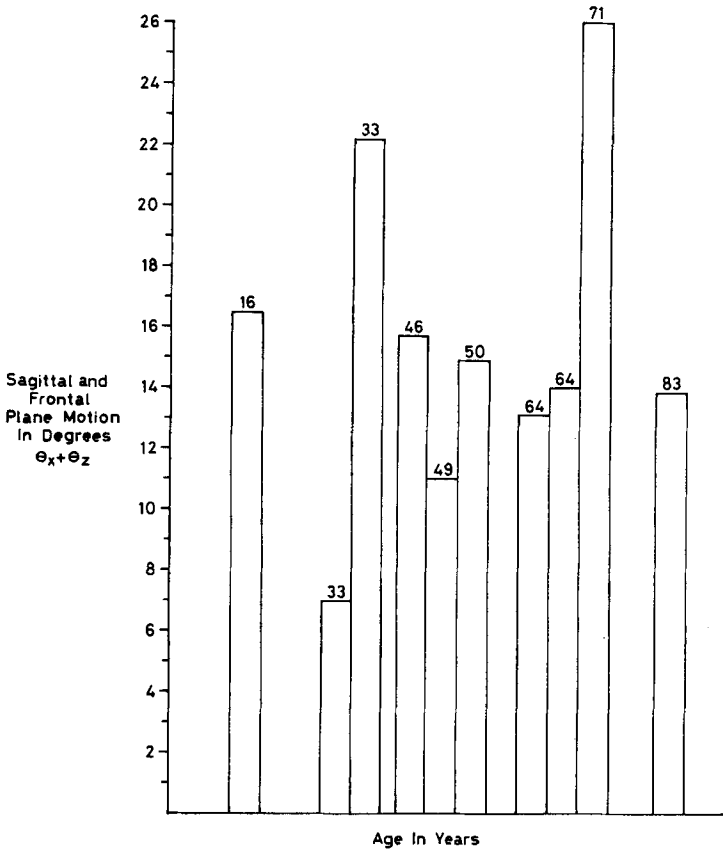


Fig. 21. Graph shows total motion (combined sagittal and frontal planes) for Th 7-8 of each subject as related to age of subject. See text for discussion.

takes place (*Fick*, 1904; *Keller*, 1924; *Wiles*, 1935; *Lucas* and *Bressler*, 1961). In evaluating this hypothesis it was possible to make further use of the experimental controls employed and look at the SM as related to the disc heights and diameters. For all the motion segments the disc height was measured on roentgenogram at three points; the anterior, middle, and posterior regions of its diameter in their sagittal views, and the right, middle and left regions in their frontal views. An average of each set of three values was taken as the disc height. The disc diameter was then measured on roentgenograph in the two

AGE AND MOTION

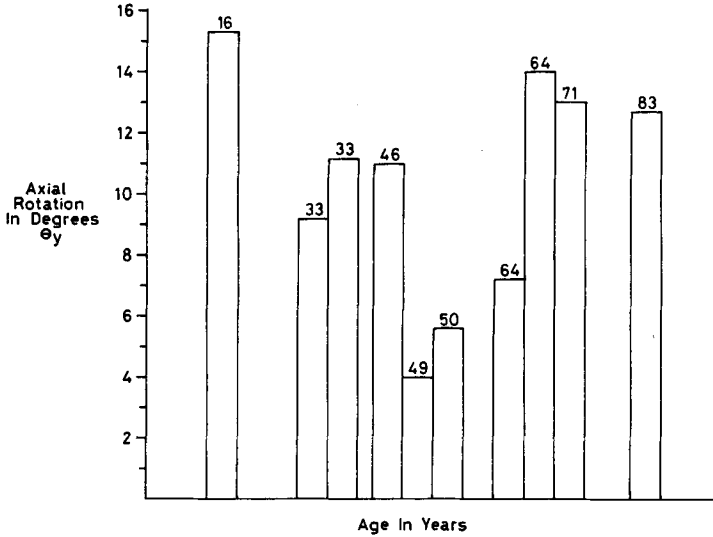


Fig. 22. Graph shows the amount of axial rotation of Th 7-8 of each subject as related to age of subject. See text for discussion.

planes. The disc height/disc diameter ratio was calculated for each MS in the frontal and sagittal roentgenographic planes. This ratio of disc height/disc diameter is what is meant by "motion ratio".

In order to test the hypothesis that an increase in "motion ratio" is correlated with an increase of motion, the Th 7-8 MS for all subjects was selected. A ranking of the motion ratio for Th 7-8 of each subject revealed almost no tendency for correlation. This was the case for motion in both the frontal and the sagittal planes with or without ablation of the posterior elements. See Table V in Appendix.

Comments

Certain considerations are relevant regarding the interpretation of the findings in this part of the investigation. In an analytical study of a mechanical nature it is important to have information about force and deformation. When such information is analysed it is possible to recognize any constant relationship between the two variables and make predictions about one based on a knowledge of the other and the constant. In engineering terms this straight line relationship between force and deformation (rotation in angles) is characterized by a *spring constant*. This is represented by the slope of the line plotted in Fig. 23 and for all the data as shown in the exemplary Figs. 12 and 13.

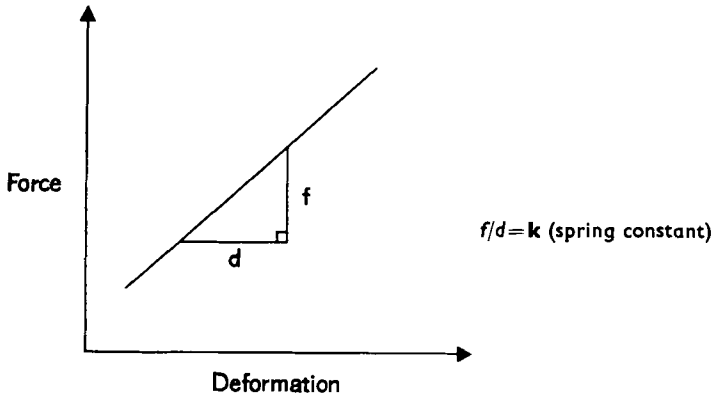


Fig. 23. See text for explanation.

It has been shown previously that for the range of forces involved in this experiment the cumulative forces and angles of rotation strongly tend to form a straight line relationship. Thus, it can be stated that in this series for the forces employed the MS behaved in a manner that can be analysed in mechanical terms of a spring constant.

The range of the loads employed in this study in relation to some gross estimates of the loads imposed by gravity at the various thoracic vertebral levels has been considered. These are given in Table 4. The calculations are

based on the estimated percentages of body weight above different vertebral levels (*Ruff*, 1950; *Henzel*, et. al., 1968), applied here to the perennial hypo-

Table 4. Estimates of Superincumbent Body Weight of a Hypothetical Subject and Experimental Load Ranges at Various Levels

Vertebral Level	% of Superincumbent Body Weight	Weight in Hypothetical 70 kg Subject	Hypothetical Load Kp/cm ²	Ranges of Experimental Loads Kp/cm ²
Th1	9%	6.3 kg	1.4	2.2-10.8
Th8	33%	23 kg	2.7	2.4- 7.2
Th12	47%	33 kg	2.3	2.1- 5.0

thetical 70 kg man. In order to estimate the area of the vertebrae at the different levels the average area for the corresponding level found in this investigation was employed. The experimental load range was arrived at by dividing the Kp load range used in this experiment for the different levels by the average area of the vertebrae for that level. The lower portion of the experimental range is close to or within the range of the estimated load imposed by the approximated superincumbent body weight. Estimations of the loads involved during the characteristic movements of the living thoracic spine would be extremely difficult. Nevertheless it appears that the selected force of 6 Kp/cm² is probably a good deal greater than the gravitational forces. A relatively high moment, 20 Kp cm, was chosen to observe rotation. In both instances a relatively strong force was employed in order to bring out the cephalocaudal differences and the intact compared with the ablated PE differences. The knowledge and control of the forces made possible meaningful and reliable interpretations of the observed differences.

Several generalizations regarding cephalocaudal variations seem reasonable based on this series. The lower portions of the thoracic spine behaved more like the lumbar spine than did the middle portion. This was apparent in two characteristics: (1) greater motion in the sagittal plane, (2) less motion in the horizontal plane (axial rotation). The vertebrae in the central portion tended to behave as a homogenous group. In lateral bending tests no salient pattern of variation at the different levels emerged.

Removal of the posterior elements resulted in greater motion in flexion, in extension and in axial rotation. This information has direct clinical applicability as regards traumatic and surgical involvement of these structures. Two dimensional analysis of the motion of these segments in the frontal and sagittal planes of their *roentgenographic* projections provide *clinically* useful

information. While the surgeon is of course thinking always in three dimensions the actual pictures before him are usually those of frontal and sagittal roentgenograms. Therefore, if he keeps in mind that the two dimensional analysis is a simplification of the true motion, the information described here can be effectively utilized in clinical evaluations.

PART II

THREE DIMENSIONAL ANALYSIS

Method

Material

The sources of the specimens are the same as for those employed in part I of this study. Table 5 summarizes the relevant data on the specimens used in this part of the investigation. There were 17 subjects. Their ages ranged from 5 to 83 years. Specimens with tumors, fractures, from patients with scoliosis and from patients with metabolic diseases known to affect bone were also excluded from this group.

Table 5. Autopsy Material Part II

Subject	Years of Age	Sex	Cause of Death
1	84	M	pulmonary edema
2	41	F	hemorrhage of external iliac artery
3	44	F	uremia
4	82	M	cerebral vascular insufficiency
5	49	M	diabetic nephrosclerosis
6	74	F	ovarian carcinoma
7	57	F	bronchopneumonia
8	55	F	chronic pulmonary disease with circulatory insufficiency
9	55	M	hypernephroma, pneumonia
10	36	M	bilateral pulmonary emboli
11	16	F	respiratory insufficiency by suspension (suicide)
12	57	M	cerebral vascular insufficiency
13	20	F	fatty degeneration of liver
14	18	M	congenital heart disease
15	16	M	suffocation by drowning
19	5	M	post traumatic intra-abdominal hemorrhage
20	5	M	cerebral contusions

Handling and Preparation of Test Material

As in Part I of this investigation the specimens were protected from physical changes by storing in a deep freeze. When working with the specimen it was always sealed in a plastic bag or kept in the high humidity chamber. A roentgenogram of the specimen was taken in its sagittal and frontal planes. Based on the roentgenograph and anatomical evaluation, it was cut so as to preserve either the upper or lower 6 or 8 vertebrae for testing. The roentgen apparatus could not accommodate any larger segment of the adult thoracic spine. It was possible to test much larger portions of the small 5 year old spines. The thawed specimen was handled in the following manner. The ribs were dissected away. The majority of the para spinous muscle mass was removed leaving a small amount of muscle tissue as an additional protective seal against dehydration of the deeper structures. Four 0.8 mm steel balls were inserted into each vertebra. The anterior ball (A) was inserted in the midline of the anterior portion of the vertebral body a few millimeters below the upper end plate and just beneath the cortex. The posterior one (P) was similarly inserted at the base of the spinous process as close as possible to the midline sagittal plane. The remaining two balls R and L were also inserted subcortically but at the right and left side of the vertebral body and slightly posterior to the middle of its anterior posterior diameter. The preparation was then fixed in a brass cup by at least one vertebra held with polyester of the type described in Part I of this work. The brass cup was specially constructed to fit into the roentgen apparatus. The specimen and cup were placed in a plastic bag. A hook was attached to the uppermost vertebra by screwing it into the cancellous bone of the body. The specimen was then ready for examination.

Apparatus and Experimental Technique

As stated previously the technique and apparatus for this portion of the investigation is the same as that used by *Lysell* (1969). A more detailed description is available in that thesis. To follow is enough detail to provide the reader with a basic understanding of the technique without having to actually search the above work.

See Fig. 24. This equipment is constructed so that the object Table (A) is circular and can rotate about a vertical axis which runs through a reference point (R). (R) is a steel ball, 8 mm in diameter placed in a pillar of plexiglass. The object table can be locked in several positions. For this study $+22.5^\circ$ (pos. I) and -22.5° (pos. II) were employed. A roentgen film holder (B) lies behind the reference point and perpendicular to the rotation plane of the object table. The film holder can be displaced parallel to the L-Square ruler (C). The front of the film holder is perforated and can be attached to a

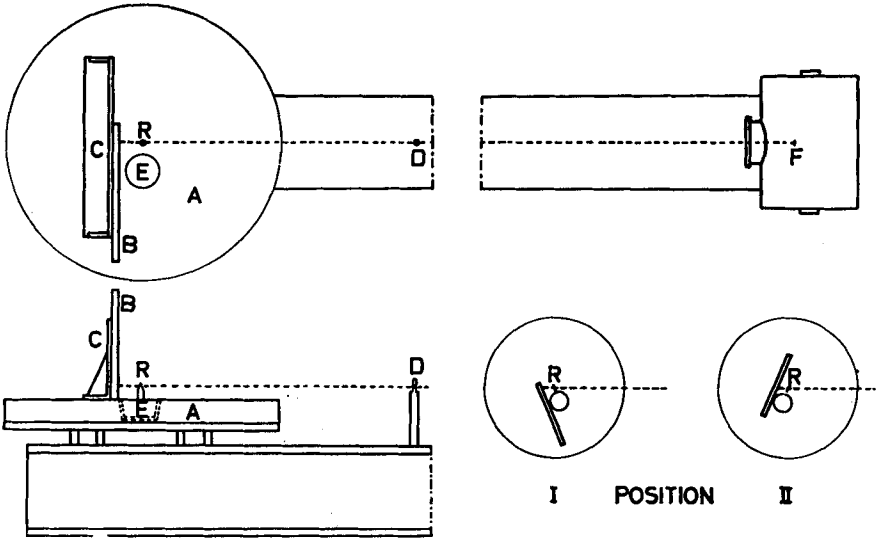
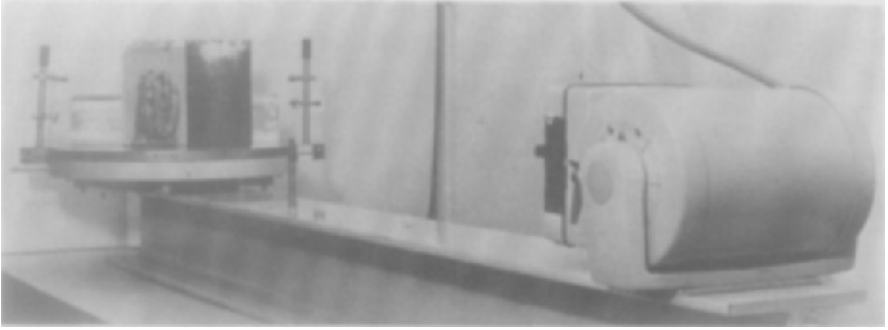
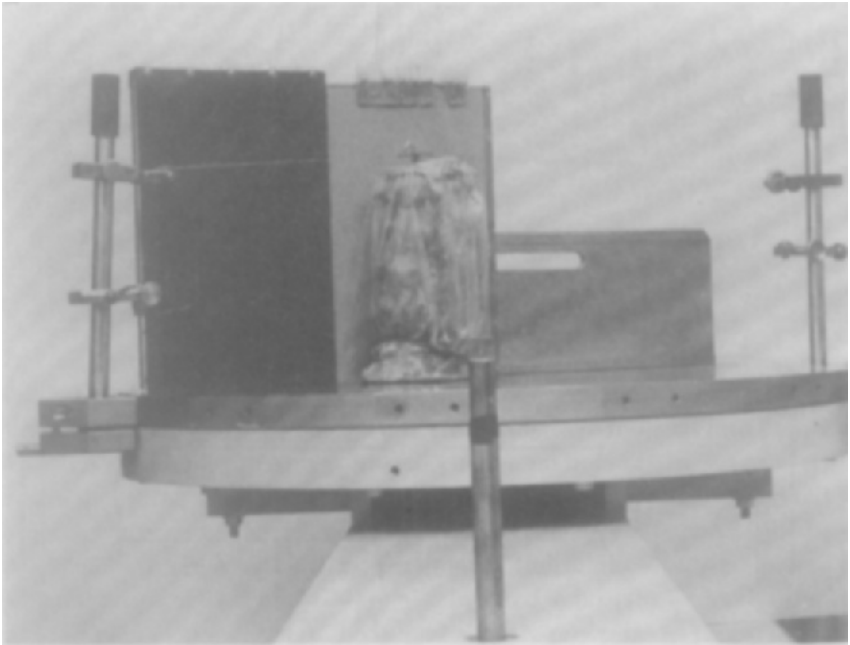


Fig. 24. Roentgen apparatus. For description see text.

vacuum. This makes it possible to secure an uncovered roentgen film fixed flat against the holder. The position where the brass cup which holds the specimen is located, is represented by E. Between the roentgen tube and the object table there is a metal rod (D) which has a hole in its flattened top. The position of this hole is such that an imaginary line drawn through its center, and the center of the reference point, is parallel with the rotation plane of the object table. The described line is also perpendicular to the axis of rotation and to the film plane in position 0 (the middle position between positions I and II). Before measuring the tube is adjusted and fixed so that the reference point is projected in the center of the projected hole (of the metal rod) onto the roentgenfilm. With this adjustment it follows that a roentgen beam from the focus through the reference point strikes the film perpendicularly if it is in position 0.

I A



II B

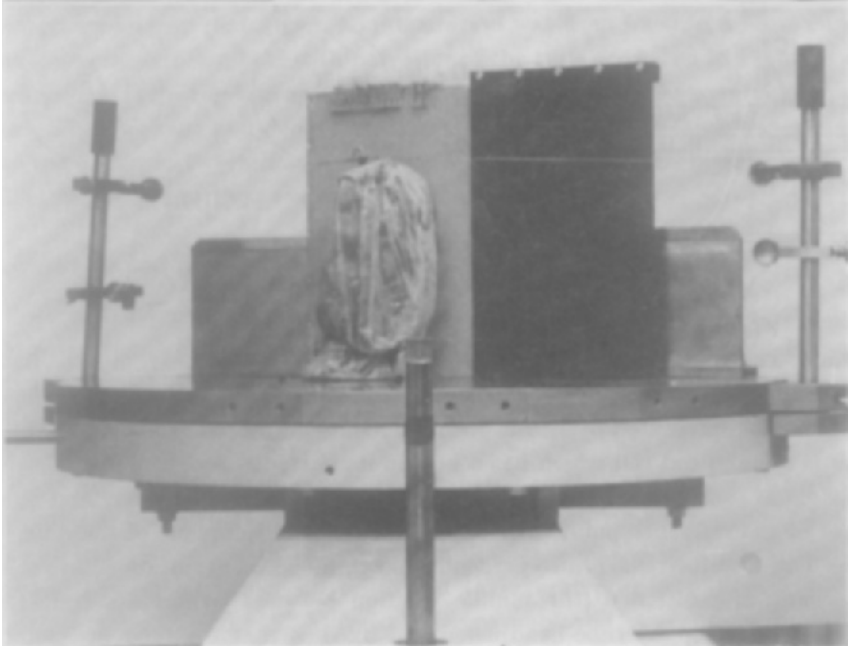


Fig. 25. Object table with mounted specimen in position I(A) and position II(B). Pictures are taken from focus of roentgen tube.

During the actual taking of the roentgenographs of the specimens, the object table is first turned to position I (Fig. 25 A). The film holder is moved to the left and the left part of the film is covered with a roentgen opaque shield. The exposure for this position can be made. The object table is now rotated 45° to position II (Fig. 25 B). The film holder is displaced to the right and the right part of the film is covered. Now the second exposure can be made. Considerable care is taken not to alter in the least either the position of the specimen or the position of the film on the holder, during the time between the two exposures.

The geometry, the mathematical analysis employed and the method of measuring on the radiographs are exactly as described on pages 23–28 in the thesis by *Lysell* (1969). Only the coordinate system is different in this investigation.

Manipulation of Specimen

The specimen was moved in flexion and extension and lateral bending by attaching thin metal wires to the previously described hook in the uppermost vertebra. See Fig. 26. Nine exposures were taken of motion in the sagittal plane starting with full extension and ending with full flexion. Three of these exposures were to the extension side of the “resting position” (Re) (position of spine with no external load applied). An exposure of the Re was made along with 5 more to the flexion side of the Re. Motion in the frontal plane totalled seven exposures three on either side of the Re and the Re itself. This movement was started with full right lateral bending and ended with full left lateral bending. Axial rotation was taken from complete counter-clockwise rotation to complete clockwise rotation in seven steps with three on either side of the Re and including the Re. This maneuver was made possible by drilling a stainless steel pin through the body of the uppermost vertebra. Through a specially constructed metal “fork” which could be attached to this pin the rotary force could be applied.

The end points for the full range of these motions was readily recognizable by this investigator. At the extremes of the ranges there is a gradually increasing moderate resistance followed by a distinct abrupt rapidly increasing strong resistance. This latter very narrow range of resistance was taken as the end point for the total ranges in these experiments.

Data Processing, Description and Comments

The data from this portion of the study was analysed by two approaches. From the primary measuring points on the radiographs it was possible to obtain precise information about the position in space of each of the 4 steel balls placed in each vertebra. Mathematical computation included calculation of

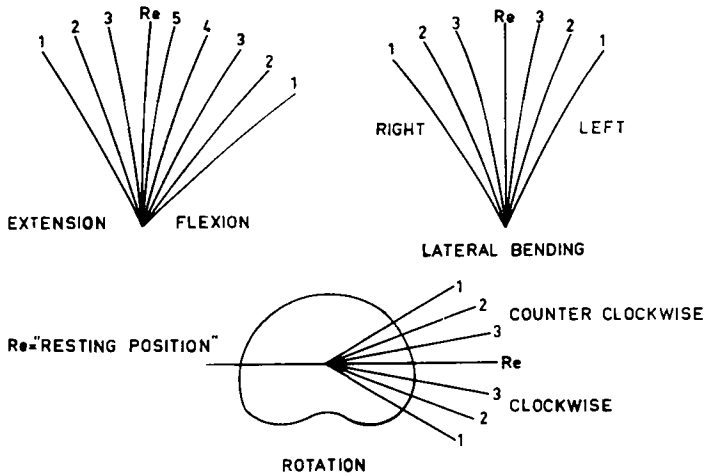


Fig. 26. Diagrammatic representation of steps within ranges of motion studied. See text for explanation.

numerical vectoral quantities of the relative positions of the secondary measuring points A, P, R and L in adjacent vertebrae. Secondary measuring points are mathematically determined points, which facilitate the study of relative motion by establishing symmetrical and comparable neutral positions (*Lysell, 1969*). Thus, it was possible to plot the positions of these points in relation to the subjacent vertebra at various steps within the total range of movement in the sagittal, frontal and horizontal planes. Points were plotted from all the subjects in the three planes of motion. It is from this analysis that it was possible to determine the actual *patterns* of motion.

The second portion of the data analysis begins with the positions of A, P and L on the x , y and z coordinates in relation to the reference point (R). Calculations are made of a number of different informations to be reported and discussed in the following section of this investigation. Even though the experimental error is small, it proved to be out of the range of precision necessary for standard available mathematical approaches. Consequently, a special system had to be devised; one that would allow for the experimental error and still provide a true three dimensional analysis of the motion. Mathematical evaluation of the amount of the resultant error has found it to be 4% for angles of 5° and 8% for angles of 10° .

The mathematics were worked out in cooperation with a mechanical engineer. The details and the theoretical basis of this analysis is to be published in a separate work (*Panjabi and White, 1969*).

From the 17 subjects included in this part of the study the motion of 141 vertebrae was analysed by two programs producing 219,000 informations.

Results and Interpretation

The Pattern of Motion

The 5th thoracic vertebrae of subject 3 was selected to demonstrate the pattern of motion, for it is thoroughly representative both qualitatively and quantitatively. Its pattern of motion is depicted in Figs. 27, 28 and 29. One will note immediately that there is very little motion. This is perhaps a salient characteristic of the movement of the thoracic spine.

Sagittal motion is depicted in Fig. 27. Looking at the x, y plane, the relative motion can be defined as translation in the negative direction of the x axis and rotation in the positive direction about the z axis. The dashed line connects the A and P points in the position of full extension. In the neutral or resting position they are connected by the uninterrupted line. The position of full flexion is indicated by the point dashed line. The range of extension can be seen to represent about 1/3 of the total range. The movement of points R and L in Fig. 27 is over simplified due to the limitation of space in which to represent it.

The view of this motion is shown again on the same figure in the x, z plane. The subjacent reference vertebra 6 is not shown on this view. In this plane the predominant motion one notes is translation along the x axis.

The pattern of motion in lateral bending is shown in Fig. 28. A study of these diagrams shows that in motion from full right lateral bending to full left lateral bending, there is translation along the z axis in the positive direction and rotation about the x axis in the positive direction. There is also a rotation about the y axis in the positive direction. This is seen best in the horizontal (x, z) view. However, it can also be observed by a study of the motion of points A and P in the frontal (y, z) view. In different terms it can be stated that in this example *with lateral bending the vertebra rotates into the concavity of the lateral curve*. There is coupling of rotation about the x and y axes with directions positive about both axes. *Lysell* (1969) found such motions to be strongly coupled and in these same directions in the cervical spine.

Axial rotation is patterned in Fig. 29. The specimen is taken from a full counterclockwise to a full clockwise position. The coupling of rotation about the

x and y axes can again be observed in both the frontal and horizontal views. This is the same coupling as was seen in lateral bending except that the directions are reversed due to the fact that the specimen was moved from counterclockwise to clockwise, the negative direction about the y axis rather than in the positive direction.

Flexion and Extension

From the three dimensional analysis information regarding linear movement in the sagittal plane was extracted. This was done in order to show for large segments of the thoracic spine what portion of the total sagittal motion could be called extension. Thus, the linear motion of ball A of the top vertebrae of the thoracic spine segment was divided into two portions. These portions were that to the extension side of the initial resting position (positive direction of x axis), and that to the flexion side of the initial resting position (negative direction of x axis). The segments of the upper one half of the spine showed a mean percentage extension of 33.4 % of the total range. The middle and lower portions showed means of 26.3 and 33.3 % respectively. The mean of the percentages of extension for all segments tested was 31.0 %. The figures on which these statements are based are given in the Appendix Table VI.

The movement to the flexion side and to the extension side of the resting position was compared. For each vertebra the movement was separated into what was called the first and second portion of θ range. The first portion was the movement between full extension and the resting position. The second portion was the movement between the resting position and full flexion. Only those vertebrae about which there was information on all the steps along the total range were used. Inspection of Table VII in the Appendix shows that for a great majority of the vertebrae the amount of extension was less than the amount of flexion. For each of the vertebrae Th 1-11 inclusive the means of the movement in the first and then the second portion of range θ were taken. In order to look at the over all pattern for the spine the mean total extension for all the vertebrae in all the subjects was compared with the same total for flexion. The extension was less than the flexion (1.4° vs. 1.9°) and was 42 % of the full sagittal motion. The full motion in the sagittal plane was evaluated for this series by taking the total θz for each vertebra in the different subjects. The mean for each level was then calculated and is recorded in Table 6. The angles for individual subjects and vertebrae are given in Table VIII of the Appendix. Fig. 30 shows the average motion for the different levels of the spine. The total of the averages for flexion and extension is 34.4° . The pattern of cephalocaudal variation shows a tendency for greater sagittal motion at the lower levels.

FLEXION EXTENSION

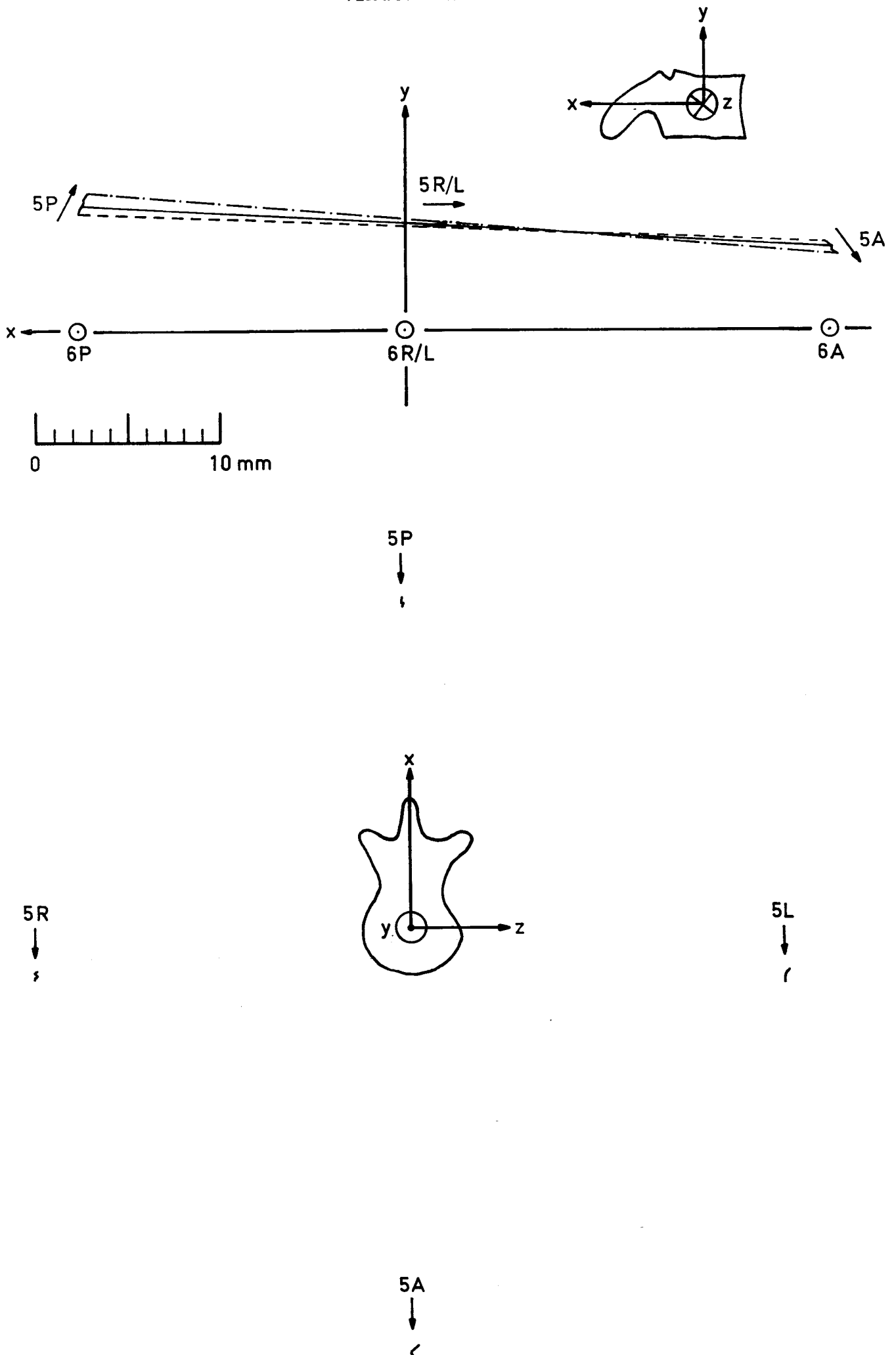


Fig. 27. Shows two views of pattern of sagittal motion. Lower view does not show points of subjacent vertebra but the motion indicated is in reference to it. See text for description.

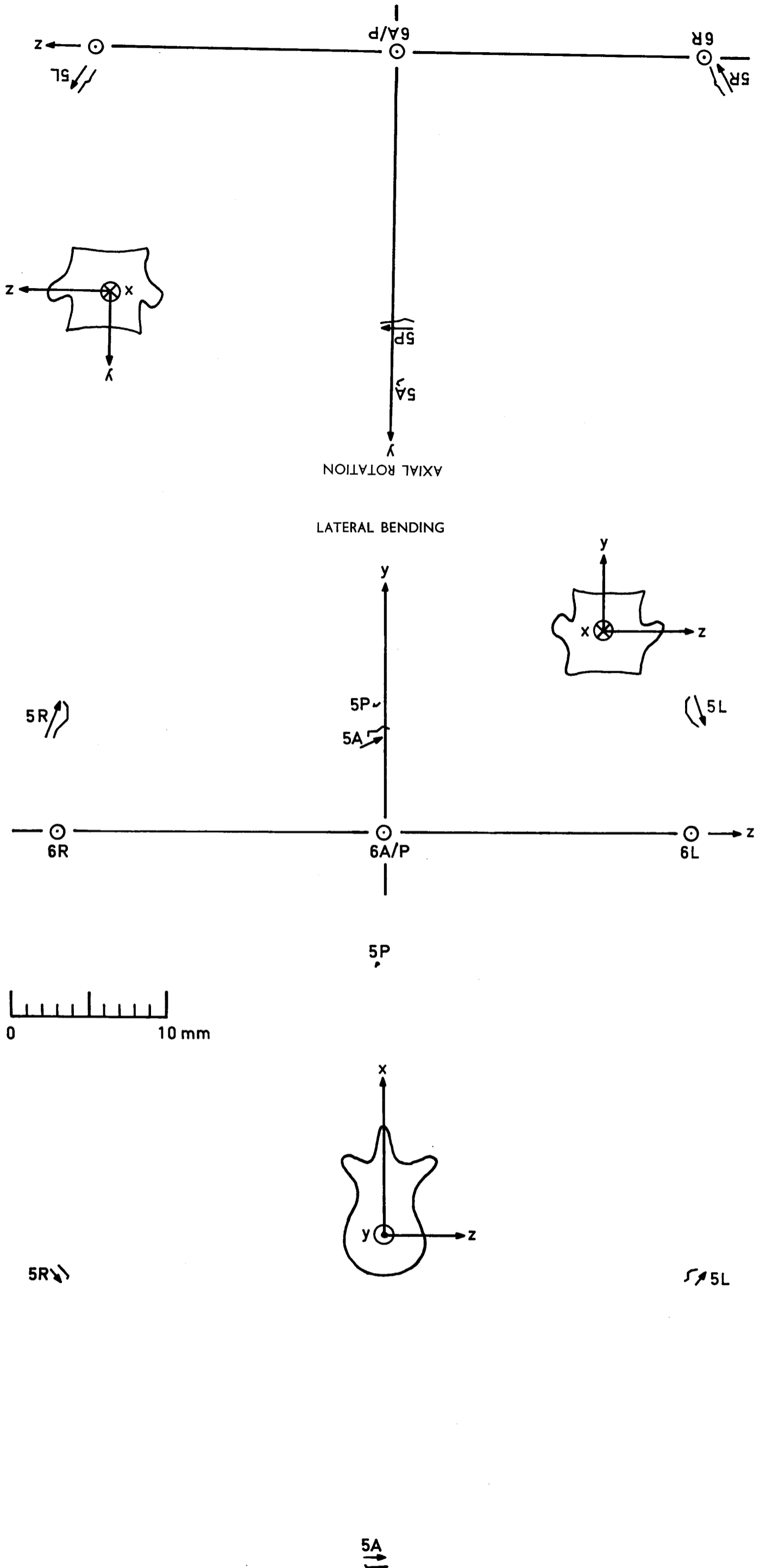
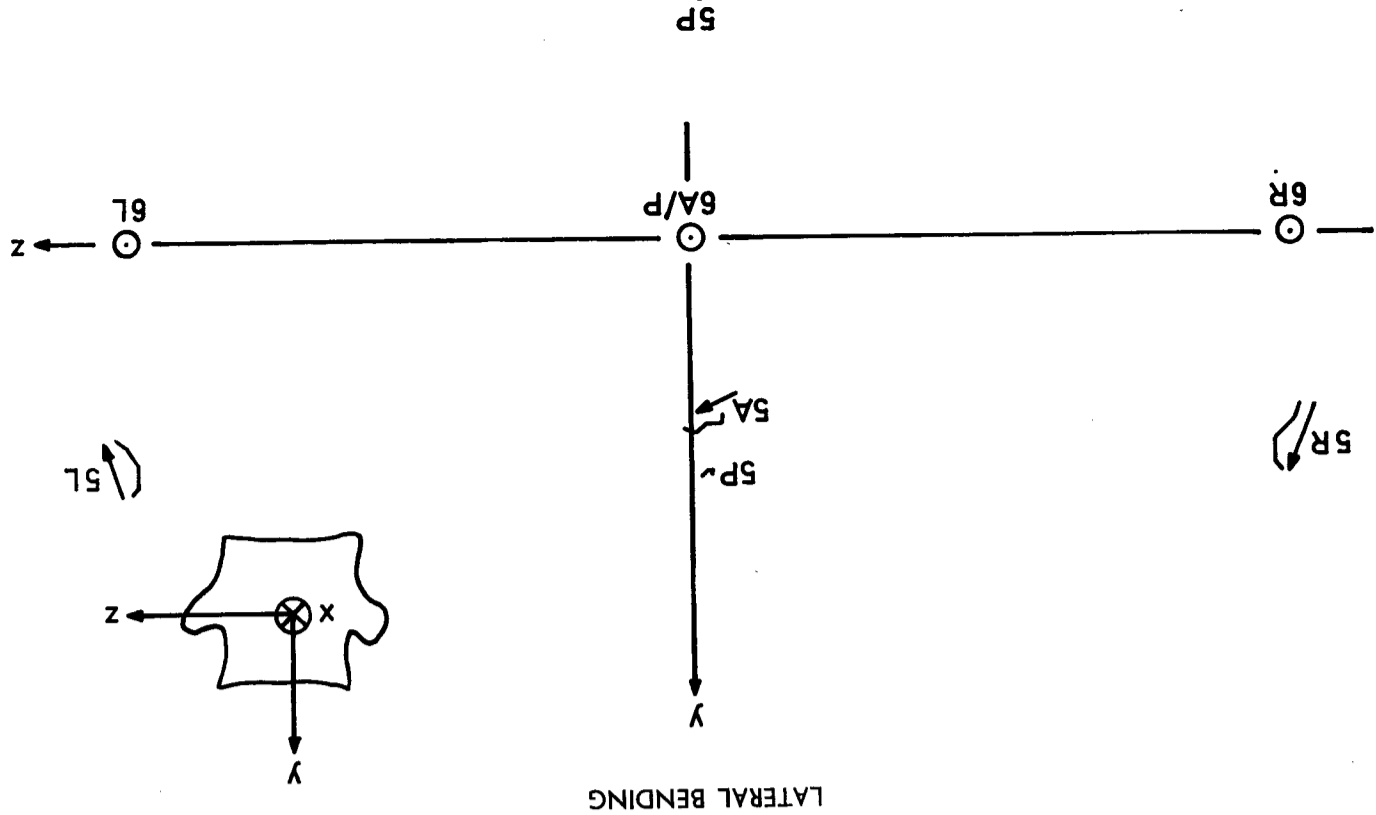
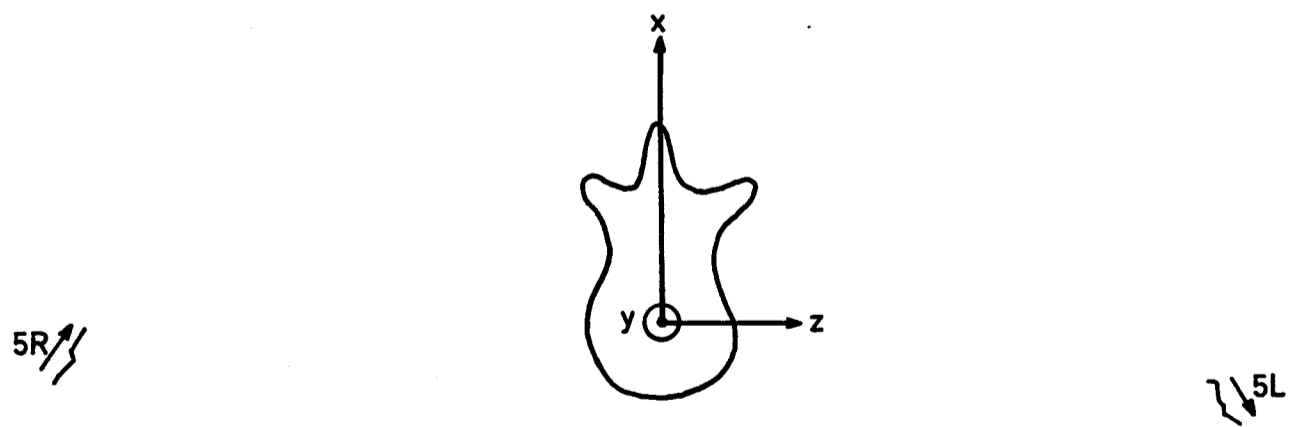
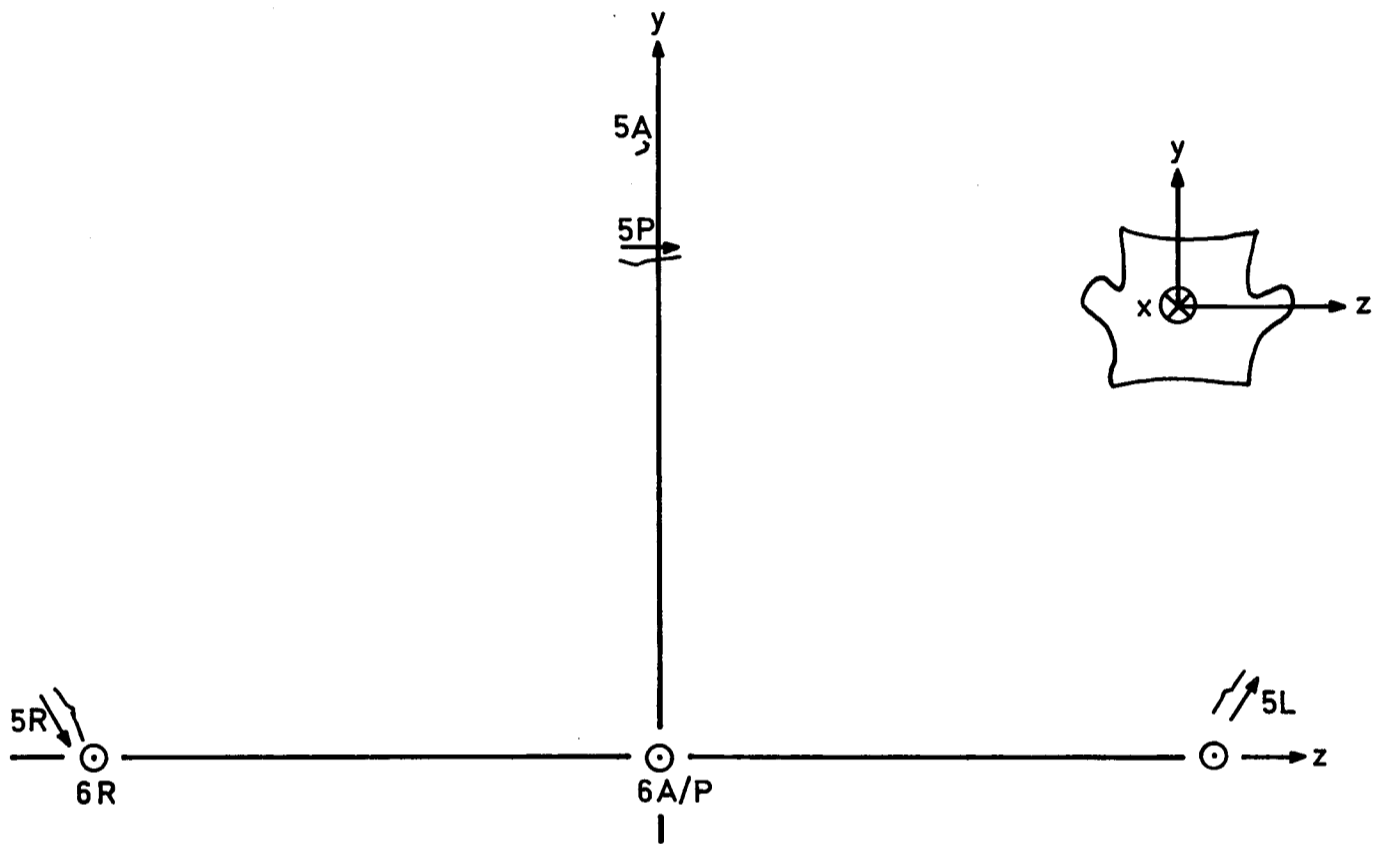


Fig. 28. Shows two views of pattern of motion in lateral bending. Lower view does not show points of subjacent vertebra but the motion indicated is in reference to it. See text for description.



LATERAL BENDING

AXIAL ROTATION



5A

Fig. 29. Shows two views of pattern of motion in axial rotation. Lower view does not show points of subjacent vertebra but the motion is in reference to it. See text for description.

Table 6. Means of Total Flexion and Extension for the Various Subjects at Each Level

Vertebral Level	1	2	3	4	5	6	7	8	9	10	11	
Mean θZ	2.8°	2.6°	2.3°	1.8°	2.6°	2.3°	3.3°	3.2°	3.1°	3.9°	6.5°	Total 34.4°
Range of Mean	2.3	2.7	3.9	2.0	2.8	2.4	3.1	3.7	2.4	5.7	8.6	

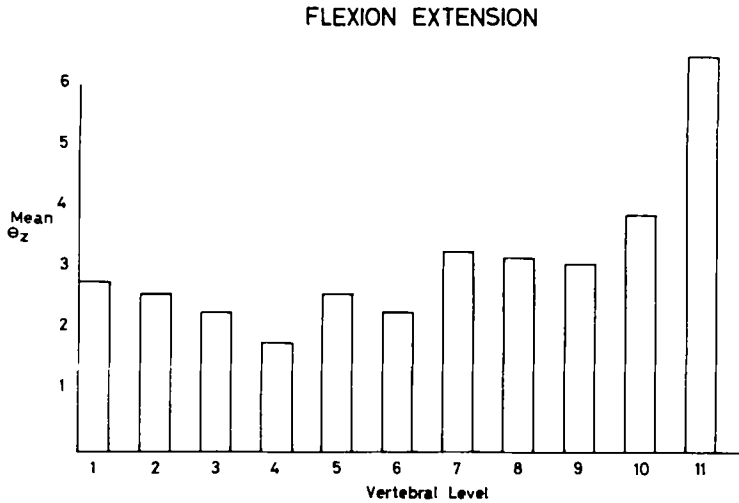


Fig. 30. Graph shows cephalocaudal variation of flexion extension for the subjects in this series. See text for explanation.

Lateral Bending

The motion here is evaluated as described in the preceding paragraph for flexion and extension except that it is rotation about the x axis (θx) that is under consideration. The total average movement for all the eleven vertebrae is 52.0°. These observations suggest no particular pattern for cephalocaudal variation. See Table 7 and Fig. 31. In the Appendix Table IX gives the data for specific subjects and vertebrae.

Table 7. Means of Total Lateral Bending for the Various Subjects at Each Level

Vertebral Level	1	2	3	4	5	6	7	8	9	10	11	
Mean θX	6.0°	4.8°	3.7°	5.0°	5.3°	5.9°	4.1°	4.7°	4.4°	4.4°	3.7°	Total 52.0°
Range of Mean	6.3	5.6	3.9	7.3	6.3	10.7	5.9	3.2	3.8	4.0	4.4	

LATERAL BENDING

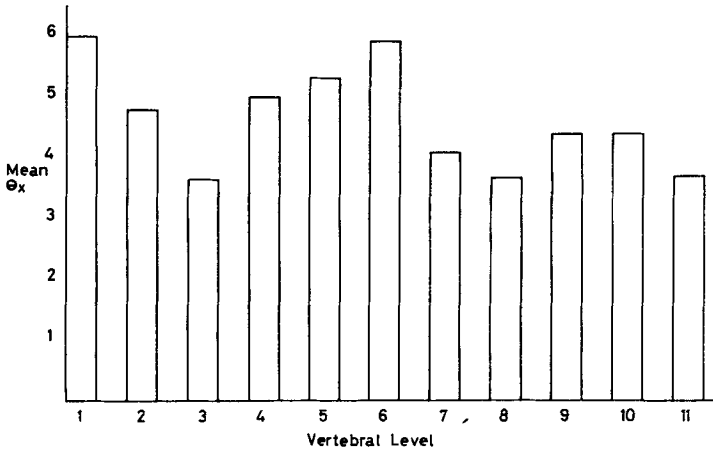


Fig. 31. Graph shows cephalocaudal variation of lateral bending for the subjects in this series. See text for explanation.

Axial Rotation

Similar analysis of this movement resulted in the mean angles shown in Table 8. The total of the means for axial rotation is 41.1° . Fig. 32 suggests less axial rotation at the lower vertebral levels. Appendix Table X gives the θ_y for the various individual subjects and vertebrae. The attachment of the rotation apparatus to Th 1 precluded complete observations at that level.

Table 8. Means of Total Axial Rotation for the Various Subjects at Each Level

Vertebral Level	1	2	3	4	5	6	7	8	9	10	11	Total
Mean θ_Y		4.0°	5.1°	3.9°	5.0°	4.1°	4.3°	5.5°	3.2°	3.4°	2.6°	41.1°
Range of mean		3.9	6.4	3.4	5.4	3.8	4.2	4.8	3.2	2.9	2.5	

Coupling

This aspect of thoracic spine mechanics was evaluated by analysis of the data in the following manner. The coupling to be examined is the motion about the x and y axes when the spine moves in lateral bending. In other words, what is the association, if any, of θ_y and θ_x during lateral bending? In this section the motion discussed is in relation to the external reference point (R), (Fig. 24) not to the subjacent vertebra. Examination of the data revealed some associated rotation about the z axis during lateral bending. Thus, it was

AXIAL ROTATION

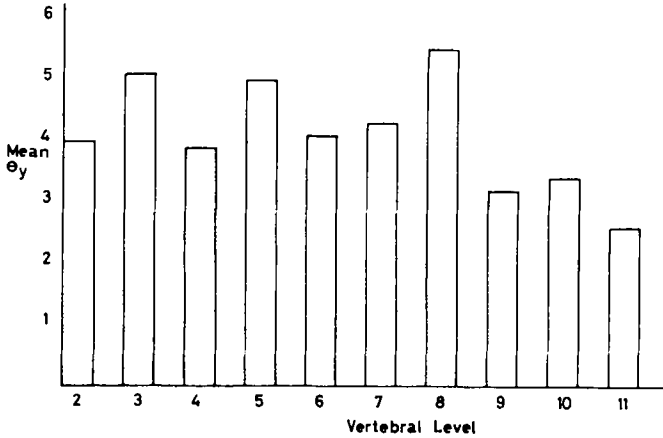


Fig. 32. Graph shows cephalocaudal variation of axial rotation for the subjects in this series. See text for explanation.

necessary to look at the variation of θ_z and θ_y when θ_x was the predominant motion. In the lateral movement under analysis, that is from complete right lateral bending to complete left lateral bending, the major motion is about the x axis to the *positive* direction. When there is coupling about the x and y axes a graphic plotting of the cumulative θ_x and θ_y of the vertebrae under analysis should show any association that exists. In a direct variation coupling, the cumulative curve would be positive on both the θ_y and θ_x axes. An inverse relationship coupling but in the opposite direction, would show negative on the θ_y axis. Finally, with little or no association (no coupling), the line of cumulative θ_x and θ_y values would hunt about the zero point of the θ_y coordinate. As there was some associated θ_z rotation it was necessary to look simultaneously at the cumulative θ_z and θ_x angles. This would make possible a differentiation between specific θ_x and θ_y coupling and generalized associated movement including some element of change of θ_y and θ_z with θ_x . In this particular coordinate system and for this particular motion a *positive θ_y associated with positive θ_x is the same as rotation of the vertebral body into the concavity of the lateral curve*. The 2nd, 6th and 11th thoracic vertebrae were selected for analysis of the question of coupling. Though it may seem unlikely on initial inspection, a study of Figs. 33, 34 and 35, will elucidate certain information about coupling. At the Th2 level four subjects were available for analysis. For *all* subjects analysed there was a definite direct relation between

θy and θx . At the same time there was very little associated cumulative movement about the θz axis. This series shows at the Th2 level a definite pattern of coupling of axial rotation into the concavity of the curve with lateral bending. (Fig. 33.)

The motion of Th6 was analysed and depicted in the same manner as Th2. See Fig. 34. One can recognize here that there is again a direct variation of θx and θy . The relation is not as strong, nor as distinctly different from the relation of θx and θz as was noted for the Th2 vertebrae. There were 11 subjects in which Th6 could be studied. The 8 subjects depicted in Fig. 34 all showed a relation of positive θy associated with a positive θx . In each of the 8 individual cases the positive association of θx and θy was stronger than that of θx and θz for the particular subject under analysis. In the remaining 3 cases this situation did not exist. Some of the examples at the Th6 level which did not show the pattern of coupling at Th2, actually *showed the reverse*. They showed rotation of the vertebrae into the *convexity* of the lateral curve. Thus, at the Th6 level for this series coupling of axial rotation with lateral bending was found in 8 of 11 examples. The rotation in these examples was into the concavity of the lateral curve and not as marked as at the Th2 level.

With the same graphing techniques the motion of five Th11 vertebrae was studied. Fig. 35 shows that some of the subjects demonstrated coupling of motion with positive θx and θy varying directly. In these examples 3 out of 5 of the subjects show the coupling of the pattern described above. Here too, the trend is less strong than at the Th2 level.

Average Curvature

So as to have some mathematical description of the steepness of the arch that one vertebra takes in relation to the subjacent one, the average curvature was taken. Curvature is defined as one divided by the radius ($1/r$). Thus, a very flat arch (that of a huge circle) will have a small value for curvature. A steep arch will have a relatively larger value. The point used for curvature was the relative motion of point (ball) A between adjacent vertebrae. This quantity was calculated for each step in the sagittal and the frontal planes and the average taken for each plane. The data is shown for sagittal and frontal motion in Appendix Tables XI and XII respectively. The ratio $1/r$ is multiplied by 100 for convenience. Examination of the means of the average curvature for each level in different subjects provides some impression of the over all pattern. There is no suggestion of any scheme of cephalocaudal variation in the sagittal plane in the steepness of course traveled by the different vertebrae relative to their subjacent member (Fig. 36). In frontal plane motion there is a suggestion of a more steep pattern in the vertebrae at the lower thoracic levels (Fig. 37).

THORACIC 2 Θ_X vs. Θ_Y and Θ_Z CUMULATIVE VALUES

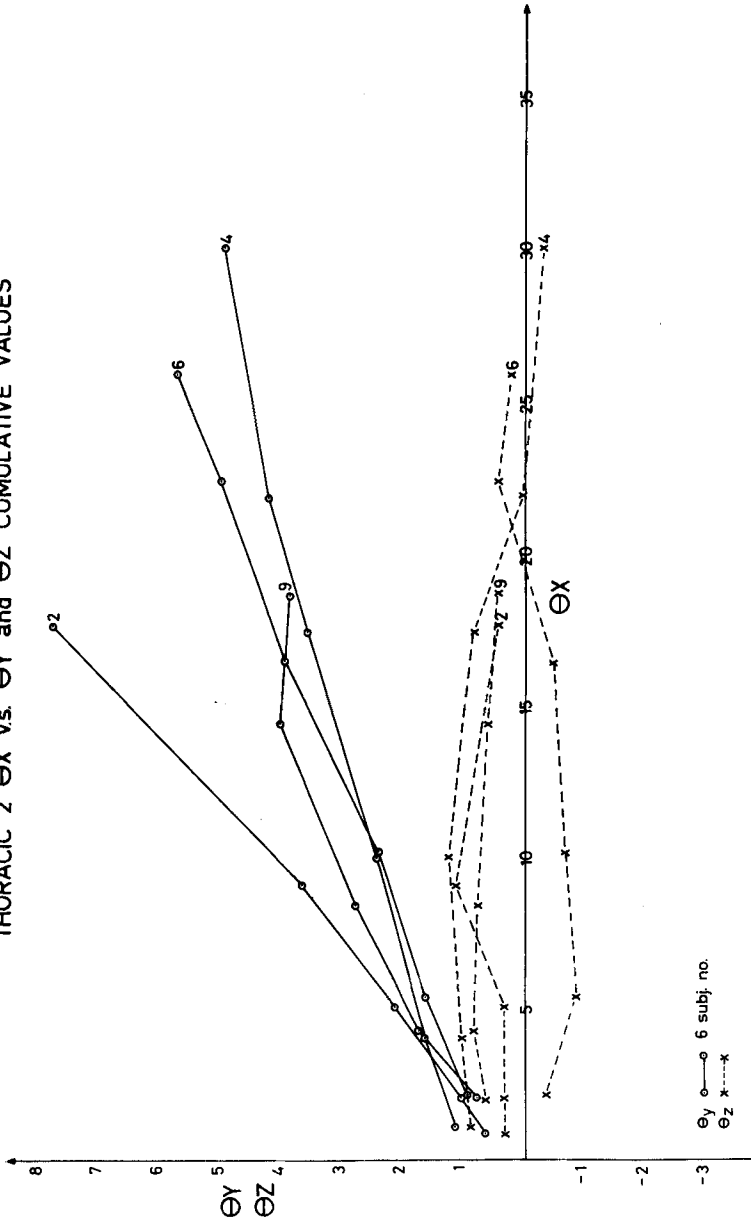


Fig. 33. Shows extent of coupling of rotation about the y and the z axes with rotation about the x axis at Th2. See text for description.

THORACIC 6 ΘX vs. ΘY and ΘZ CUMULATIVE VALUES

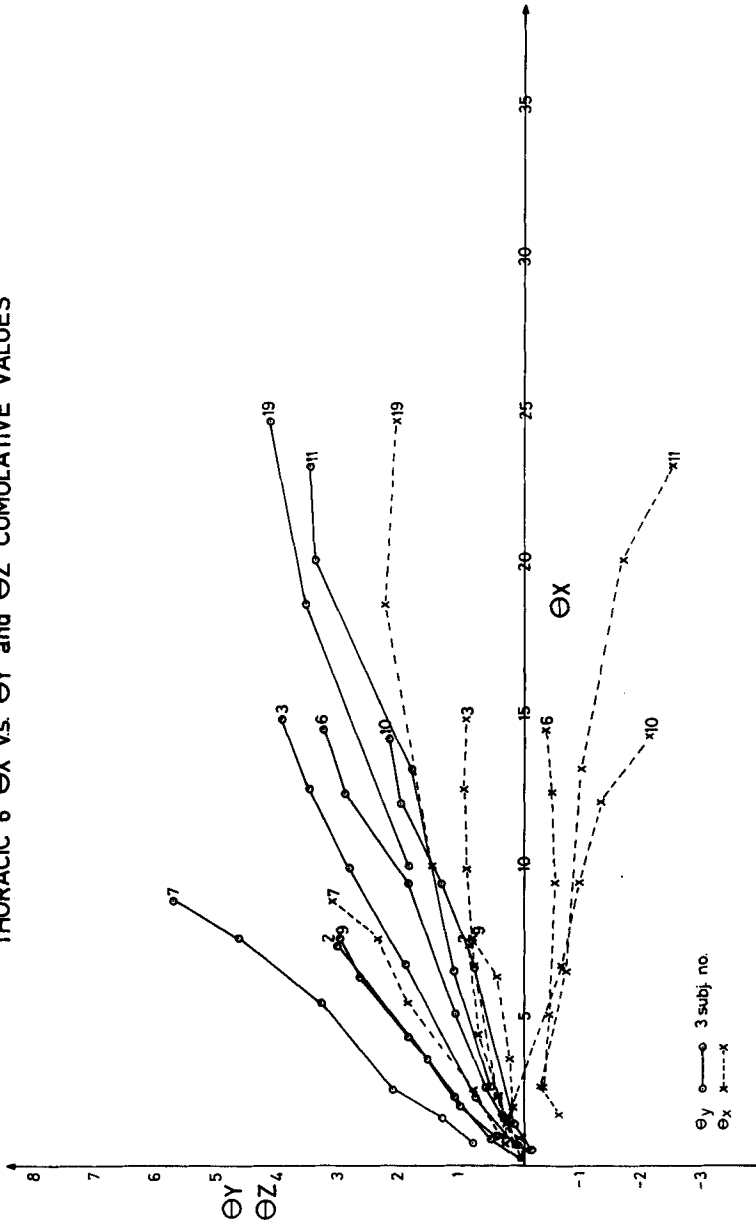


Fig. 34. Shows extent of coupling of rotation about the y and the z axes with rotation about the x axis at Th6. See text for description.

THORACIC 11 ΘX v.s. ΘY and ΘZ CUMULATIVE VALUES

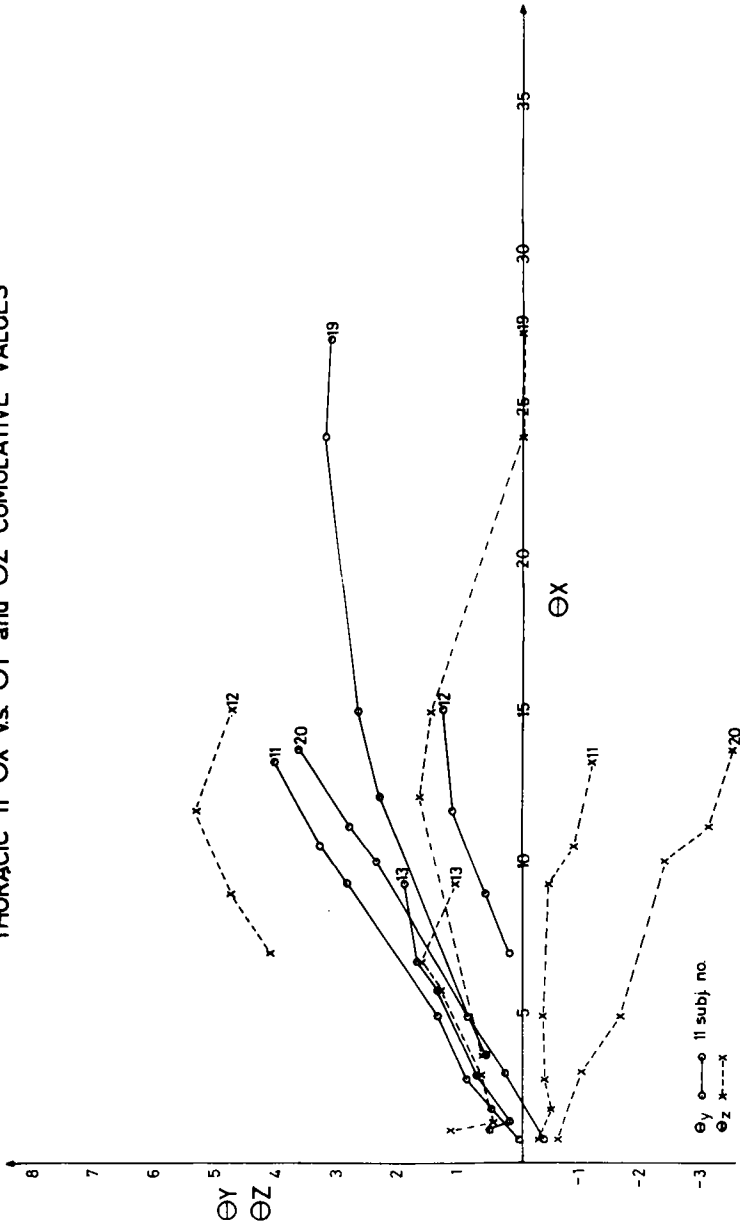


Fig. 35. Shows extent of coupling of rotation about the y and the z axes with rotation about the x axis at Th11. See text for description.

MOTION CURVATURE SAGITTAL PLANE

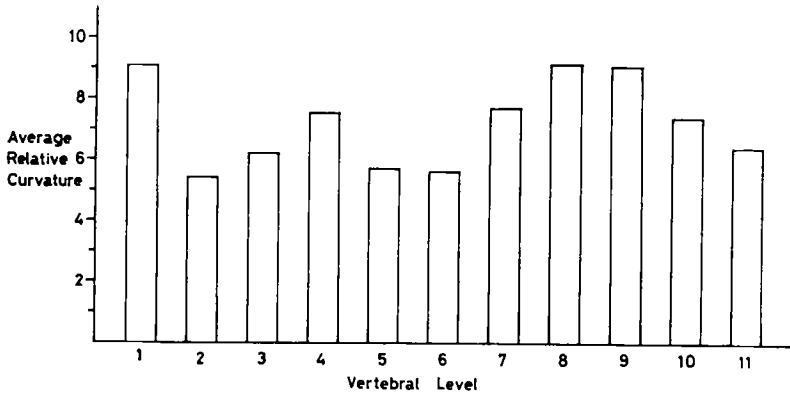


Fig. 36. Shows motion curvature in sagittal plane at different vertebral levels. See text for explanation.

MOTION CURVATURE FRONTAL PLANE

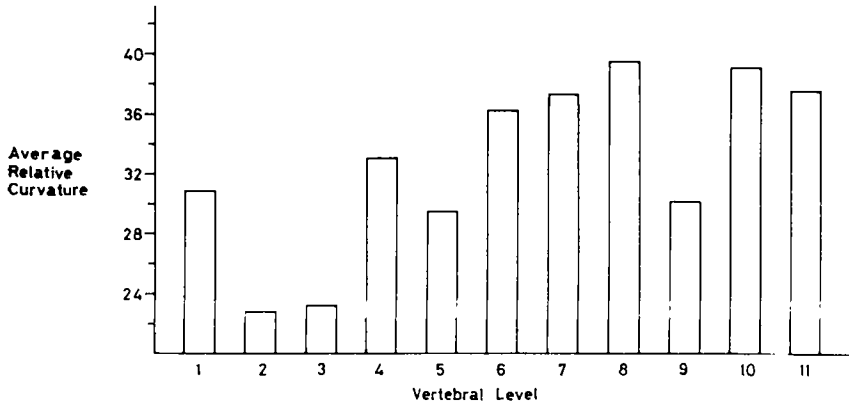
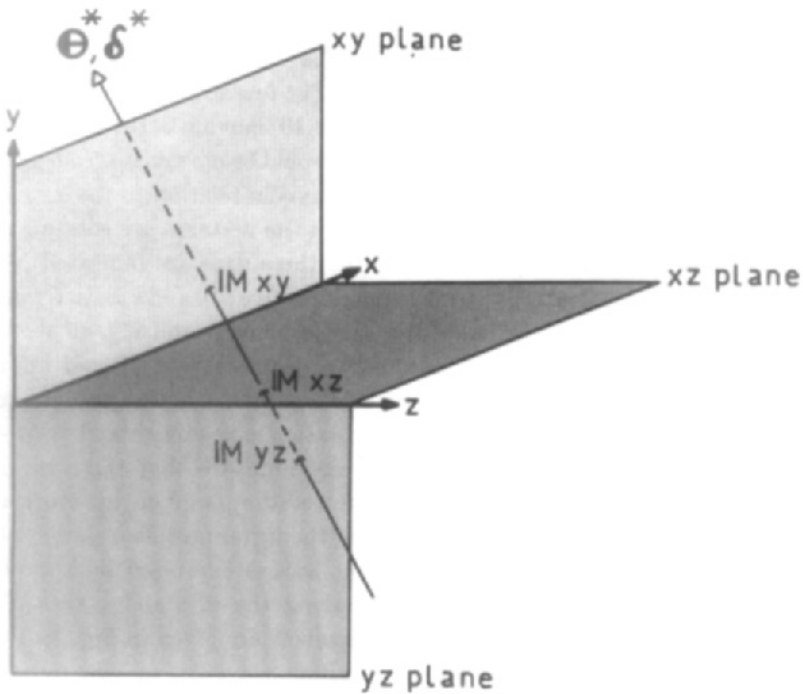


Fig. 37. Shows motion curvature in frontal plane at different vertebral levels. See text for explanation.

Instantaneous Helical Axis of Motion

The instantaneous motion pattern for a rigid body can be analysed as a simple screw motion. The screw motion is a superposition of rotation and translation about and along the same axis (*Christie, 1952; Shames, 1966*). This axis has the same direction as the resultant of the three rotation components about the x, y, z axes. Vector quantities Θ^* for rotation, and a δ^* for translation lie on this axis. The above described axis is referred to as the *helical axis of motion*. For a given moving rigid body the location of this axis and the

HELICAL AXIS OF MOTION



$$\begin{aligned}\Theta^* &= \Theta_x^* + \Theta_y^* + \Theta_z^* \\ \delta^* &= \delta_x^* + \delta_y^* + \delta_z^*\end{aligned}$$

Fig. 38. Shows graphical representation of helical axis of motion. See text for explanation.

designation of the quantity of its rotation and translation constitute a complete precise three dimensional analysis of the motion. In this section a description of the use of this three dimensional analysis on the intersegmental motion of the thoracic vertebrae of man will be presented and exemplified.

The reference in relation to which the motion is analysed is point A of the subjacent vertebra. The coordinate system is thus established about point A and the respective planes indicated as shown in Fig. 38. The position of the resultant axis for any given rotation can be defined by the point at which the axis intersects any two of the three planes Mxy , Mxz and Myz . Data analysis included calculation of this point of intersection of the helical axis with each of these three planes. This calculation was done for every step of flexion extension, lateral bending and rotation for all the subjects and all the vertebrae. Data processing also included calculation of the ratio of translation to rotation (RTR) along the helical axis.

Three examples have been selected quite deliberately to elucidate the characteristic positions of the helical axis of a vertebra in each of the three predominant patterns of motion in the spine. The first example Figs. 39 and 40 gives the helical axis of motion of Th10 (subject 19) moving in the sagittal plane on the flexion side of the resting position. This would be movement from position 5 to 4 on Fig. 26. The position of the helical axis in relation to the x , y and z axes locates the line about which all points in the vertebra are rotating. Also the relative quantities of rotation about the three axes are indicated by the extent to which the helical axis parallels the respective x , y and z axes. Examination of Fig. 39 shows the position of the axis graphically and Fig. 40 shows its approximate position in relation to the two vertebrae. Additional information in the graphic demonstration is the direction of the helical axis indicated by the arrow which shows that the major rotation is positive about the z axis. The lack of parallelism about the y or x axis indicates that there is only a small element of rotation about them. The rotation is given by the mathematical analysis and is the vector sum θ^* of the instantaneous rotation about the x , y and z axes. The translation of the axis is expressed by the vector sum δ^* of the instantaneous translation along the x , y and z axes. These quantities are indicated in Fig. 39. Their symbols are given in Fig. 38.

Motion in the frontal plane is illustrated by subject 6 Th7 moving from position Re to 3 (Fig. 26). The position and direction of the axis indicates predominant rotation about the x axis in the positive direction (Fig. 41). There is also a moderate amount of y axis and some z axis rotation involved. In this example the helical axis actually goes through the vertebra (Fig. 42). The θ^* and δ^* are also shown to complete the analysis by describing the respective rotation and translation of the axis. The motion in the horizontal plane is similarly indicated in Figs. 43 and 44. The subject is moving in the clockwise direction

from position 2 to 3 in Fig. 26. This motion is in the $-\theta y$ direction. The major rotation is negative about the y axis with a very small component of rotation about the z and x axes. The translation and rotation of the helical axis is also indicated in this example.

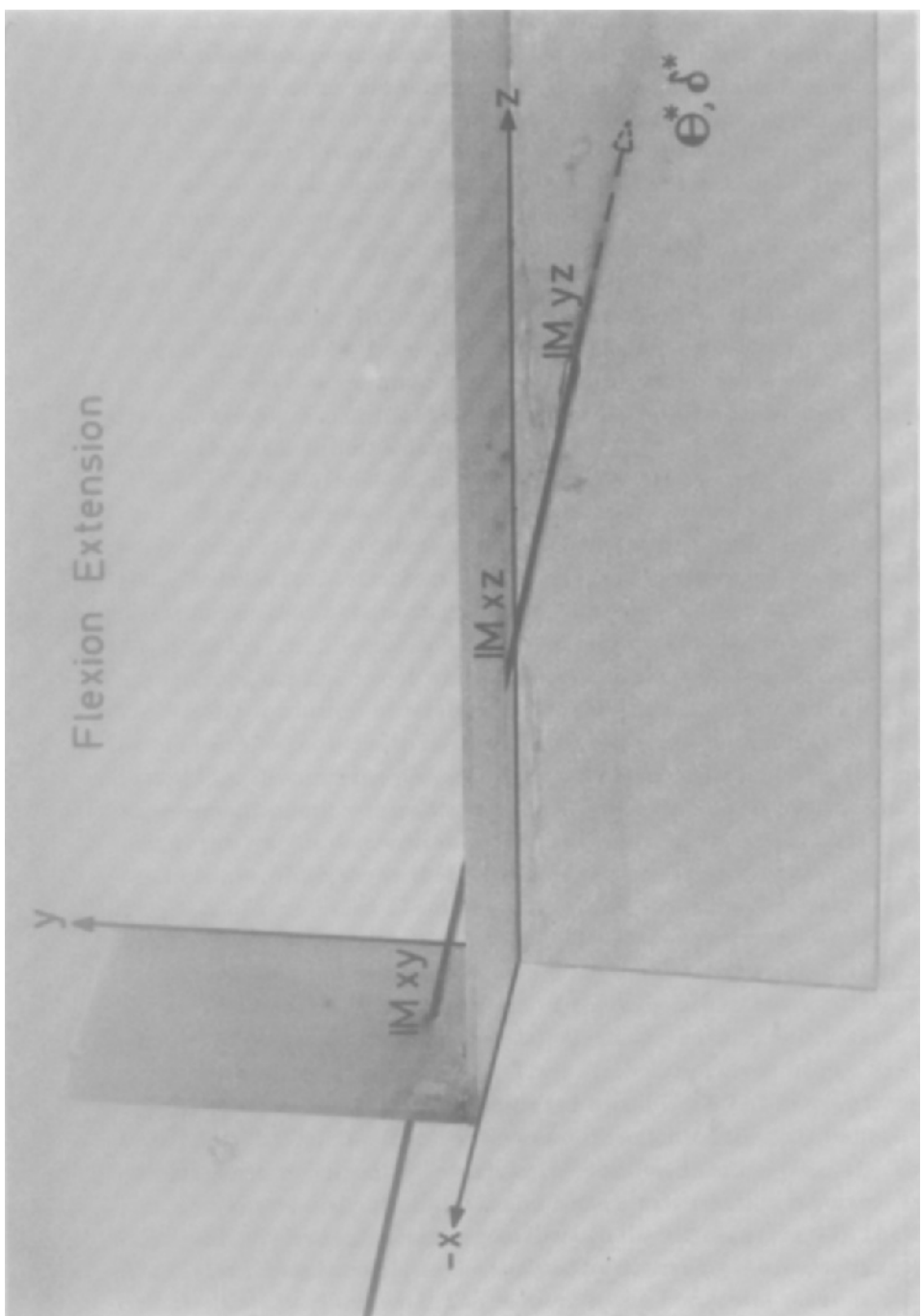


Fig. 39. Plexiglass model constructed to show instantaneous helical axis of motion in three dimensions. Points M_{xy} , M_{xz} and M_{yz} were plotted from the actual data on a scale causing a 5:1 magnification.

$$\theta^* = \begin{Bmatrix} -.12 (\theta^*_x) \\ -.2 (\theta^*_y) \\ 3.75 (\theta^*_z) \end{Bmatrix} \quad \delta^* = \begin{Bmatrix} -.01 (\delta^*_x) \\ .02 (\delta^*_y) \\ -.26 (\delta^*_z) \end{Bmatrix}$$

RTIR 6.78

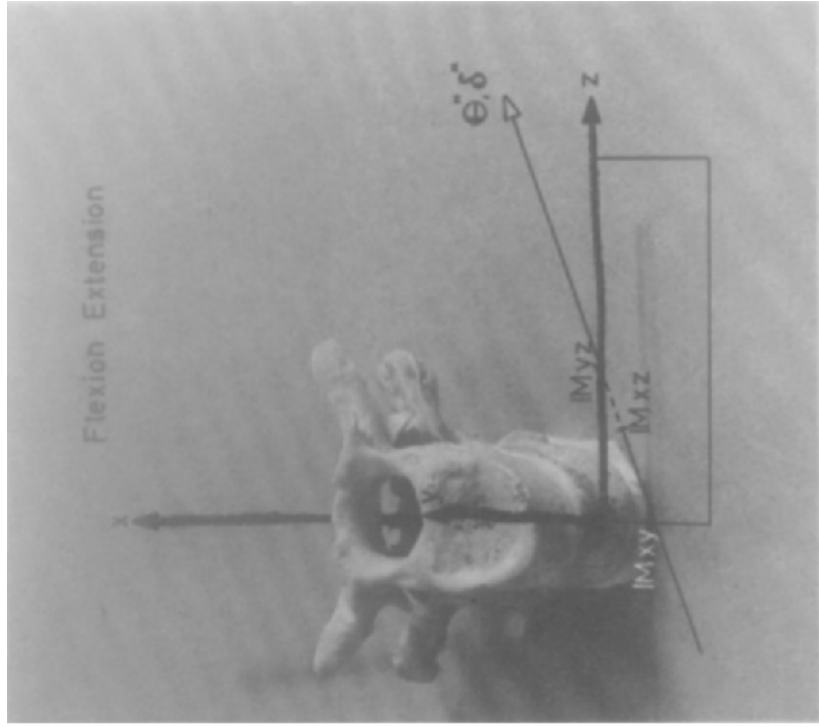
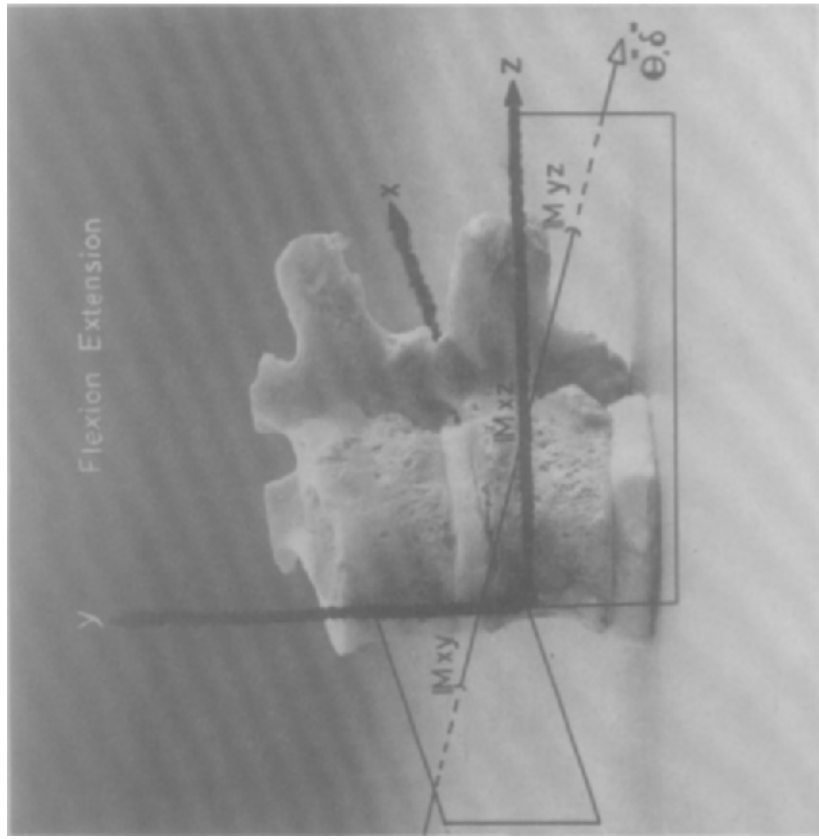


Fig. 40. Shows two views of adjacent vertebrae with the instantaneous helical axis of motion represented for the upper vertebra. Motion is from extension toward flexion. See text for explanation.

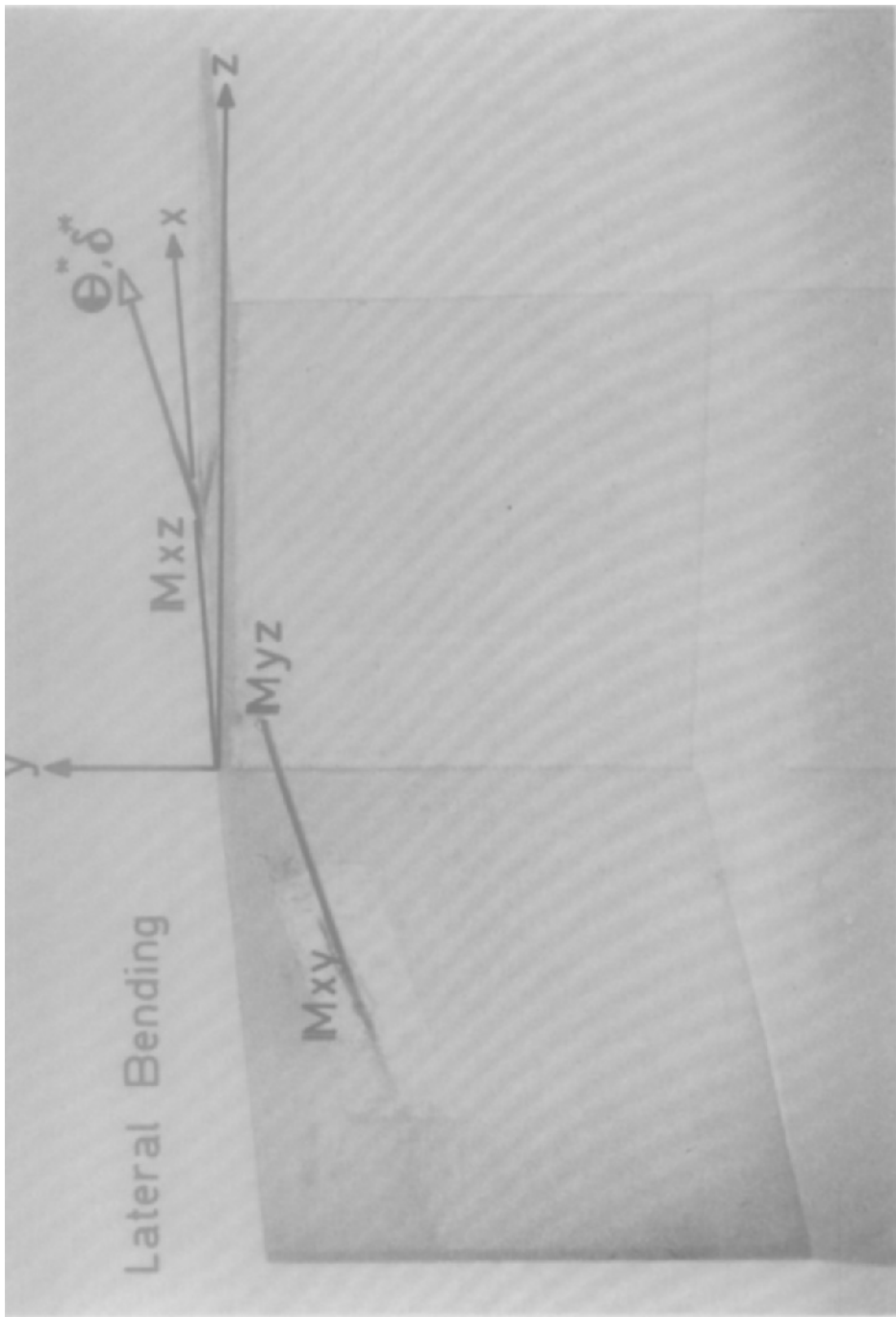


Fig. 41. Plexiglass model constructed to show instantaneous helical axis of motion in three dimensions. Points M_{xz} , M_{rz} and M_{yz} were plotted from the actual data on a scale causing a 5:1 magnification.

$$\theta^* = \begin{cases} 2.99 (\theta^*_x) \\ .48 (\theta^*_y) \\ .11 (\theta^*_z) \end{cases} \quad \delta^* = \begin{cases} .27 (\delta^*_x) \\ .03 (\delta^*_y) \\ .02 (\delta^*_z) \end{cases}$$

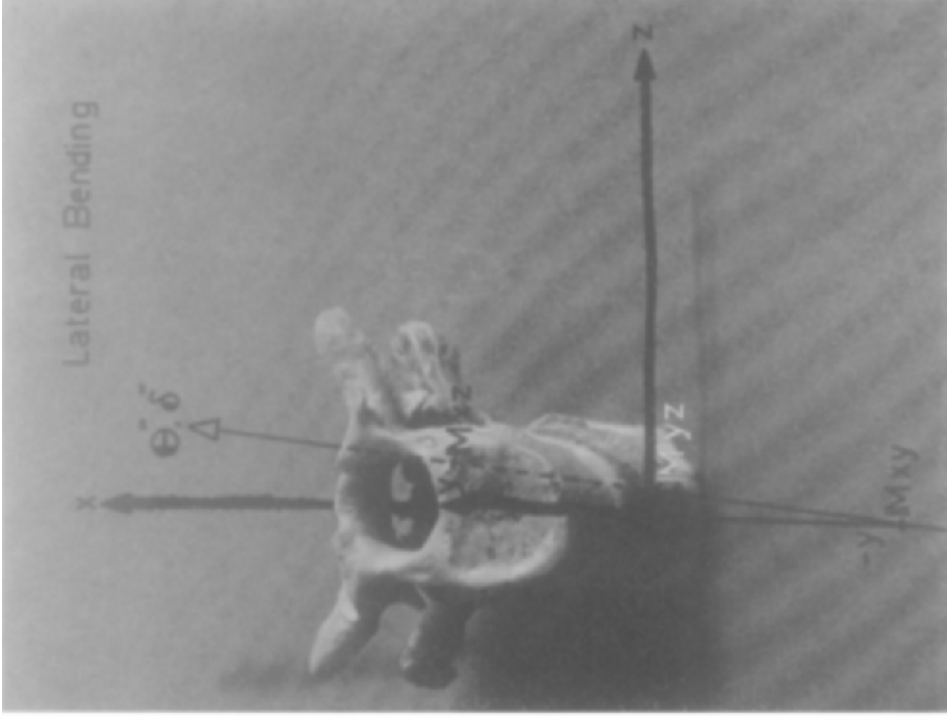
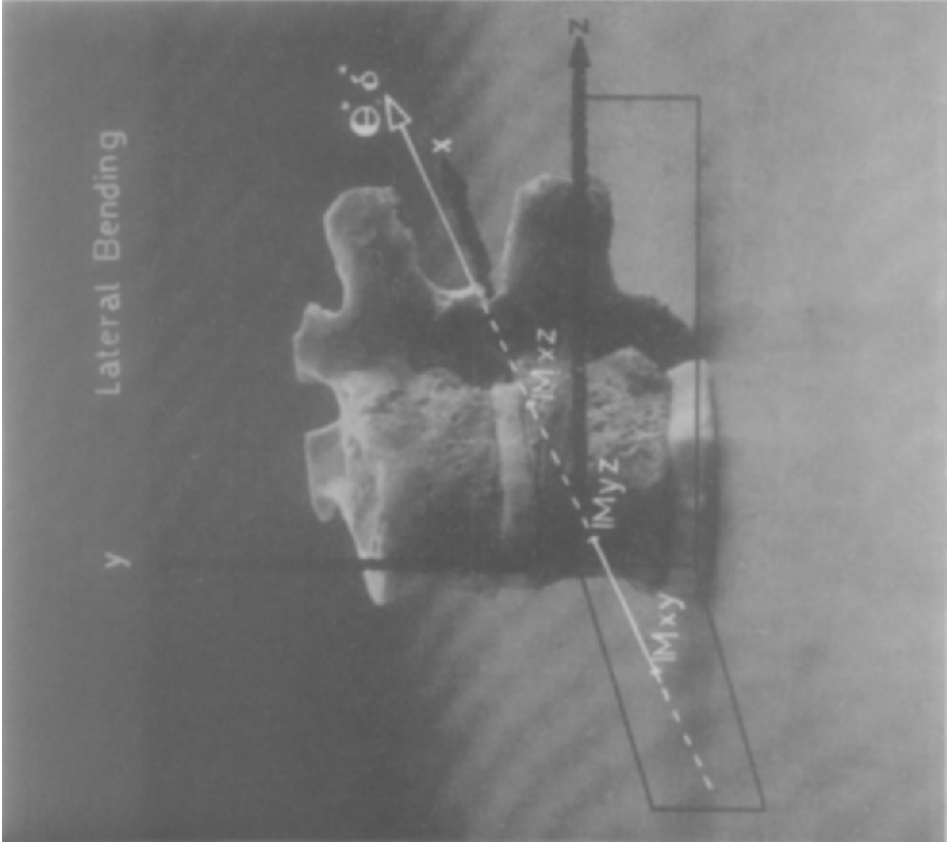


Fig. 42. Shows two views of adjacent vertebrae with the instantaneous helical axis of motion represented for the upper vertebra. Motion is from the resting position toward left lateral bending. See text for explanation.

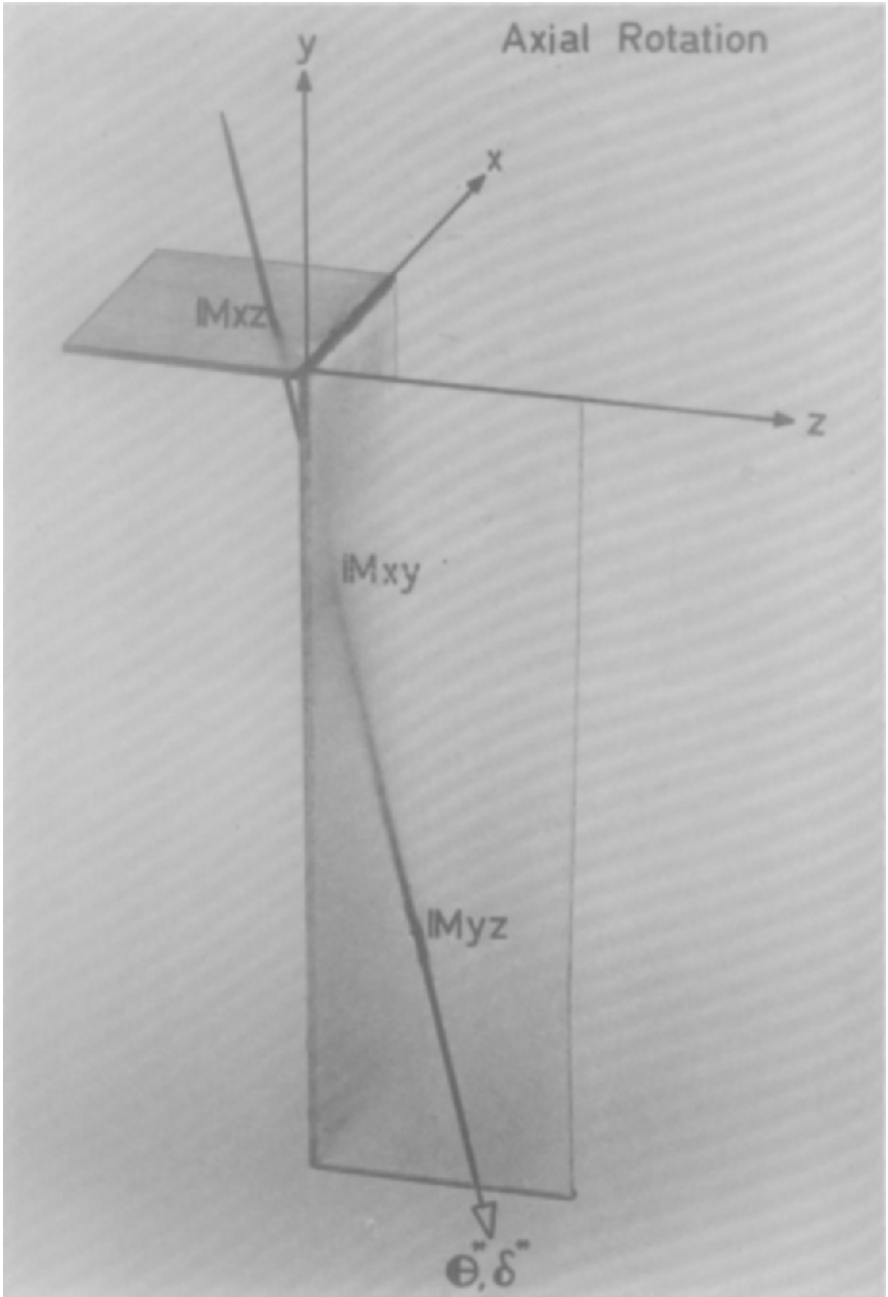


Fig. 43. Plexiglass model constructed to show instantaneous helical axis of motion in three dimensions. Points M_{xy} , M_{xz} and M_{yz} were plotted from the actual data on a scale causing a 5:1 magnification.

$$\theta^* = \begin{Bmatrix} -.28 (\theta^*_x) \\ -1.05 (\theta^*_y) \\ .32 (\theta^*_z) \end{Bmatrix} \quad \delta^* = \begin{Bmatrix} -.01 (\delta^*_x) \\ -.05 (\delta^*_y) \\ .01 (\delta^*_z) \end{Bmatrix}$$

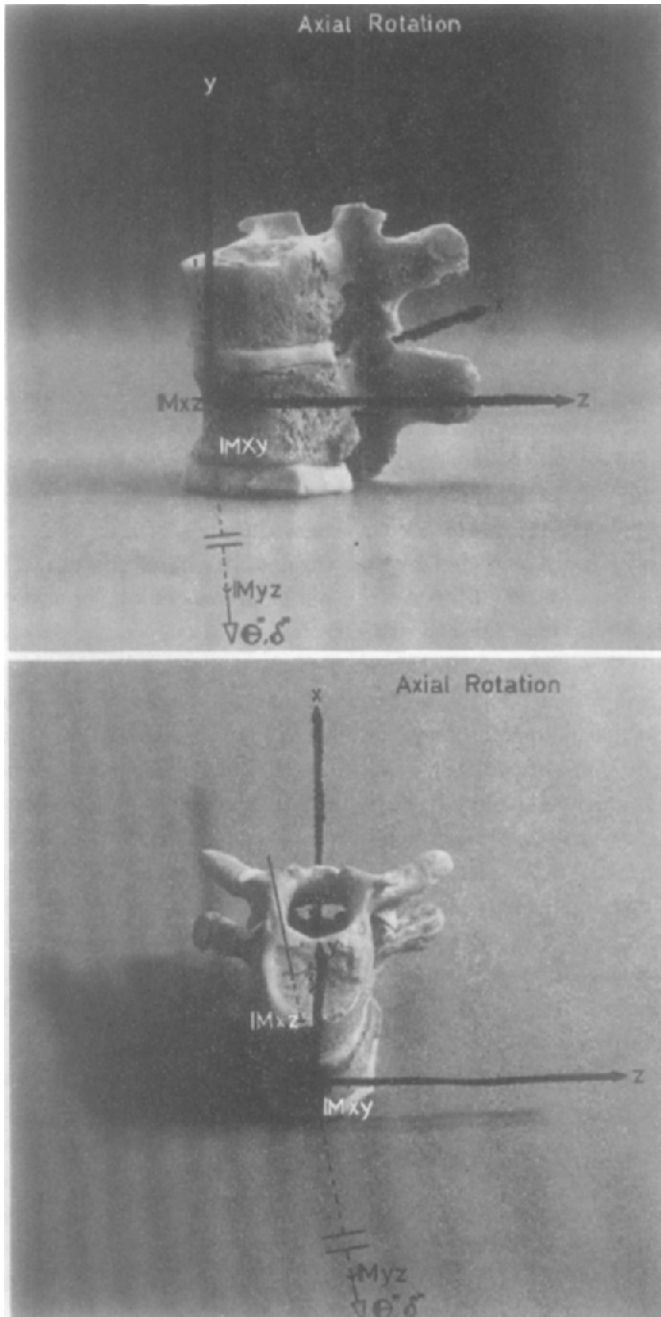


Fig. 44. Shows two views of adjacent vertebrae with the instantaneous helical axis of motion represented for the upper vertebra. Motion is from counterclockwise toward clockwise. See text for explanation.

Comments

The important characteristics of this part of the investigation are the fact that larger segments of the spine were tested and a truly three dimensional analysis of the motion was achieved. The method of testing the vertebrae within the full range of their "allowable" motion afforded observations that may be considered representative of their in vivo behavior. The patterns of motion of the individual vertebrae seem to have their own variation of the spinal theme of translation and rotation. In the thoracic spine both elements are small. Information about the contraversial question of coupling of motion in the thoracic spine is provided by this three dimensional analysis of the data. The graphic representation of the sample vertebrae (Th2) showed rotation of the vertebral body into the *concavity* of the lateral curve. The graphic analysis of the cumulative angles of rotation showed the same coupling but less markedly and less frequently in the middle and lower portions than in the upper. This series supports the conclusion that coupling of the type described is the predominant pattern. However, this pattern diminishes cephalocaudally. It has been shown that there can be essentially no coupling at all or the *reverse* situation of axial rotation into the *convexity* of the lateral curve. This was noted at the Th6 level. This crucial mechanical point about the behavior of the normal thoracic spine based on three dimensional analysis provides important basic background knowledge relevant to the study of scoliosis. In these observations there is again a tendency for the upper part of the thoracic spine to behave somewhat like the cervical spine and the lower part somewhat like the lumbar spine. The pattern of coupling noted to be more marked in the upper thoracic spine is characteristic of the coupling of the cervical spine. (Lysell, 1969). The data from this section of the investigation displayed a propensity for greater flexion extension at the lower portion of the thoracic spine. There was also less rotation noted at the caudal end. Greater sagittal mobility and less axial rotation are both characteristics of the lumbar spine. (Steindler, 1955; Gray, 1967; Gregersen and Lucas, 1967).

This part of the investigation is thought to contain the initial introduction of a complete three dimensional analysis of intersegmental spinal motion in terms of the *helical axis of motion*. The meaning and interpretation of this type of analysis is described and exemplified. The advantages of such a designation

are precision and thoroughness of description. Expression of motion with the helical axis also allows for direct comparison of the motion of bodies of different sizes and shapes. Consequently, there are no limitations on the choice of the measuring points and secondary measuring points are not required. It would not have been possible to introduce the helical axis of motion without the previously mentioned three dimensional mathematical analysis.

SUMMARY AND CONCLUSIONS

The clinical importance of the thoracic spine as regards scoliosis, pain syndromes, surgical and traumatic considerations provided the motivation for this investigation. It seemed apparent that reliable descriptive information about the normal mechanical function of this region of the spine would serve as a basis for better understanding of disease and therapy. Inquiry of the available literature on the motion of the thoracic spine pointed up the fundamental questions to be answered in a thorough description. Previous studies have not combined precise modern techniques with substantial numbers of subjects and reported on all parameters of the motion. Consequently, there is considerable variation among statements in the literature about the motion of the thoracic spine.

There are available at present two well developed and accurate biomechanical experimental methods to describe movement of rigid bodies. One method has been used effectively in the lumbar spine, the other in the cervical spine. The information offered by the two methods is similar, different and complementary. Thus, it was elected to employ them both in this investigation.

In view of the fact that the goal of this endeavour was to offer descriptive information about the mechanics of the thoracic spine, this summary of the results will begin with general descriptive remarks based on measurements and analysis of the data from both parts of the investigation. There is wide variation among the different subjects and different vertebrae of the same subject both in terms of quantity and quality of motion. Nevertheless, some general patterns emerge. There is *more flexion than extension*. One can expect *2-6° of motion at each interspace in the sagittal plane 30-42% of which will be extension, the rest flexion. At the lower thoracic levels, especially Th10 and Th11, there is relatively more sagittal plane motion. Lateral bending is in the range of 3-6° at each interspace.* No pattern of cephalocaudal variation emerged here. The total motion in this plane was found to be greater than for the sagittal plane. *Axial rotation was in the range of 2-6° with the most caudal portion (Th10 and Th11) at the lower end of that range.*

Other findings related to specific questions are also summarized here. This data did not show any correlation positive or negative between age and amount of motion. Tests of the relationship of the "motion ratio" (disc height/disc

diameter) to the amount of motion did not show any significant correlation. Examination of the data for cephalocaudal trends regarding the steepness of arch that each vertebra traveled in relation to its subjacent fellow was made. There was no cephalocaudal pattern in sagittal plane motion, but a more steep pattern was noted in the caudad half in frontal plane motion.

The rather important and contraversial question of coupling was evaluated carefully and the following description is offered. In the upper portion of the thoracic spine there is relatively marked and consistant coupling of axial rotation with lateral bending. The direction of the coupling is such that the *axial rotation of the vertebral body is into the concavity of the lateral curve*. In the middle and also in the lower regions of the thoracic spine this same pattern still exists and probably dominates. However, it is neither as marked nor as consistantly present. Furthermore, the direction of the *coupled axial rotation in the middle regions was noted in some cases to be the reverse of the above described pattern*. A number of observations were made under controlled conditions on the mechanics of the motion segments with and without their *posterior elements*. *The removal of these structures resulted in significant increases in the amount of motion in flexion, in extension and in axial rotation*. This information is valuable to the clinician in terms of his understanding of the effects of surgical or traumatic involvement of these structures on the mechanics of the thoracic spine.

Analysis of the data to designate the *positions of the instantaneous axes of rotation* in the frontal, sagittal and horizontal reontgenographic planes was carried out. These points were clustered and fairly consistantly located for the ranges tested. *For extension they were above the disc, for flexion they were below. In lateral bending they were at or near the disc and slightly away from the midline to the contralateral side of the direction of lateral bending*. The axes in the horizontal plane with axial rotation tended to cluster at points along a line from the *anterior middle portion of the vertebra to the region of the spinal canal*. Removal of the posterior elements caused a small but definite shift in the location of these clusters.

The portion of this study in which known loads were employed revealed that for the range of loads involved a *spring constant could be determined* for the relationship of force and deformation of the motion segments.

From the three dimensional part of this investigation it was possible to introduce the application of the *instantaneous helical axis of motion* in a bio-mechanical study of the intersegmental motion of the spine. The designation of the motion in this manner is complete, precise, graphic and truly three dimensional. The instantaneous helical axis of motion was shown for three thoracic vertebrae. Each of the three exemplified a different one of the three characteristic movements: that is, flexion extension, lateral bending and axial rotation.

This descriptive analysis of the normal thoracic spine includes some considerations of considerable clinical import, especially in the field of traumatology. The characteristic patterns and ranges of motion for the different portions of the thoracic spine is of value in the interpretation of and the protection from offending forces. The same information assists in the recognition of those portions most likely to be susceptible to damage by forces of particular magnitudes and directions. Even more important perhaps is the complete mathematical description of three dimensional motion employing the helical axis of motion. The use of this thorough precise mathematical description in conjunction with the spring constant offers extensive possibilities. Examples would be the construction of representative mechanical models, and the accurate mathematical prediction of expected behavior of the spine in response to normal and pathological forces.

The findings of this investigation of 27 autopsy specimens admit the following remarks about the thoracic spine. Its upper and lower portions behave quite differently and have certain traits suggestive of their neighboring adjacent regions of the spine. That portion of the spine between the two extremes is fairly homogenous in most of its characteristics none of which are particularly distinguishing. The main generalization that characterizes this region of the spine situated in the thorax is that it moves very little.

The analysis of the mechanics has been carried out and presented in a manner that can be meaningfully interpreted and employed by the biological as well as the engineering scientist.

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APPENDIX

Table I. Sums of Ranks, for Statistical Interpretation of Cephalocaudal Variations of Slopes for all Subjects*

Level of MS	Th 1-2	Th 3-4	Th 5-6	Th 7-8	Th 9-10	Th 11-12
<i>Sums of Ranks</i>						
<i>Sagittal Intact</i>						
25% position	12	8	5	9	13	13
75% position	8	9	7	9	12	15
<i>Sagittal Without PE</i>						
25% position	14	9	6	7	11	13
75% position	9	8	9	9	11	14
<i>Frontal Intact</i>						
25% position	13	13	6	7	9	12
75% position	7	11	9	9	11	13
<i>Frontal Without PE</i>						
25% position	14	11	6	8	9	12
75% position	11	10	8	10	10	11
Rotation Intact	14	11	10	11	9	5
Rotation Without PE	11	15	10	10	8	6

* Reading from left to right any difference among the groups of six numbers equal to or greater than 7 can be considered significant at the 0.10 level of confidence. Thus, the slopes for the indicated movements at different vertebral levels may be compared.

Statistics based on, "Balanced incomplete block design". Cox, D. R. Planning of experiments. Wiley, New York, 1958.

Vertebral Level	Th 1-2		Th 3-4		Th 5-6		Th 7-8		Th 9-10		Th 11-12	
	25%	75% bined	25%	75% bined	25%	75% bined	25%	75% bined	25%	75% bined	25%	75% bined
Subjects IV	SI	1.10 0.70 1.80	0.80 0.20 1.00	1.30 1.00 2.30	4.90 3.70 8.60	1.90 0.55 2.45	3.85 2.20 6.05					
	SS	2.60 3.20 5.80	2.80 2.30 5.10	2.05 2.00 4.05	4.90 6.35 11.25	2.20 3.20 5.40	8.25 8.60 16.85					
V	FI	0.20 1.15 1.35	1.20 2.25 3.45	0.95 0.65 1.60	2.30 3.05 5.35	1.05 0.95 2.00	3.25 3.80 7.05					
	FS	2.45 4.00 6.45	1.55 2.55 4.10	1.30 0.50 1.80	3.10 3.15 6.25	0.95 1.40 2.35	3.70 4.35 8.05					
	RI	9.50	1.95	8.65	14.05	1.70	0.90					
	RS	16.70	5.05	13.85	18.55	1.95	2.35					
VI	SI	1.55 0.70 2.25	1.55 0.70 2.25	2.40 2.90 5.30	5.75 7.70 13.45	10.20 4.75 14.95	27.80 17.70 45.50					
	SS	5.25 5.55 10.80	5.25 5.55 10.80	3.40 8.30 11.70	7.70 14.70 22.40	9.80 13.10 22.90	23.50 18.10 41.60					
	FI	2.75 1.70 4.45	2.75 1.70 4.45	3.95 4.00 7.95	6.60 6.00 12.60	7.80 2.80 10.60	15.00 10.30 25.30					
	FS	3.25 2.00 5.25	3.25 2.00 5.25	5.80 5.00 10.80	12.00 11.40 23.40	10.50 1.20 11.70	17.60 11.20 28.80					
VII	RI	12.80	15.30	12.00	13.05	5.95	4.35					
	RS	19.90	21.20	19.00	13.50	8.15	9.45					
	SI	6.55 3.45 10.00	6.55 3.45 10.00	2.40 2.90 5.30	8.50 1.10 9.60	6.50 0.40 6.90	14.30 9.90 24.20					
	SS	11.35 7.85 19.20	11.35 7.85 19.20	3.40 8.30 11.70	3.70 4.35 8.05	3.45 4.60 8.05	14.30 18.20 32.50					
VIII	FI	5.20 3.10 8.30	5.20 3.10 8.30	3.95 4.00 7.95	2.20 2.00 4.20	2.40 3.35 5.75	5.10 3.70 8.80					
	FS	5.20 6.90 12.10	5.20 6.90 12.10	5.80 5.00 10.80	3.05 1.75 4.80	1.15 1.45 2.60	5.60 7.10 12.70					
	RI	15.30	15.30	12.00	12.65	11.20	11.20					
	RS	21.20	21.20	19.00	16.25	18.20	11.80					
IX	SI	5.30	2.80 0.25 3.05	7.10 1.65 8.75	6.35 2.20 8.55	11.85 3.50 15.35						
	SS	8.20 1.35 9.55	3.40 3.60 7.00	5.70 5.70 11.40	5.60 4.10 9.70	10.60 7.10 17.70						
	FI	13.40 2.95 16.35	4.60 3.00 7.60	6.90 1.15 8.05	8.45 5.20 13.65	6.70 3.85 10.55						
	FS	13.40 3.10 16.50	3.10 3.25 6.35	5.10 1.90 7.00	7.05 4.30 11.35	4.85 3.85 8.70						
X	RI	19.20	10.95	18.00	11.20	5.70						
	RS	28.10	20.80	25.05	18.20	6.35						

SI Sagittal intact

SS Sagittal without posterior elements

FI Frontal intact

FS Frontal without posterior elements

RI Rotation intact

RS Rotation without posterior elements

* Missing entities due to a variety of experimental conditions

Table II. *Continued*

Vertebral Level	Th 1-2		Th 3-4		Th 5-6		Th 7-8		Th 9-10		Th 11-12	
	25%	75% bined	25%	75% bined	25%	75% bined	25%	75% bined	25%	75% bined	25%	75% bined
Subjects VIII	SI	4.85	0.20	5.05	4.80	0.80	5.60	5.20	2.40	7.60		
	SS	6.70	1.80	8.50	4.70	3.80	8.50	3.80	11.30	15.10		
	FI	5.00	0.85	5.85	2.95	2.60	5.55	5.60	3.30	8.90		
	FS	4.70	1.70	6.40	2.60	4.25	6.85	5.70	6.30	12.00		
	RI	21.50			15.70			15.30				
	RS	27.90			18.50			22.20				
IX	SI	6.05	0.60	6.65	2.10	0.40	2.50	3.20	0.70	3.90	4.20	1.20
	SS	7.20	4.20	11.40	3.40	2.70	6.10	0.50	0.20	0.70	3.25	2.10
	FI	1.95	3.25	5.20	2.95	2.60	5.55	2.40	1.40	3.80	1.40	1.70
	FS	5.40	5.00	10.40	2.80	1.85	4.65	0.90	0.40	1.30	1.50	3.30
	RI	4.40			12.10			8.10			9.20	
	RS	16.60			16.10			11.20			11.30	
X	SI	5.80	1.75	7.55	4.75	1.30	6.05	0.75	0.50	1.25	2.20	2.05
	SS	8.70	0.50	9.20	6.20	2.85	9.05	1.15	1.40	2.55	3.20	3.00
	FI	2.90	1.40	4.30	6.20	6.95	13.15	1.80	2.30	4.10	4.05	2.40
	FS	5.70	2.60	8.30	6.00	5.80	11.80	2.15	1.75	3.90	5.10	3.25
	RI	16.30			14.75			4.00			4.10	
	RS	25.00			19.10			5.50			4.50	
										3.15		1.05
										3.55		0.90
										3.35	2.70	6.05
										5.65	4.35	10.00
										5.75	3.90	9.65
										5.35	3.85	9.20
												2.30
												2.40
												3.45
												2.50
												5.95

SI Sagittal intact
 SS Sagittal without posterior elements
 FI Frontal intact
 FS Frontal without posterior elements
 RI Rotation intact
 RS Rotation without posterior elements

Table II. *Continued*

Vertebral Level	Th 1-2		Th 3-4		Th 5-6		Th 7-8		Th 9-10		Th 11-12		
	25%	75% bined	25%	75% bined	25%	75% bined	25%	75% bined	25%	75% bined	25%	75% bined	
Subjects XI	SI	6.65	1.10	7.75	5.50	1.00	6.50	8.85	2.30	11.15	7.85	2.80	10.65
	SS	5.10	3.80	8.90	4.65	3.65	8.30	4.50	5.15	9.65	8.70	6.15	14.85
	FI	6.05	1.95	8.00	3.50	2.00	5.50	2.05	2.50	4.55	4.80	4.90	9.70
	FS	3.85	4.05	7.90	2.15	1.70	3.85	0.80	3.35	4.15	5.25	4.20	9.45
	RI	11.25			12.70			11.05			6.40		
	RS	17.80			11.10			13.00			6.70		
XII	SI	4.25	1.60	5.85	3.10	0.90	4.00	8.80	0.95	9.75	4.50	1.95	6.45
	SS	3.20	5.20	8.40	3.00	1.40	4.40	6.05	3.00	9.05	4.30	4.30	8.00
	FI	5.60	4.60	10.20	5.15	2.25	7.40	3.20	1.95	5.15	0.70	2.40	3.10
	FS	4.65	5.95	10.60	3.65	2.30	5.95	1.90	3.30	5.20	0.65	2.80	3.45
	RI	12.60			8.90			5.70			4.95		
	RS	15.15			12.35			8.35			5.35		
XIII	SI	2.95	0.20	3.15	1.50	0.70	2.50	1.90	3.15	5.05	2.40	2.50	4.90
	SS				2.90			1.90	4.35	6.25	2.40	3.00	5.40
	FI				1.30	2.70	4.00	2.80	5.25	8.05	3.00	3.50	6.50
	FS				1.05	2.70	3.75	3.10	4.00	7.10	2.50	1.65	4.15
	RI	12.85			7.10			7.30			4.20		
	RS	21.65			12.90			8.80			3.90		

SI Sagittal intact
SS Sagittal without posterior elements
FI Frontal intact
FS Frontal without posterior elements
RI Rotation intact
RS Rotation without posterior elements

Table III. Means of Standardized Motion of all Subjects Under Various Loading Conditions at the Various Vertebral Levels

Vertebral Level	Th 1-2		Th 3-4		Th 5-6		Th 7-8		Th 9-10		Th 11-12					
	25%	75%	25%	75%	25%	75%	25%	75%	25%	75%	25%	75%				
MSI	4.34	0.69	4.92	4.91	3.21	1.09	4.30	5.57	2.63	8.20	5.86	2.26	8.12	12.22	7.11	19.43
MSS	6.68	2.21	8.89	9.33	3.02	3.31	6.45	4.46	5.84	10.30	5.75	5.43	11.18	11.38	12.52	23.68
MFI	4.69	1.92	6.61	7.19	3.24	2.16	5.40	3.87	3.34	7.21	3.83	3.04	6.87	7.19	6.15	13.34
MFS	6.33	3.28	9.61	7.39	2.82	2.22	5.04	4.33	4.41	8.74	3.67	2.62	6.29	8.71	6.91	15.61
MRI	13.96			10.98	10.49			10.36			4.57			3.36		
MRS	22.66			16.44	13.82			13.47			5.31			4.66		

MSI Mean sagittal intact
MSS Mean sagittal without posterior elements
MFI Mean frontal intact
MFS Mean frontal without posterior elements
MRI Mean rotation intact
MRS Mean rotation without posterior elements

Table IV. Sums of Rank, for Statistical Interpretation of Cephalocaudal Variation of the Mean Values for Extracted Angles at 6 Kp/cm² Load and 20 Kp cm Moment. For all Subjects*.

Level of MS	Th 1-2	Th 3-4	Th 5-6	Th 7-8	Th 9-10	Th 11-12
Sums of Ranks at 6 kp/cm² load						
<i>Sagittal Intact</i>						
25% position	10	7	5	11	13	14
75% position	8	9	7	10	12	14
combined	10	8	6	11	11	14
<i>Sagittal Without PE</i>						
25% position	13	9	6	7	11	14
75% position	8	7	9	10	11	15
combined	10.5	8	6.5	10	11	14
<i>Frontal Intact</i>						
25% position	10	12	7	8	9	14
75% position	8	8	9	12	9	14
combined	10	11	7	11	7	14
<i>Frontal Without PE</i>						
25% position	12	9	8	10	7	14
75% position	10	8	7	13	10	12
combined	12	8	8	10	8	14
Sums of Ranks at 20 kp cm moment						
Rotation Intact	13	12	11	11	8	5
Rotation Without PE	15	13	10	10	7	5

* Reading from left to right, any difference among the groups of six numbers equal to or greater than 7 can be considered significant at the 0.10 level of confidence. Thus, the extracted angles of motion at different vertebral levels may be compared.

Statistics based on "Balanced incomplete block design". Cox, D. R.: Planning of experiments. Wiley, New York, 1958.

Table V. Rank Order of Disc Height/Disc Diameter With Associated Total Sagittal Motion of Th 7-8 for Each Subject.

Motion Ratio $\times 100$ Disc Height/Disc Diameter	Subject	Sagittal Intact	Sagittal Without Posterior Elements
8.90	VI	9.6°	8.1°
9.90	IV	8.6°	11.3°
9.90	XII	9.8°	9.1°
9.92	X	4.3°	6.2°
12.35	XI	11.2°	9.7°
12.76	IX	4.0°	5.4°
12.98	XIII	5.1°	6.3°
16.35	VIII	7.6°	15.1°
17.19	V	13.5°	22.4°
18.18	VII	8.6°	9.7°

Coefficient of correlation 0.05 0.25

Table V (cont.). Rank Order of Disc Height/Disc Diameter With Associated Total Frontal Motion of Th 7-8 for Each Subject.

Motion Ratio $\times 100$ Disc Height/Disc Diameter	Subject	Frontal Intact	Frontal Without Posterior Elements
8.32	IV	5.4°	6.3°
9.46	XI	4.6°	4.2°
10.34	IX	3.1°	4.8°
11.60	VII	13.7°	11.4°
12.50	XIII	8.1°	7.1°
12.85	VI	4.2°	4.8°
12.90	XII	5.2°	5.2°
13.67	X	6.5°	8.4°
14.06	V	12.6°	23.4°
15.00	VIII	8.9°	12.0°

Coefficient of correlation 0.17 0.27

Table VI. Shows Amount of Linear Movement in Sagittal Plane and Percentage of Extension

Portion of Thoracic Spine	Extension		Flexion		Total	% Extension
	(mm displacement on X axis to resting position)	(mm displacement on X axis to resting position)	(mm displacement on X axis beyond resting position)	(mm displacement on X axis beyond resting position)		
1-7	12.20		24.60		36.80	33
1-7	19.60		33.38		52.98	37
1-7	12.73		19.98		32.21	39
1-7	11.42		27.61		39.03	29
1-7	12.78		27.27		40.05	32
1-7	10.15		35.78		45.93	22
1-6	10.58		17.18		27.76	38
1-8	25.20		48.30		73.50	34
2-7	6.38		11.87		18.25	35
						Mean 33.4
						Range of Mean 30.5
6-11	7.20		29.40		36.60	29
6-11	19.87		32.79		52.66	33
6-10	6.30		17.26		23.56	17
						Mean 26.3
						Range of Mean 23.0
4-11	24.40		54.95		84.35	34
3-10	40.85		74.72		115.57	35
5-10	10.30		21.90		32.20	31
						Mean 33.3
						Range of Mean 32.5

Mean of % Extension for all Segments 31.0%
 Range of Mean 28.0

Table VII. Shows Angles of Motion in Flexion and Extension for Indicated Vertebra of the Different Subjects

Subjects	Extension											Means					
	1	2	3	4	5	6	7	8	9	10	11		12	13	14	15	19
Vertebral Level																	
1			2.35	1.81		0.55	1.09										1.5
2		0.83	1.79	1.77	1.10	0.44	1.14									0.40	1.1
3			1.90	1.58	0.56	0.17	0.79	1.43	0.79				0.38	0.12			0.9
4		0.35	0.87	0.98	0.69	1.04	0.72	0.94	0.80				1.36	0.17			0.45
5			0.80	1.66	0.70	0.99	1.11	1.87	0.66	0.53			1.07	0.85	1.13	2.45	1.2
6	0.19		1.56	1.39	1.64	0.70	0.22		0.55	0.26	0.22		-0.07		1.12	1.31	0.67
7	0.42	0.99	1.26	2.53			1.25	1.77				0.02	0.78	1.30	2.33	2.17	1.4
8	0.21									0.63	0.56		1.14	1.90	2.94	1.52	1.3
9	0.52									0.60	0.57	1.19	1.13		2.35	2.12	1.62
10	0.62								1.08	0.67	0.95	1.63			3.16	2.61	1.90
11										0.83	1.85	1.76				2.31	10.48
																	3.5
																	Average of Means 1.4

Subjects	Flexion											Means					
	1	2	3	4	5	6	7	8	9	10	11		12	13	14	15	19
Vertebral Level																	
1			1.16	1.44		1.15	1.81										1.4
2		1.75	1.63	1.88	0.72	1.28	1.68									1.76	1.5
3			1.03	1.02	0.58	1.62	0.53	1.17	0.84				0.80	6.49			1.6
4		0.43	0.96	1.40	0.40	1.61	1.03	0.96	0.53				0.67	0.41		3.09	1.0
5			1.75	1.30	1.13	2.98	0.94	0.62	0.80	0.42			2.28	1.08	1.49	2.16	1.4
6	0.69		1.03	1.86	1.12	2.16	1.69		0.82	-0.15	0.19		1.84		2.23	2.29	3.66
7	0.68	1.49	2.19	2.01			2.19	3.62			0.56		1.53	2.57	3.24	2.24	2.0
8	1.06									1.17	1.03		2.48	2.76	3.57	2.72	2.2
9	1.53									1.17	1.34	1.87	2.10		2.76	2.38	2.93
10	1.80								1.13	1.47	1.17	2.11			6.12	2.71	3.95
11										2.06	2.84	3.09				4.93	3.84
																	Average of Means 1.9

Table VIII. Flexion Extension, Total θz

Subjects	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	19	20
Vertebral Level																	
1			3.51	3.25		1.70	2.90										2.16
2		2.58	3.42	3.65	1.82	1.72	2.82										
3			2.12	2.60	1.14	1.79	1.32	2.60	1.63					1.18	6.61		
4		0.78	1.83	2.38	1.09	2.65	1.75	1.90	1.33					2.03	0.58		3.54
5			2.55	2.96	1.83	3.97	2.05	2.49	1.46	0.95				3.35	1.93	2.62	4.61
6	0.88		2.59	3.25	2.76	2.86	1.91		1.37	0.41	0.41		1.84				4.33
7	1.10	2.48	3.45	4.54			3.44	5.39			0.58		1.53	3.87	5.57	4.41	
8	1.27									1.80	1.59		2.48	4.66	6.06	4.24	
9	2.05									1.77	1.91	3.06	2.10		5.11	4.50	4.55
10	2.42									2.21	2.14	2.12	2.11		9.37	5.32	5.85
11										2.89	4.69	3.09				7.24	14.32

Table IX. Lateral Bending, Total θ_x

Subjects	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	19	20
Vertebral Level																	
1			2.46	5.52	10.05												
2		1.22	10.02	2.98	6.28				3.63								
3		3.88	6.63	5.17	1.07	1.82			3.76								
4		1.85			6.18	2.59			1.04								13.50
5		3.78	6.13	6.52	1.70	3.41			2.82				10.92	8.15			4.24
6		2.28	4.47	0.46	5.24	1.23			1.58	2.64	3.43		2.66	1.93	20.97		3.49
7		4.45	1.34	4.70	6.53		1.34			2.22	2.07			10.47	4.18		
8		5.69								0.78	4.58			4.02	3.46		
9		1.74											5.26	4.58			5.86
10		1.53											2.38	6.04	6.50		5.43
11											2.34					7.78	1.03

Table X. Axial Rotation, Total θ_y

Subjects	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	19	20
Vertebral Level																	
1																	
2		2.09	6.73	4.87		5.15	4.71		3.64					1.06			
3		0.91	5.87	3.22		11.95	3.36		2.94					6.25			6.56
4		1.69	5.29	3.06			3.65		3.99					5.20		3.64	4.45
5		2.95	4.83	2.64		7.92	3.64		3.07	3.60			5.86		8.13		6.97
6		2.65	3.22	3.85	3.49	4.32	3.99		1.73	3.84	5.69		5.43		5.61		5.76
7		1.68	2.78	3.27					3.82	3.82	6.35	3.94	5.24	5.30	6.67		
8		2.29								6.89			4.46		7.32	6.53	
9		1.45								3.78			3.64		3.96	5.50	0.99
10		0.50								2.12			2.40		3.58	4.64	5.03
11													2.77			2.70	2.19

Table XI. Average Relative Curvature Sagittal, $1/r \times 100$

Vertebral Level	1	2	3	4	5	6	7	8	9	10	11
Subjects											
1						3.70	6.41	6.07	2.38	5.09	
2		3.98		6.38			6.41				
3											
4	6.62	5.16	6.13	4.47	3.79	5.13	5.40				
5		5.01	4.50	11.33	12.66	4.64					
6	8.62	5.25	4.85	4.58	5.03	5.20					
7	11.98	5.38	3.74	4.47	5.18	7.35	7.49				
8			8.00	5.76	4.34		6.56				
9			4.41	4.63	4.26	3.48					
10					4.66			5.01	6.15	2.84	
11						4.04	7.56	10.88	6.64	12.75	5.06
12											
13						7.39	10.78	4.32	6.95	6.81	9.62
14			14.39	6.86			5.14	6.63			
15			3.99	12.97	4.74	11.99	7.84	7.85	30.38	10.29	
19					11.90	4.60	11.94	23.44	5.22	6.48	5.95
20		7.82		14.27	1.26	5.00			5.96	7.48	5.11
Means	9.07	5.43	6.25	7.57	5.78	5.68	7.55	9.17	9.10	7.39	6.44
Range of Means	9.27	5.90	9.07	9.37	7.59	7.74	8.49	13.88	16.38	8.00	7.34

Table XII. Average Relative Curvature Frontal, $1/r \times 100$

Vertebral Level	1	2	3	4	5	6	7	8	9	10	11
Subjects											
1						21.43	36.79	34.44	14.23	29.96	
2		24.43		39.11	25.93		40.07				
3	4.70	3.87	3.00		3.95	4.20	6.31				
4	38.05	29.80	35.79		22.37	29.55	32.04				
5											
6	49.78	30.49	28.21	26.86	29.50	31.17	36.07				
7			21.97	26.22	30.23	42.01	43.45				
8											
9		25.79	26.97	27.97	26.21	22.07					
10						47.35	22.49				
11					26.34	23.06	43.07				29.36
12											
13									39.35	38.87	55.57
14											
15					27.36	67.52	44.86	44.69		59.53	
19					66.87	27.46	68.12		29.97	37.21	34.80
20				44.96		82.75			37.09	42.69	30.47
Means	30.84	22.88	23.19	33.02	28.75	36.23	37.33	39.57	30.16	41.65	37.55
Range of Means	27.24	17.13	20.90	35.60	35.41	43.48	37.22	39.57	26.79	36.33	57.15