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STUDIES OF THE HUMAN SPINE

Final Report to the Air Force Office of
Scientific Research (AFOSR), Air Force Systems Command, USAF

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The techniques and equipment to take biplane and stereo roentgenographs of the spine and pelvis in various positions of flexion-extension, lateral bend and axial rotation are explained. The in vivo load-deflection characteristics are given both for the whole spine and for individual motion segments. Moiré fringe topography for the back is introduced and results given. Application of these techniques to USAF ejection seats, the MAST suit and clinical measures of disc space height and rotation are reported. Measurements of the pelvis of various racial groups are reported. There is discussion of →(over)

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↳ interactions between the pelvis and the spine.



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Technical Information Officer

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1. INTRODUCTION

Anatomic (2,4,5,7,8,9,12,14), motion (1,3,11,17,20), and biodynamic (6,10,25,27) studies of the human spine are numerous. Previous investigators have determined in part the response of the spine to various loading conditions (21,33,34); others have sought insight into deformities (e.g. scoliosis) (24,32), and to degenerative diseases of the spine.

Most biodynamic studies have used isolated cadaveric spine (3,11,21,26) segments, though some investigators have used radiographic techniques in living subjects (1,20). Each of these approaches has met with serious drawbacks. Ideally, biomechanical and kinematic studies should be performed on the spines of living persons with all ligamentous and muscular attachments intact, or at least on intact postmortem specimens. Radiographic techniques must be precisely controlled and reproducible.

We have attempted to combine these two essential elements of precise radiographic technique in living and fresh postmortem subjects (16,22,23,29,30). Equipment has been developed to perform both radiographic, kinematic and force deflection studies (15,30). Additional modifications of this apparatus are now in progress and will increase its capability. An important emphasis of

the work has been to obtain an improved understanding of the behavior of the spine in Air Force seats, as well as to generate accurate input data for utilization in computer models of the spine. Such studies presently have been restricted by the limited reliable static and kinematic input data.

Our original efforts were directed towards developing the technology for evaluating spinal mechanics in vivo in the human. It was evident that classic studies of the mechanical properties of vertebral motion segments were limited because of absence of muscle, abdominal tone and normal (or abnormal) positions. The importance of such data to realistic mathematical models of the spine, as well as developing an understanding of mechanical factors operational in low back pain, was evident.

The first year of funding permitted the development of an apparatus originally designed to evaluate standard radiographic methodologies, and to analyze some aspects of intervertebral motion (28). Also, biplanar radiography was adapted for use in the spine, bony landmarks identified and validated, and methods developed for the analysis of vertebral motion, flexion-extension, and subsequently of intervertebral disc space (IVDH) (30,35). Computer algorithms to describe motion were developed.

During the second year of funding, the methods were applied to analysis of vertebral motions and the coupled characteristics of each motion segment in the lumbar spine more completely. Adaptation of our apparatus was carried out to measure the load-deflection characteristics of the recumbent spine in living persons. Hysteretic behavior in flexion-extension and axial rotation were demonstrated. Similarly, the limitations of instant center analysis in live subjects were characterized, and some of the factors responsible for these limitations investigated (29,36,37, 28). These methods were directly applied to Air Force operational needs in studies of the Air Force HAC ejection seat.

During the latter part of the second year it was evident that future studies must incorporate the following:

- 1) Ability to measure motion and load-deflection characteristics of the normally standing and seated individual;
- 2) A system free of restraint which would allow these postures to be simulated easily, either actively or passively;
- 3) A flexible system which would permit posture to be viewed from standing to seated or recumbent;
- 4) A method to impose loads both actively and passively on the spine with three-dimensional analysis of input-output data.

From a technical standpoint, two features of importance were identified: 1) the ability to insure accuracy of x-rays

and reduce x-ray exposure; and, 2) The ability to measure non-radiographically some aspects of lumbar spine deflection (39).

The funding period of 1976-77 saw the development of a new and improved apparatus. The stereo x-ray heads permit quasi AP roentgenographs to be made, thus increasing the accuracy and decreasing the amount of x-ray exposure. The Moiré Fringe grid achieves the goal of measuring the back topography which we can correlate to the motion of the spine (40,41,42,43,44). A variety of topographic measurement techniques was tested or evaluated (vector-stereography, holography, Moiré Fringe, etc.). Moiré Fringe topography was evaluated in the greatest detail, and methods established with computer programs for the analyses of the data. Simultaneously, Moiré Fringe topography, vectorstereography and biplanar radiography were analyzed to determine the relationships between internal vertebral positions and external topographical shape and motion (40,45,46). A relationship has been partly defined in the past and data analysis is continuing. These data suggest that topographic analyses can be a powerful tool in assessing motion of the lumbar spine but will not define specific motion segment behavior. The greatest benefit is that areas of the spine can be analyzed in a far

greater number of positions and motions than possible with biplanar radiography. The incorporation of both topographic methodologies and stereoradiography into the apparatus therefore has the benefit of allowing motion segment behavior to be attained in a reasonable number of positions with a greater amount of data from the entire lumbar and thoracic spine generated from the topographic analysis.

During the 1976-77 funding period, we have applied these methodologies to a study of normal human spine behavior in live human subjects in a vertical position and initial results have been presented (40-45). This work has included the preliminary measurement of load-deflection behavior with the musculature included and preliminary isometric load tests. Other work has included the measurement of motion at the sacroiliac joint.

The clinical ramifications of these studies are numerous. We have presented data demonstrating the motion of lumbar segments under known force inputs, as well as force-deflection relationships (29). Radiographic and kinematic studies completed to date have resulted in an improved method of determining vertebral rotation (22,23). The difficulties in assessing intervertebral disc space height have been clarified (18). Techniques developed in this project have been applied in long-term follow up studies of patients with low back disorders (16). Currently, kinematic analyses of

the lumbar spine in these patients is in progress. The Moiré Fringe techniques have been utilized in the assessment of scoliosis patients.

2. OBJECTIVES

Objectives of the research project were as follows:

- 1) To determine the kinematics of the thoracic and lumbar spine of intact subjects manipulated through flexion-extension ranges in the USAF seats.
- 2) To measure the motion and load-deflection characteristics of the spine of both living and cadaveric subjects in normal planes of movement (flexion-extension, lateral bend, and axial rotation).
- 3) To determine the relationships between external (input) motion and resultant motion of given vertebral bodies.
- 4) To refine the techniques of localization of vertebral bony landmarks in space.
- 5) To study the interactions of the pelvis with respect to the overall biomechanics of the spine.

- 6) To develop an apparatus as a clinical tool in the evaluation of degenerative and traumatic disease of the spine.
- 7) To study the changes of back topography as a function of various external loads and postural changes.
- 8) To ascertain the isometric and isotonic strength of the back in various postures.
- 9) To develop improved radiographic methodology to:
 - a) Assess whether stereo-radiography would provide a method of improved accuracy and reduced x-ray exposure. This is particularly desirable in living human subjects such that a greater number of observations can be made through various spine motions.
 - b) Further develop and apply digitizing techniques to insure the efficiency of data collection and analysis.
- 10) To further develop the radiographic identification of pelvic bony landmarks for the purposes of assessing spinal pelvic interactions in axial rotation, flexion-extension and lateral bend.

- 11) To describe the anthropometry of the pelvis so as to permit the incorporation of this in computer models of the spine.

3. RESEARCH REPORTS

3.1 Original Spine Machine (Supine Tests)

METHODS

Apparatus.

An apparatus has been constructed which allows evaluation of the mechanical and biplane radiographic characteristics of the spine in the intact, fresh, human cadaver as well as living subjects (15,30). This apparatus has the capability of imparting controlled degrees of flexion-extension, lateral flexion and axial rotation singularly or in combination. (Figures 20 and 21) Freedom of upper and lower table segments reduces restraint on experimental subjects and allows cephalo-caudad translation. This has allowed a study of the effects of motion and force loads on the lumbar spine. Developed biplanar radiographic studies permit evaluation of output of these motions and forces.

Controlled loading of axial rotation has been incorporated by motorization of the apparatus in axial rotation with introduction of load and deflection on chart recorders.

A calibration device has been devised to improve the accuracy of biplanar radiographs. This device was found to be necessary to localize accurately the source of the x-ray beam in space. Calibration rings placed in the unit allow these sources to be determined in both the AP and lateral planes as shown diagrammatically in Figure 1. The calibration jig is constructed of radiotransparent aluminum and locates on the machine via steel dowels (Fig. 2).

Radiographic techniques also have been developed to establish clearly known bony landmarks in space. We have found, in common with Rab and Chao (31), that the superior articular facet, the inferior articular facet, and the base of the pedicles are reliable bony landmarks in the thoracolumbar spine (22,23). These chosen bony landmarks may be identified and their three-dimensional positions in space established by means of X,Y and Z coordinates taken from a reference coordinate system (Fig. 3). Magnification errors introduced on these bony landmarks are corrected for by means of the information derived from the calibration device, and calculated on a computer program. A plane in space consisting of these bony landmarks is generated by intersections of vectors. The centroid of the triangular plane determines motion of that body (Figure 4). In the case illustrated

(Fig. 4), a triangular plane is formed by the inferior bases of the left and right pedicles and the cephalad-most projection of the right superior articular facet.

A polynomial in cartesian coordinates is used to describe the motion of the centroid, as well as outputs in terms of X, Y and Z translation and axial rotation. The instant centers of rotation for sequential motions are computed from intersections of these planes and planar instant centers for bony landmarks of vertebral pairs.

The accuracy of these bony landmarks has previously been determined by Rab and Chao (31). We have confirmed these observations by inputting known rotations into isolated spine segments (22), and measuring output vertebral rotation from biplanar radiographs (22,23). A mathematical technique was used to compute the angle of rotation and yielded an average error of 2.5% (Fig. 5).

The procedures described have been carried out in chosen vertebral levels in both the lumbar and thoracic spine. Our initial tests were done in cadaveric subjects, with the remaining tests carried out in living human volunteers. Tests were carried out in flexion (with and without articulation of the knee), lateral bend and axial rotation.

As an inherent part of this study, load-deflection information is reported. Simultaneous load measurements

are made using force transducers with load-deflection curves displayed on chart recorders. Thus we can generate data about load-deflection not only in terms of the overall movement of the spine in space but also as a function of individual levels.

MATERIALS

All studies carried out to date have been reviewed and accepted by the Human Experimentation Committee of the University of Vermont and the Medical Center Hospital of Vermont.

The cadaveric material is chosen from the subjects available to the Pathology Department of the Medical Center Hospital of Vermont. We have restricted cadaveric material to male subjects, ages 18-40, with intact thoracic and lumbar spine and pelvis, in whom material can be obtained within thirty [30] minutes postmortem.

Live subjects are chosen from normal male volunteers ranging from 18-35 years. Primarily, subjects have been students and staff of the Medical School and Hospital who receive a small remuneration for their service. Permission of the subjects is documented and the protocols are established in line with those agreed upon by the Human Experimentation Committee.

RESULTS

Load-Deflection Tests.

The flexion-extension curves under conditions of loading of a cadaveric spine is shown in Figure 6. This shows the hysteretic behavior as the cadaver is moved from a starting position to maximal extension, and back to the starting position. Axial rotation, likewise, exhibited hysteresis as illustrated in Figure 7. Figure 7 also illustrates the differences between a cadaveric subject which has been fixed to a table with metallic rods, and a live subject in axial rotation. The average angular stiffness in vivo was found to be 46.5 Nm/radian.

Motion Studies.

A study of the motion of various vertebral bodies has been carried out. The movement of the three-point triangular reference system in space is illustrated by figures 8,9,10,11. These shows respectively a view of L₂, L₃ and L₄ in vivo in the neutral position with the head to the right, followed by the addition of 10° of clockwise axial rotation, 0° of axial rotation and 20° of right lateral bend, and 10° of clockwise axial rotation and 20° of lateral bend.

Figure 12 illustrates additional tests on axial rotation. We have found, confirming the work of others (26), that vertebral motion is coupled and is always associated with lateral bend. Figure 12 illustrates that lateral bend and axial rotation result in the summation of the two effects. Figure 13 demonstrates lateral translation associated with the input motions. Again, note the coupling effect of axial rotation and lateral bend. This concept of coupled motion is further illustrated in Figure 14. Input axial rotation of 10° resulted in ventral translation, cephalad translation, and right lateral translation, as well as the inputted axial rotation.

Instant Center Studies.

Analysis of these data allows calculation of the instant centers of rotation. Figure 15 illustrates on the ventral aspect the pathway of the instant center of L₄ when that vertebra moves from neutral to 10° of extension, to 30° of relative extension, to 20° of flexion to neutral and back to 5° of lateral bend. Figure 16 shows the instant center pathway visualized from the superior aspect of the vertebral body.

Figure 17 is the compilation of instant centers on the superior aspect of the lumbar vertebra. Although there is considerable scatter, the instant centers in pure

rotation and bending are mostly located within the posterior disc region, confirming Farfan's observations (13). We have found that the instant center moves towards the side towards which rotation is forced. Right lateral bend instant centers were mostly confined to the left posterior disc space. Under conditions of combined loading, the instant centers showed no consistent pattern, with many such centers located outside the vertebral body. Thus, the position of the instant center varied with both loading magnitude and muscle activity, which has important implications to the interpretation of such data. Figure 18 illustrates additional instant center analyses for the lateral aspect of vertebral bodies, as well as seen from the ventral aspect (Fig. 19).

CONCLUSIONS

- 1) The protocol and equipment have been devised to take accurate biplanar roentgenographs of both live subjects and cadavers in various positions of flexion-extension, lateral bend, axial rotation and in combinations of these positions.
- 2) Some of the in vivo load-deflection characteristics of the lumbar spine have been established in both live and cadaveric specimens. Input

motion has been imparted in flexion-extension, axial rotation, lateral bend and combinations thereof.

- 3) The lumbar spine exhibits coupled motion (motion in one direction is not independent of motion in the other directions).
- 4) The motion segments exhibit hysteretic behavior in vivo in all directions of motion.
- 5) The instantaneous center varies in position depending upon:
 - a) The properties of the motion segment.
 - b) The direction of the load.
 - c) Load combinations.
 - d) Magnitude of load.
 - e) Muscle activity.

[This has clinical significance in terms of the ability to use the instant center as a diagnostic tool.]

3. RESEARCH REPORTS

3.2 Multiorientation Spine Machine.

INTRODUCTION

In our early studies, we used a biplanar radiographic system which permitted fairly accurate measurements of segmental vertebral motion in prone human subjects. The coupled characteristics of spinal motion, instant center behavior of vertebral motion segments, muscle strength in resisting torsion, and hysteretic behavior of the spine were analyzed. This report will detail a new apparatus designed to evaluate more completely muscle strength and spinal kinematics in living humans in a variety of standing postures. The results of preliminary studies of normal subjects will be described.

MATERIALS AND METHOD

The apparatus (Fig. 22) consists of a frame fixed to an x-ray table which can be tilted from the horizontal to the vertical position. Subjects are fixed by means of a strap around the pelvis which is secured by ropes to the pelvic holder. The pelvic holder is suspended by four wires set at 120° to each other in space, each containing a load cell in a known position whereby reaction forces at the hip can be monitored. Reaction axial rotational torque about the long axis of the body is monitored within the

pelvic ring via three beam load cells (Fig. 23). The apparatus is designed so that subject may contract isotonicly or isometrically. The subject may actually move isotonicly, or resist motion imparted by a thoracic holder attached by a specially-designed harness. This thoracic ring is activated by cables to an inner ring to impart axial rotation, or can be moved in other planes, for example, flexion-extension, lateral bend. The thoracic ring can be suspended by load cells so reaction forces at the thorax (the load application point) can be monitored. All the load cells are oriented in such a way that their axes, were they to continue, would intersect at a point approximately corresponding to the subject's center of gravity.

Measurement of imparted motion can be obtained by either a stereo x-ray system (Fig. 24) or by analysis of surface topography by the Moiré Fringe interferometry technique.

The radiographic method depends upon locating x-ray sources by means of a calibration device. The position of each vertebra in space is defined from identifiable bony landmarks, ususally inferior bases of the right and left pedicles, and the cephalad-most projection of the right superior articular facet. The centroid of the triangle created by these bony landmarks is used as the reference plane for segmental vertebral motion. In the studies presented here,

gross displacements usually have been measured by topographic analysis, with radiographs used for confirmation in selected postures. Motion segment behavior has been attained from the roentgenographs.

The Moire Fringe technique essentially creates a topographic "contour map" on the subject's back which can be photographed or videotaped and subsequently analyzed. Various digitizing and graphical analysis algorithms have been developed to evaluate this data. Transverse and vertical profiles at specific levels can be used to compare the subject's positions and displacements. Currently, studies are in progress to define the relationship between the vertebral body positions in space, and the positions of the spine as determined by the topographic method.

Analog data acquisition techniques are being automated currently so that up to sixteen channels of information can be monitored and stored in a digitized form, ready for computer processing.

Eleven male subjects, ages twenty to thirty-seven, with no evidence of low back disease were studied. The subjects performed the following tests: 1) Lateral bend isometrically against an infinite resistance; 2) Lateral bend against a 4.5 Kg resistance to a known displacement; 3) Isometric forward flexion; 4) Isotonic forward flexion; 5) Isometric axial rotation; 6) Axial rotation against 8 Nm; 7) Passive axial rotation applied via the thoracic ring, and; 8) Active resistance of axial rotation imparted by the thoracic ring at a constant rate.

RESULTS

Table I lists the mean reaction forces and torques measured from the load cells fixed to the pelvic ring. In this table, the conventions are as follows: F = Force in Newtons, θ = torque in Newton-meters, +X = superior (cephalad) direction, -X = inferior (caudad) direction, +Y = right bend, -Y = left bend, +Z = posterior, -Z = anterior (i.e. flexion).

Figure 25 shows the regression line and 85% confidence intervals in lateral bend for all the data, both isometric and limited deflection, $-F_y$ represents a force in a direction opposite to that of lateral bend and $-F_z$ represents the anterior direction. This apparent linear relationship between reactive forces (Fig.26) is also seen between the reactive moments. θ_z is the lateral bend (or scoliotic) torque and θ_x is the axial rotation.

TABLE I: LIMITED DEFLECTION TESTS (ISOTONIC),
11 SUBJECTS. (Mean Reaction Forces
in Newtons and Torques in Newton-Meters)

<u>Right Lateral Bend</u>	<u>Forward Flexion</u>	<u>Right Axial Rotation</u>
Fy = 53.95	Fz = 56.14	Fz = 22.64
Fz = 6.61	Fx = 3.07	Fy = 12.91
$\theta_z = 49.46$	$\theta_y = 7.76$	$\theta_x = 5.87$
		$\theta_y = 7.17$

LIMITED DEFLECTION TESTS (ISOMETRIC),
11 SUBJECTS. (Mean Reaction Forces
in Newtons and Torques in Newton-Meters)

<u>Right Lateral Bend</u>	<u>Forward Flexion</u>	<u>Right Axial Rotation</u>
Fy = -80.10	Fz = -187.84	Fz = 34.47
Fz = 4.64	Fx = 145.15	Fy = 43.94
$\theta_z = 74.46$	$\theta_y = 0143.76$	$\theta_x = 20.33$
$\theta_x = 336.43$		$\theta_y = -27.96$

Likewise (Fig. 27), in axial rotation we see a similar relationship between the reactive forces and the reactive torques (Fig. 28). This raises the question as to whether the body is using some postural mechanism to optimize the resisting forces and torques. Again, in flexion a similar phenomena exists (Fig. 29).

Figure 30 gives the results of the tests using the thoracic ring in axial rotation. The passive torque averages 500 in lb or 56 NM, and the active about 1500 in lb (170 (Nm)). This is nearly twice the average isometric torque that was found.

The displacements of the vertebral bodies in space, as obtained from the stereo radiographs, are given in Figures 31-33. Axial rotation is depicted in Figure 31. Note that there is considerable axial rotation associated with lateral bend. Note the relative increase in the thoracic region. In Figure 32 we can see anterior translation at the various vertebral levels in forward flexion, axial rotation and lateral bend. Figure 33 shows the lateral translation associated with the input motions depicted in Figures 30-32. Note the coupling effect of axial rotation and lateral bend. Forward flexion on the other hand is far less sensitive.

The Moiré Fringe topography technique was found to be a rapid non-invasive method of quantifying body shape. This

technique also lends itself to analysis via digitizer and computer. Figures 34-37 are examples of computer-produced "contour maps" of the back of a low back pain (LBP) patient in various positions. In addition, the patient's "cross-section" is shown at various levels in both the vertical and horizontal directions. Motion analysis was performed using the Moiré Fringe technique in conjunction with video equipment. Figures 38-47 give examples of the "contour map" of the patient's back as he moves. This has shown differences between LBP and controls.

Analysis of the Moiré topographs showed that rib hump height, which was the highest contour, was about 1.4 cm in the neutral position. In axial rotation the highest contour was found to be an average of 2.3 cm. Its displacement inferiorly is indicative of the fact that this represents the mass of the paraspinal muscles, rather than the rib hump (Figure 48). The Moiré photographs also enabled us to assess axial rotation. This was minimal in the neutral position, an average of 3° in lateral bend, and 9° with a rotation input (Fig. 49).

DISCUSSION

The relevance of these data is two-fold: First, it gives semiquantitative, controlled estimates of muscle force in both isometric and isotonic motion performed in the usual directions of spinal mobility. Since the subjects were healthy, athletic males, these generated forces can be viewed as rather maximal for humans. Secondly, these preliminary data suggest a postural mechanism may exist to optimize resistance to forces and torques imparted to the spine, either isometrically or isotonically, irregardless of the position of the thorax.

These data are viewed as preliminary. Methodologic problems remain in achieving a reliable interface between the subject and the thoracic and pelvic holders. This is undoubtedly reflected in these data which contain some element of friction and soft tissue elasticities and displacements. Similarly, the forces represent both displacements and attempts to maintain the center of gravity.

The displacements in these studies have been measured largely by surface topography, with limited radiographic exposure, primarily for confirmation. Although preliminary analyses suggest a reproducible relationship between topographic and radiographic displacement measurements, this has yet to be precisely quantitated. Thus, the displacement

data should be viewed as an approximation.

Our long range plans are to develop these methodologies, and to analyze the variations between subjects with and without lumbar spine disease. By electromyographic analysis, the muscle groups responsible for displacements can be evaluated more precisely. In the long term, such analyses may give valuable insights into the normal behavior of the lumbar spine, as well as serve as important data for mathematical modeling.

3. RESEARCH REPORTS

3.3 Pelvic Anthropometry

INTRODUCTION:

Following the work of Hoaglund, et al. (47), it became apparent that there were considerable racial differences between the onset of osteoarthritis. This was complementary to the study of Chalmers and Ho (48), who showed the relationship between racial groups and senile osteoporosis. The pathogenesis of both secondary osteoarthritis and osteoporosis involves biochemical processes which are influenced by the mechanical loading. The loading of a specific joint is influenced by such factors as the anthropometry, posture, joint congruity and the activity of the subject. The following study resulted from a specific interest in the hip joint and in variations in the anthropometry in different racial groups.

In addition, the specific works of Pope, et al. (28,29,30), have demonstrated a need to study the anthropometry of the hip joint and pelvis, so as to establish interrelationship between the femur, pelvis and spine.

Thus, the emphasis on this study has been on measuring those anthropometric variables important in determining the contact stresses in the femoral head and acetabula, and the interactions between the pelvis and spine.

Previous investigations of the angles of inclination and declination of the acetabula and femoral head include roentgenographic studies (49,50,51,52), and physical measurements (53-62). None of these, however, involved a comprehensive study of all important variables.

MATERIALS:

Skeletal material was obtained from the Anatomy Departments of the following institutions: The University of Vermont, The University of Rochester, Johns Hopkins School of Medicine, and Kobe University (Japan). The material was obtained from cadavers donated for medical research purposes. The pelvis and femora were prepared according to standard protocol. For each specimen, a reference number was given and its source, cause of death, age, sex, and weight (if known) were recorded.

APPARATUS & METHOD:

For accurate measurement of the pelvis, it was necessary to construct a standardized positioning jig capable of holding the pelvis repeatedly in their anatomical position. The jig was similar to that used by Schmidt(61&62) and was constructed of plexiglas (figure 50). Dimensional measurements were made with a vernier caliper and angles

measured by means of a specially designed goniometer.

Figure 51 shows the standardized orientation of the pelvis with the anterosuperior iliac spines and the upper end of the symphysis pubis describing a vertical plane. The tip of the coccyx was generally on a level with the upper half of the body of the pubis.

The internal diameters of the lesser pelvis were measured, as shown in Figure 52. These included the following diameters of the superior aperture: anteroposterior, transverse, left oblique (positive slope), and right oblique (negative slope). Similarly, on the inferior aperture, the anteroposterior and transverse diameters were measured. Figure 56 shows the caliper measurements made between the iliac spines and between the acetabulae.

On both sides of the pelvis, a large number of measurements were made. This included the diameter of the acetabula (normal to the plane of the fossa), Figure 53, the depth of the acetabula and fossa (made with a vernier depth gauge). Parafilm replicas of the surfaces were used to determine the surface area of the fossa and the areas of attachment of the gluteus medius and minimus. Figure 57 shows the measurements that were made of the distance from

the tip of the acetabula to the transverse plane from the centre of the acetabula, to the iliac crest and from the ASIS and the PSIS is also measured in the cephalo-caudal direction. Other measurements included the width of the ischium at the fusion line, and the goniometric measurements (figure 54 & 55) of the saggital and transverse inclination of the acetabula and of the lumbosacral angle.

RESULTS:

These are given in Table II.

CONCLUSIONS:

These data should be invaluable in developing mathematical models to simulate forces across the hip joint and spine-pelvic interactions. There do appear to be differences between the racial groups, but presently the numbers are too small for statistical validity. Work in this area is continuing.

TABLE II
 PELVIC MEASUREMENTS
 (number of results, mean, SD) (inches, inches², degrees)

MEASUREMENT	CAUCASIAN		NEGRO		JAPANESE	
	♂	♀	♂	♀	♂	♀
Diameters of superior aperture of lesser pelvis	45, 4.241 0.437	19, 4.625 0.438	2, 3.785 0.170	4, 4.818 0.678	2, 4.009, 0.746	2, 4.081, 0.107
a) Anteroposterior diameter	45, 5.065 0.266	19, 5.245 0.246	2, 4.816 0.549	4, 5.281 0.865	2, 3.977, 0.892	2, 4.579, 0.089
b) Transverse diameter	45, 4.747 0.236	19, 4.853 0.239	2, 4.586 0.146	4, 4.681 0.396	2, 4.320, 0.021	2, 4.327, 0.037
c) Oblique diameter	(1) Positive slope 45, 4.805 0.204	19, 4.937 0.193	2, 4.628 0.426	4, 4.800 0.211	2, 4.335, 0.057	2, 4.314, 0.099
(ii) Negative slope	45, 4.001 0.468	19, 3.965 0.582	2, 4.004 0.380	4, 3.882 0.278	2, 3.450, 0.228	1, 4.096, 0.0
Diameters of inferior aperture of lesser pelvis	45, 4.306 0.451	19, 4.919 0.579	2, 4.108 0.521	4, 4.132 0.670	2, 3.142, 0.033	2, 3.544, 0.845
a) Anteroposterior diameter	45, 8.414 0.388	18, 8.214 0.392	2, 8.253 0.074	4, 8.046 0.774	2, 7.920, 0.071	2, 7.104, 0.454
b) Transverse diameter	45, 7.265 0.402	18, 7.316 0.477	2, 7.148 0.200	4, 6.985 0.723	2, 6.454, 0.325	2, 5.969, 0.698
Distance between outer edges of acetabulae (max.)	45, 11.007 0.650	18, 10.647 0.625	2, 10.561 0.566	4, 10.411 0.599	2, 10.857 0.125	2, 10.069, 0.027
Distance between outer edges of acetabulae (midplane)	35, 160.797 11.634	15, 155.653 10.474	2, 147.600 6.930	4, 160.850 4.453	2, 150.250 8.839	-
Lumbosacral angle	28 3.221 0.325	14 3.509 0.36	-	-	-	-
PSIS - PSIS	11 10.863 0.591	6 10.955 0.449	-	-	-	1 2.756 0.0
Distance between iliac tuberosities	4 1.347 0.051	4 1.356 0.045	-	-	1 1.470 0.0	-
Pelvic width/max. acetabula distance	4 1.259 0.095	4 1.387 0.040	-	-	1 1.486 0.0	-
Pelvic width/height						

MEASUREMENT	CAUCASIAN				NEGRO				JAPANESE			
	♂	♀	♂	♀	♂	♀	♂	♀	♂	♀	♂	♀
Diameter of acetabula (dia. normal to plane of fossa)	45 2.083	45 2.065	18 1.849	18 1.823	2 1.920	2 1.872	4 1.904	4 1.959	2 1.911	2 1.894	2 1.671	2 1.693
Depth of acetabula	45 0.143	45 0.156	18 0.169	18 0.161	2 0.298	2 0.203	4 0.137	4 0.130	2 0.065	2 0.065	2 0.030	2 0.004
Distance from tip of acetabula to transverse plane	45 0.881	45 0.878	18 0.845	18 0.836	2 0.850	2 0.991	4 0.847	4 0.821	2 0.826	2 0.813	2 0.786	2 0.784
Distance from iliac crest to center of acetabula (max.)	45 1.176	45 1.171	19 1.132	19 1.126	2 1.032	2 0.992	4 1.145	4 1.148	2 1.280	2 1.310	2 1.217	2 1.180
Distance from mid plane to center of acetabula	45 4.795	44 4.848	19 4.919	18 4.939	2 4.381	2 4.333	4 4.545	4 4.460	2 4.508	2 4.553	1 4.817	1 4.825
Depth of fossa	45 0.295	45 0.313	18 0.418	18 0.349	2 0.089	2 0.200	4 0.352	4 0.383	2 0.064	2 0.124	0 0	0 0
Surface area of fossa	45 1.156	45 1.137	18 1.068	18 1.070	2 1.054	2 1.075	4 1.040	4 1.049	2 0.970	2 0.925	2 0.935	2 0.944
Mean width of ischium at fusion line	45 0.800	45 0.789	19 0.732	19 0.751	2 0.817	2 0.735	4 0.747	4 0.722	2 0.950	2 0.879	2 0.590	2 0.583
Angle of sagittal inclination of the acetabulum	45 42.102	44 41.741	18 39.533	18 39.594	2 42.630	2 42.750	4 44.500	4 44.137	2 45.750	2 45.750	2 45.750	2 45.900
Angle of transverse inclination of the acetabulum	45 68.258	44 68.352	18 66.544	18 66.850	2 60.850	2 60.600	4 70.350	4 75.475	2 78.500	2 82.700	2 79.750	2 78.900
Distance between ASS and PSS (ant. - post.)	45 8.085	45 8.238	19 7.519	19 6.949	2 10.394	2 16.405	4 7.615	4 8.127	2 1.414	2 0.788	2 13.081	2 12.587
Distance between ASS and PSS (ceph. - caud.)	45 5.471	45 5.481	19 5.450	19 5.435	2 5.213	2 5.149	4 4.966	4 4.835	2 4.804	2 4.793	2 4.243	2 4.251
	0.369	0.372	0.390	0.384	0.095	0.049	0.329	0.485	0.026	0.008	0.682	0.678

3. RESEARCH REPORTS

3.4 Pelvic-Spine Interactions

a) MOTION SPECIFIC TO THE SACROILIAC JOINT

INTRODUCTION:

The allowable movement of the sacroiliac joints has always been controversial. The dense ligamentous attachments of these joints, their complex, irregular topography, and the magnitude of forces necessary for its disruption have been cited as evidence against any clinically significant motion. The diarthroidal nature of the joint, histologic and radiographic evidence of age related degenerative changes, and the widening of the pelvic outlet in pregnancy are cited as evidence for clinically significant motion.

Attempts to measure sacroiliac joint motion in living human subjects has been difficult. Colachis (78) implanted steel wires into the posterior superior iliac crests of human volunteers, ages 22 to 45. The measured deflections of the wires was interpreted as sacroiliac motion. Small parallel and angular displacements were observed, but true rotatory motion did not occur. Radiographic measurements have included analysis of the true or diagonal conjugates of the pelvis. Conflicting data has resulted both to the amount and type of allowable motion that occurs at the sacroiliac joints. Most recently, biplanar orthogonal

radiographic techniques have been used in cadaveric specimens, and one living human subject. Those investigators concluded that significant motions of the sacroiliac joints do occur, as well as significant deflections of bones of the pelvis during various static manipulations.

Our interest has been stimulated by the role of the sacroiliac joints in low back syndromes, and particularly persistent symptoms observed at graft donor sites in patients undergoing spinal fusion. Furthermore, the importance of these joints in the development of meaningful mathematical models of the lumbar spine is apparent. This report deals with the analysis of biplanar and stereoradiographic measurements of sacroiliac motion in living and cadaveric subjects.

METHODS AND MATERIALS:

Cadaveric specimens which included the pelvic ring, sacrum, and lower lumbar vertebrae were affixed to the upper table of our original spine machine by means of two threaded steel rods, 9.5 mm in diameter. This apparatus has been described in detail previously and has the capability of imparting movements of flexion-extension, axial rotation, and lateral bend singularly or in combination to the specimen. A second jig was affixed to the sacrum and to

fixation rods (Figure 58) which enabled us to wedge the sacroiliac joint into a new position and to precisely measure the relative motion between the sacrum and iliac crests. A typical chart record is given in Figure 59. Using our biplanar x-ray system, we then measured radiographically the displacements between the neutral and the deflected, i.e., wedged position.

The biplanar radiographic method and apparatus have been described previously. This system allows the source location of radiographic beams to be accurately established. Identification of bony landmarks or implanted steel markers allows deflections and translations to be measured with an accuracy of $\pm 1^\circ$. Data collection and analysis is facilitated by developed computer programs, outputting motions in a Cartesian Coordinate System.

Once the best bony landmarks had been established, these techniques were applied to live subjects. For these purposes, we utilized a series of biplanar radiographs of patients up to 10 years post disc surgery. These were taken in flexion-extension and neutral. Within the range of resolution of our techniques, we did not detect any statistically significant motion in this joint in vivo.

FUTURE WORK:

The specimens will be manipulated in the following positions: sacrum anatomic position, pelvis at 5° increments of flexion extension, over 20°, 5° increments of axial rotation over an arc of 20°, pelvis neutral, sacrum manipulated at 5° increments of flexion extension, and axial rotation over an arc of 20°; and combinations of pelvic rotation or flexion extension, combined with flexion extension movements or axial rotation of the sacrum. Measurements will be carried out using the stereoradiographic method. This will be accomplished by incorporation of the table top of the original spine machine into the improved spine apparatus.

The stereoradiographic system is similar in its principle to the biplanar radiographic method. However, the radiographic sources are relocated at an angle of 16 to 20° relative to one another rather than at 90°. This system has particular advantage in study of the pelvis where bony landmarks are widely separated, and are obscured by other bone densities particularly on the lateral radiograph. The same experiments will be carried out in this radiographic configuration, as were done in the biplanar technique.

To assess the repeatability and reliability of bony landmarks, 1 mm steel balls will be implanted into the

sacrum and pelvis of the cadaveric specimens. At least 4 steel balls were implanted in locations in the pelvis and sacrum. The accuracy of the bony landmarks will therefore, be compared to easily identified steel ball landmarks, as well as to the known inputs of sacral and pelvic motion.

The stereoradiographic method will be applied to human volunteers, ages 20 to 35. Gonadal shielding will be carried out in male subjects and each subject will be subjected to no more than 3 radiographic stereo pairs. Post-partum females, 3 to 5 days after delivery and tubal ligation will be used to measure pelvic mobility using the same techniques. The following positions will be assigned to each subject:

1. Position 1: Neutral prone position, recumbent with hips a neutral abduction-adduction, 20 external rotation.
2. Position 2: Right hip in frog leg position (Patrick's test).
3. Position 3: Left hip in frog leg position (Patrick's test left).
4. Position 4: Patient side lying, neutral position, legs in neutral position with bolster between legs to minimize adduction of the hip.
5. Position 5: Patient side lying with right hip

- flexed and left hip extended.
6. Position 6: Patient side lying with right leg flexed 30° , trunk axially rotated to right.
 7. Position 7: Patient standing in normal posture, hips abducted 20° .
 8. Position 8: Patient standing on either right or left leg with opposite leg flexed 20° at hip.
 9. Position 9: SLR

The sequence of radiographs will be taken such that a single patient had either the recumbent prone, recumbent side lying, or standing position as the neutral position (three patients each group), or the recumbent, side lying, recumbent prone position followed by either one of the side lying or recumbent postures (3 patients), or the recumbent, followed by the standing posture and one other position (3 patients).

The bony landmarks will be identified on the stereoradiographic pairs, digitized, and treated according to computer programs, previously described for analysis of lumbar spine motion.

b) GROSS MOTION OF THE PELVIS WITH RESPECT TO
THE REST OF THE SKELETAL SYSTEM.

METHODS & MATERIALS:

Blinking Light Emitting Diodes are placed over the ankle,

knee, and hip joints, and the thorax of a subject prior to the straight leg raising exam. The exam is performed in a darkened room while being viewed by a camera set on "time" exposure. When the limit of motion, due to tightness or pain, is reached, the subject indicates this verbally and by pushing a button which activates another "LED" thereby providing evidence on film of this limit.

RESULTS:

We have analyzed 40 subjects, and it appears there are two different responses to the test. In one group, the femoral instant center of rotation remains stationary (i.e., single axis), (Figure 60), whereas the other group demonstrates a variation in position of the center of rotation (anterocephalo translation). The latter group appears to have tight hamstrings and preliminary analysis suggests the presence of accentuated lumbar lordosis (Figure 61).

3. RESEARCH REPORTS

3.5 Measurement of Intervertebral Disc Space Height.

Following the work of Hampton and Robinson (63), the value of roentgenography to assess the disc is well accepted. Herniated nucleus pulposus is the result of a continuing degenerative process within the disc (13,14, 64-67) and thus, the frequent clinical measurement of disc dimensions is of particular interest. However, radiologists often fail to agree in their assessment of lateral lumbar roentgenographs (68) and frequently a single observer is unable to make repeatable measurements. This is partly because of the difficulty of repeatably picking up bony landmarks, particularly if the tube-vertebra-film plane relationships are not identical in all planes in successive roentgenographs, and partly because there is no general agreement on the measurement method (landmarks and treatment of data) to be employed. Thus, there is a very real risk that a given patient may have his disc degeneration misread due to measurement error or different measurement, or roentgenographic techniques. The present study is a comparison of some of the methods of disc space height (IVD) (13,69) an assessment of some new techniques and a study of potential errors.

METHODS

A. Isolated Vertebrae.

Isolated vertebrae were drilled in an axial direction and fixed on a radiotransparent rod into a jig previously described (22). This permitted lateral, axial and transverse translation and rotation of the vertebrae to take place. As each new position AP and lateral roentgenograms were taken.

B. Cadaveric Studies.

Cadavers were fixed into a machine capable of obtaining roentgenograms by means of transfixation rods through the iliac crests and a thoracic vertebra. As described elsewhere (36), this machine permits lateral bend, flexion-extension, axial rotation and axial translation to occur relative to the fixed x-ray sources and orthogonal film planes.

C. Live Subjects.

Roentgenographs were taken of 137 patients who underwent lumbar disc surgery at the Medical Center Hospital of Vermont, between 1952 and 1962 (132 roentgenograms were usable). The AP and lateral x-rays were taken utilizing a special apparatus designed specifically for this purpose (18). These tests enabled us to check our previous findings over a large clinical population.

D. Measurement Methods:

The roentgenographs were measured using a Summagraphics digitizer. This was used in conjunction with an Infoton teletype terminal with CRT display which was remotely on line with the Sigma 6 computer at the University of Vermont computation center. This enabled us to make rapid measurements and to compute simultaneously ratios, areas and heights.

The first method used was that suggested by Hurxthal (69). This involved the measurement of the greatest midline distances between the two distal rims and the two proximal rims and then averaging them. Measurement in this system merely involves the touching of the digitizer pen to the appropriate points on the x-rays. Also, on each roentgenograph we used Hurxthal's (69) alternate method, the distance between the bisection points between the lower ring of one vertebra to the bisection between the upper ring of the vertebra below.

Also, on each vertebra, we used Farfan's (13) suggestion and established the ratio between the posterior height/mean diameter, and the anterior height/diameter. Three measurements were made also (Fig. 62-A) of mid-intervertebral disc space height (A), mid-intervertebral height of the superior body (B), and AP diameter of the disc (C). In order to correct for magnification or

distortion of the image, disc space heights are expressed in ratios of the mid-intervertebral disc space measurement to the adjacent measurable structures mentioned above.

$$R' = \frac{A}{B} = \frac{\text{mid-intervertebral disc space height (mm)}}{\text{mid-vertebral body height (mm)}}$$

$$R'' = \frac{A}{C} = \frac{\text{mid-intervertebral disc space height (mm)}}{\text{Diameter of the disc (mm)}}$$

A further measurement method which we attempted (Fig.62B) was to measure the projected area of the two end plates and subtract one-half of their sum from the total projected area of the disc. This is then divided by the width of the disc to give the average height. Areas were simply measured by touching the pen to as many points as were necessary to define the area.

It was also attempted to compensate for lateral bend by using the simple trigonometric relationships given in figure 63.

RESULTS

Table III gives the results of the tests done on the isolated vertebrae. For comparison, all are referred to the IVD computed using Farfan's recommendation (13), i.e. the average posterior height. Using the standard deviation as a measure, it was established that the average posterior height and the mim-IVD were much better than Hurxthal's (69) average IVD, or IVD at estimated end plate centers. The area method allowed no improvement of the former two. The trigonometric method showed no significant improvement when small angles were involved. Generally speaking, measurements coincided within 0.5mm, except above 40° of rotation and at 20° of lateral bend where it became impossible to make accurate measurements. All of the ratios showed an improvement over the simple IVD measurement with Farfan's (13) method slightly superior.

The cadaveric studies showed the same findings. An additional finding was that the error in IVD increased as the x-ray beam was centered further from the disc of interest (Table IV). A wide range and extreme variations were found to exist in measured disc space heights at each level of the lumbar spines of the live subjects. R' (ratio of mid-intervertebral disc space height over mid-vertebral body height) and R" (ratio of mid-intervertebral disc space height over diameter of the disc)

were found to give similar results, although R'' was always slightly smaller than r' ($p < 0.01$); as a function of the disc diameter being greater than the axial height of the vertebral body. For convenience, R' was selected as a measure of disc space height in the evaluation of our data.

Figure 64 graphically illustrates the mean disc space height at each level for all fused and non-fused patients. At each level there is essentially no difference in mean R' , regardless of the type or result of surgery ($p > 0.05$). Further subdivision of the data reveals that this finding does not vary, with one exception: Patients with documented disc excision at L_4-5 and L_5-S_1 have significantly smaller disc spaces at the previously operated level ($p < 0.01$).

Analysis of intervertebral disc space height reveals extreme variation in the ratio of mid-intervertebral disc space over mid-vertebral body height (R'). We also found the mean R' is smallest at the L_5-S_1 and L_4-5 levels. We report a mean R' of less than 0.25 at L_5-S_1 only and approximately 0.25 and L_4-5 . Although anatomic variation of the disc thickness at these levels must be considered a factor, these findings are consistent with documented disc herniation and surgery at either one or both of these interspaces.

TABLE III ISOLATED SPINE SEGMENTS (MEANS AND NORMALIZED MEANS)

Motion / Method	Ant. Ht.	FARRAN					HURXTHAL			U.V.M.		Area IVD
		Post. Ht.	a/c	b/c	IVD	Avg. IVD	Centre IVD	Mid. IVD	R ₁	R ₂		
Neutral	.99	1.01	.140	.145	1.00	1.05	1.16	.99	.180	.140	.96	
.5° 1b, 10.9° E	1.01	.95	.150	.145	.97	.99	1.08	1.02	.185	.150	.85	
.2° 1b, 7.1° E	1.09	1.09	.145	.150	1.09	1.08	.99	1.08	.200	.145	.92	
.5° 1b, .6° E	1.10	1.06	.155	.145	1.08	1.15	.65	.56	.195	.150	.95	
.4° 1b, .5° E	1.04	.97	.140	.135	1.02	1.03	1.01	1.07	.195	.140	.87	
10.6° 1b, .9° E	1.11	.99	.150	.135	1.00	.65	.51	1.06	.205	.145	.63	
11.8° 1b, 10.5° E	1.03	1.03	.145	.130	.99	.64	.62	1.00	.190	.135	.64	
12.6° 1b, 6.1° E	1.00	1.00	.140	.130	.98	.53	.44	.96	.185	.130	.63	
.1° 1b, 6.0° E	.98	.98	.135	.125	.94	.84	.81	.97	.165	.125	.69	
11.7° 1b, 10.2° E	.94	.88	.130	.125	.90	.71	.55	.92	.175	.130	.67	
11.4° 1b, 6.1° E	.86	.85	.110	.110	.82	.75	.64	.83	.155	.115	.67	
11.7° 1b, 10.3° E	.93	.93	.120	.115	.91	.63	.58	.89	.165	.125	.70	
6.6° 1b, 6.2° E	.97	.98	.135	.125	.96	.68	.59	.95	.175	.135	.78	
Mean	1.00	.96	.140	.130	.98	.82	.88	.98	.185	.135	.79	
SD	.09	.12	.010	.015	.09	.22	.28	.11	.020	.010	.14	

TABLE IV
CADAVER STUDIES

Motion / Method	FARFAN				HURXTHAL			U.V.M.		Area IVD	
	Ant. Ht.	Post. Ht.	a/c	b/c	IVD	Avg. IVD	Centre IVD	Mid. IVD	R ₁		R ₂
0-8 cm axial	1.390	.765	.340	.190	1.080	1.030	1.000	1.100	.450	.265	.845
0-4	1.310	.797	.313	.190	1.053	1.000	1.010	1.040	.403	.250	.875
N	1.307	.693	.317	.167	1.000	-	-	1.023	.393	.240	-
0+4	1.215	.530	.305	.130	.870	1.050	1.090	.875	.325	.215	.880
0+8	1.095	.570	.275	.145	.835	.970	1.040	.825	.300	.205	.850
Mean	1.263	.671	.310	.164	.968	1.013	1.035	.975	.374	.235	.863
SD	.113	.118	.023	.027	.110	.035	.040	.117	.061	.025	.018

3. RESEARCH REPORTS

3.6 MAST Suit.

The medical anti-shock trouser (MAST or G-suit) is an important addition to the initial management of the patient in shock. The inflatable suit encompasses the legs and abdomen. Commonly, this suit is applied to the traumatized patient by ambulance personnel, as one method of restoring intravascular volume. This use of this suit to date has met with enthusiastic approval. (See photo of patient in suit on "back board", Fig. 65.)

METHOD AND MATERIALS

In an attempt to determine the effect of the suit on spine fractures, spine motion was evaluated by bi-planar x-rays in normal subjects manipulated on our apparatus which permits quantitative analysis of spine kinematics. Radiographs were taken with a suit deflated, and inflated, and the intrasegmental motion of thoracic and lumbar vertebrae were determined for flexion-extension, axial rotation, lateral bend, and lateral encephalo-caudad translations. Additionally, these studies were carried out a fresh cadaveric subject with complete transection of the spine.

RESULTS

In seven normal subjects, anterior-posterior motion of up to 0.5" was observed as the suit was inflated and deflated (Fig. 66). The cadaveric subject, the posterior elements of L₁-L₂ having been transected, demonstrated AP and Cephalo-caudad instability at that segment (Fig. 67).

By appropriate modifications of the inflation and deflation technique, these variations in force can be reduced. These biomechanical studies will be complemented by a review of patients with spine injuries seen at the Medical Center Hospital of Vermont in the past five years.

3. RESEARCH REPORTS

3.7 USAF Ejection Seats.

A model of the USAF HAC seat (Figs. 68, 69) (adjustable) has been constructed to fit on our original experimental apparatus. This allows biplanar radiographic study of the orientation changes in the spine as the seat position is changed from the normal (ejection) to combat positions and returns to normal. The importance of such studies are to allow optimal seating configurations to be designed, to reduce injury to the pilots during ejection. The apparatus was used with the side arms removed. Axial rotation was locked such that the cephalad portion of the table was flat relative to the caudal portion. With the x-ray machine in place, the system was calibrated using the jig (Fig. 70), and the Air Force seat then affixed (Fig. 71).

Subjects were belted into the seat which was in the normal seating position (Figs. 72, 73). Care was taken to assure that the ischium was firmly against the bucket of the seat.

Subjects were conditioned to allow themselves to be moved without muscle interaction, and this was re-emphasized during testing procedures.

Biplanar radiographs were taken in the normal position, the seat was moved to the combat position (Figs. 74-77), and a second biplanar radiograph was taken. The seat was then returned to the normal position and a final biplanar radiographic set taken.

RESULTS

Each subject (Fig. 78) demonstrated a caudal displacement (Fig. 79) of each vertebral body of at least 4.5 cm when moved from the normal to combat position. Anteroposterior displacement (Fig. 80) was insignificant in this sequence and within the experimental error in the system of .4cm to .5cm. Subject D8S had an average posterior displacement of 1.37 cm which may have been due to his moving involuntarily.

As each subject was moved from the normal to combat position (Figs. 81-83), there was a shortening of the glabella to xiphisternal junction distance on an average of 11.86 cm. The line between those points had an average location of 41.82° from the horizontal.

The instant centers of rotation (Figs. 84-86) appeared to be located throughout the Y-Z plane at the level of the centroid for each vertebral body considered in this seating sequence.

There were few final orientations of the subjects that were significantly different from the original position in the Air Force seat. The few instances in which alterations were seen were most likely due to the subject moving unintentionally, or due to the discomfort of the unpadded seat. A well-padded seat, in conjunction with a firmer fixation system, would provide more definitive fixation. In the future we feel that radiographic technique can be significantly improved upon by removing the sides of the seat, or by building the hinging apparatus into the existing apparatus which we are using in other experiments.

3. RESEARCH REPORTS

3.8 Range of Motion.

INTRODUCTION

Clinical methods of objectively measuring range of motion have been lacking. As a result of our radiographic work we have devised such methods which are clinically applicable.

METHOD

A subject is restrained at the hips and a device capable of monitoring motion (Fig. 87) is attached by a belt over the spinous process of T-10. The line connected to the body can be thought of as a vector in two-dimensional space, and this equipment monitors its length and angle change relative to a fixed point and neutral position.

RESULTS

Results are given in Figures 88 through 91.

DISCUSSION

Although in the prototype stage, this device looks very promising.

3. RESEARCH REPORTS

3.9 Vertebral Rotation

INTRODUCTION

The precise radiographic evaluation of vertebral rotation in vivo remains an enigma. Various bony landmarks have been used in assessing this modality of spine motion. Cobb in 1978 (70) used the tip of the spinous process in relation to the underlying vertebral body. Moe in 1968 (74), Nash and Moe in 1969 (75) and Fait and Janovec in 1970 (71) estimated the position of the convex pedicle outline on anteroposterior radiographs. Most recently, Mehta (73) has used three bony landmarks, the pedicle, the transverse process, and the intervertebral foramen, all on the convex side. Each author has recognized that these methods allowed only an approximation of rotation.

We are reporting a method of more accurately measuring rotation in the thoracic and lumbar spine using biplane radiography of the isolated anatomic and fresh cadaveric specimens. This method is adaptable to clinical material and utilizes standard radiographic equipment.

MATERIALS & METHODS:

The apparatus for biplane radiography has been described elsewhere (72). Its essential feature is a fixed relationship between roentgen tube and film which allows precise and reproducible radiography of a subject under controlled conditions.

Three different sets of normal cadaveric vertebrae were obtained from the lumbar, thoraco-lumbar and thoracic spine. Each set of vertebrae was mounted on a radiolucent rod placed just anterior to the posterior longitudinal ligament. The rod was fixed to a rigid support structure which allowed free axial rotation of the vertebrae. A protractor was fixed to the support structure to provide direct measurement of vertebral rotation (Figure 92). Serial biplane radiographs, oriented at 90 degrees with respect to one another, were obtained of each vertebral set at 5 degree increments of axial rotation between 0 and 90 degrees. To determine the effect of precise radiographic centering on measurement determinations, one set of films was obtained with the roentgen beam precisely centered, and a second with the beam centered by visual alignment alone. All radiographs were analyzed and measured for rotation using bony landmarks (vide infra). The method

for radiographically assessing rotation is based on fundamental principles of plane geometry illustrated in Figure 93. The results obtained from measurements between bony landmarks was then compared to the known rotational input determined from the protractor.

ROENTGENOGRAPHIC INTERPRETATION:

An analysis of several bony landmarks confirmed known anatomic differences between the thoracic, thoraco-lumbar and lumbar spine. Difficulty was encountered in finding landmarks which were radiographically consistent at all vertebral levels when axially rotated through a 90 degree arc. Because the lumbar vertebrae are structurally heavier and are more widely separated by their intervening intervertebral discs, radiographic interpretation at this level is easiest to perform. The tips of the inferior articular facets proved to be reliable landmarks in the thoraco-lumbar junction and lumbar spine, but were not readily visible in the thoracic region. The tips of the superior articular facets could be visualized in the thoracic spine, but could not be relied upon for the determination of lumbar rotation. The inferior bases of the pedicles proved to be reliable landmarks in both the thoracic and lumbar spine. In these experiments we have compared all three landmarks, i.e., the tip of the

superior articular facet, the tip of the inferior articular facet, and the inferior base of the pedicles.

The angle of vertebral rotation present at any segmental level can be found by determining the arcsine, arc cosine or arctangent of that angle. The geometric solution for the sine and cosine of this angle requires an initial unrotated view of the vertebra, and thus are of limited clinical value when fixed structural rotation is encountered. The geometric solution for the arctangent of the angle of rotation does not require an initial unrotated view and may be calculated from the measured distance between the bony landmarks determined from carefully oriented antero-posterior and true lateral radiographs.

All measurements of the three selected sets of bony landmarks were made directly from the radiographs using a divider which was then held next to a steel centimeter rule in order to obtain a numerical value. Experience is required to consistently identify these landmarks.

It is helpful to have on hand an articulated spine or an isolated vertebra corresponding to the segment to be measured for reference the first few times rotational

measurements are attempted. This will aid in more precise identification of these bony landmarks as they appear in different angles of rotation. As vertebral rotation approaches 20° to 35° and posterior elements become superimposed, precise localization of the inferior base of the pedicle on the side toward which the vertebrae is rotating becomes somewhat difficult, particularly on the anteroposterior radiographs. However, it is usually marked by a readily identifiable area of increased bone density along the lateral vertebral border on the side toward which the vertebrae is rotating. Optimal radiographic technique for visualizing these structures is mandatory to overcome interference from soft tissue, bowel gas and the rib cage.

RESULTS

Lumbar Spine.

Figure 94 illustrates the typical accuracy obtained in the lumbar spine using the tips of the inferior articular facets and the inferior bases of the pedicles as bony landmarks on three different sets of radiographs. The mean average difference between the calculated vertebral rotation and actual rotation using the arctangent formula was 1.79 degrees for the tips of the inferior facets and 3.02 degrees for the base of the

pedicles. When the mean of the results from the arctangent, arc sine and arccosine formulas were used, a mean error of 2.24 degrees was found. Rotational calculations were not significantly influenced by precise centering of the roentgenographic beam as compared to visual alignment alone. The results were not significantly influenced by moving the vertebra four centimeters caudally or cephalad with respect to fixed radiographic equipment.

Thoracic Spine

The mean average difference between calculated vertebral rotation and actual rotation using the arctangent formula was 3.40 degrees for the base of the pedicles and 4.03 degrees for the tips of the superior articular facets. While this mean difference is somewhat greater than that observed at the lumbar level, it still gives a close approximation of true vertebral rotation. As in the lumbar spine, longitudinal movement of the vertebra for a distance of four centimeters in either direction beneath the fixed radiographic equipment had little effect on results.

In our studies on the thoracic and lumbar spine, we corrected for variations that these slight degrees of magnification had little effect on our numerical values

for axial rotation.

DISCUSSION:

Direct physical or kinematic analysis of the intact human spine in vivo is notoriously difficult. Most evaluations of spine motion or structural deformity are based on radiographic interpretation or extrapolation of data obtained from isolated spine segments (3,32,77). Clinical determinations of axial rotation in normal spines and in structural scoliosis has proved particularly difficult to accurately quantitate. Cobb qualitatively determined the progression of a spinous process toward the concavity of a scoliotic curve, grading rotation from zero to four plus. The method of Nash and Moe approximates actual vertebral rotation and is graded in 25 degree increments. They concluded that the degree of vertebral rotation approximated the percentage of displacement of the convex side pedicle toward the concavity of the scoliotic curve. Fait and Janovec also utilized the convex side pedicle as a bony landmark and published a mathematical formula by which they determined that pedicle displacement was related to rotation up to 40 degrees. They concluded that rotation was unmeasurable beyond 40 degrees. We attempted to reproduce Fait and Janovec's results, but found that their idealization of the geometry was

inherently unreliable. Mehta evaluated radiographs of the thoracic and lumbar spine by an image-matching method employing three bony landmarks. He was able to estimate vertebral rotation in 15 degree increments through a full 90 degree arc. The method proposed herein allows a more accurate computation of vertebral rotation when this is desirable. The bony landmarks used in our studies were the inferior base of the pedicles in both the thoracic and lumbar spine, the tips of the inferior articular facets for the lumbar spine, and the tips of the superior articular facets for the thoracic spine. These landmarks can be visualized through a full 90 degrees of rotation. This agrees with the work of Rab and Chao (76) who have found in their three-dimensional radiographic studies of the lumbar spine that these and other bony landmarks may have great potential in radiographically determining vertebral rotation in vivo. The inferior base of the pedicles offers the theoretical advantage that it is closer to the neutral axis of rotation and thus is less likely to be deformed in structural scoliosis.

The technique reported is more time consuming than most other plane radiographic analyses of vertebral rotation. It requires accurate linear measurements, and mathematical calculations. Figure 95 is a nomogram

which simplifies these computations.

Experimentally, we have found that one can calculate vertebral rotation within an accuracy of approximately three degrees in the lumbar spine and approximately four degrees in the thoracic spine. Although there are additional complexities in the living scoliotic spine, we have found close correlation between computations from single spine segments in this deformity and the same level spine segment analyzed experimentally. Ultimately, the accuracy of this method in scoliosis would have to be compared to known physical measurements of autopsied scoliotic spines. Clinically, one can minimize errors by optimum radiographic technique for bony detail. Strict attention must be given to the position of the patient, the location of the roentgen beam with reference to the patient and the film, and precise 90° orientation of the anteroposterior and lateral radiographs. We feel that these same considerations should be given to any of the previously published methods of determining spinal rotation. It is recommended that the vertebral level to be analyzed be marked with a felt pen in order to assist the technician in accurately centering the roentgen beam. The vertebrae analyzed should be recorded in the patient's

chart, so that future radiographs may be centered at this same level. Ideally, the roentgen tube and cassette should be locked in relation to one another so that only the patient is moved relative to this fixed radiographic equipment. An attempt should be made to keep the segment of the spine studied as nearly the same distance as possible from the cassettes on both the anteroposterior and lateral radiographs to minimize the effects of magnification.

CONCLUSION:

It is possible to accurately calculate rotation of isolated cadaveric vertebrae, using plane radiography under controlled experimental conditions. Comparable accuracy was obtained with isolated vertebral segments when visual alignment alone was used to position the radiographic equipment. This technique may be used clinically for computing vertebral rotation in the lumbar and thoracic spine. Optimal results from clinical radiography require close attention to good radiographic technique and careful positioning of the patient relative to the radiographic equipment.

Both the arcsine and arc-cosine formulae depend on measurements taken from the unrotated vertebra and thus have less utility than the arctangent formula. It should be noted that the tangent function is rapidly changing in the vicinity of 90° and thus would be subject to more error as θ approaches 90° . This is also true, but to a lesser extent, for the sine function in the vicinity of 90° and for the cosine function close to 0° .

4. SUMMARY

The work included herein has, we believe, contributed significantly to the understanding of the mechanics of the low back. The techniques and algorithms developed are applicable both to basic research and to an improved clinical diagnostic methodology. Much of the data have been, and will continue to be, invaluable to those who are developing mathematical models of the back.

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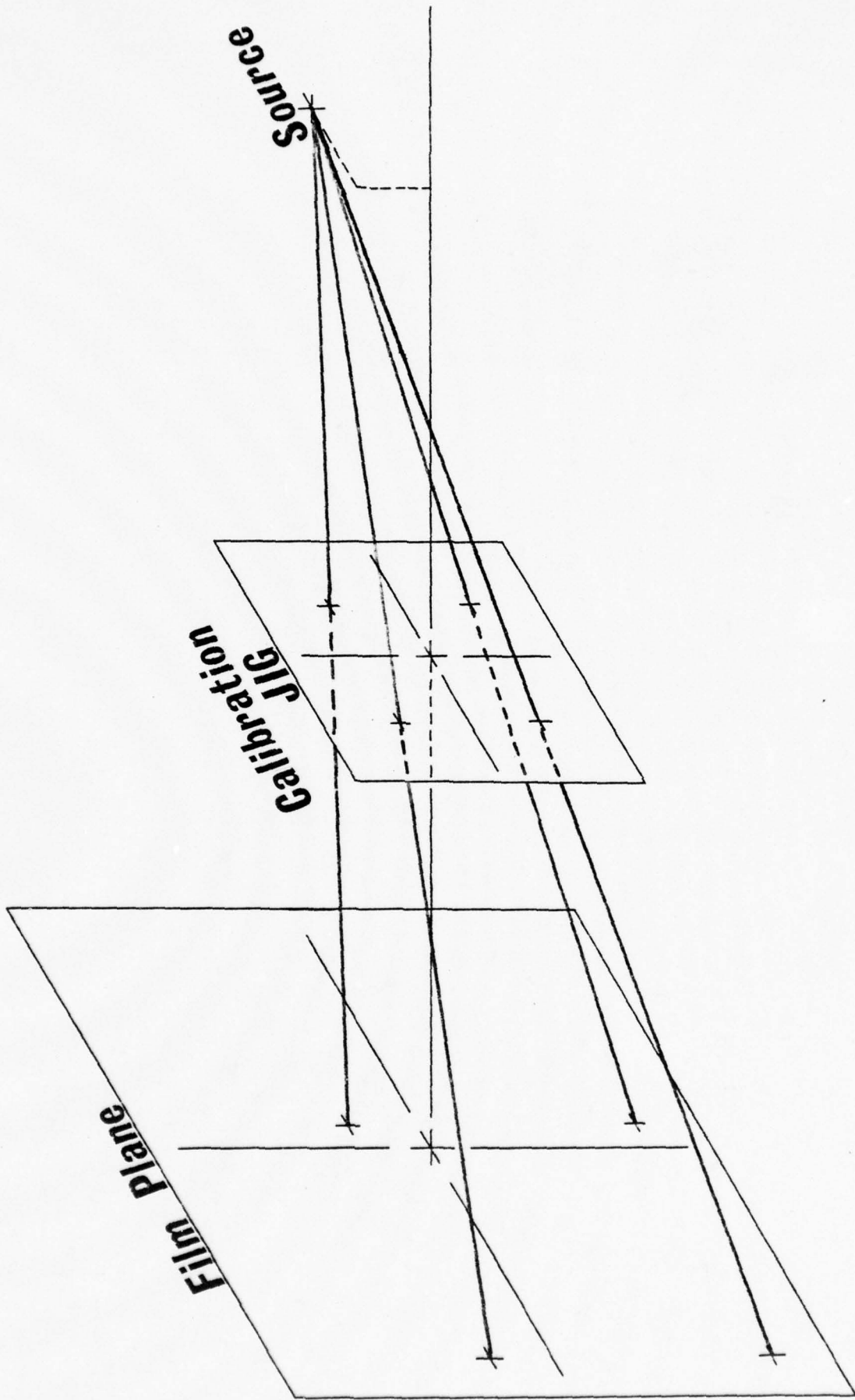
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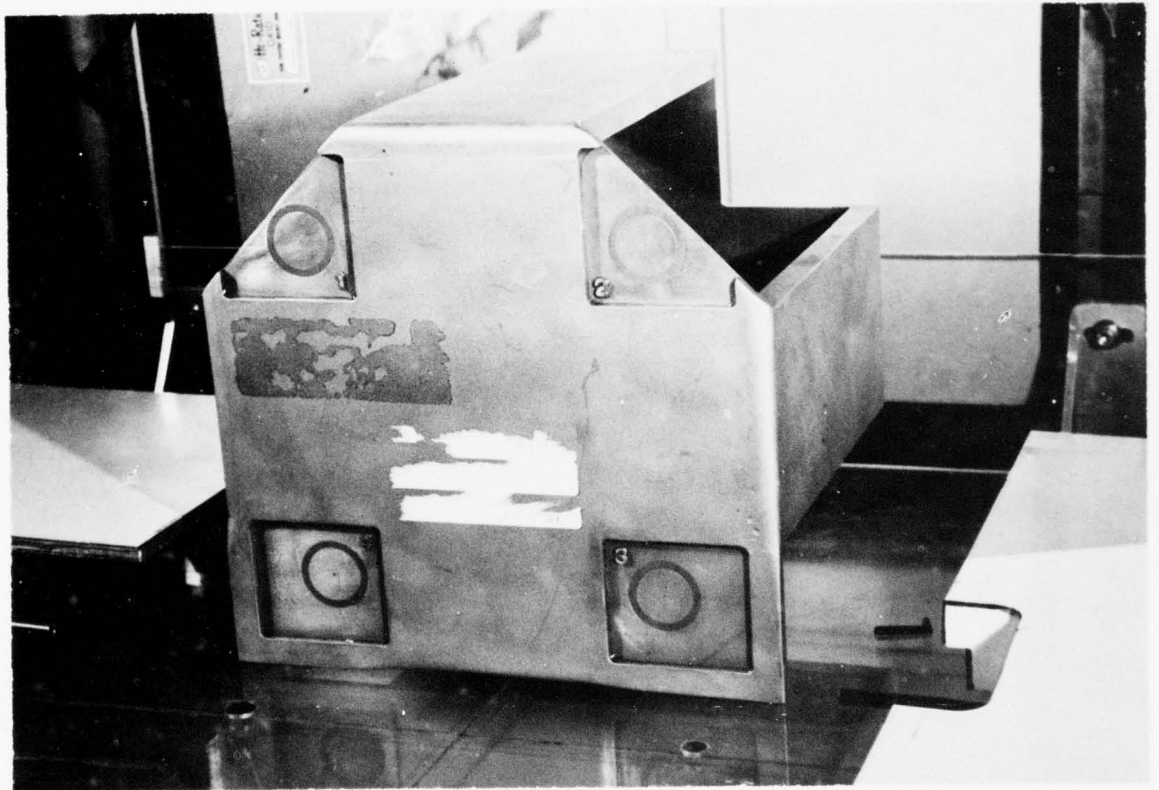
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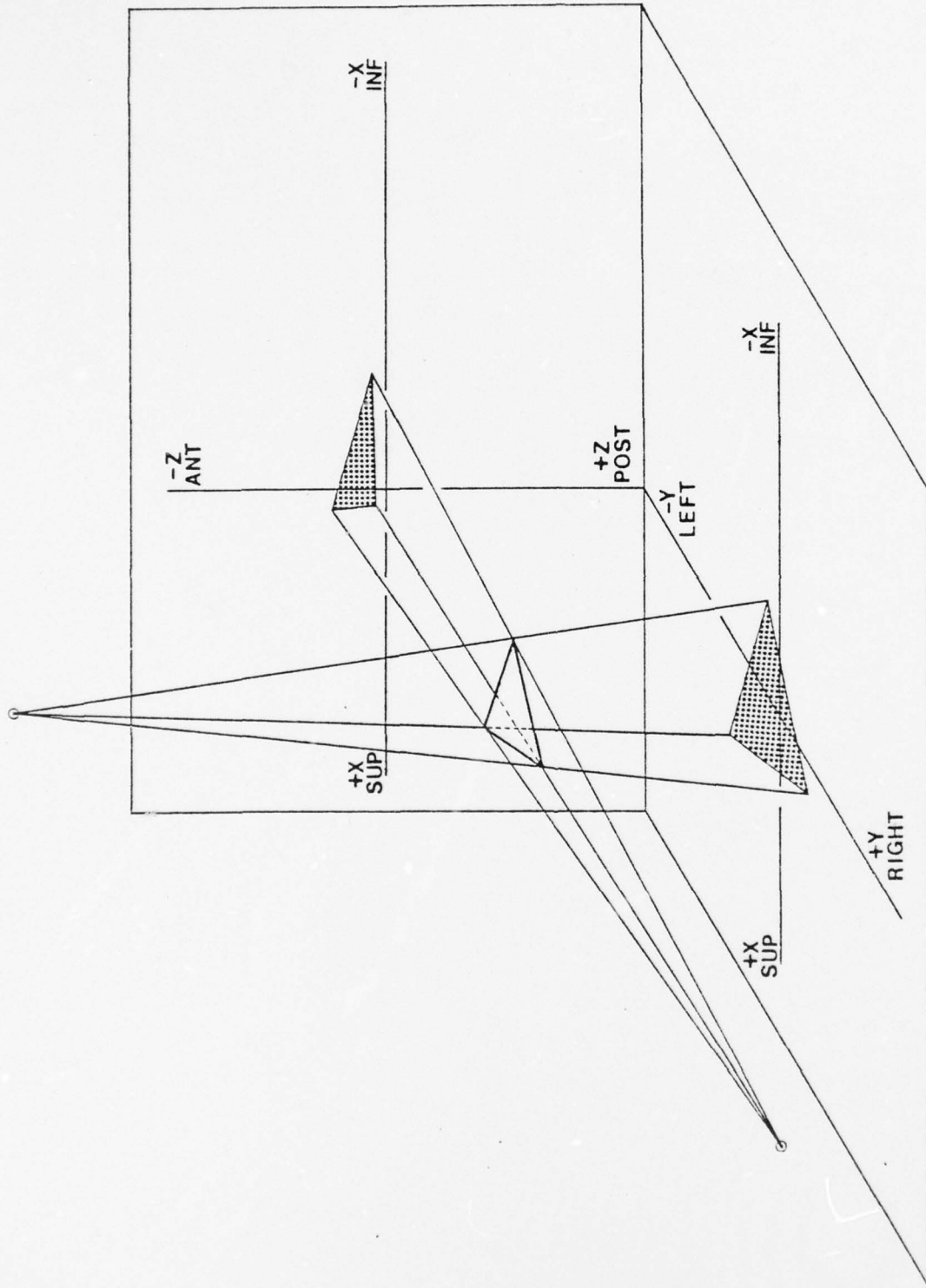
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95. Nomogram for Computing Rotation.



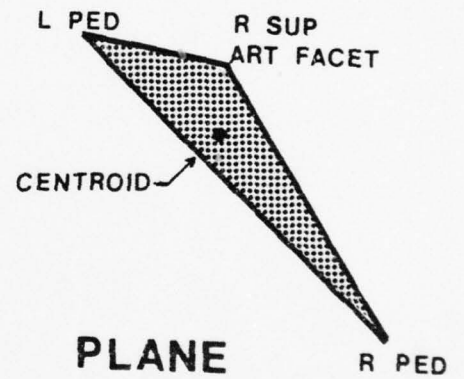
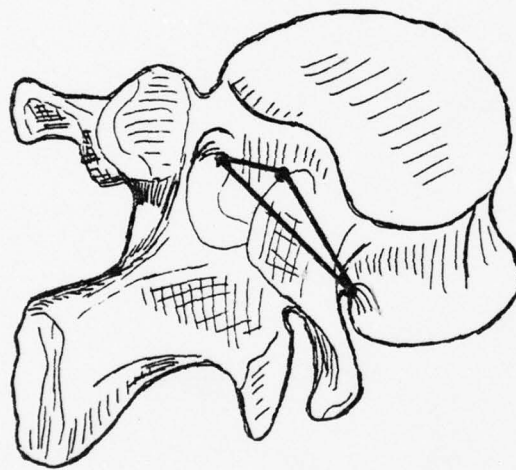
1. Calibration Jig: Diagram.



2. Calibration Jig: Photo.



3. Biplanar X-rays Showing AP and Lateral Sources and Triangular Plane in Space.

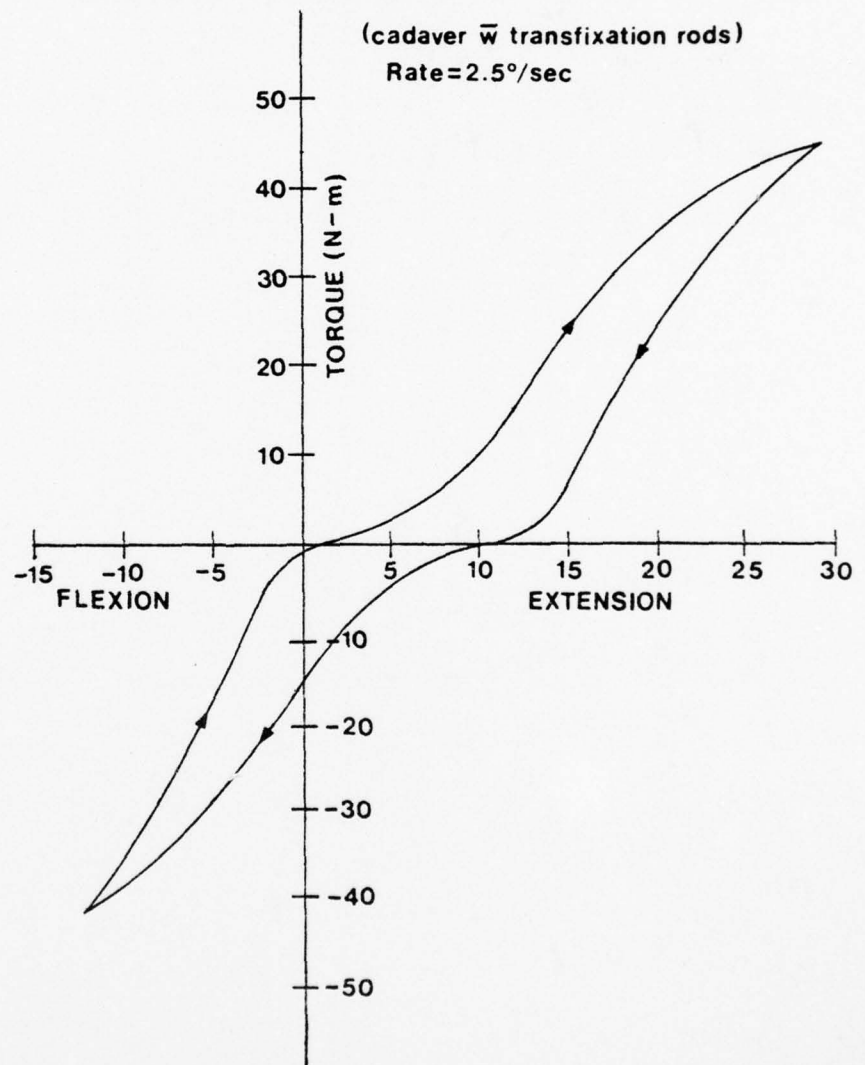


4. Vertebral Body with Bony Landmarks and Representative Triangular Plane.

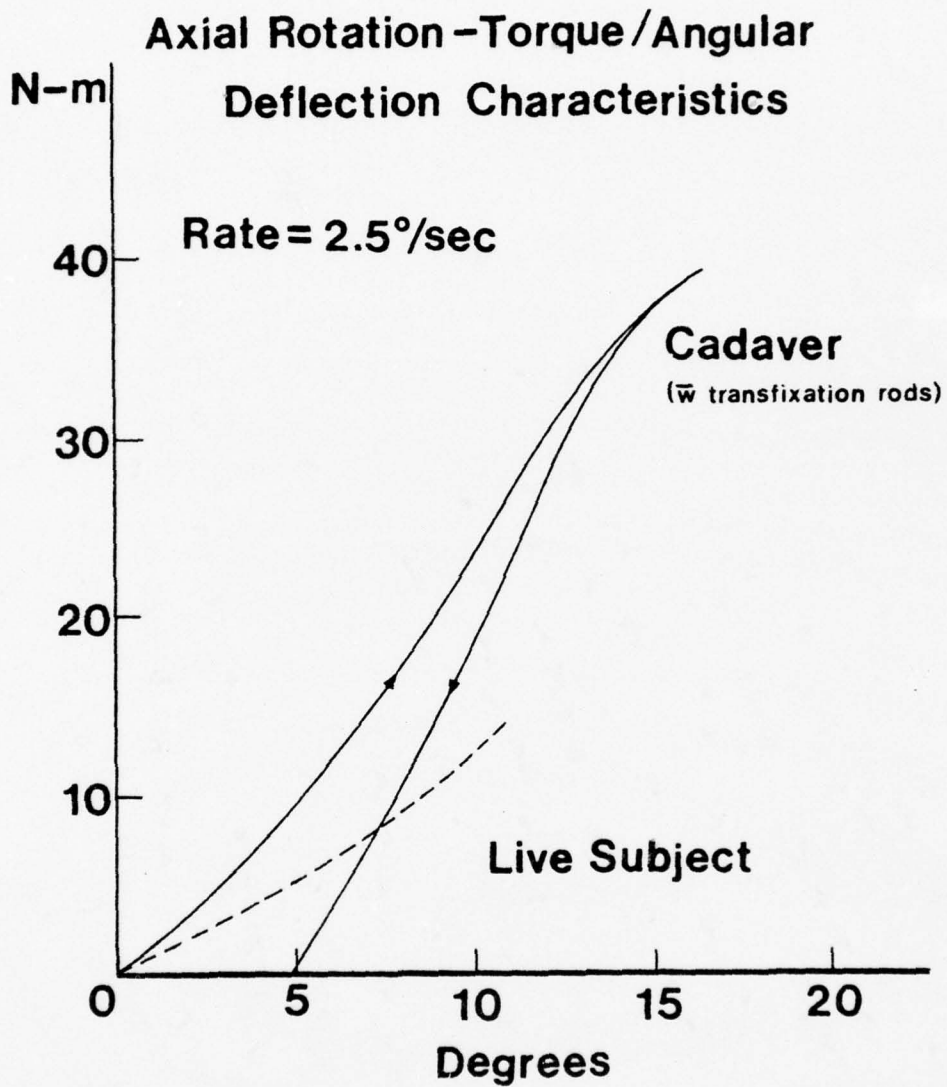
Axial Rotation (degrees)	
Actual	Computed
0.0	0.0
5.0	5.2
10.0	10.3
15.0	14.7
20.0	19.5
25.0	23.6

Average error = 0.4° (2.5%)

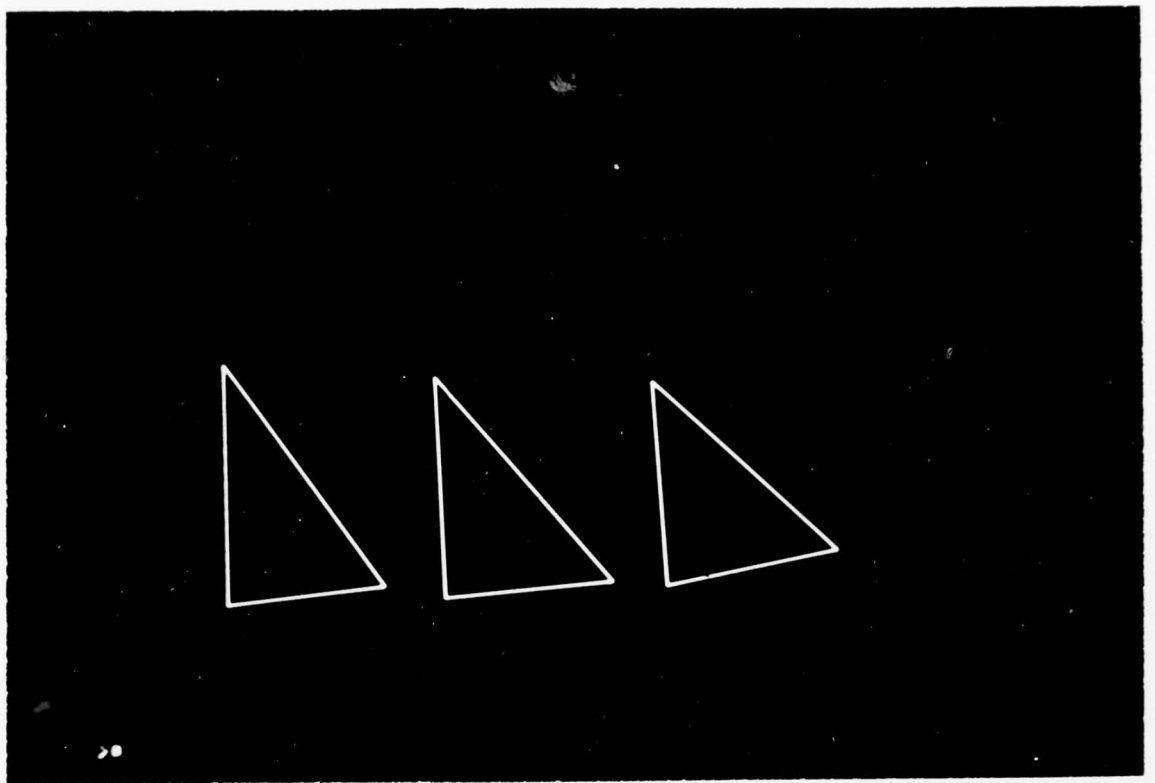
Typical Flexion-Extension Test



6. Flexion-extension Hysteresis in a Cadaver.



7. Axial Rotation Hysteresis in a Cadaver and a Live Subject.



8. Graphics Terminal Illustrations of In Vivo Vertebral Segments: In Neutral Position.

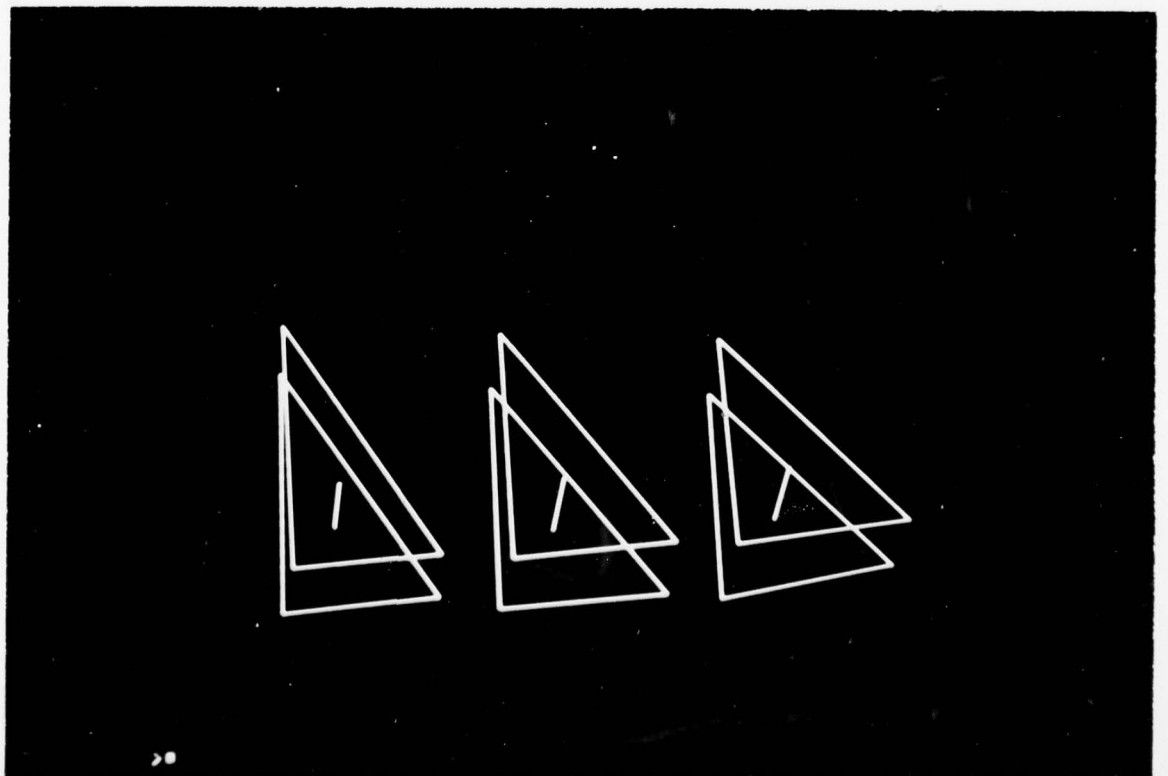


Figure 9: Graphics terminal illustrations of in vivo vertebral segments: In 10° axial rotation and right lateral bend.

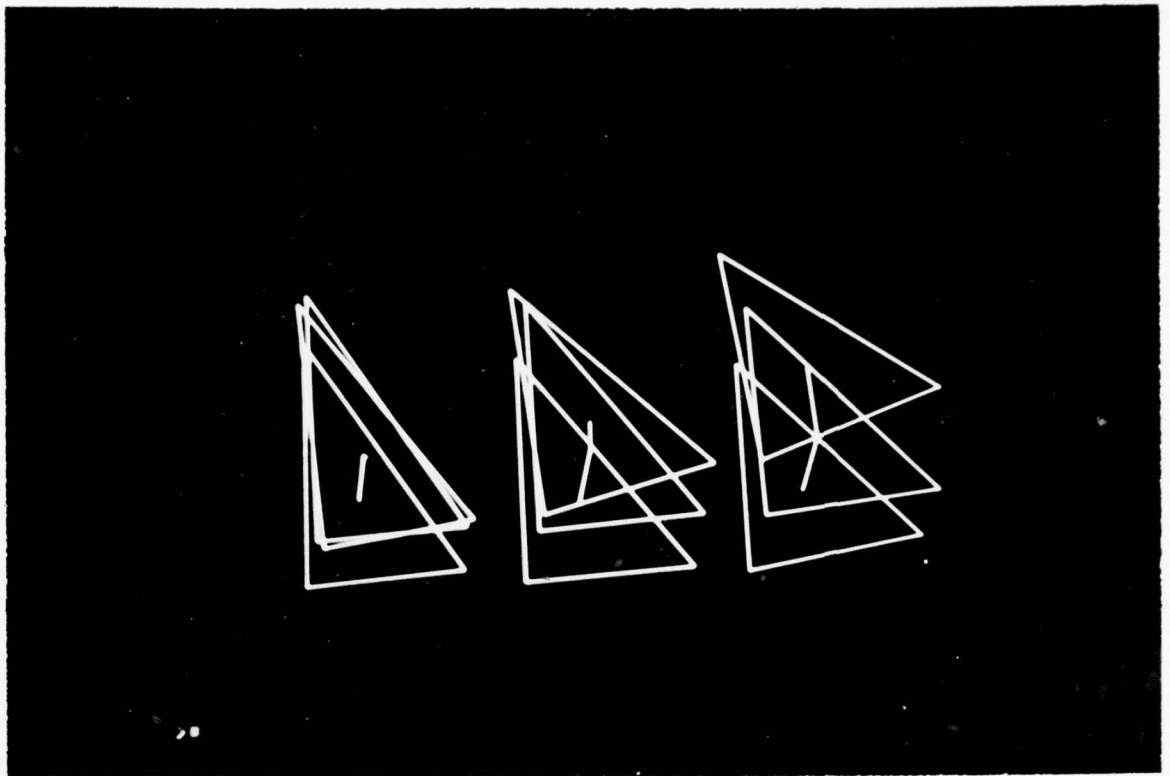


Figure 10: Graphics terminal illustrations of in vivo vertebral segments: In 10° axial rotation and right lateral bend.

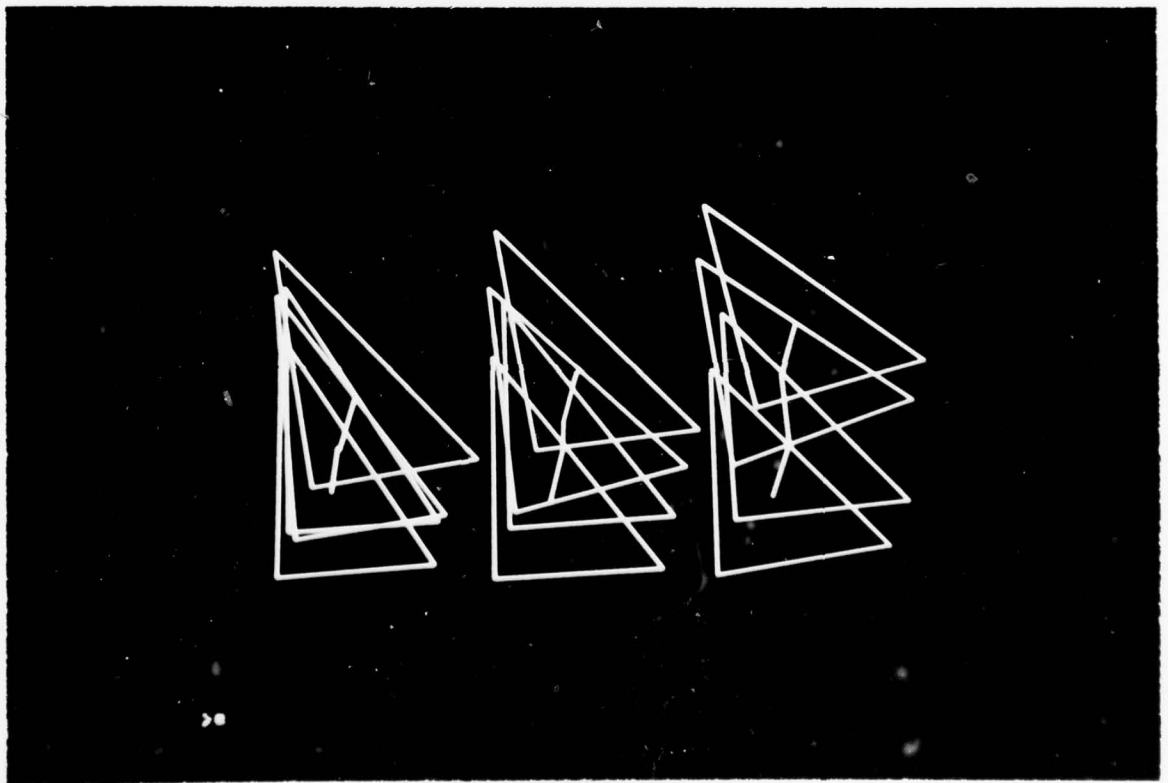
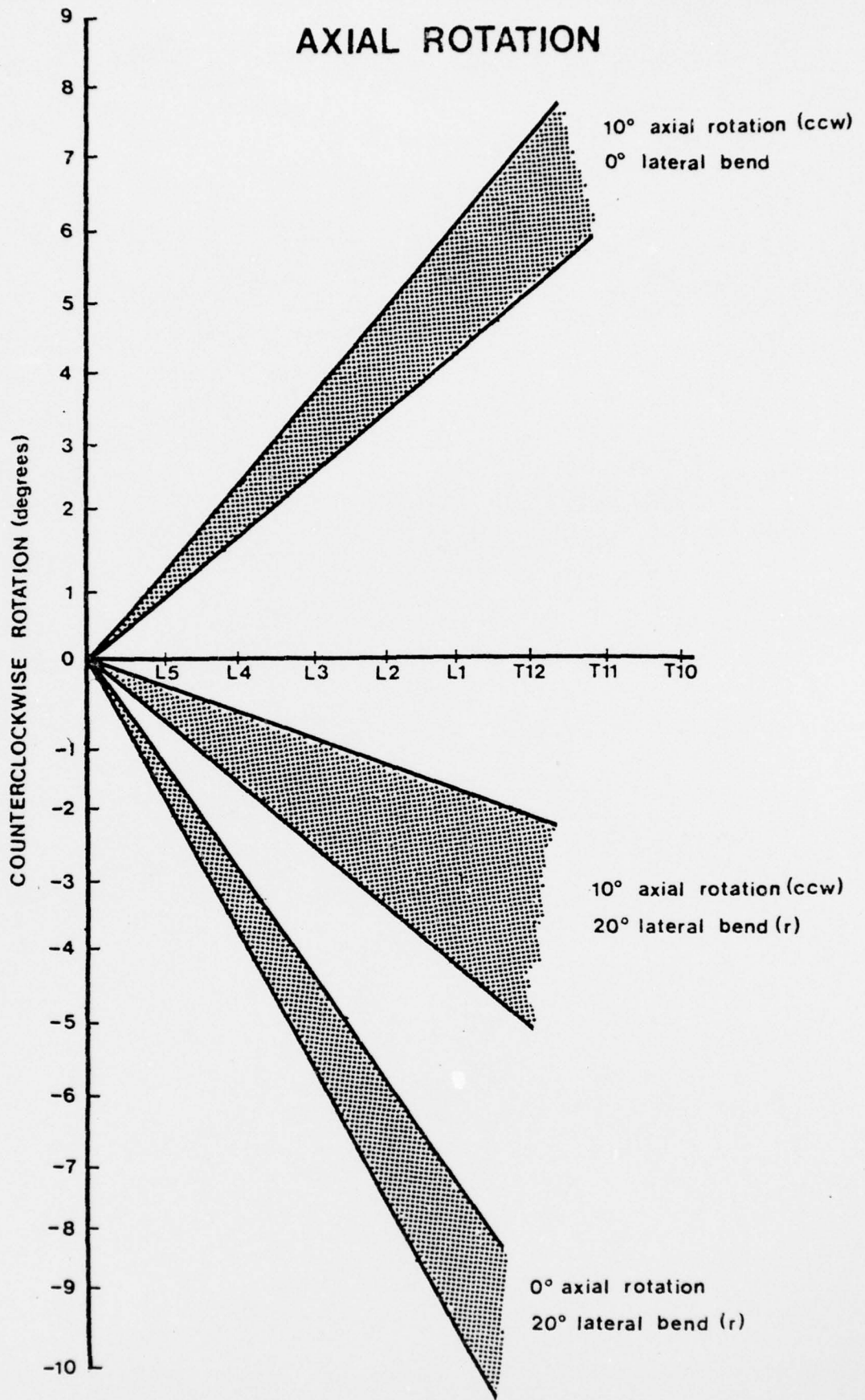


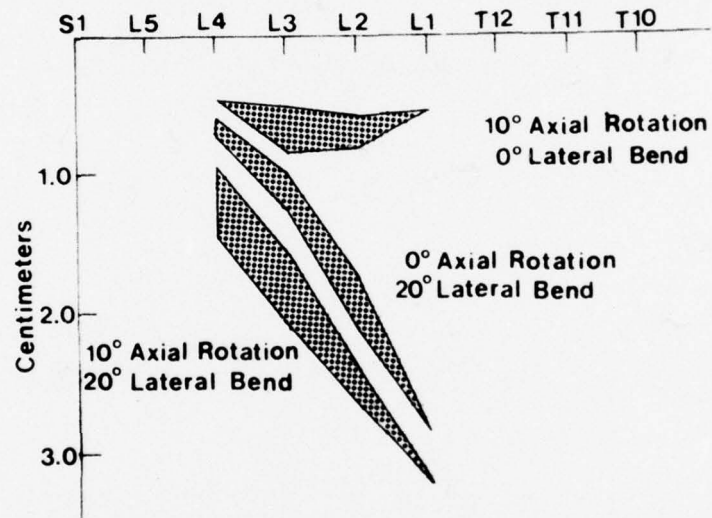
Figure 11: Graphics terminal illustrations of in vivo vertebral segments: In 10° axial rotation and 20° right lateral bend.



12. Axial Rotation Showing Coupling Effect.

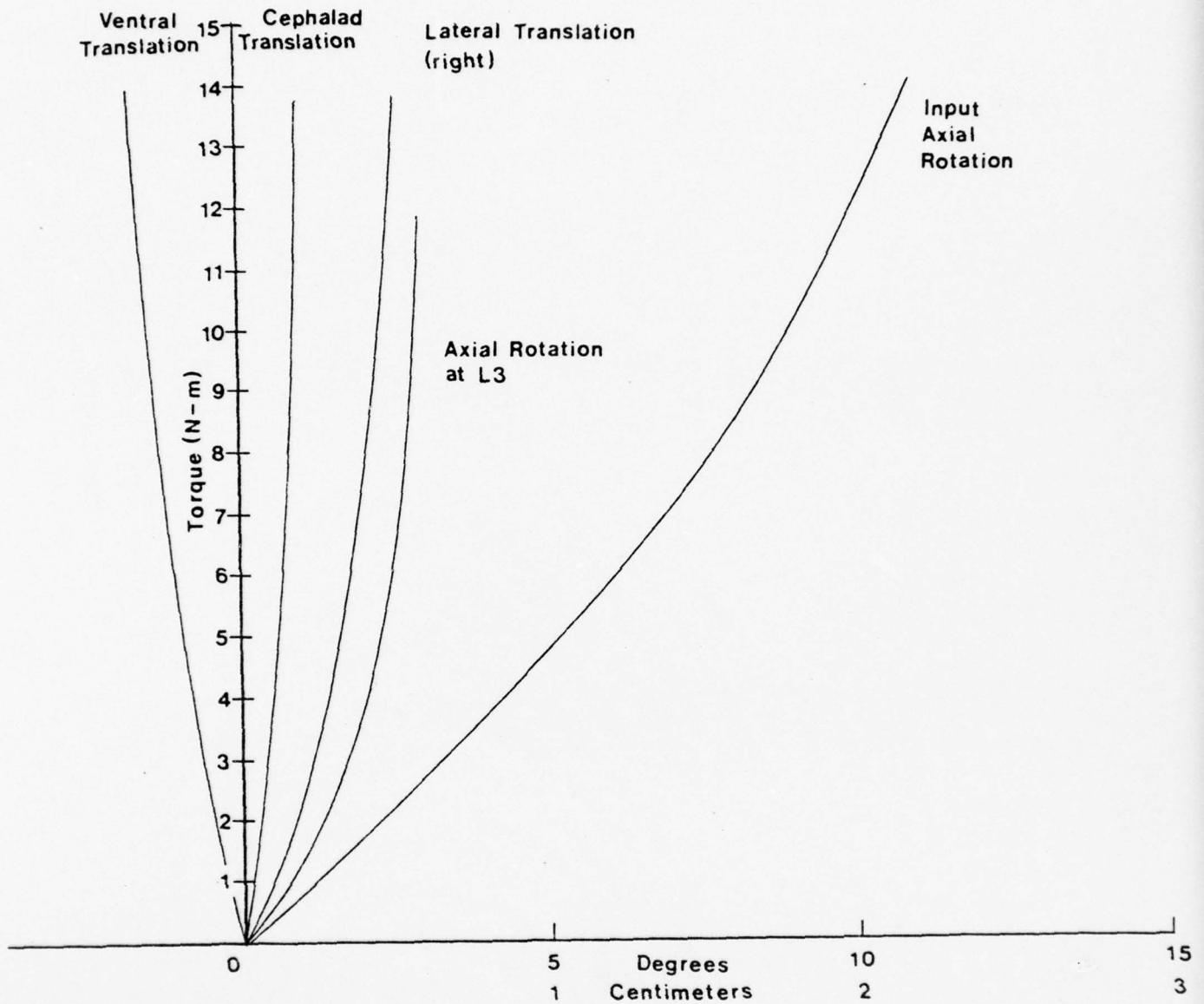
Lateral Translation

(To The Right)

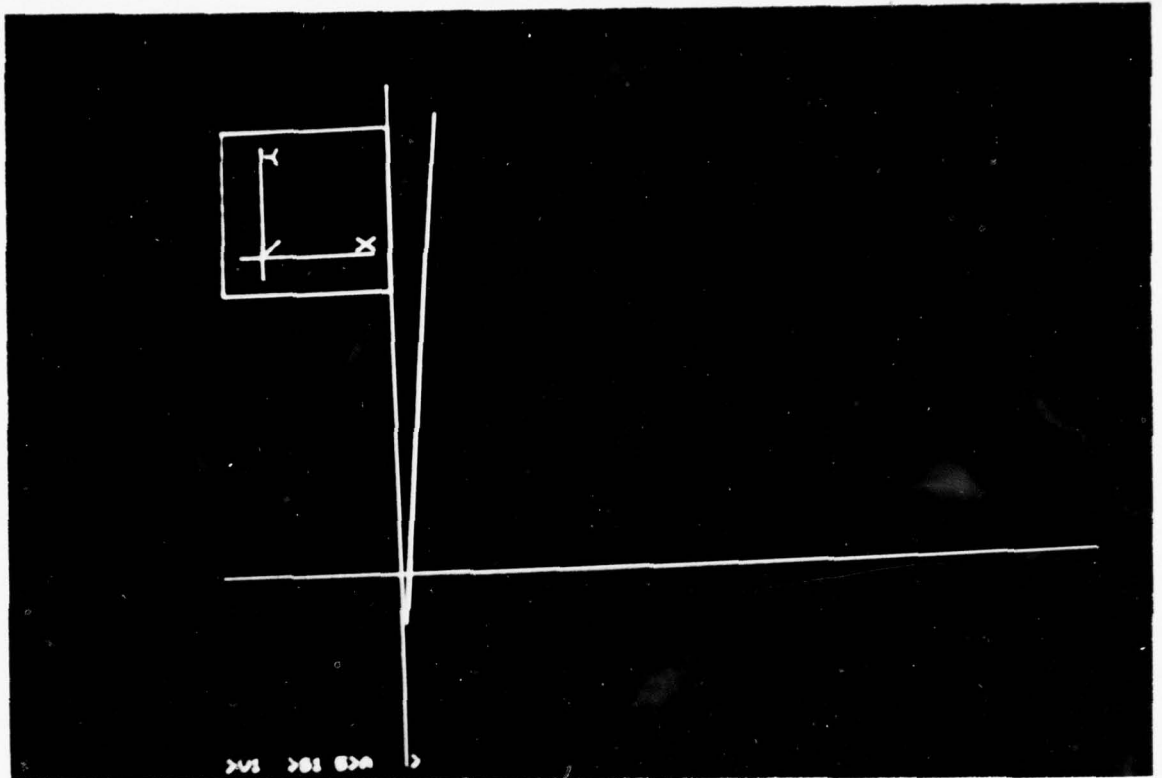


13. Lateral Translation Due to Inputs Similar to Figs. 8-10.

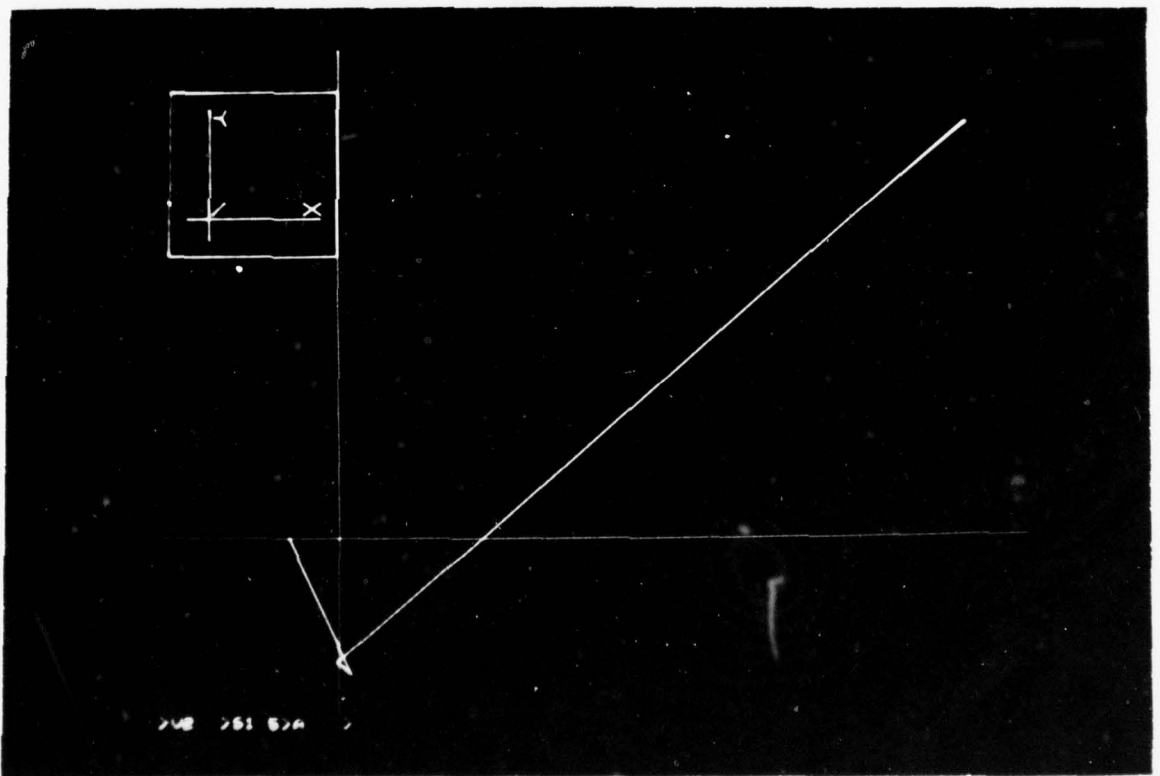
Coupled Motion at L3



14. Coupled Motion at L₃ with 10° of Axial Rotation Input.

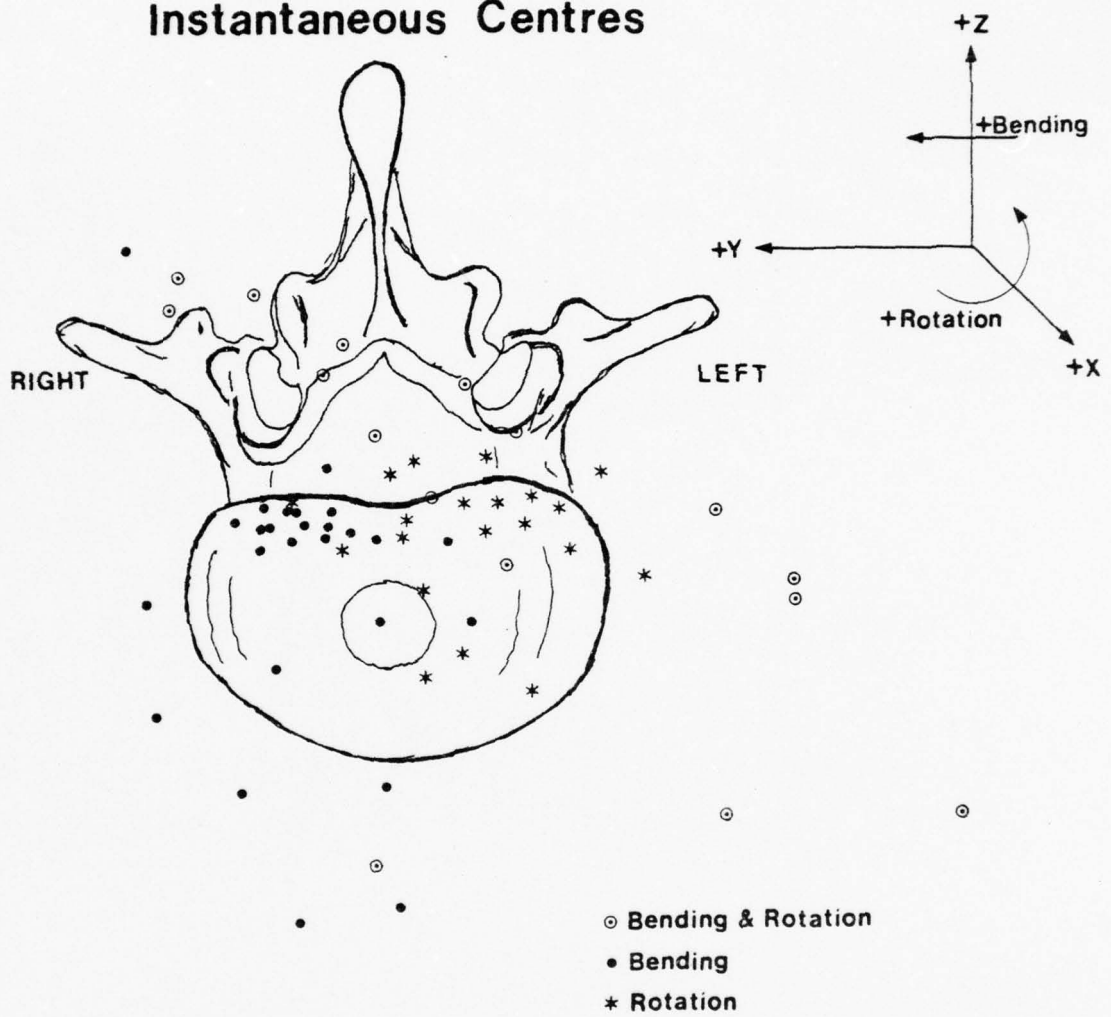


15. Instant Center Path: Ventral Aspect.



16. Instant Center Path: Superior Aspect.

Superior Aspect Instantaneous Centres



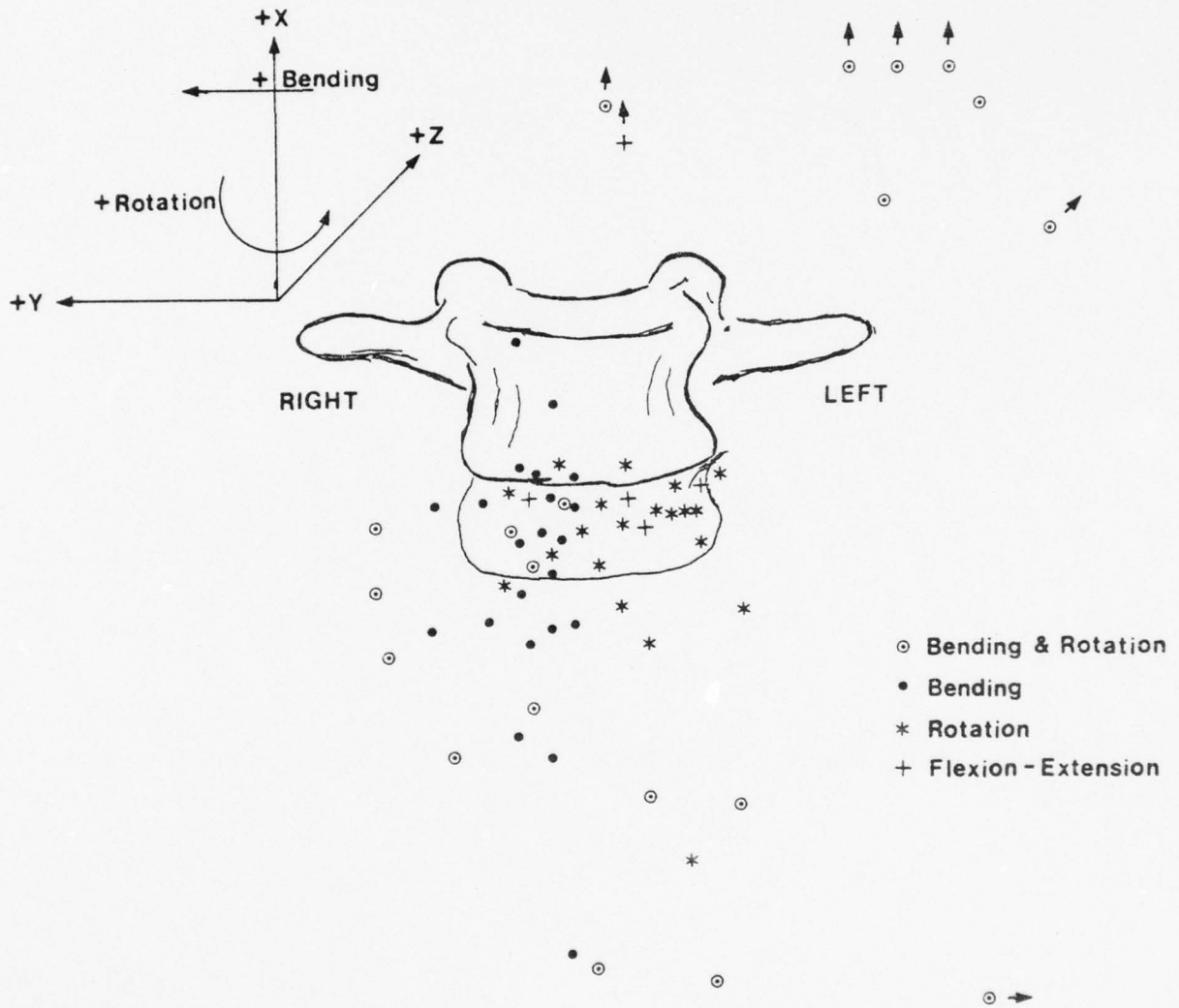
17. Instant Center Scatter Superior Aspect.

Lateral View Instantaneous Centres



18. Instant Center Scatter Lateral Aspect.

Ventral Aspect Instantaneous Centres



19. Instant Center Scatter Ventral Aspect.

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RADIOGRAPHIC AND BIOMECHANICAL STUDIES OF THE HUMAN SPINE.(U)
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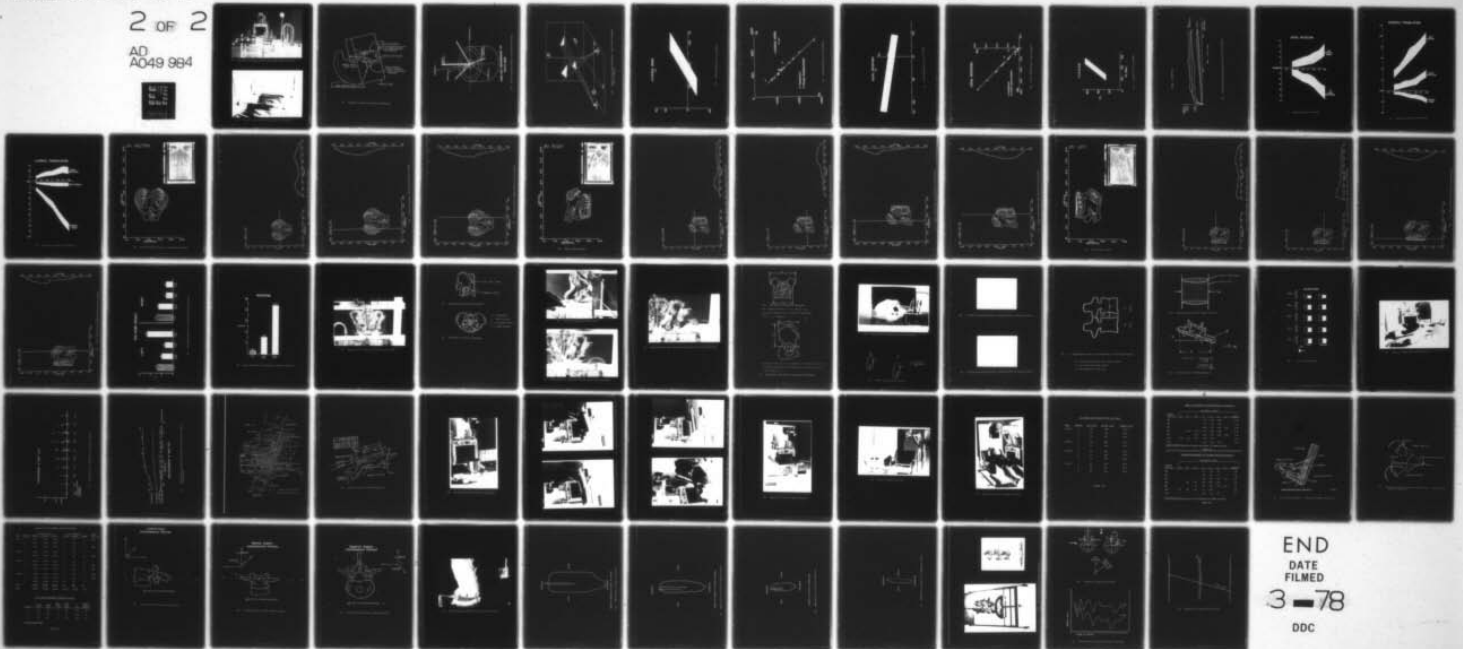
UNCLASSIFIED

AFOSR-TR-78-0063

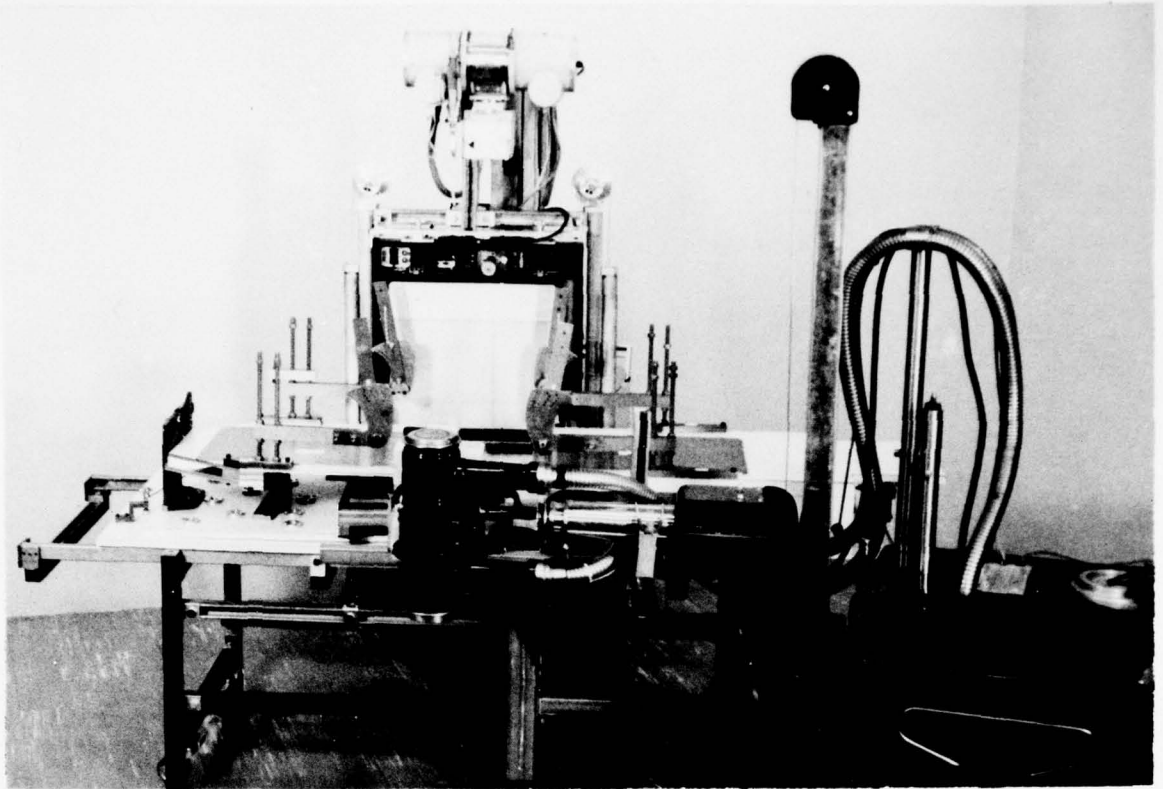
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2 OF 2

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A049 984



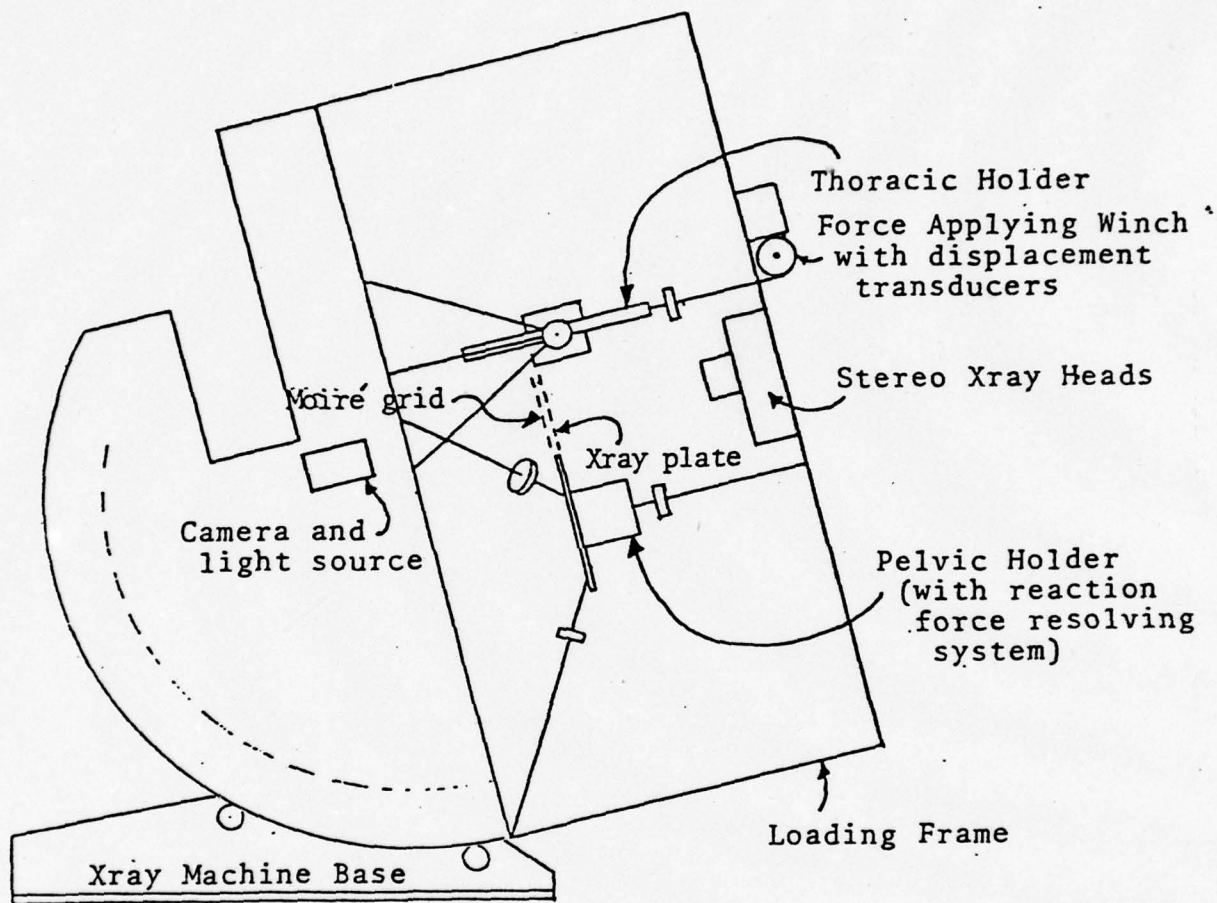
END
DATE
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3-78
DDC



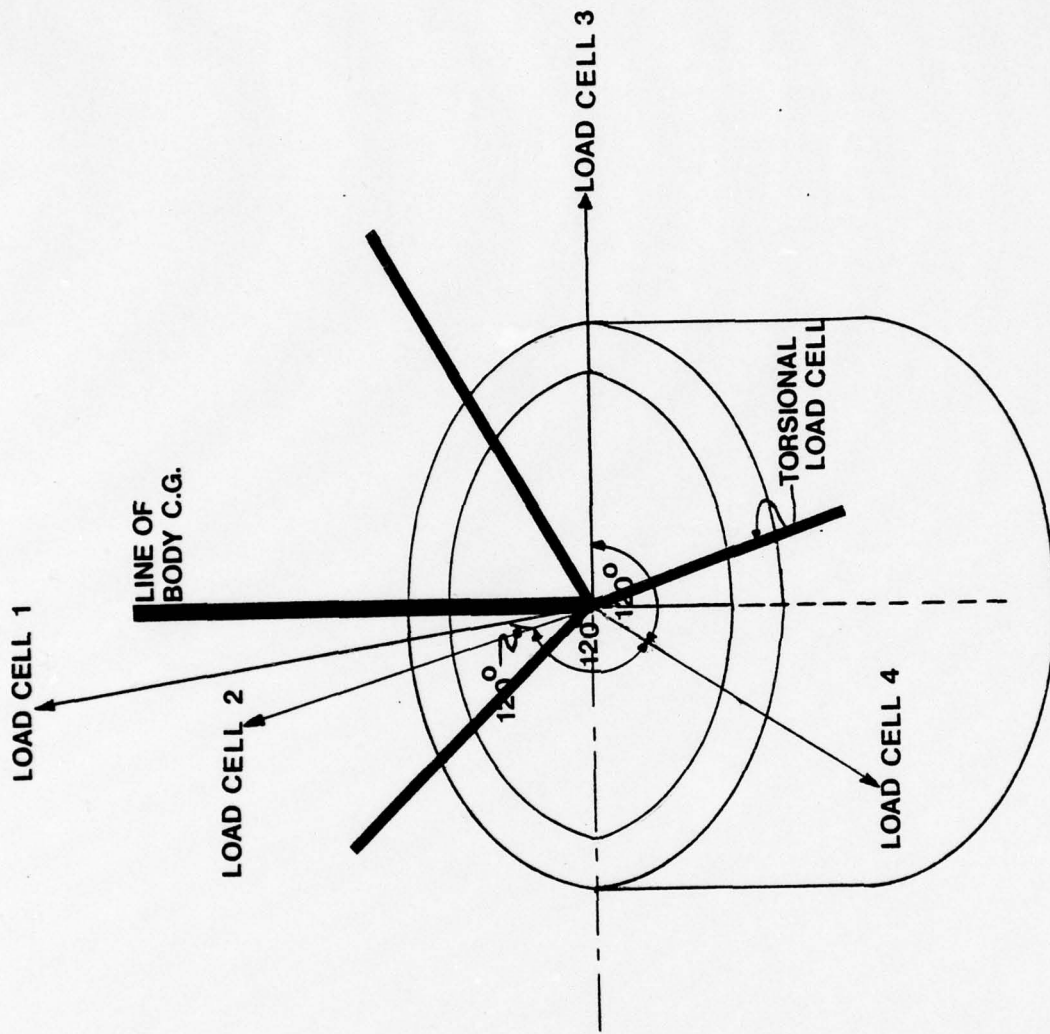
20. Apparatus with AP and Lateral X-Ray Units in Place.



21. Plaster Half-Shells Securing a Live Subject.

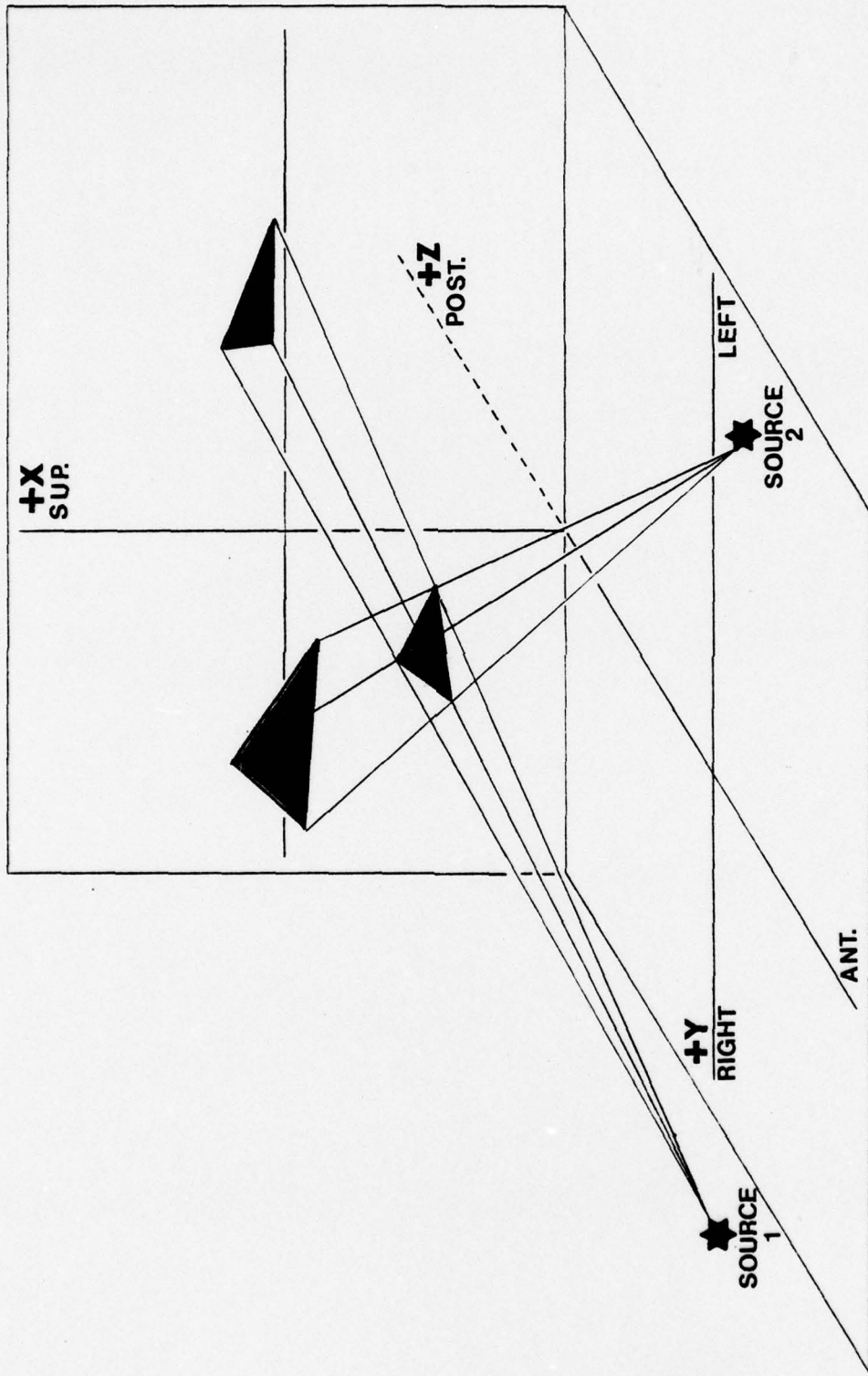


22. Diagram of Multi-orientation Apparatus.



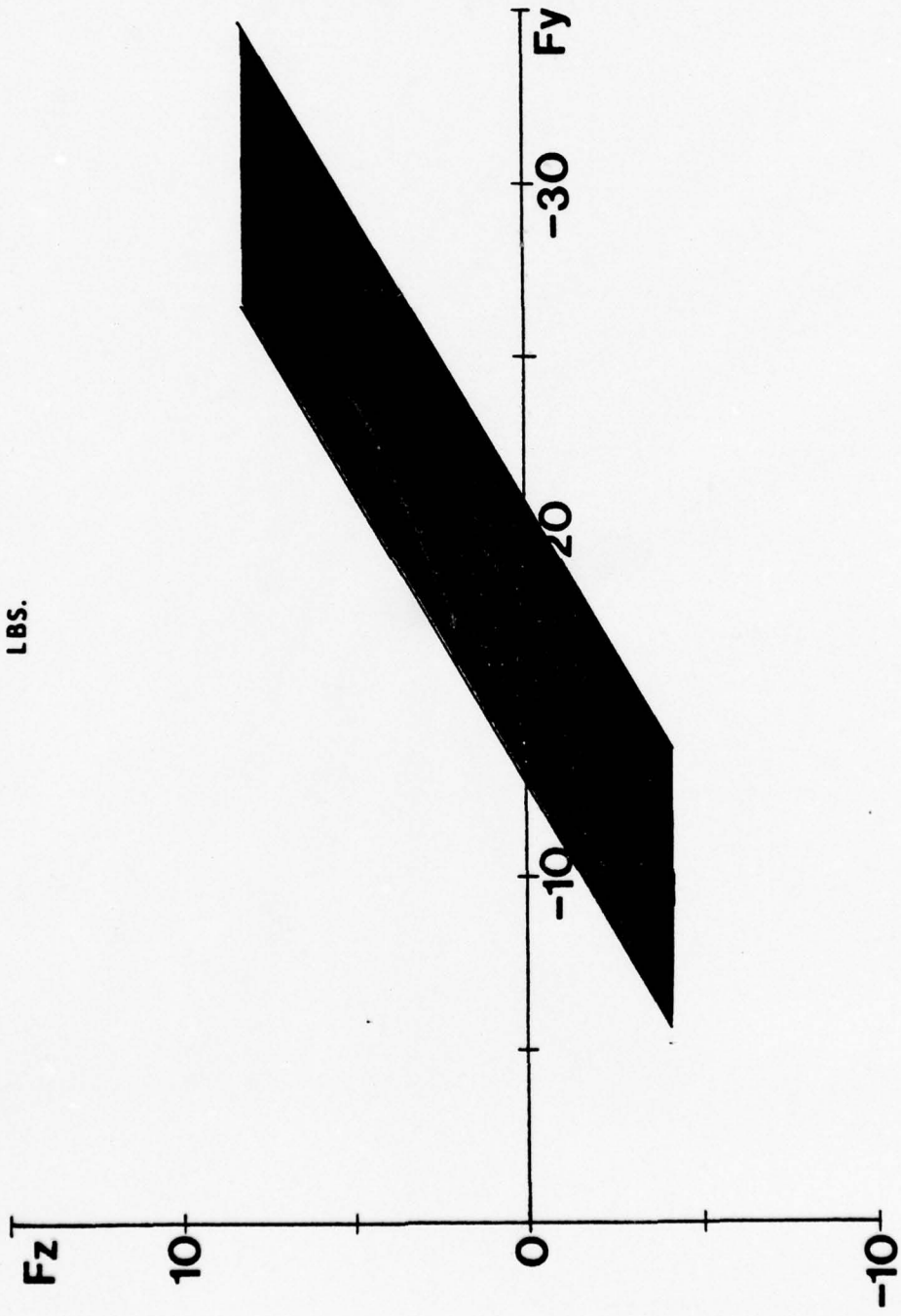
**LOAD CELL ARRANGEMENT IN
PELVIC RING**

23. Pelvic Fixation Showing Load Cell Positions.

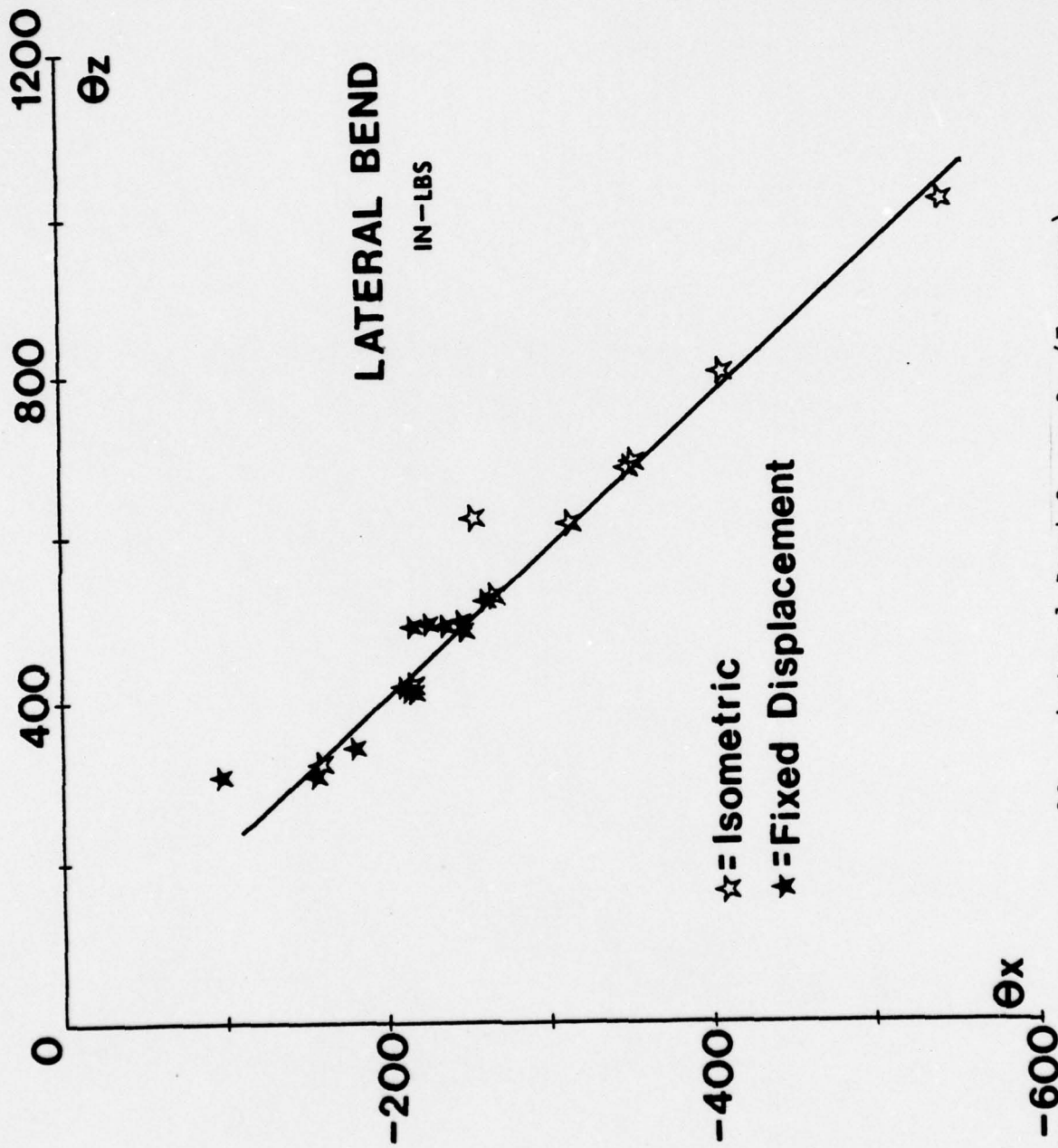


24. Stereo X-rays Showing Sources 1 and 2 and Triangular Plane in Space.

LATERAL BEND
LBS.

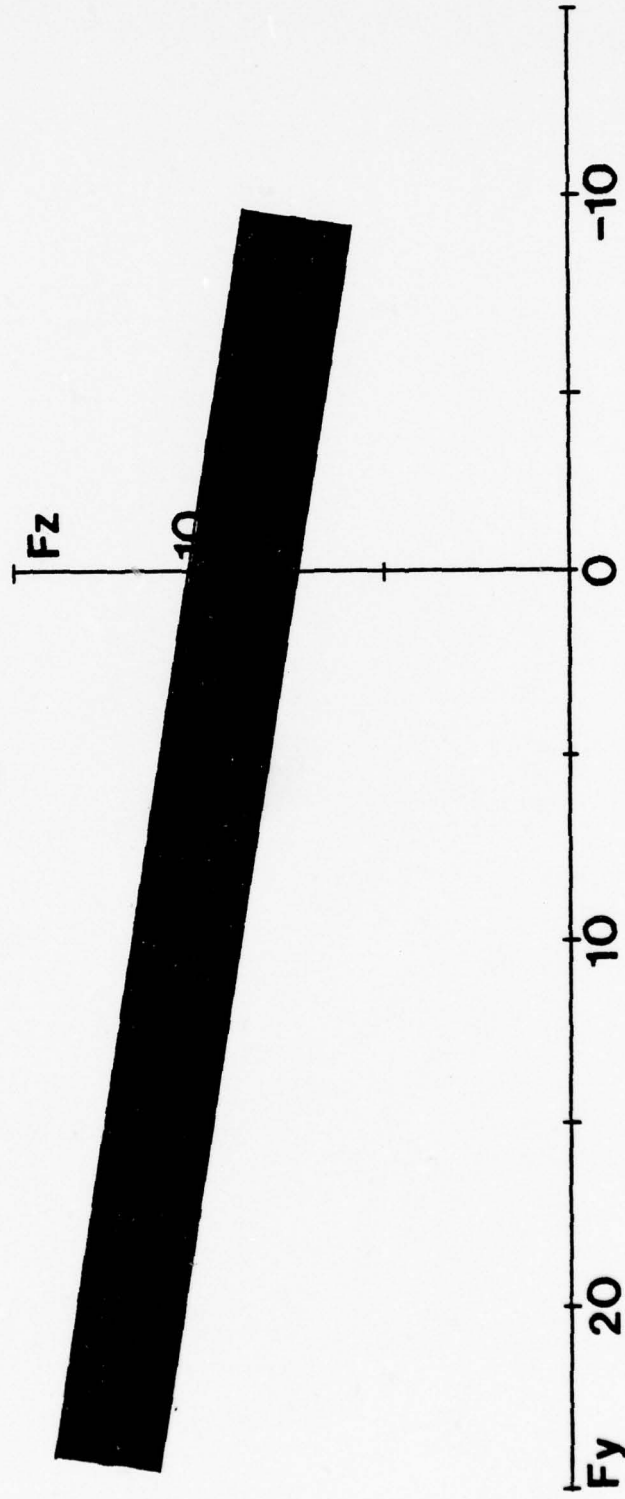


25. Lateral Bend F_z vs F_y (Loads).



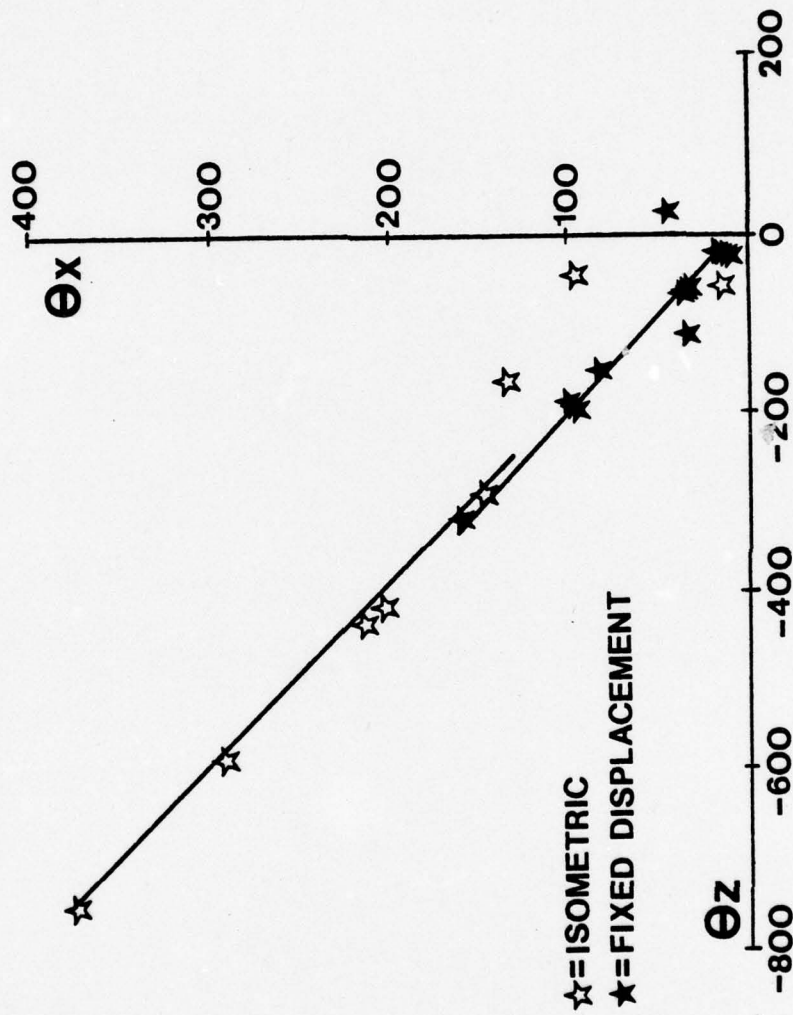
26. Lateral Bend θ_x vs θ_z (Torques).

AXIAL ROTATION
LBS.



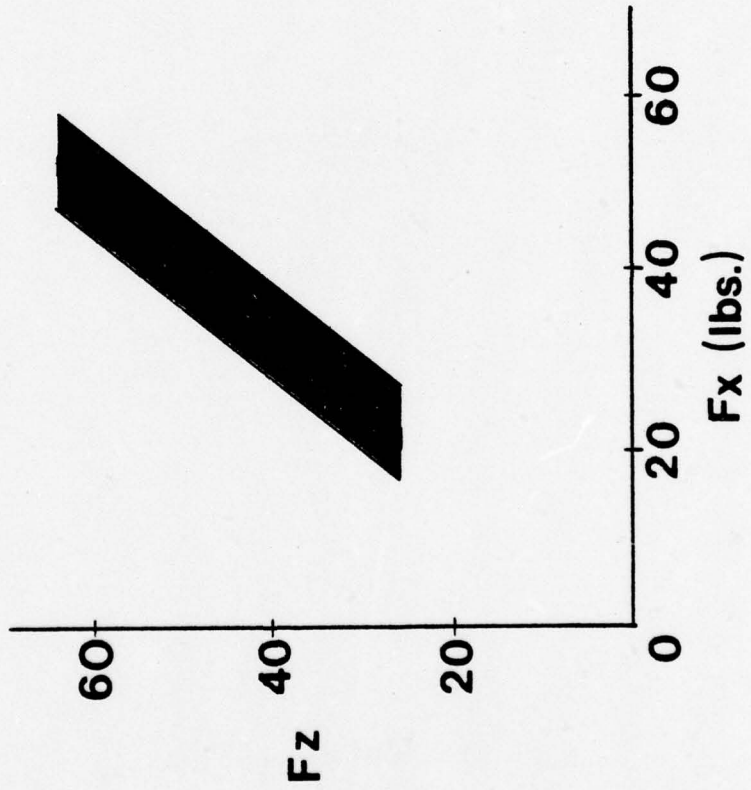
27. Axial Rotation F_z vs F_y (Loads).

AXIAL ROTATION



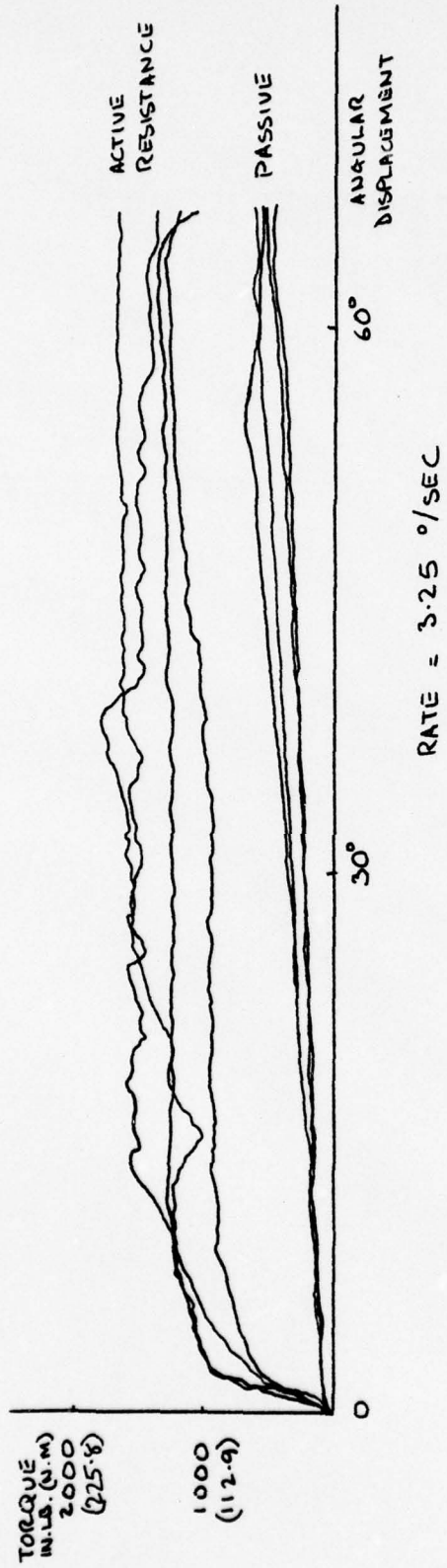
28. Axial Rotation θ_x vs θ_z (Torques).

FLEXION



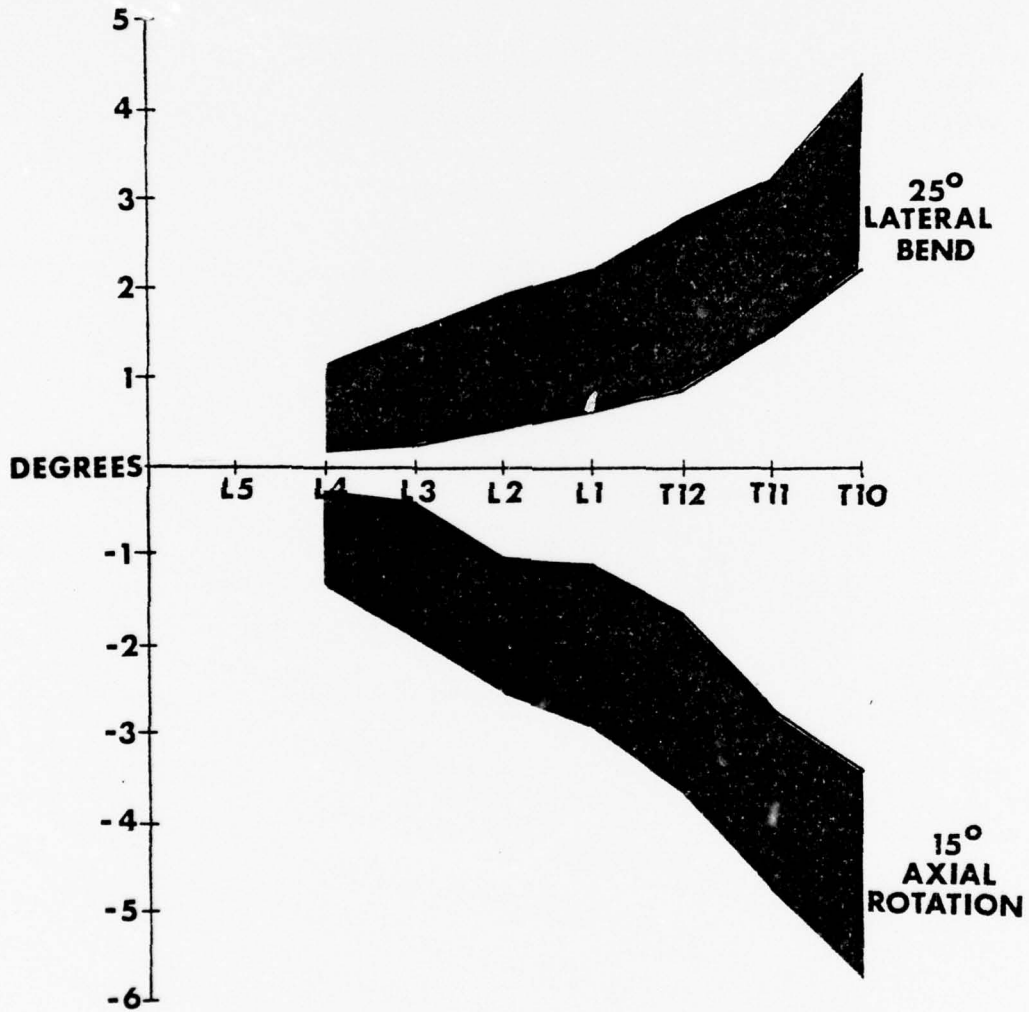
29. Flexion F_z vs F_x (Loads).

AXIAL ROTATION



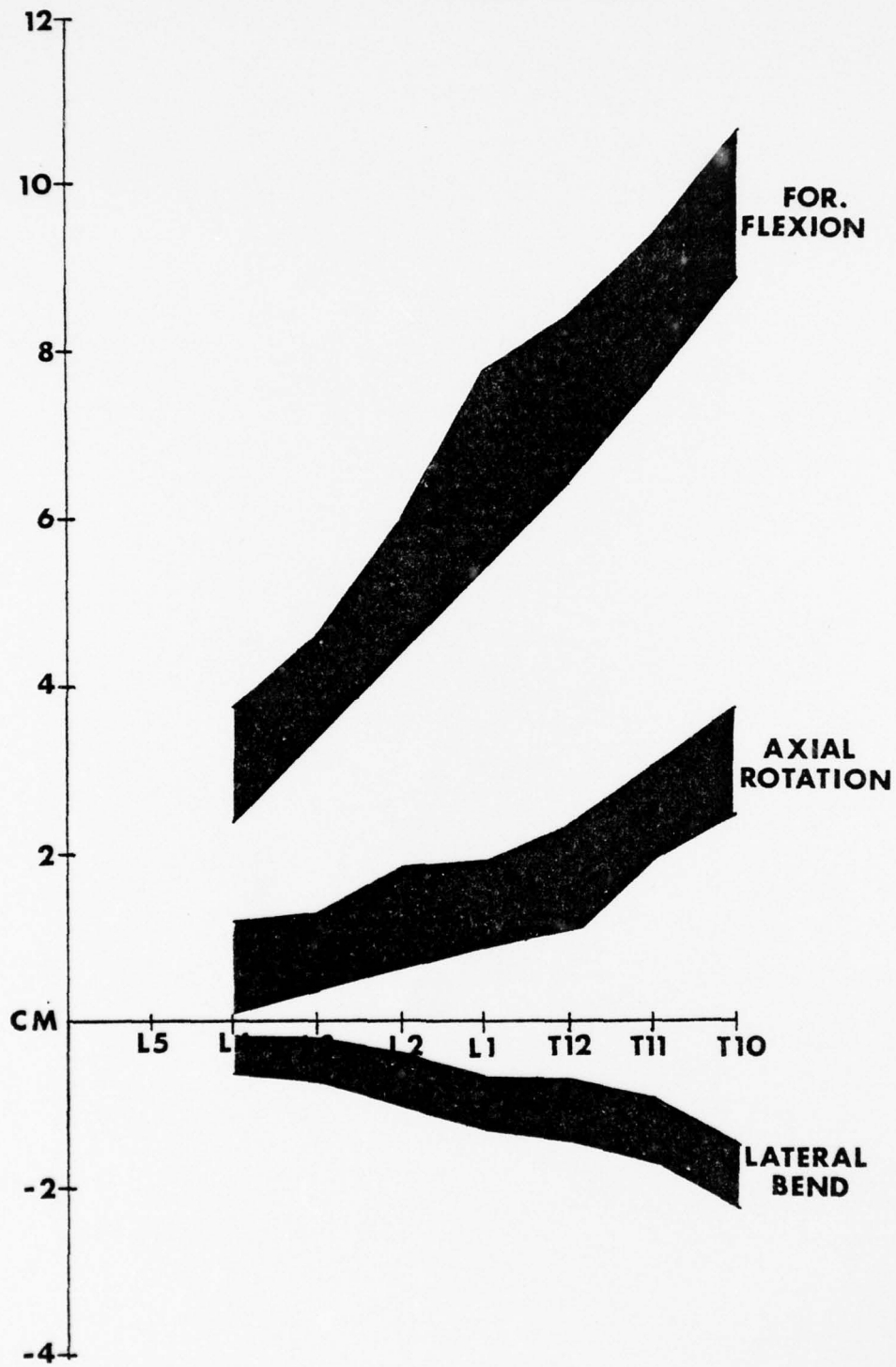
30. Axial Rotation with Active and Passive Resistance.

AXIAL ROTATION



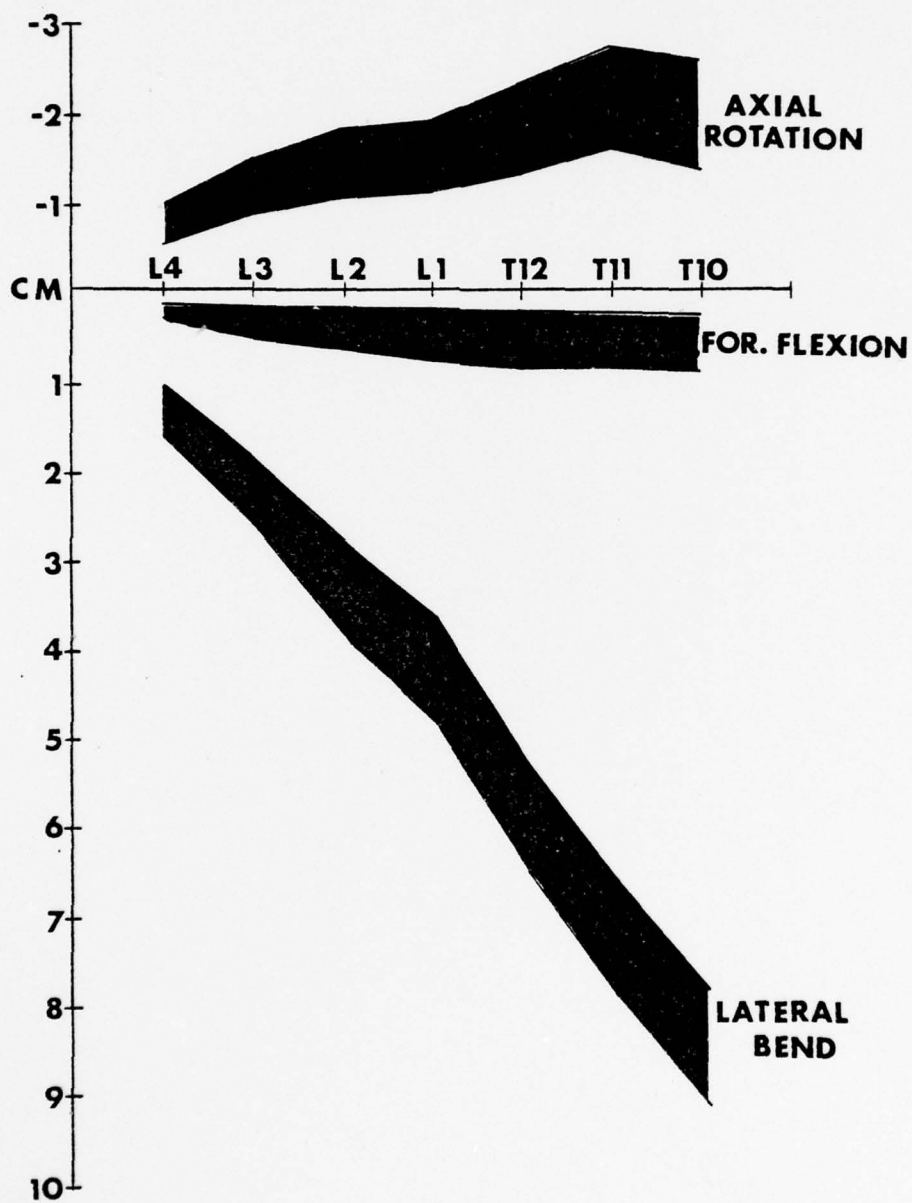
31. Resultant Axial Rotation.

FRONTAL TRANSLATION



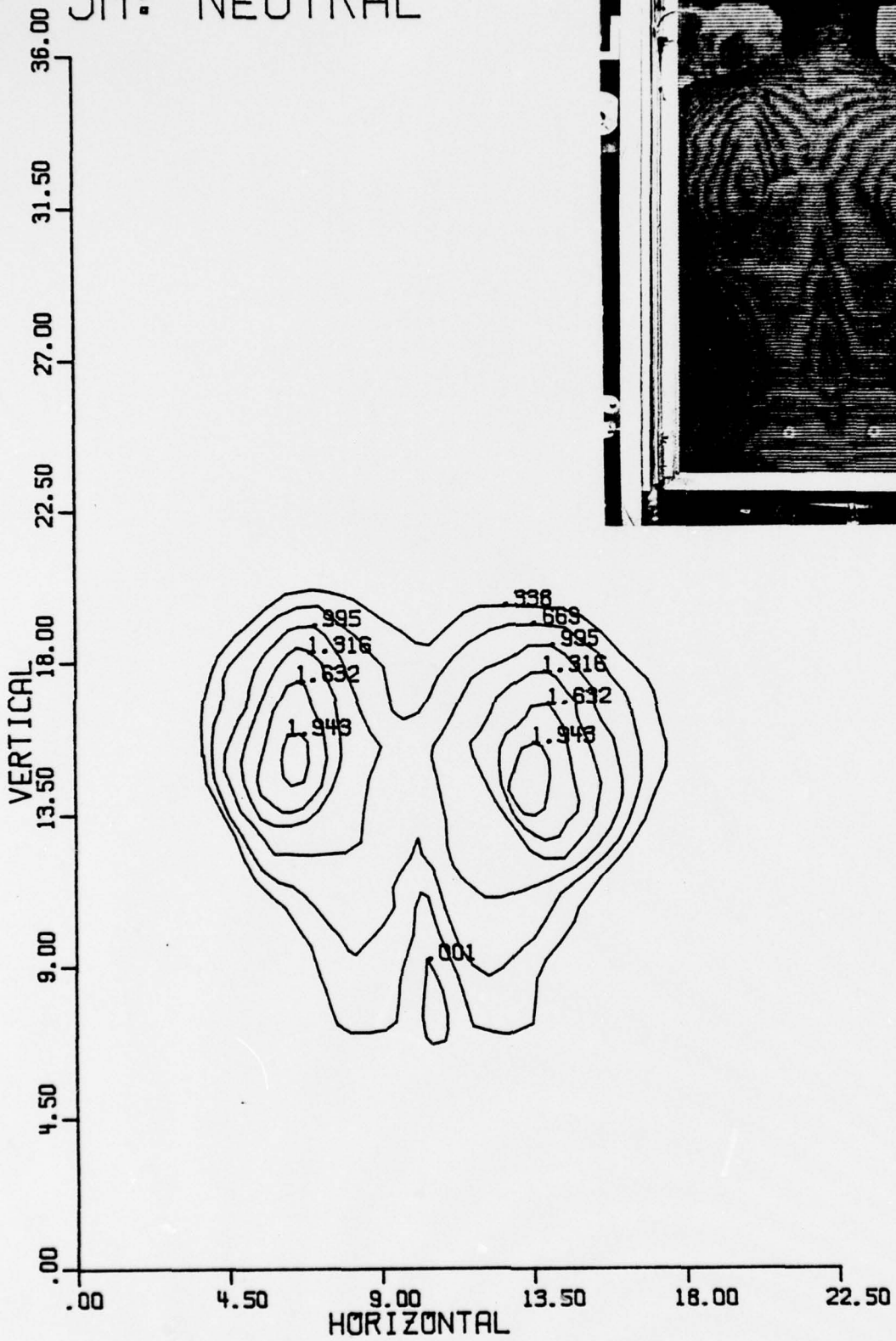
32. Resultant Frontal Translation.

LATERAL TRANSLATION



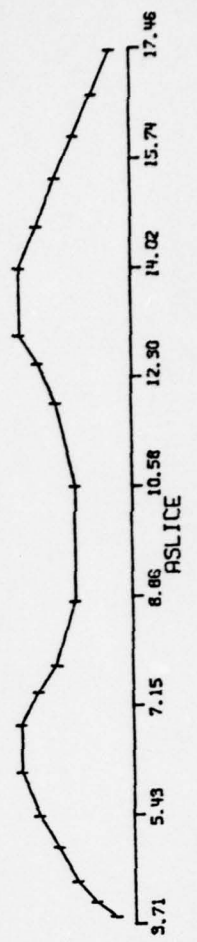
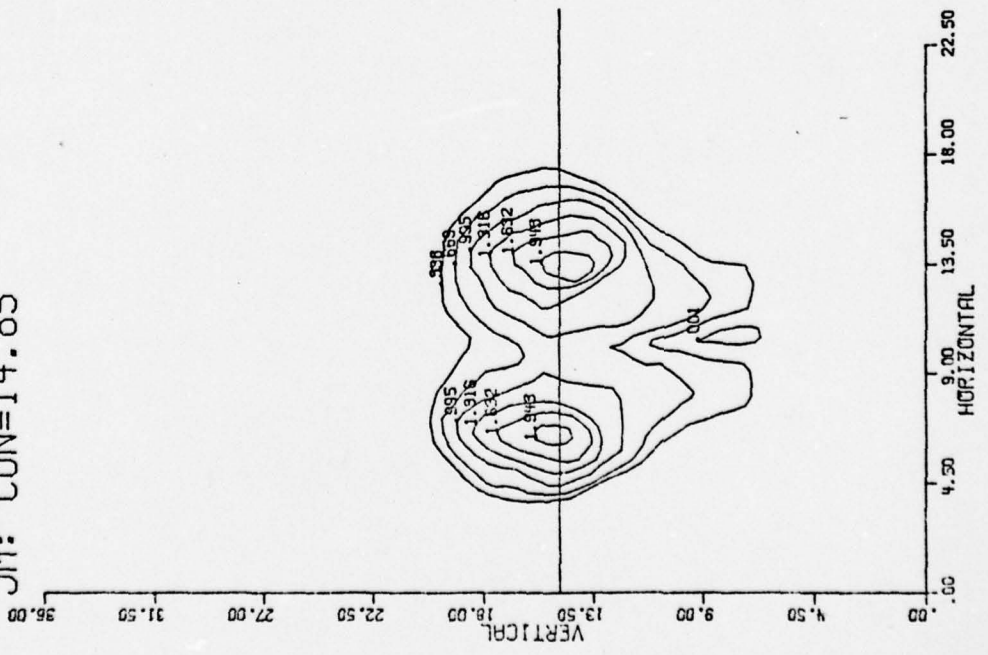
33. Resultant Lateral Translation.

JM: NEUTRAL

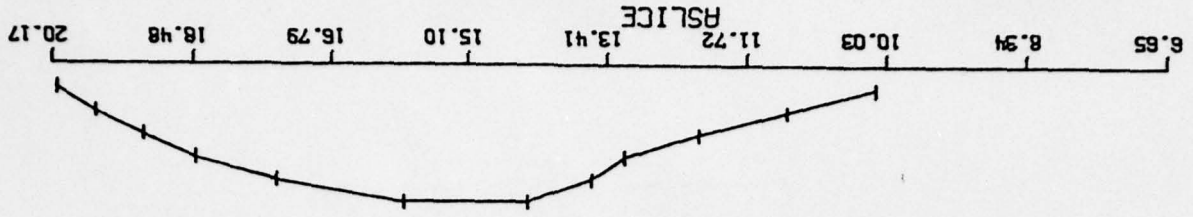
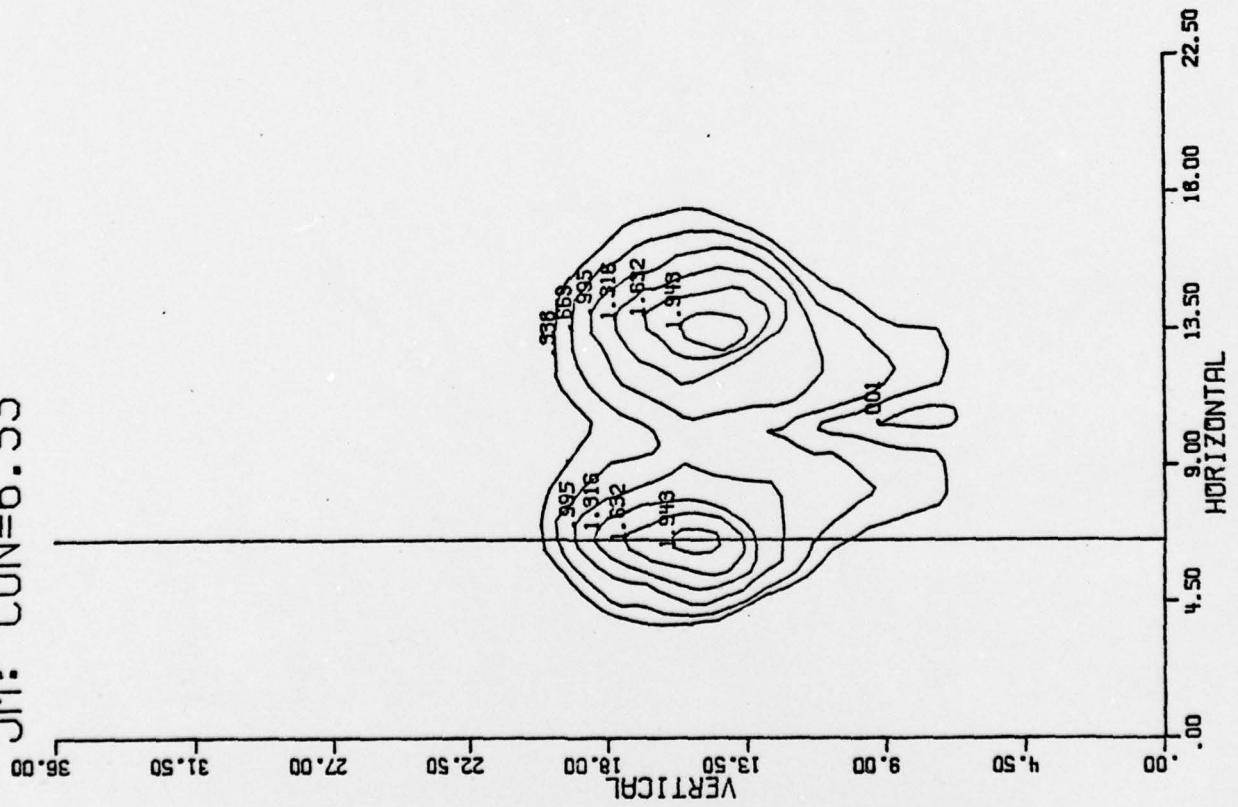


34. Low Back Pain Patient in A Neutral Position.

JM: CON=14.85

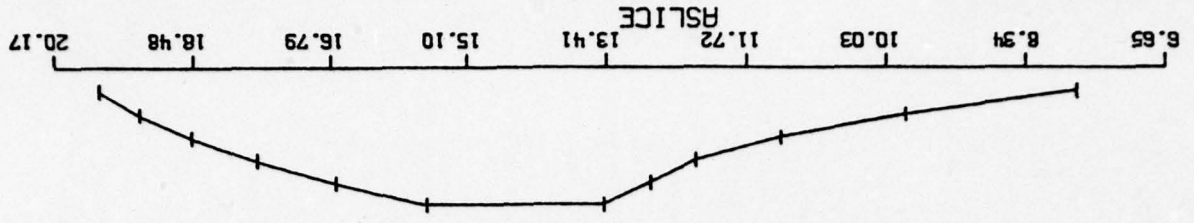
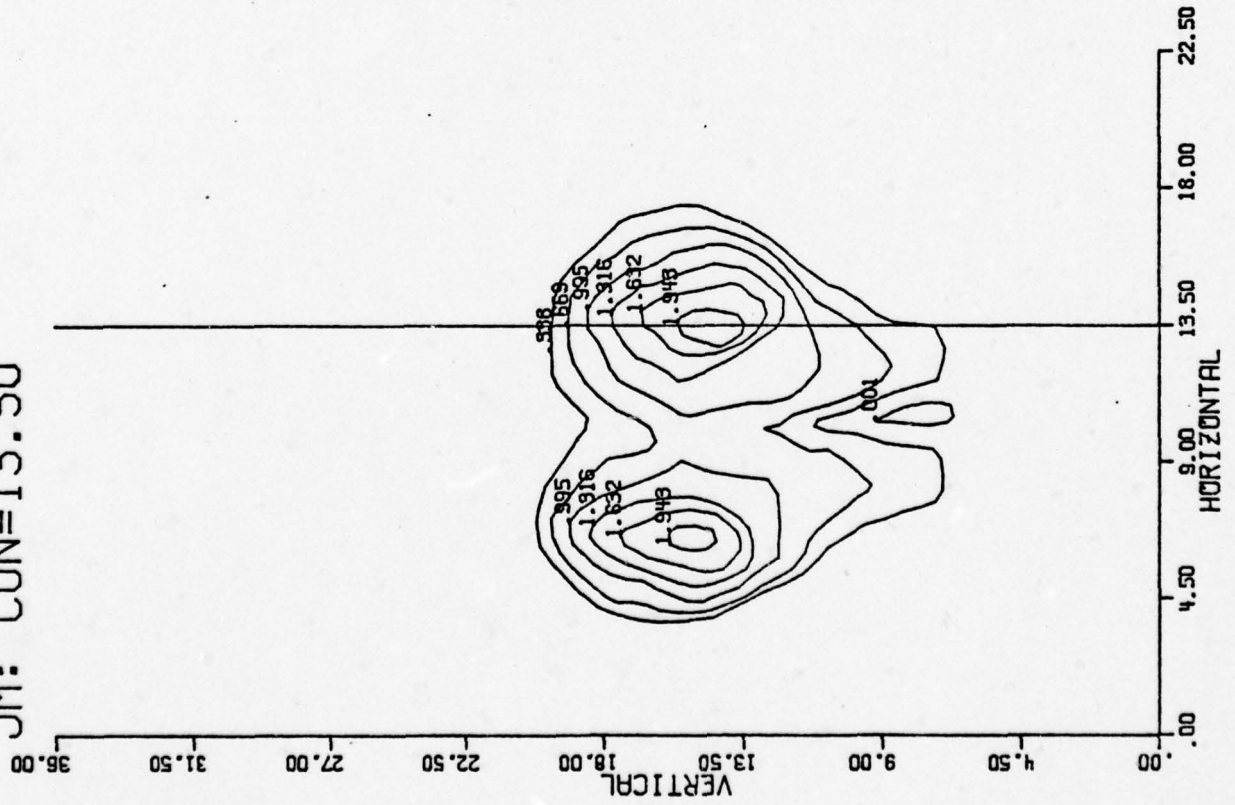


JM: CON=6.53



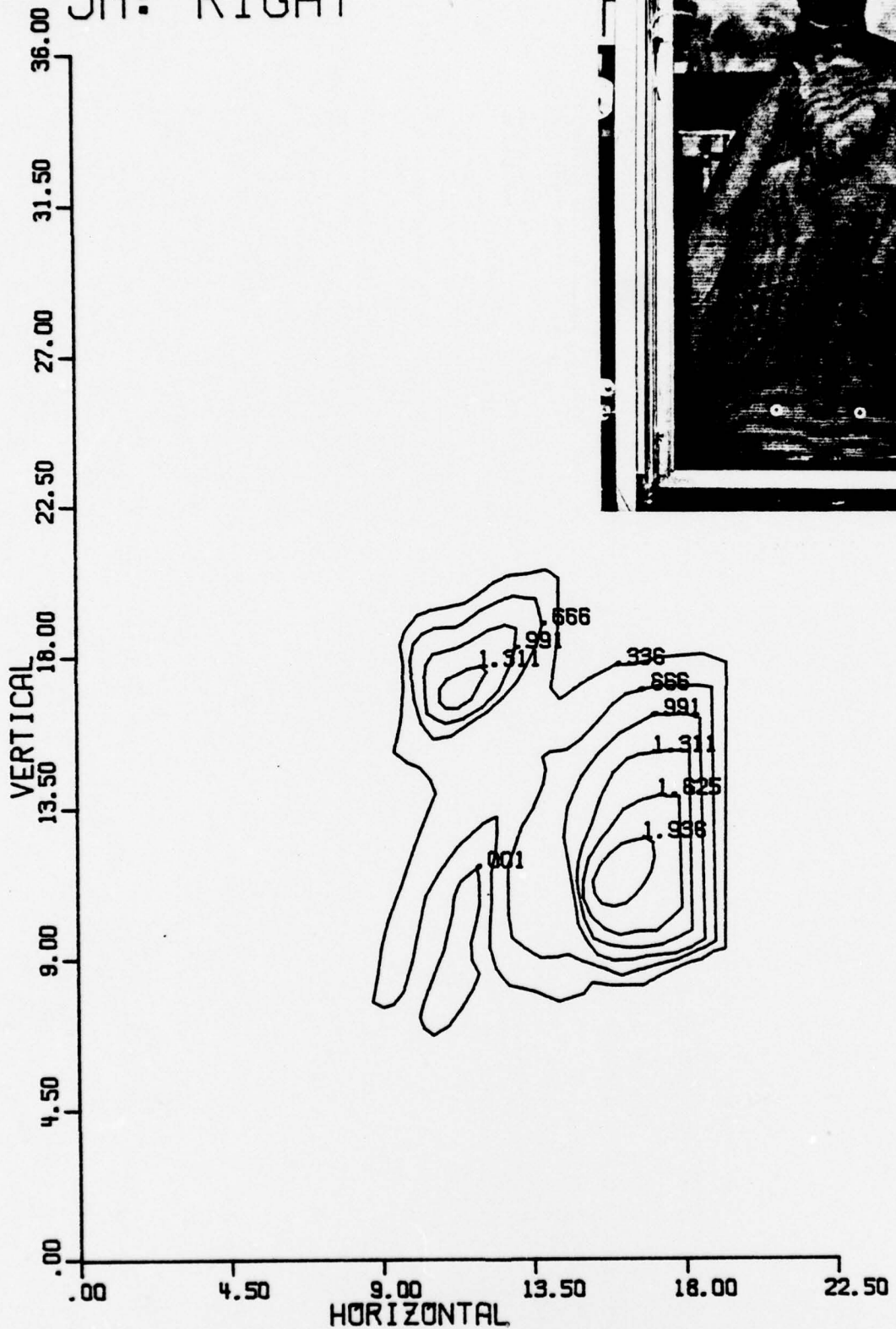
36. Neutral Position, Left Vertical Cross-section.

JM: CON=13.50



37. Neutral Position, Right Vertical Cross-section.

JM: RIGHT

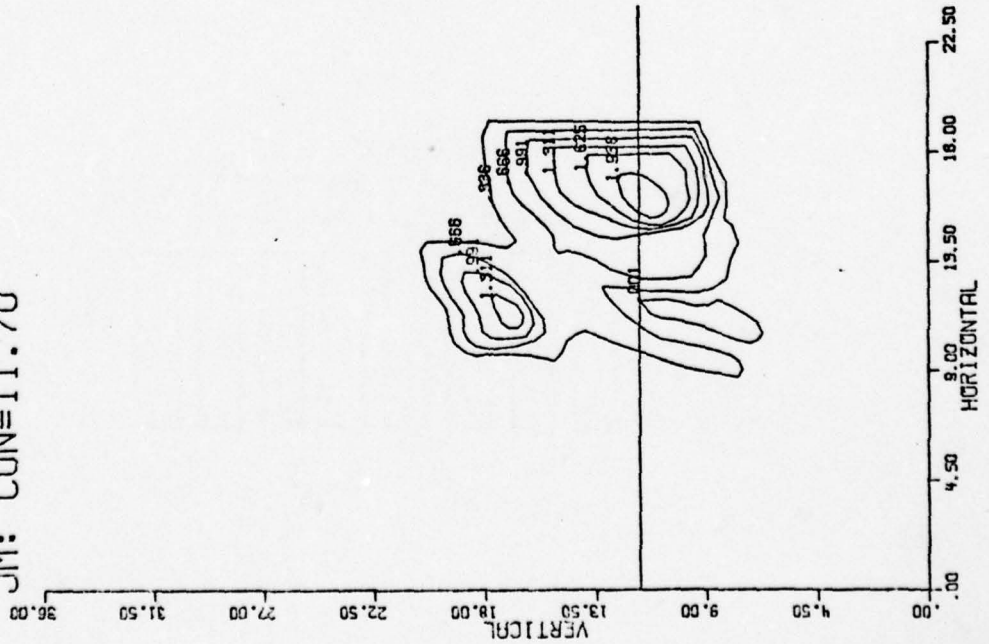


38. Right Lateral Bend.

JM: CON=16.88

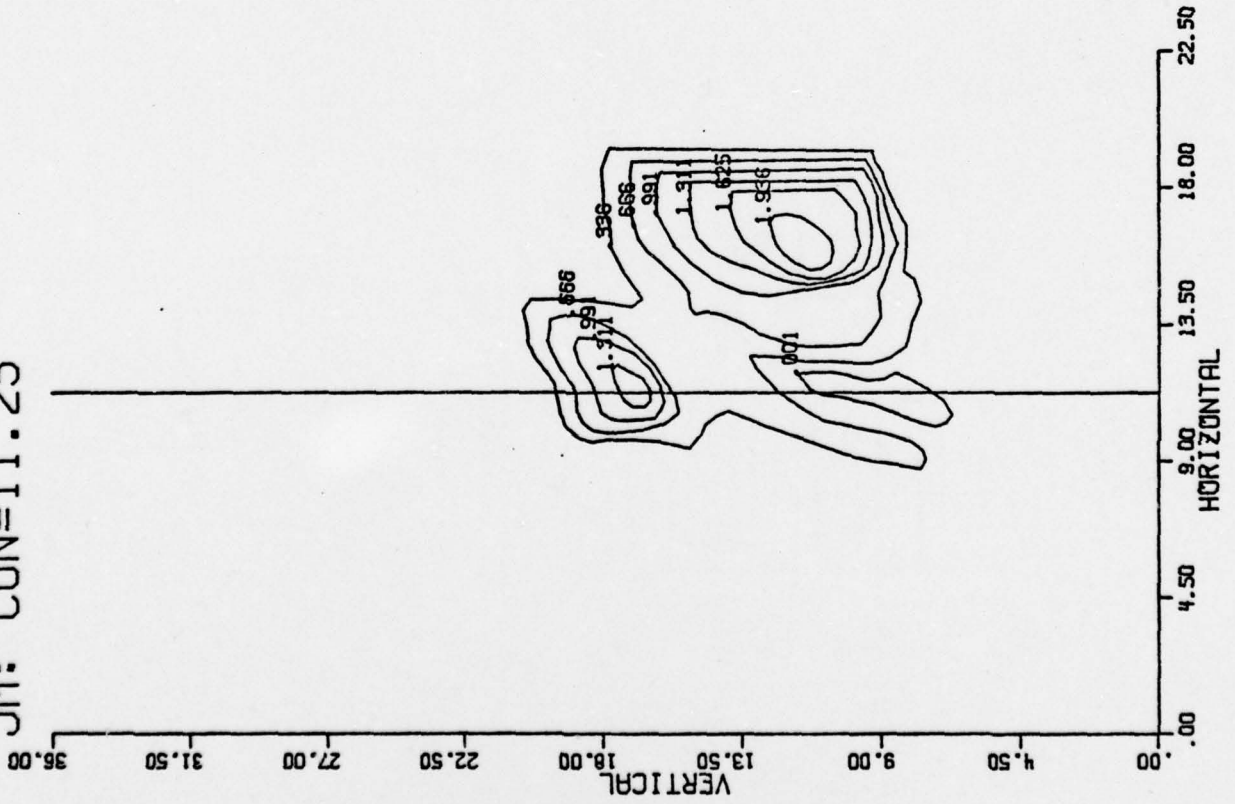


JM: CON=11.70

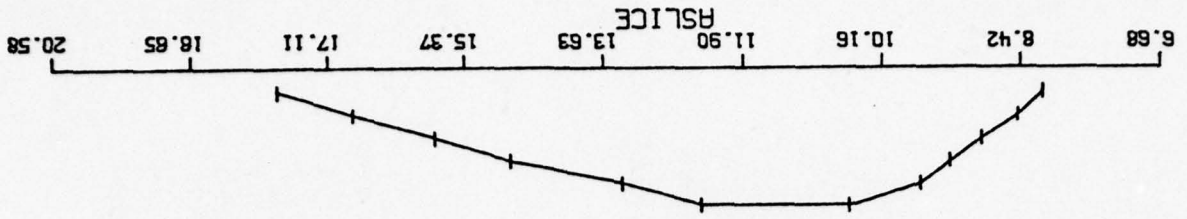
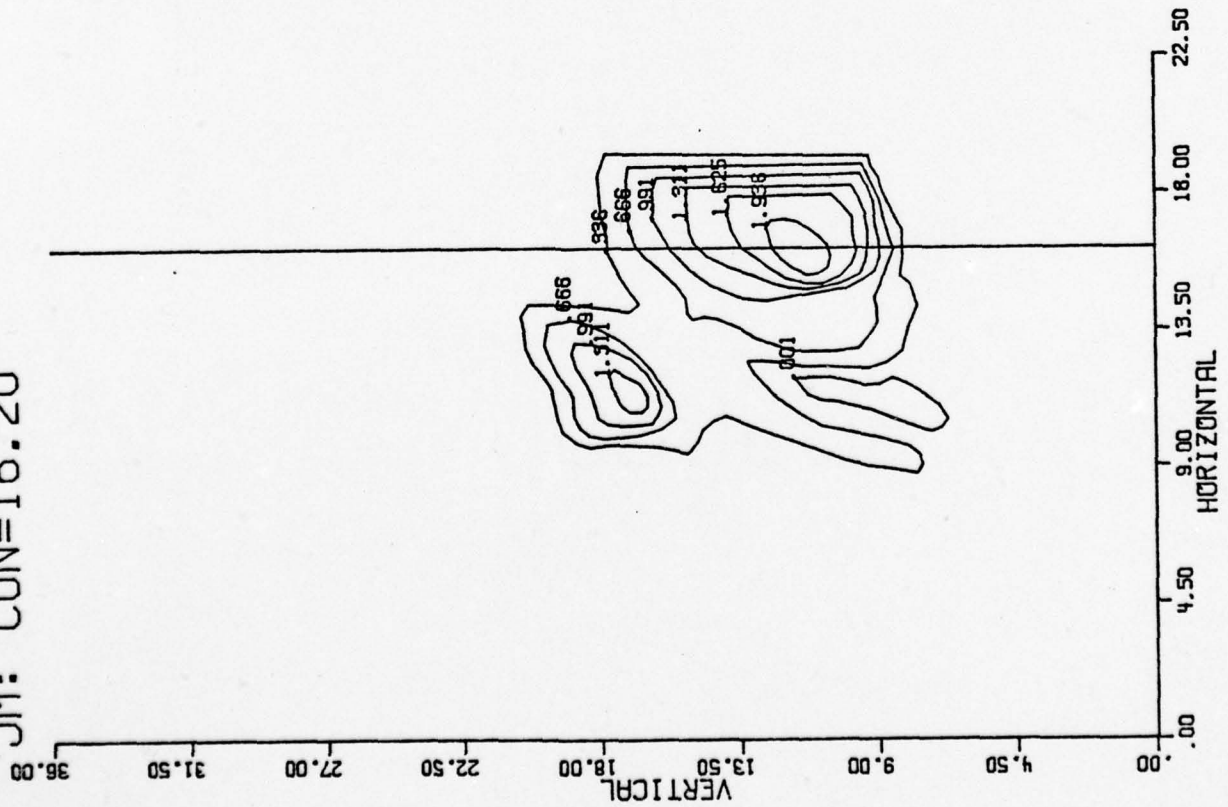


40. Right Lateral Bend, Lower Horizontal Cross-section.

JM: CON=11.25



JM: CON=16.20



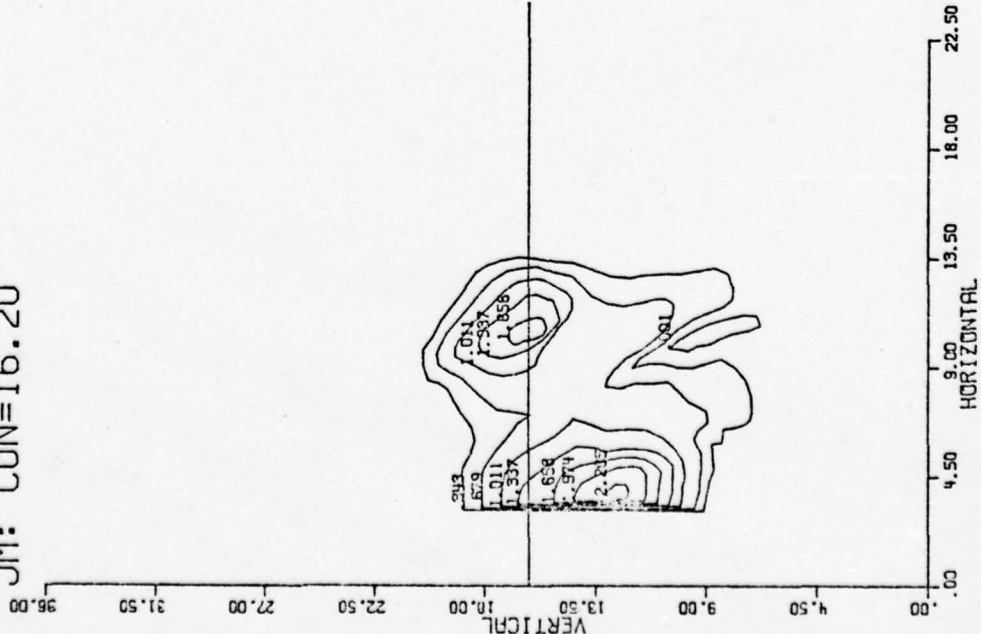
42. Right Lateral Bend, Right Vertical Cross-section.

JM: LEFT

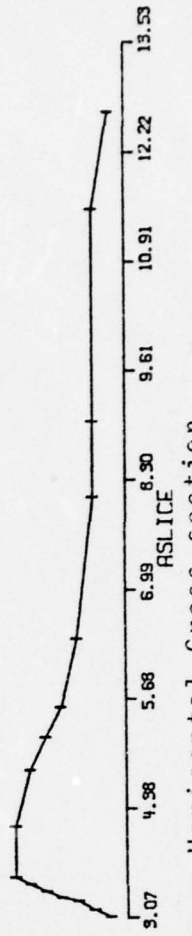
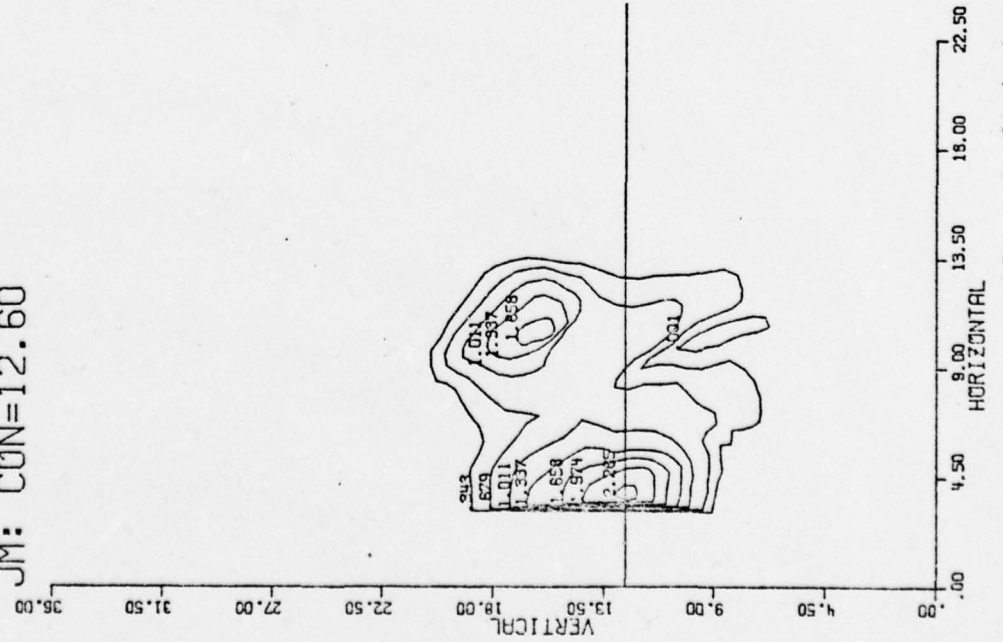


43. Left Lateral Bend.

JM: CON=16.20

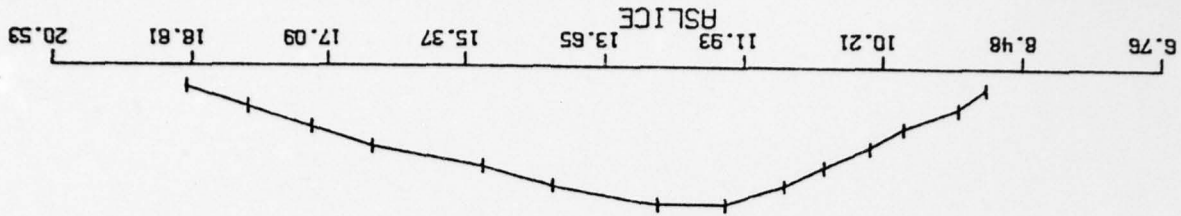
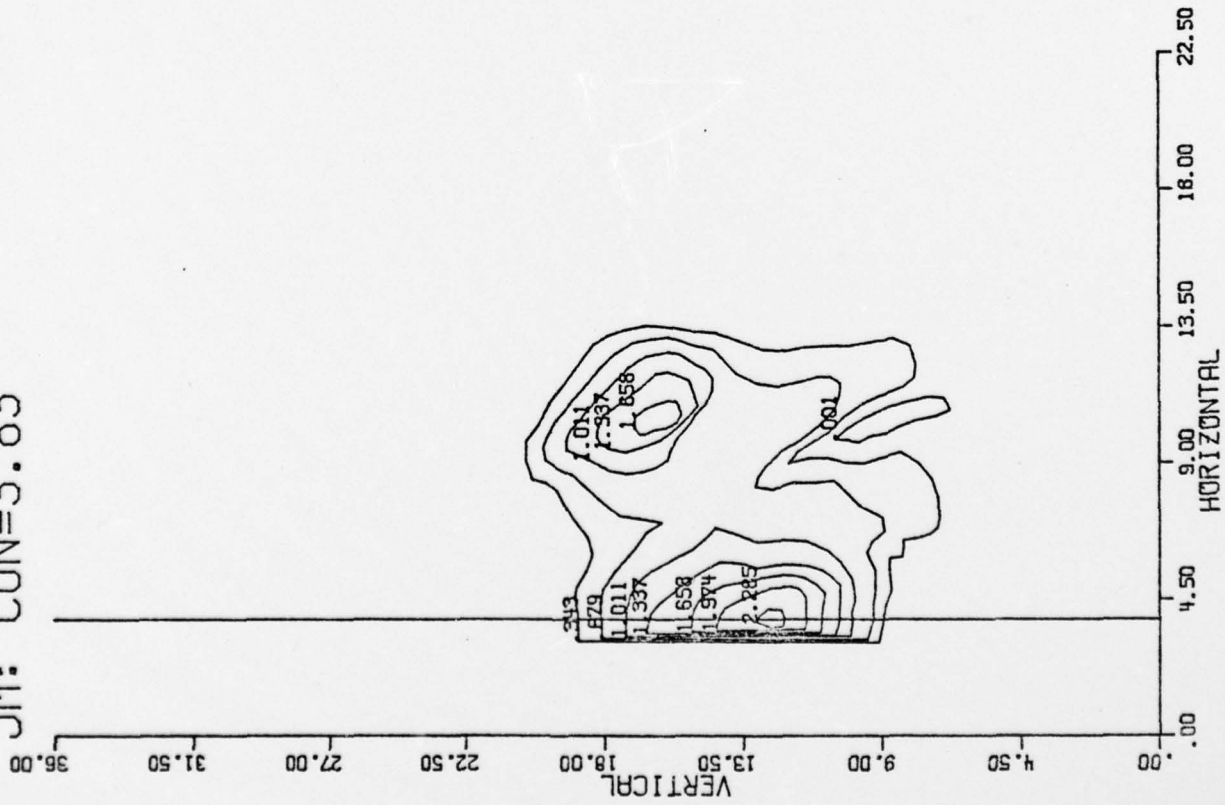


JM: CON=12.60



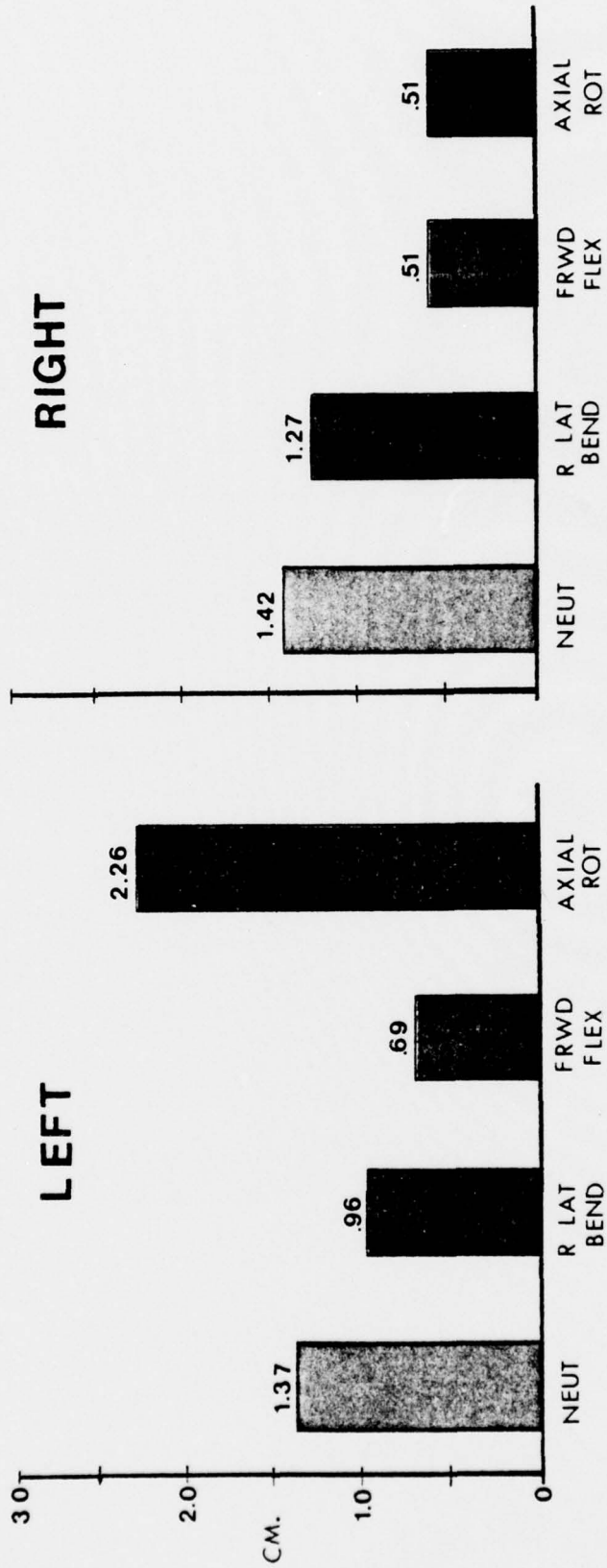
45. Left Lateral Bend, Lower Horizontal Cross-section.

JM: CON=3.83

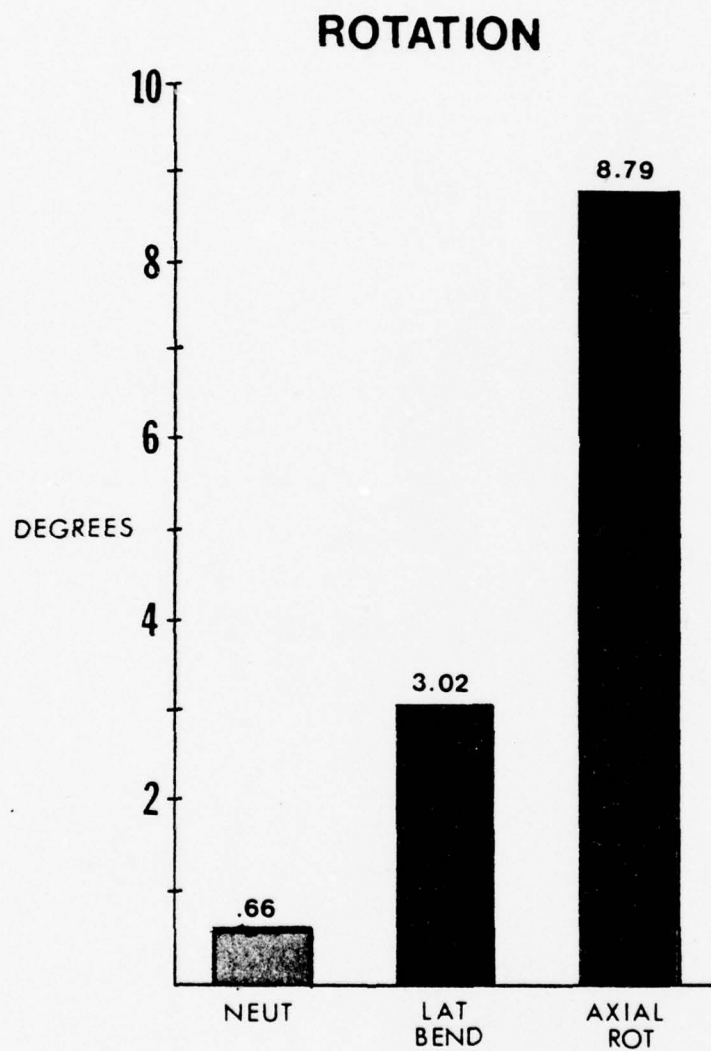


46. Left Lateral Bend, Left Vertical Cross-section.

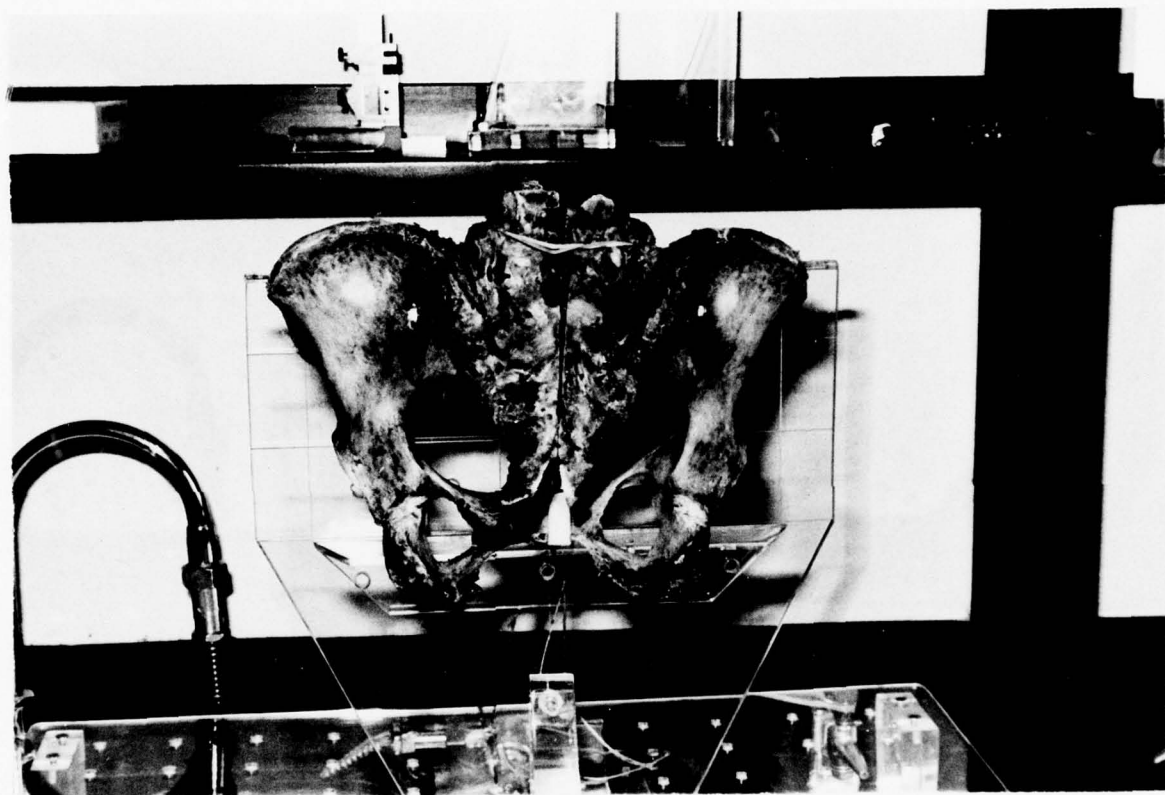
RIB HUMP HEIGHT



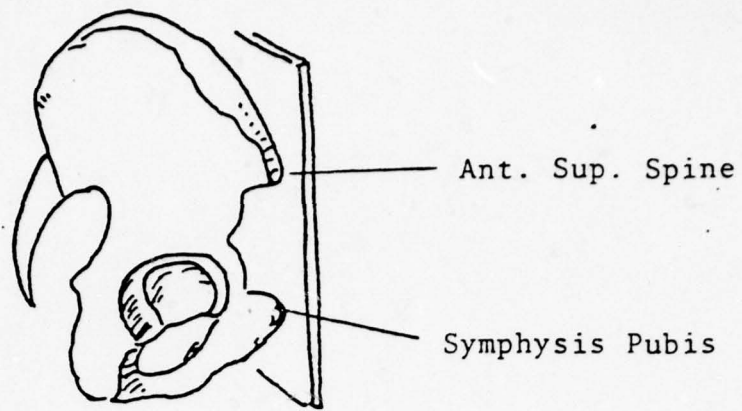
48. Rib Hump Heights as a Result of Various motions.



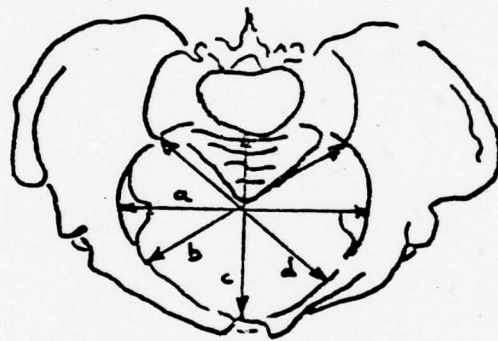
49. Axial Rotation as a Result of Various Motions.



50. Mounting of a Pelvis on the Vertical Stand.

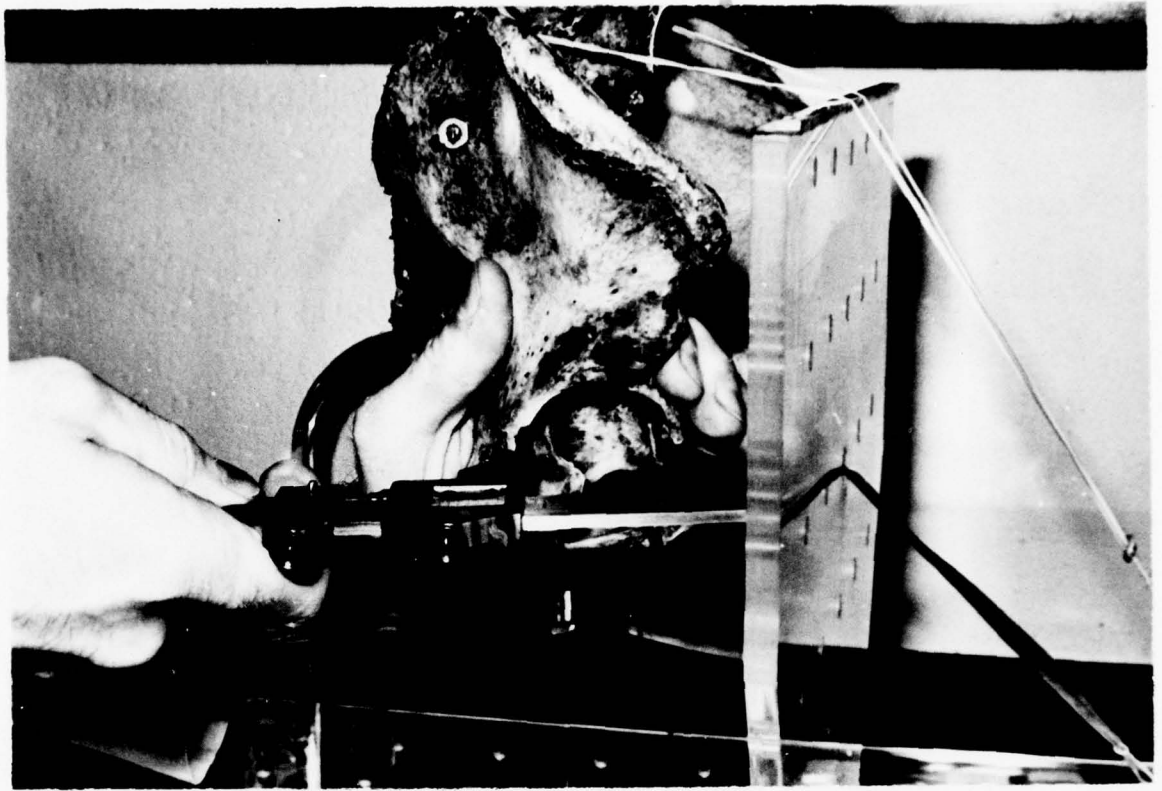


51. Orientation of Pelvis (Diagram).

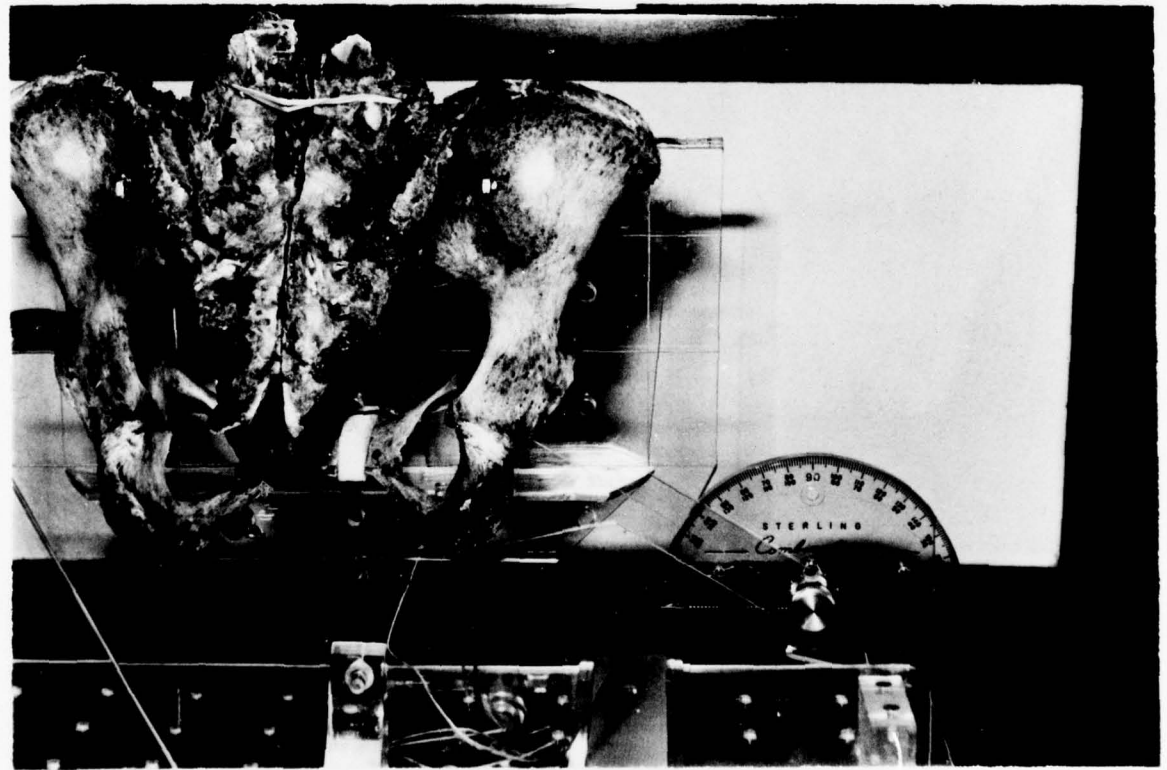


- a = transverse
- b = left oblique
- c = anteroposterior
- d = right oblique

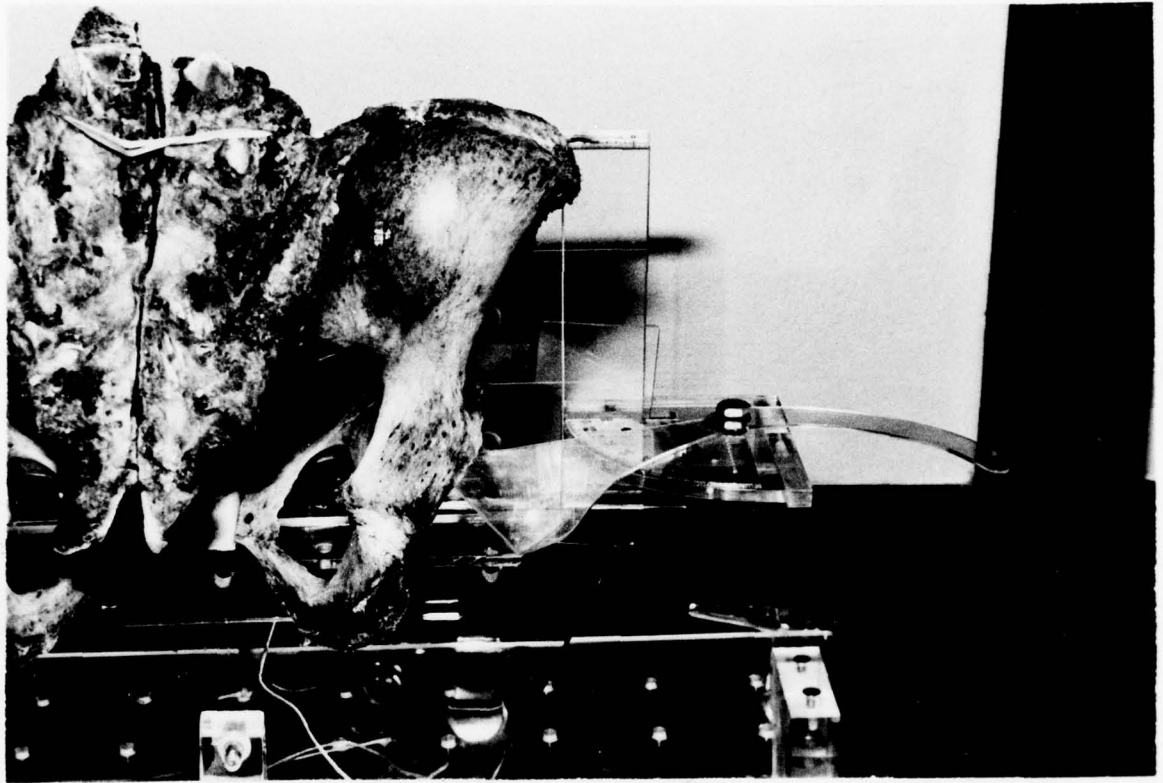
52. Diameters of Pelvis (Diagram).



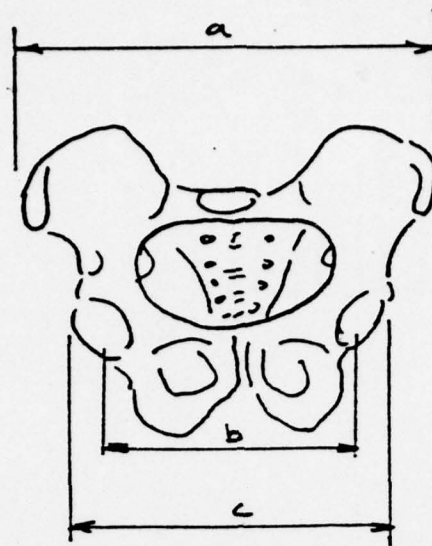
53. Acetabular Diameter Measurement.



54. Measurement of Sagittal Inclination of the Acetabulum.



55. Measurement of the Transverse Inclination of the Acetabulum.

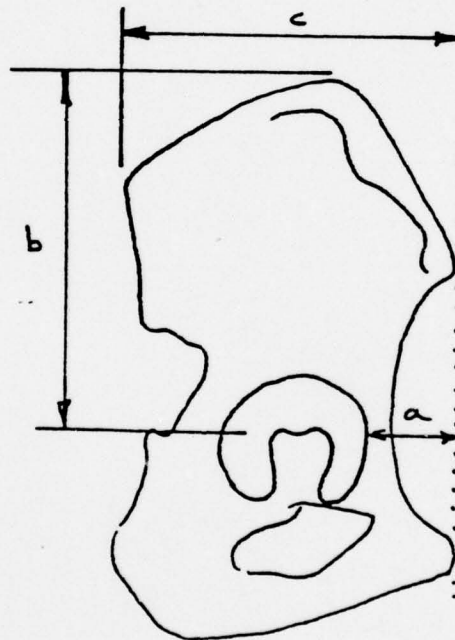


56. Horizontal Dimensions Measured.

Max. distance between iliac crests = a

Distances between outer edges of acetabulae

Max. = c, midplane = b.

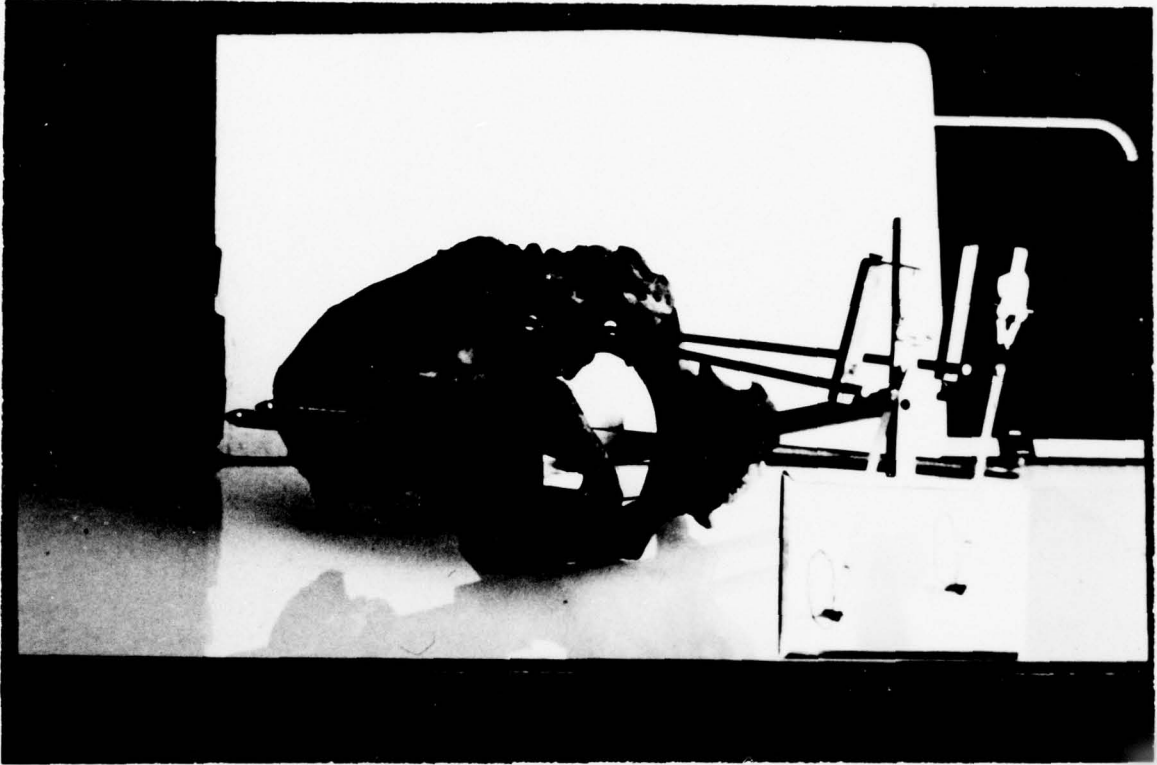


Distance from tip of acetabula to transverse plane = a

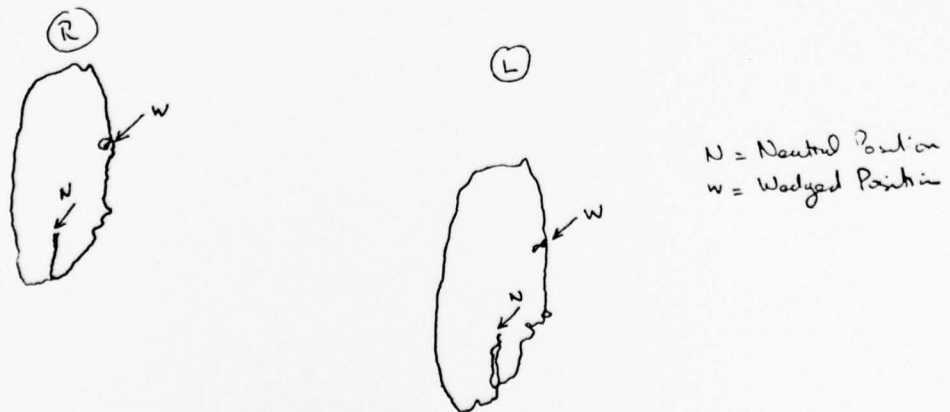
Distance from center of acetabula to iliac crest = b,

ASS to PSS = c.

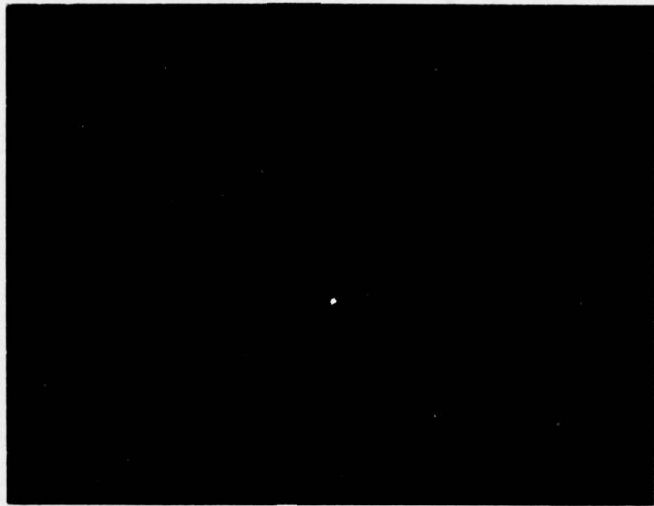
57. Horizontal and Vertical Dimensions Measured.



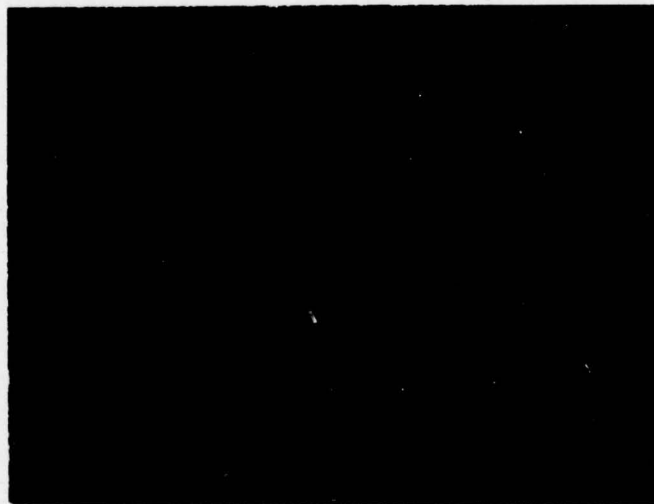
58. Jig Used for Measuring Sacroiliac Motion.



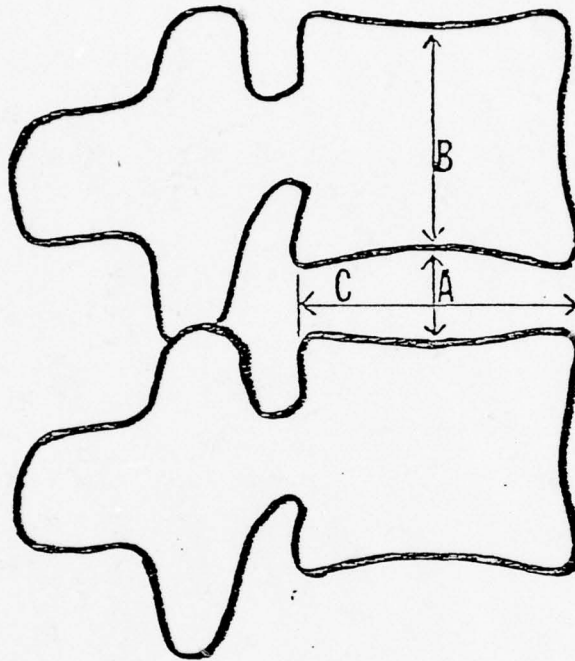
59. Chart of Sacroiliac Motion.



60. Straight Leg Raising Exam, Instant Center of Rotation Point.



61. Straight Leg Raising Exam, Instant Center of Rotation Path.



$$R' = \frac{A}{B}$$

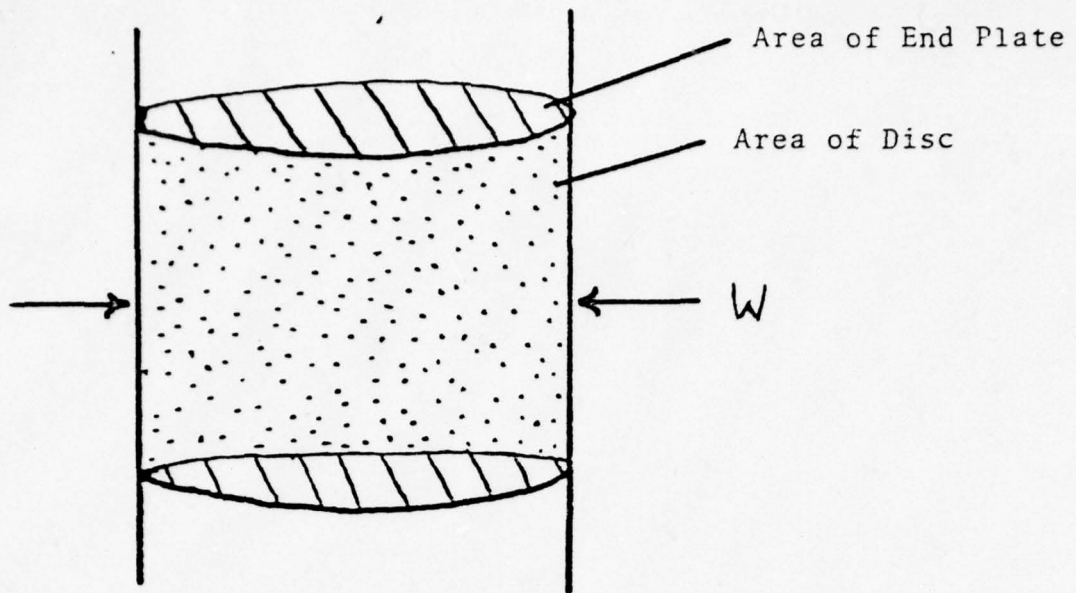
$$R'' = \frac{A}{C}$$

62. A: Measurements Used in the Analysis of Disc Space Height.

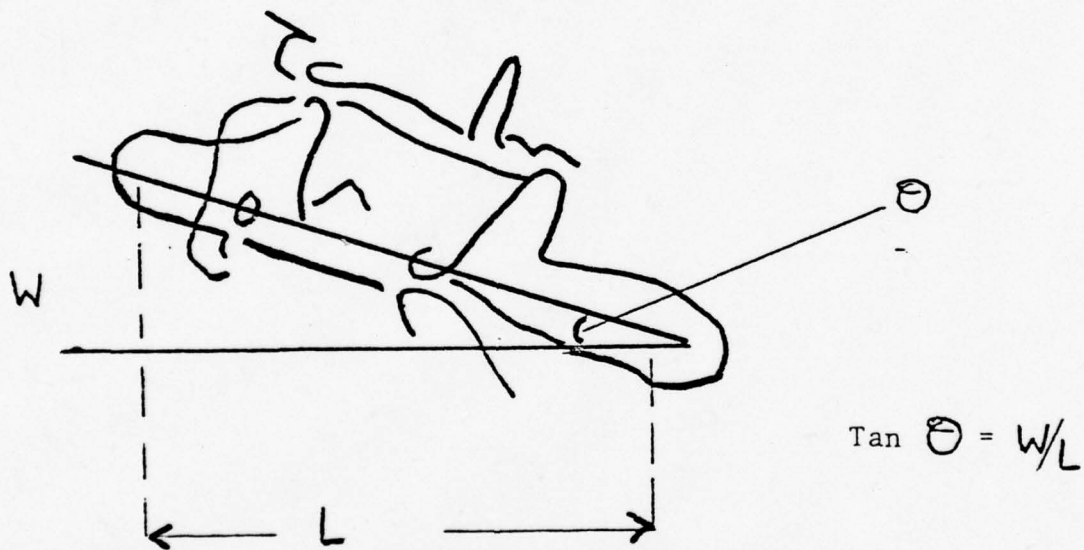
A= mid-intervertebral disc space height

B= mid vertebral body height

C= AP diameter of the disc



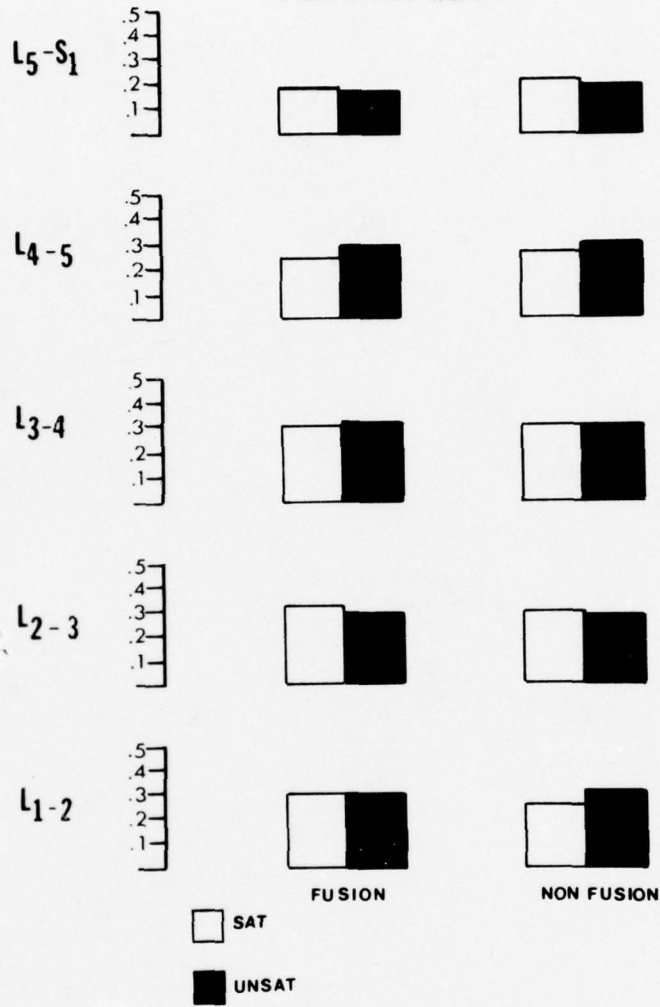
62 B: Projected Area of End Plates and Disc.



$$\begin{aligned}
 \text{Actual IVD} &= \frac{\text{Measured IVD}}{\sin \theta} \\
 &= \frac{\text{Measured IVD}}{\sin (\tan^{-1} W/L)}
 \end{aligned}$$

63. Correction for IVD Measurements.

DISC SPACE HEIGHT

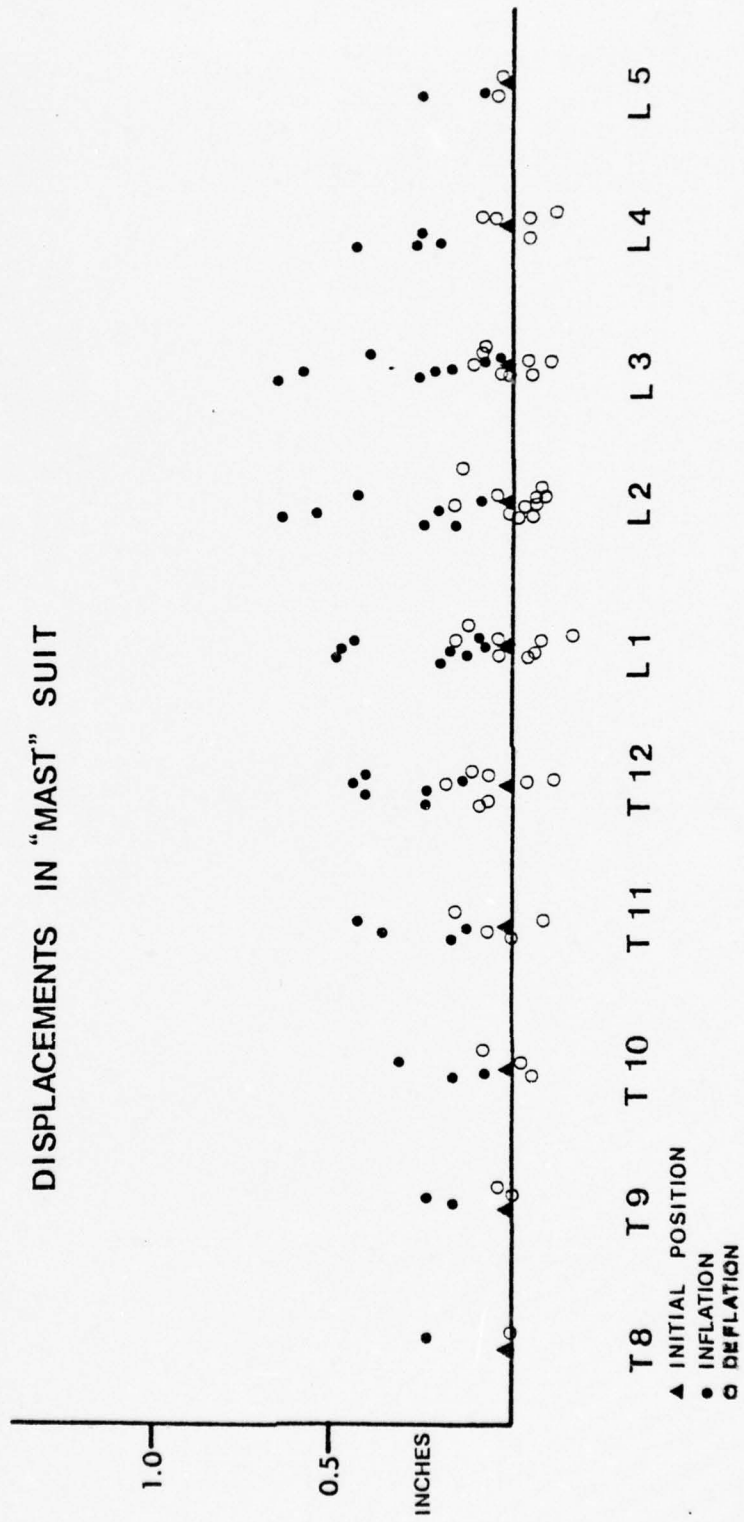


64. Chart of IVD Heights.

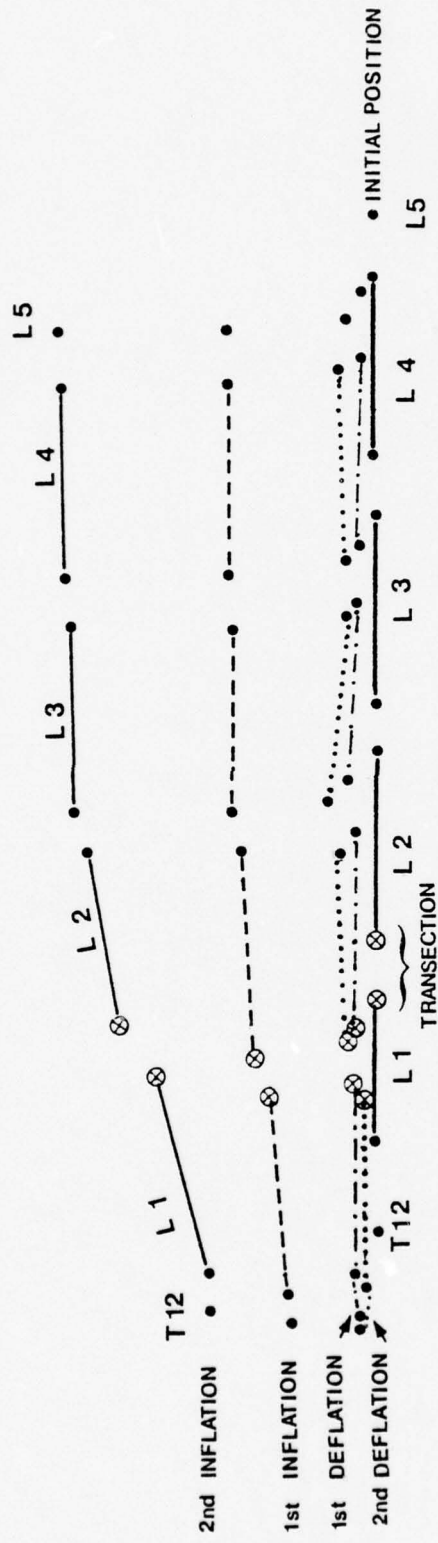


65. Subject in MAST Suit on Backboard.

DISPLACEMENTS IN "MAST" SUIT

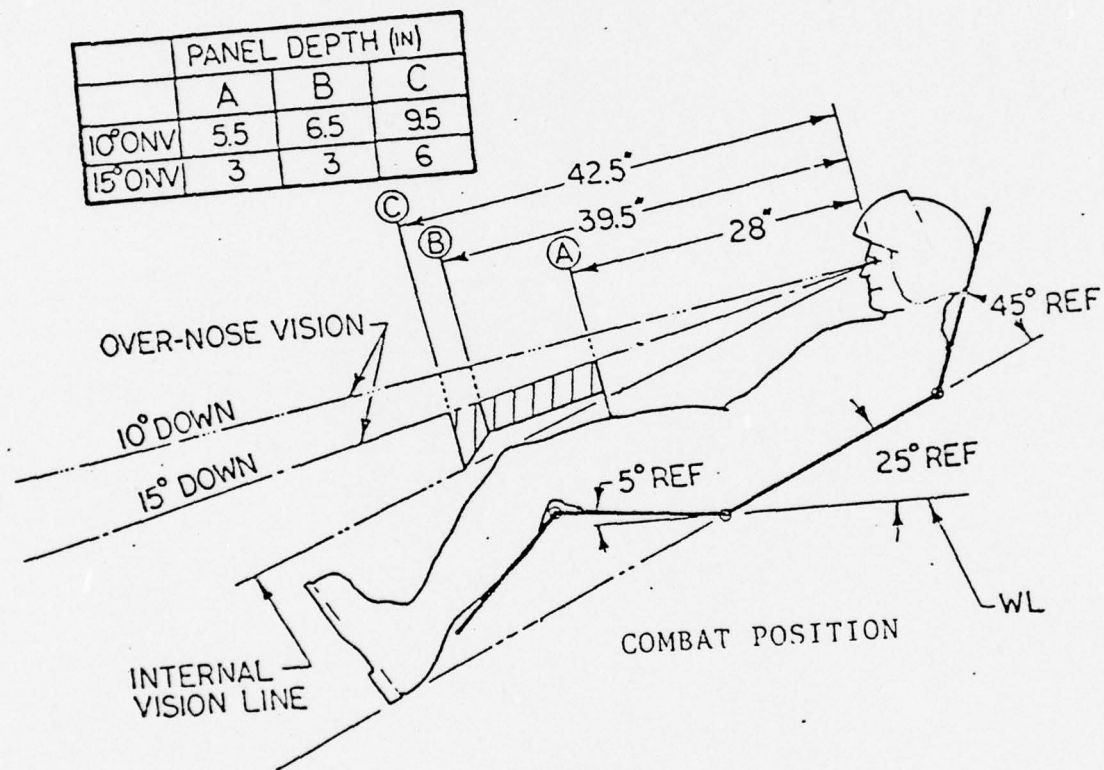


66. Spine Motion in MAST Suit for Normal Subjects.



DISPLACEMENTS IN "MAST" SUIT

67. Spine Motion in MAST Suit with L1-L2 Posterior Elements Transected.



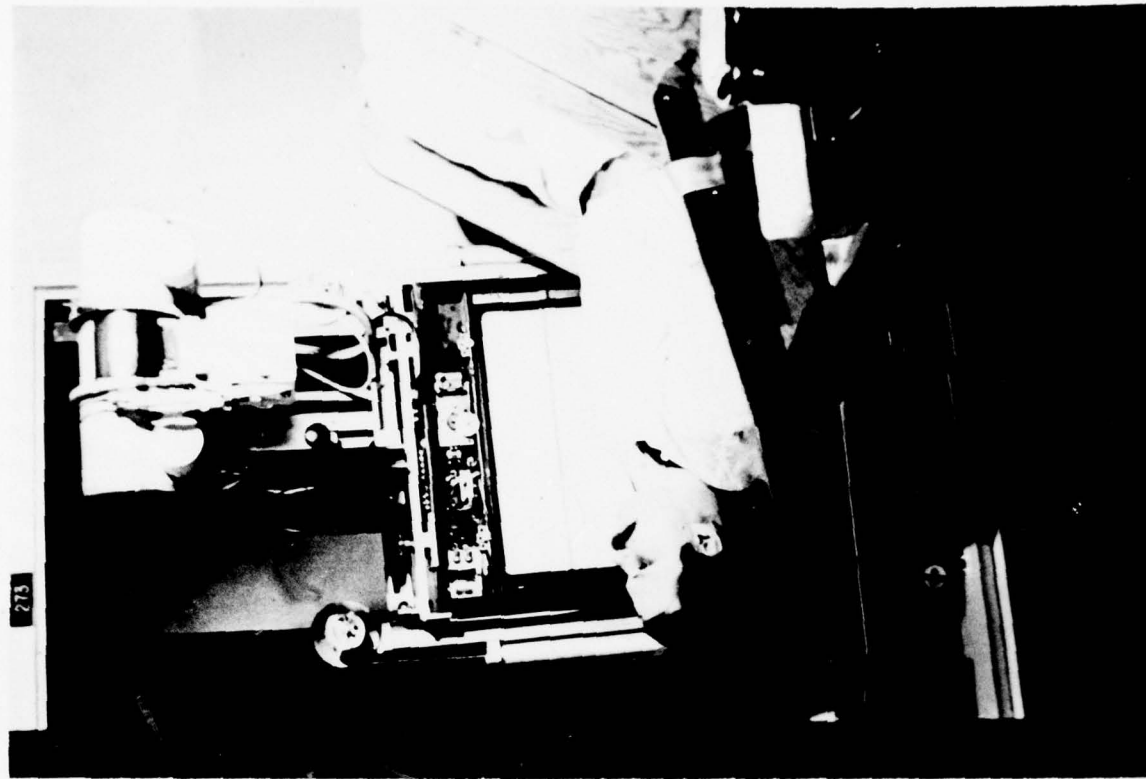
69. Pilot in Seat in Combat Position.



70. Calibration Jig in Place on Apparatus.



71. Air Force Seat Mock-up in Normal Position.



72. Subject in Air Force Seat in Normal Position.



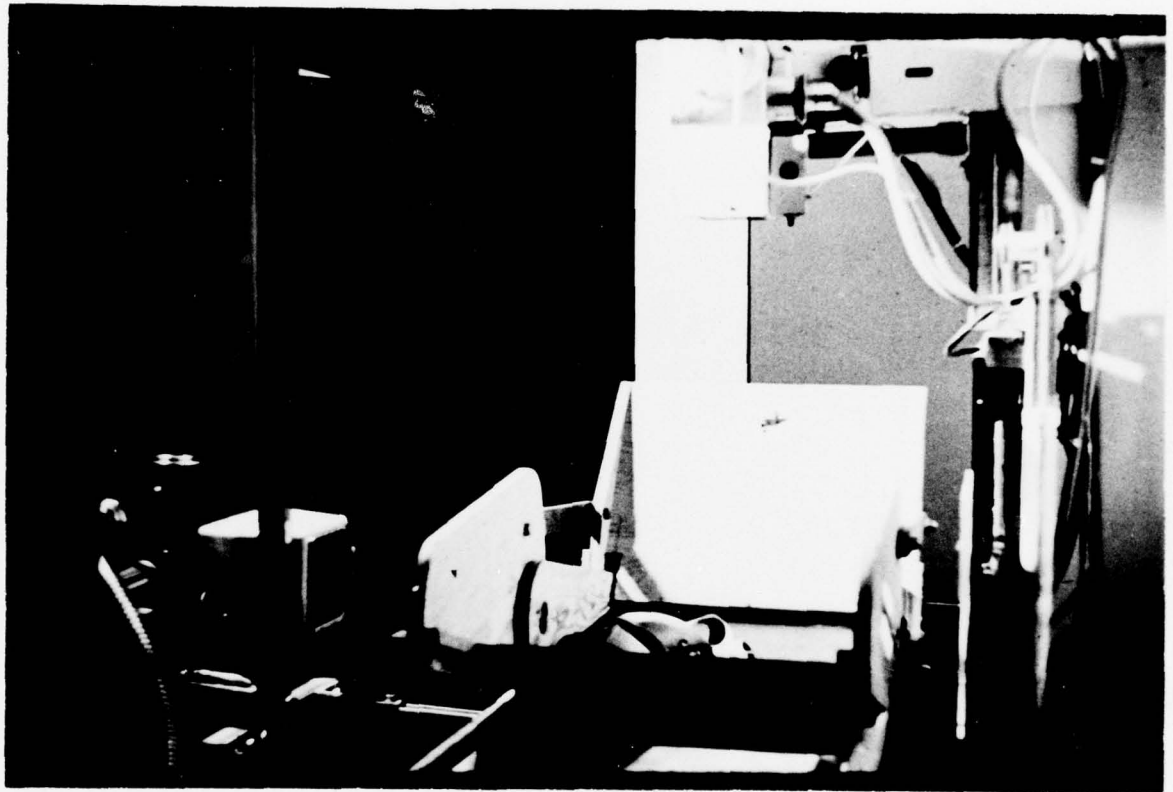
73. Subject in Air Force Seat in Normal Position.



74. Seat in Combat Position.



75. Subject in Seat in Combat Position.



76. Seat in Combat Position.



77. Subject in Seat in Combat Position.

AIR FORCE SEAT SUBJECT DATA (ALL MALE)

<u>Date</u>	<u>Subject</u>	<u>Age (yrs)</u>	<u>Weight (lbs)</u>	<u>Height (ins)</u>
7/2/75	1	24	180	73.5
	2	21	150	66.5
	3	22	145	69.0
7/9/75	1	20	200	73.0
	2	20	156	70.5
7/15/75	1	21	175	68.0
	2	27	165	72.0
	3	19	165	69.0
/17/75	1	20	160	70.0
	2	18	130	70.5
	3	33	170	72.0

FIGURE #78

CAUDAL DISPLACEMENTS OF VERTEBRAL BODIES (Centimeters)*

LUMBAR FILE I.D.	VERTEBRAL LEVELS							AVERAGE
	T10	T11	T12	L1	L2	L3	L4	
D5S				7.28	7.65	4.66		6.53
D6S				7.11	7.34	7.30		7.25
D7S				5.88	6.01	5.98	6.25	6.03
D8S		11.02	11.16	11.27	11.46	11.59		11.30
D9S			5.33	5.67	5.92	5.89	5.85	5.73
D10S	7.08	7.16	7.35	7.60	7.48			7.33
D11S				7.27	7.25	7.16		7.23

*Occurring when subjects were moved from Normal to Combat positions.

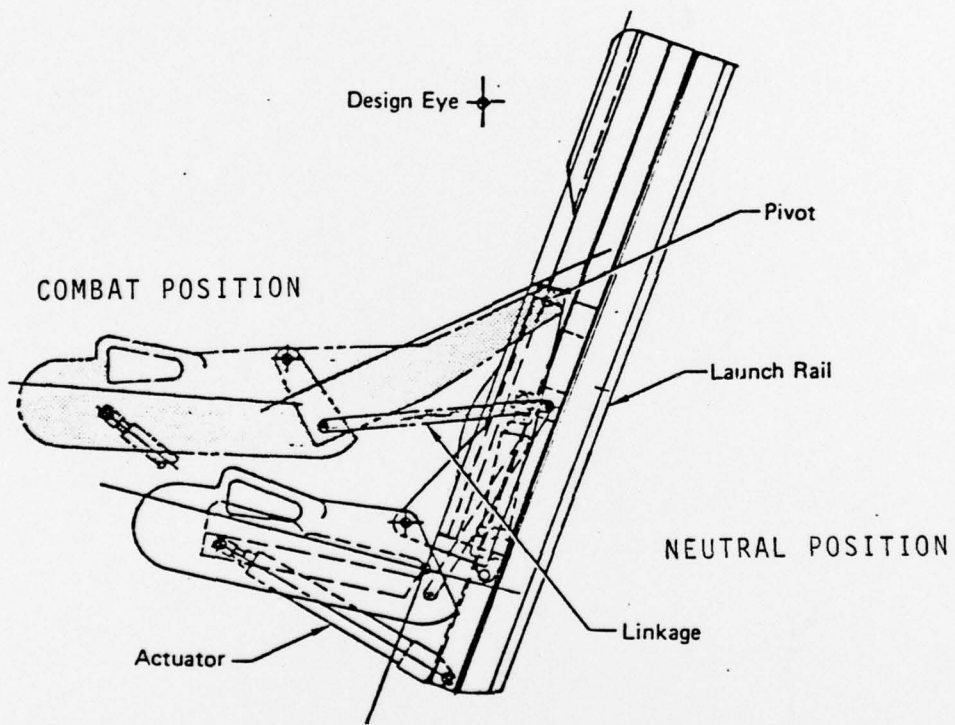
FIGURE #79

POSTERIOR DISPLACEMENTS OF VERTEBRAL BODIES (Centimeters)*

LUMBAR FILE I.D.	VERTEBRAL LEVELS							AVERAGE
	T10	T11	T12	L1	L2	L3	L4	
D5S				.61	.53	.07		.40
D6S				-.03	-.35	-.71		-.36
D7S				-.64	-.44	-.34	-.18	-.40
D8S		.96	1.24	1.43	1.55	1.50		1.37
D9S			.31	.61	.46	.15	-.44	.22
D10S	-.70	-.40	-.22	-.17	-.44			-.39
D11S				.50	.09	-.37		.07

*Occurring when subjects were moved from Normal to Combat positions

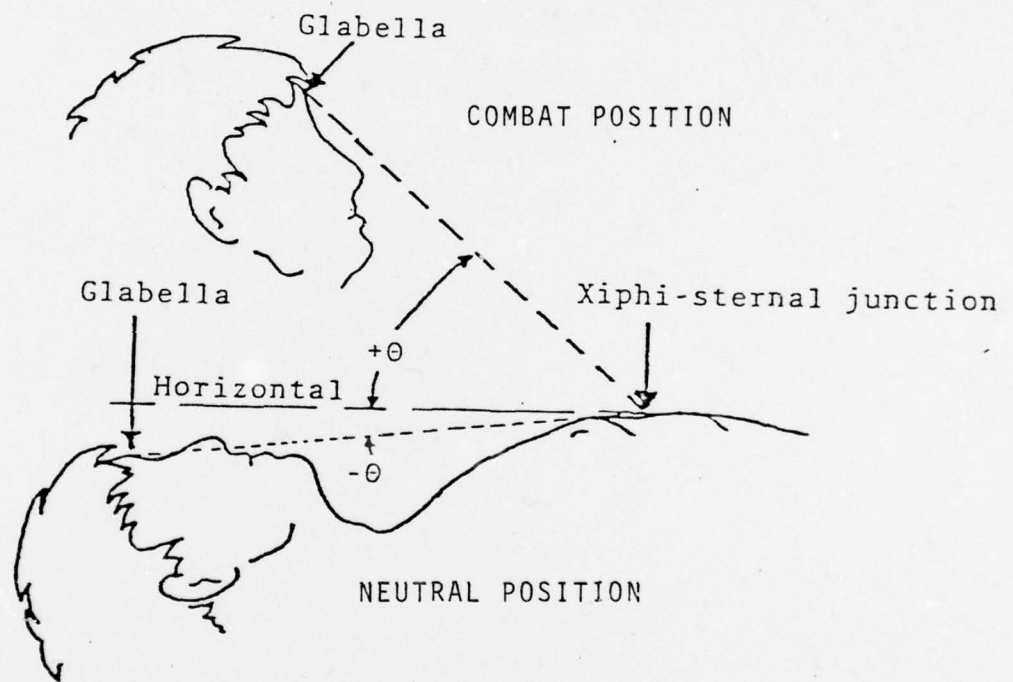
FIGURE #80



SHOULDER PIVOT SEAT GEOMETRY

GP73-1085-53

81. Seat Configurations - Normal and Combat Positions.



82. Glabella to Xiphi-sternal Junction Line: Distance and Angle Definitions.

GLABELLA TO XIPHI-STERNAL JUNCTION DIMENSIONS

Date	Subject	Distance (Inches)			Angle (Degrees)			Lumbar File I.D.
		Normal	Combat	Normal	Normal	Combat	Normal	
7/2/75	1	16.5	12.25	16.00	1	37	-3	D5S
	2	15.0	10.50	15.50	-5	40	-4	
	3	17.0	11.00	17.25	-1	41	-5	D6S
7/9/75	1	16.25	12.75	16.25	-2	48	2	
	2	16.75	13.25	16.75	-1	44	-2	D7S
7/15/75	1	16.00	10.50	15.50	-2	42	-2	
	2	16.50	11.50	15.88	-3	43	-2	D8S
	3	15.75	11.25	14.50	-1	46	0	D9S
7/17/75	1	16.00	12.50	15.00	-1	39	1	D10S
	2	17.50	12.00	17.00	3	42	4	D11S
	3	16.50	13.00	17.00	-2	38	0	
TOTAL		<u>179.75</u>	<u>130.50</u>	<u>176.63</u>	<u>-14</u>	<u>460</u>	<u>-11</u>	
MEAN		<u>16.34</u>	<u>11.86</u>	<u>16.06</u>	<u>-1.27</u>	<u>41.82</u>	<u>-1.0</u>	

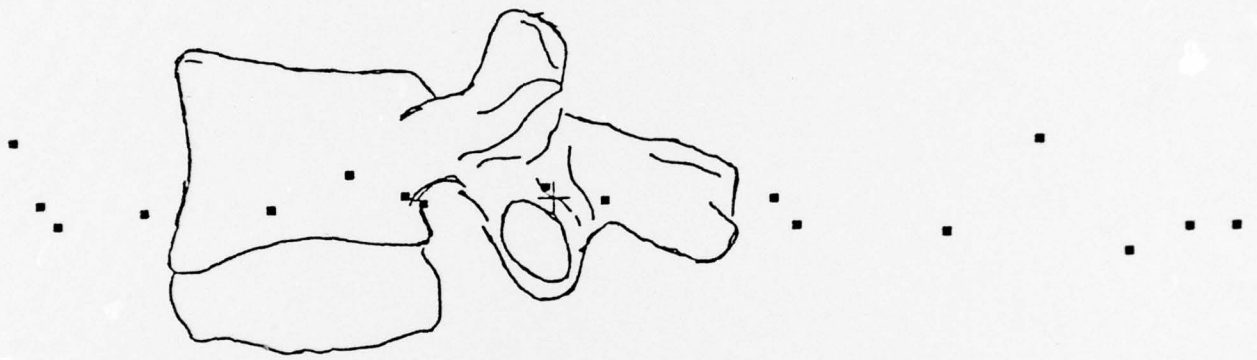
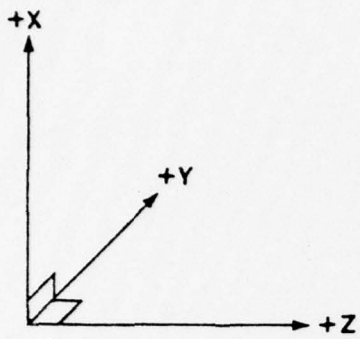
EYE TO HEART MEASUREMENT DIMENSION (6/18/75)

Subject	Height (Ins)	Weight (Lbs)	Head Length (Ins)	Trunk Length (Ins)	A (Ins)	Angular Change Degrees*
A	68	132	9	26	14.5	43
B	69	160	9	27	16.5	48
C	68	147	9	26	15.0	45

*Pivoting about heart.

FIGURE #83

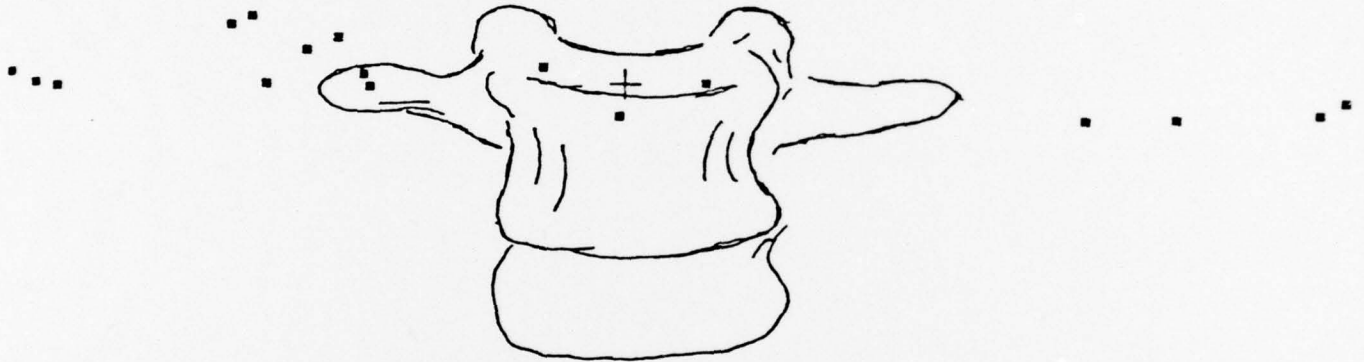
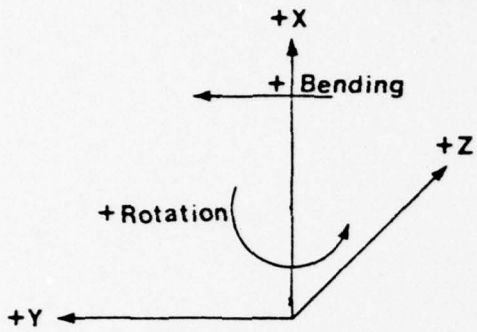
Lateral View Instantaneous Centres



HAC SEAT IN FLEXION-EXTENSION

84. Instant Center Scatter Lateral View.

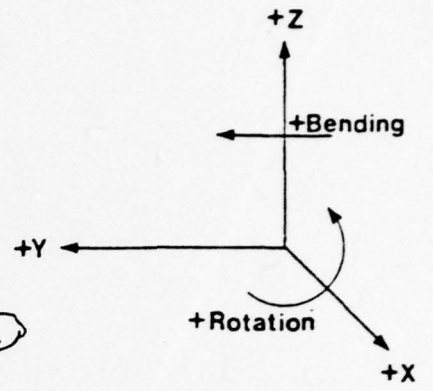
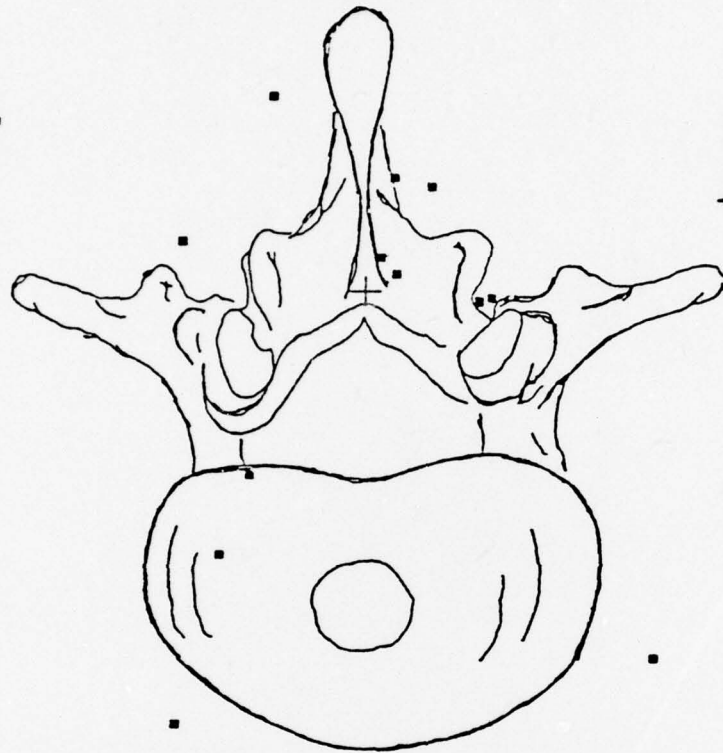
Ventral Aspect Instantaneous Centres



HAC SEAT IN FLEXION-EXTENSION

85. Instant Center Scatter Ventral Aspect.

Superior Aspect Instantaneous Centres

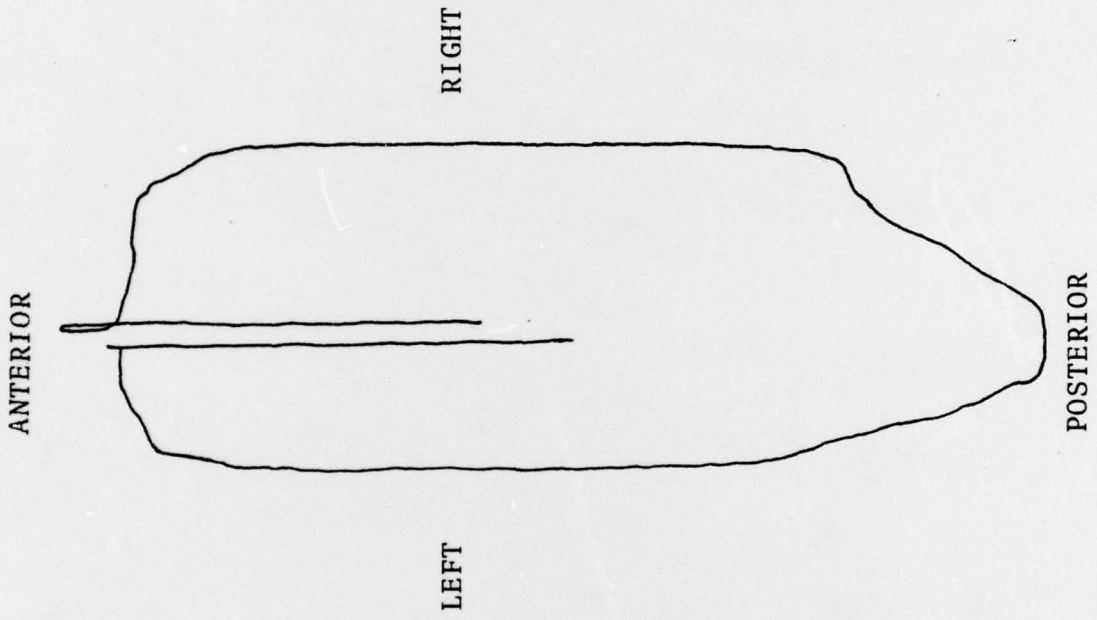


HAC SEAT IN FLEXION-EXTENSION

86. Instant Center Scatter Superior Aspect.



87. Spinal Range of Motion Measurement Apparatus.



RANGE OF MOTION AT LEVEL OF AXILLA

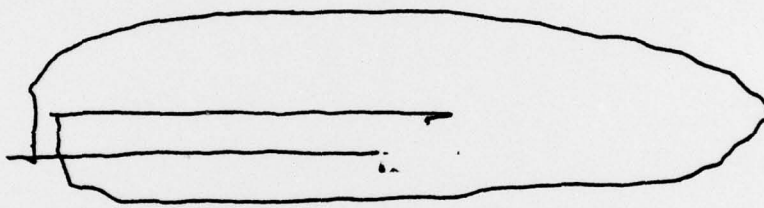
88. ROM Results at Level of Axilla.

ANTERIOR

LEFT

RIGHT

POSTERIOR



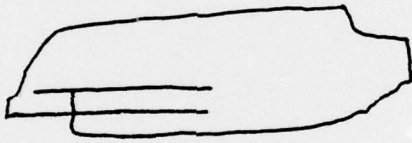
RANGE OF MOTION AT XIPHOID PROCESS

89. ROM Results at Level of Xiphoid Process.

ANTERIOR

RIGHT

POSTERIOR

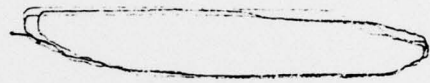


LEFT

RANGE OF MOTION AT UMBILICUS

90. ROM Results at Level of Umbilicus.

ANTERIOR

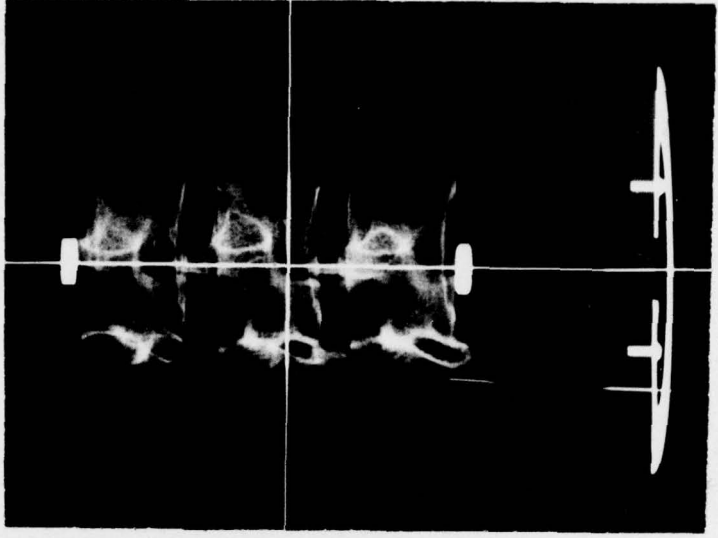
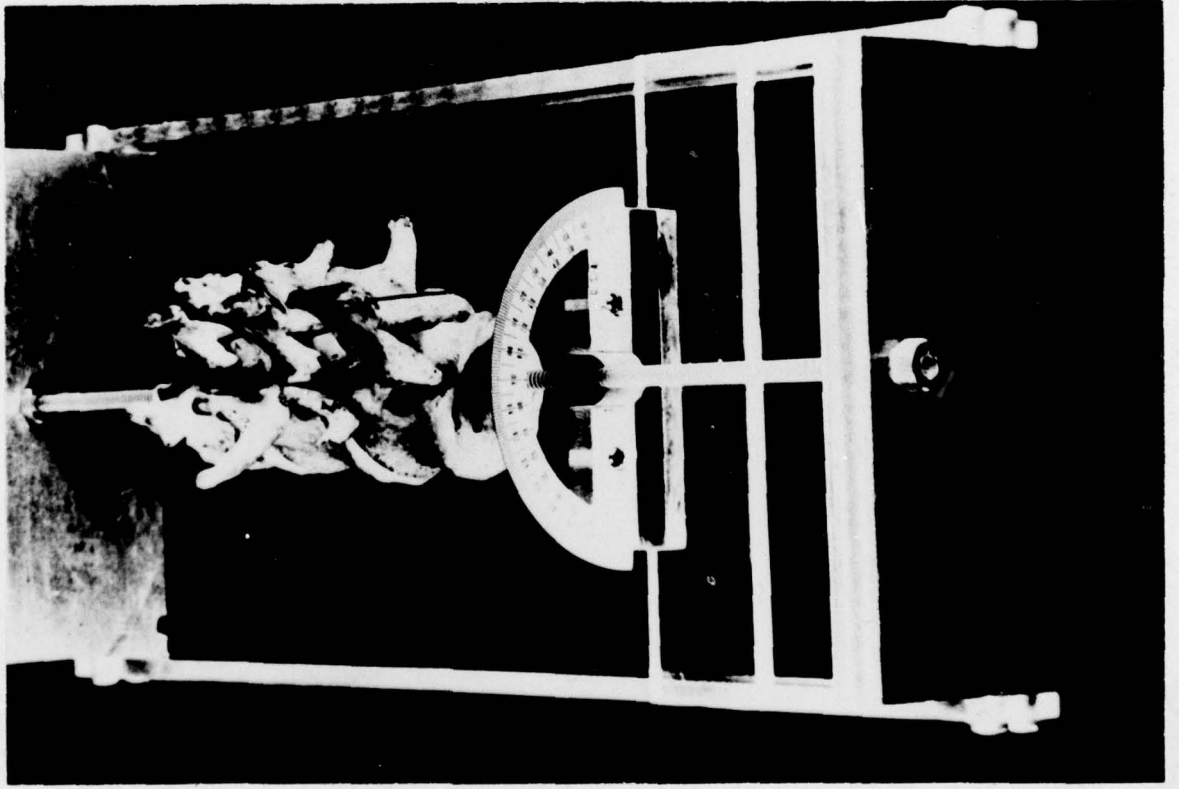


LEFT

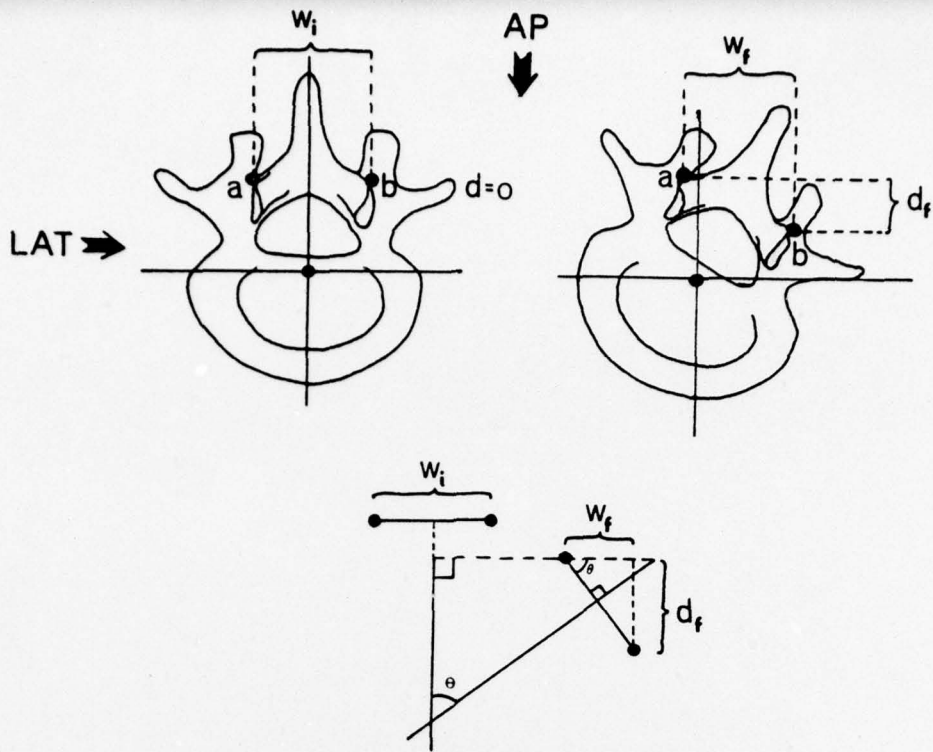
RIGHT

POSTERIOR

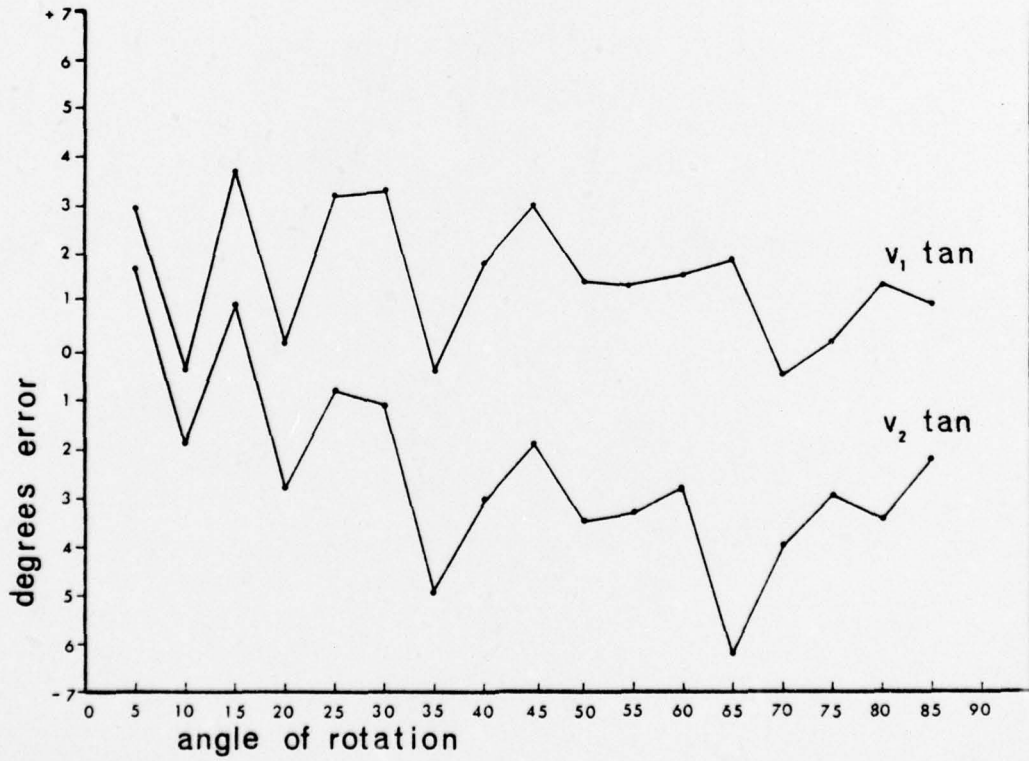
91. ROM Results about a 5.9" Diameter Circle.



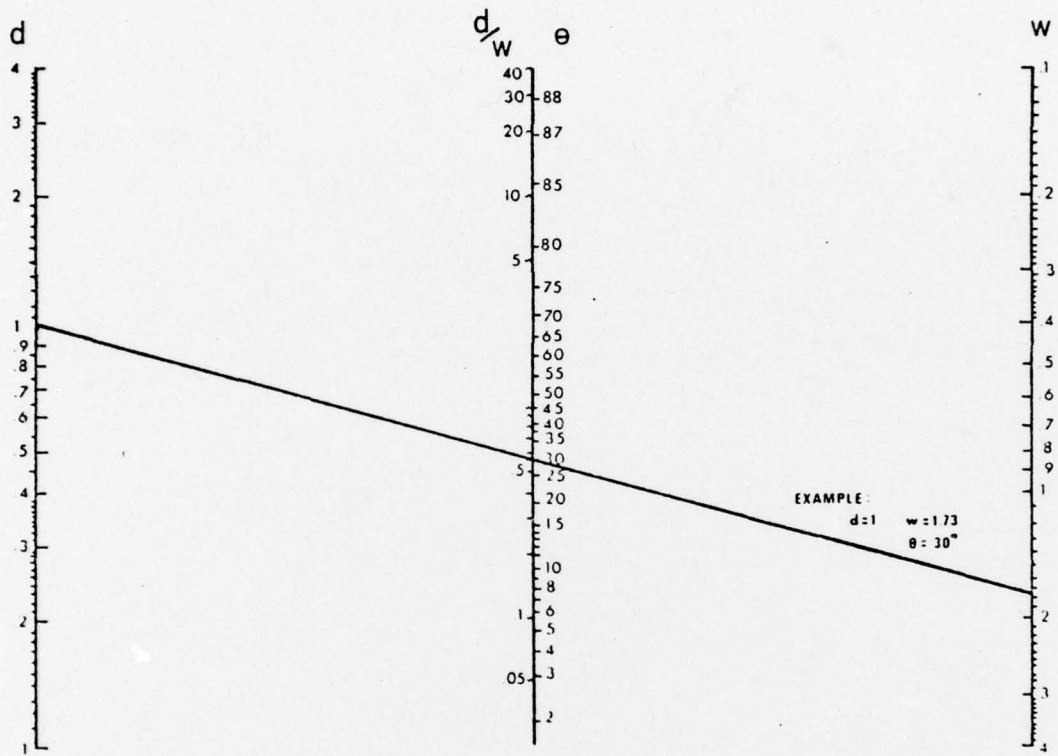
92. Jig for Assessing Vertebral Rotation.



93. Vertebral Geometry (Diagram).



94. Accuracy of Vertebral Rotation Technique.



95. Nomogram for Computing Rotation.