Stereo radiography of lumbar spine motion

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Contents

Foreword

This study represents a compilation of work conducted over a period of four years. It is based on three papers published in scientific journals (23, 25, 26), but draws together these papers and augments them with raw data from each indvidual which are presented in the appendices.

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The literature referenced in the text is not meant as a complete survey of all existing publications on the measurement of lumbar movements. However, it does give a review of the most relevant research that has been undertaken and the methods used, and would enable any further references to be followed up from the sources cited.

Although this study is concerned with normal movements of the lumbar spine, the technique has been used to investigate patients with back pain and spinal pathologies (24, 27–29, 38, 40, 45).

Mark Pearcy,
May 1985, Durham

Introduction

There have been many attempts to measure spinal movements since the 1930s (1, 2, 5–7, 10–13, 15–19, 21, 22, 37, 39, 41). However, because of the inaccessibility of the spine, and the complex nature of its movements, the results reported do not always agree. The most accurate measurements in vivo inevitably rely upon radiography, although other more invasive techniques have been used, such as the insertion of Steinman pins into the spinous processes (12, 15).

Normal plane radiographs have three-dimensional information projected onto a plane, but their interpretation is usually restricted to two dimensions, as in lateral views of flexion/extension (13) and anterior-posterior (A-P) views for scoliosis or other pathologies (2, 5, 16, 39). These two-dimensional measurements may be erroneous due to movements in the third dimension; and measurements of movements out of the plane of the radiographs are liable to large errors (3).

The three-dimensional structure of the articulations between vertebrae, and the complexity of the ligamentous and muscular attachments results in complex movements. Whatever the primary movement in one direction there are likely to be accompanying movements in the other two orthogonal directions. For example, when the spine as a whole is voluntarily bent laterally, individual inververtebral joints will exhibit some flexion or extension and axial rotation.

Measurement of the true angles of these rotations and the relation between the primary and accompanying movements requires a three-dimensional technique, using some form of stereo-radiography (4, 11, 32, 34, 36). At Oxford a Biplanar Radiography system has been developed using two X-ray tubes arranged orthogonally. This system provides a full three-dimensional analysis of intervertebral translations and rotations as a subject moves from one position to another.

The characterisation of normal movements in the lumbar spine is essential before an understanding of pathological movements can be gained. In the literature there are no reports of three-dimensional measurements of active lumbar movements in normal standing subjects. There have been reports of passive movements imposed on volunteers (11, 31), but the implications of these measurements and the accompanying rotations seen are difficult to assess. Axial rotation accompanying lateral bending has also been demonstrated with single plane anterior-posterior views (5, 16), but only qualitatively. In vitro studies have shown that movements in more than one plane occur when intervertebral joints have bending moments applied to them but are inconclusive as to the relation between movements in the different planes. It has been suggested that there is mechanical coupling (22, 42) of movements in the different planes but others have suggested that the relation may be defined by other factors (33), and this has not been ratified in vivo.

The aim of this study was to measure the ranges of active flexion and extension, axial rotation and lateral bending in the lumbar spines of normal volunteers in vivo, and to asses the relation between the primary and accompanying movements in the other planes.

Biplanar radiography

The subject stands in the support frame of the biplanar radiographic equipment with plastic pads against the anterior superior iliac spines and an adjustable strap around the buttocks to limit movement of the hips and pelvis (Figure 1). Initially an A-P and a lateral radiograph of the lumbar spine are taken with the subject standing upright. To examine mobility of the lumbar spine two further pairs of radiographs are taken with the subject bent forwards as far as possible and then backwards as far as possible for flexion and extension; whilst twisted maximally to the right and then to the left for axial rotation; or whilst bent sideways to the right and then to the left for lateral bending (Figure 2). For the flexed forward position the A-P X-ray tube is lowered 150 mm and inclined upwards to centre the beam on the same point on the film plate as in the first position, to produce a less distorted image of the vertebrae. For lateral bending to the left the subject stands facing backwards so that he bends towards the lateral X-ray tube, as the lateral film plate limits bending the other way. This positioning also produces a less distorted image of the vertebrae as the X-ray tube is on the concave side of the bent lumbar spine.

X-Ray Dosage

To asses the radiation dose experienced by a subject undergoing Biplanar Radiography skin entry doses were measured with thermo-luminescent dosimeters (TLDs) provided by the Radiation Protection Department of the Churchill Hospital, Oxford (35). The dosage given in the main X-ray department of the Nuffield Orthopaedic Centre during a standard lumbar spine series consisting of an A-P and a lateral of the lumbar spine and a spot lateral of the lumbo-sacral junction was also measured for comparison.

The 3 A-P views for a biplanar analysis gave an approximate skin entry dose of 0.7×10^{-2} Gy each or a total A-P dose of 2×10^{-2} Gy. The standard A-P view in the X-ray Department gave an approximate skin entry dose for one view of 2×10^{-2} Gy. The 3 laterial views for a biplanar assessment gave approximately 1.7×10^{-2} Gy each or a total of approximately 5×10^{-2} Gy whereas the standard clinical views gave approximately 5×10^{-2} Gy for a lateral and 3×10^{-2} Gy for a spot-lateral of the lumbo-sacral junction or a total of approximately 8×10^{-2} Gy. A biplanar examination consisting of six radiographs thus gave approximately 0.7 of the dose of a standard lumbar spine series.

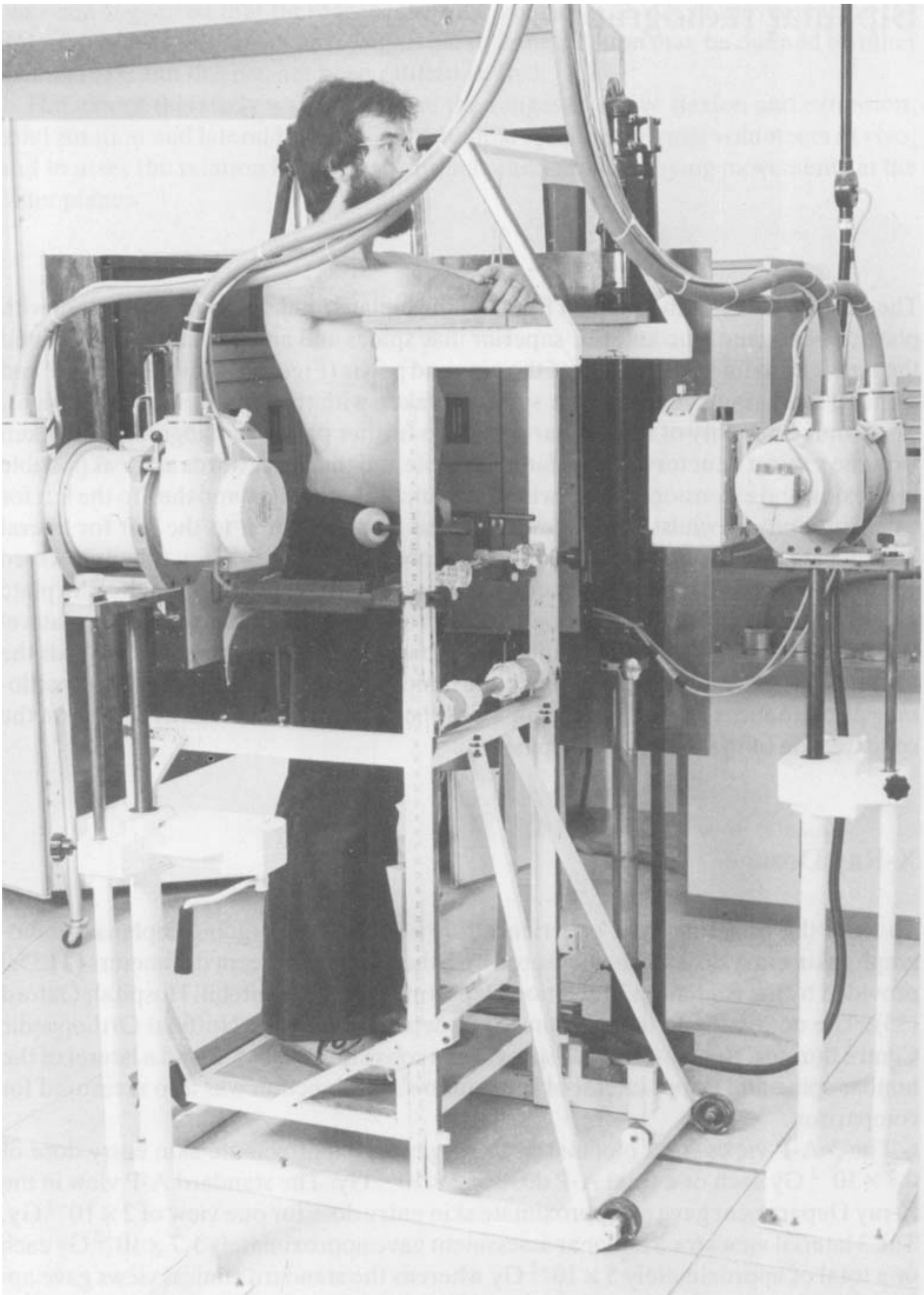


Figure 1 The biplanar rig showing a subject standing on an adjustable platform with X-ray tubes in front and to the side and with the film plates behind.

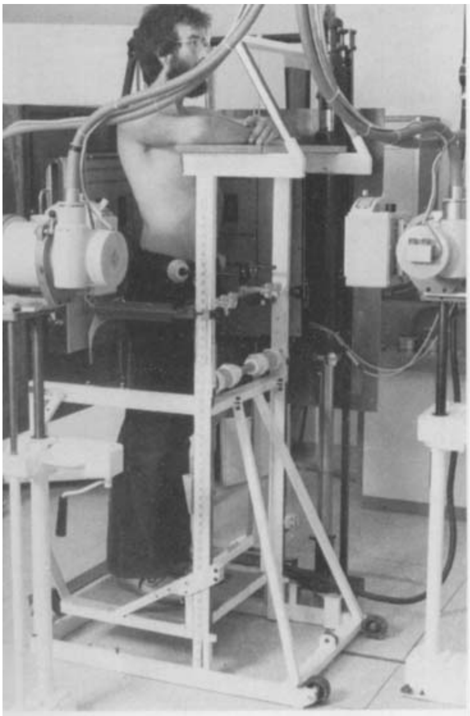
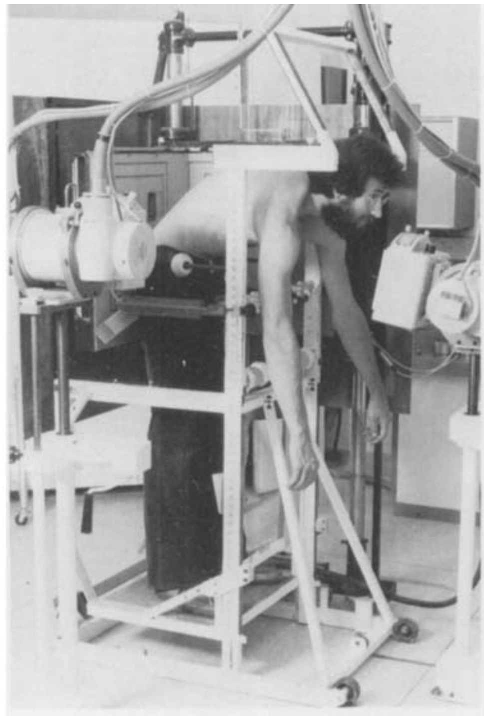
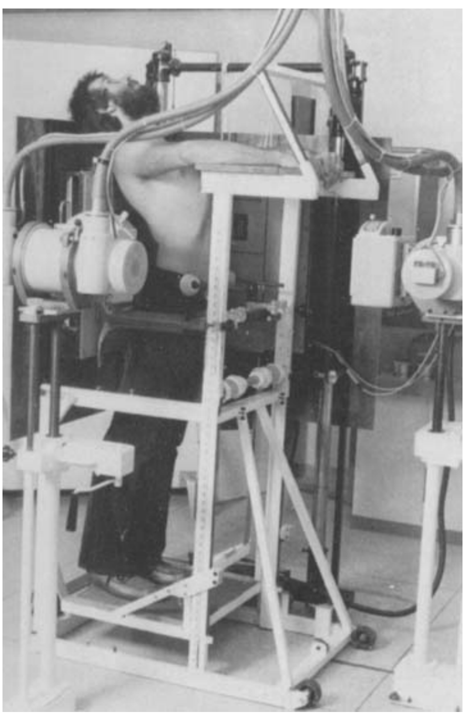
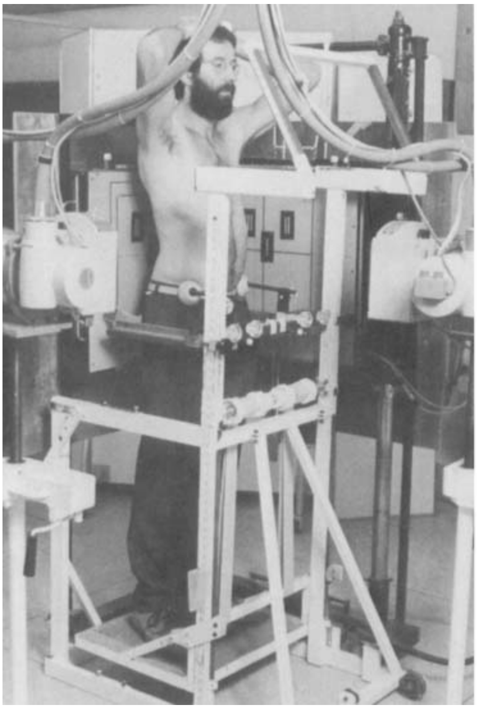
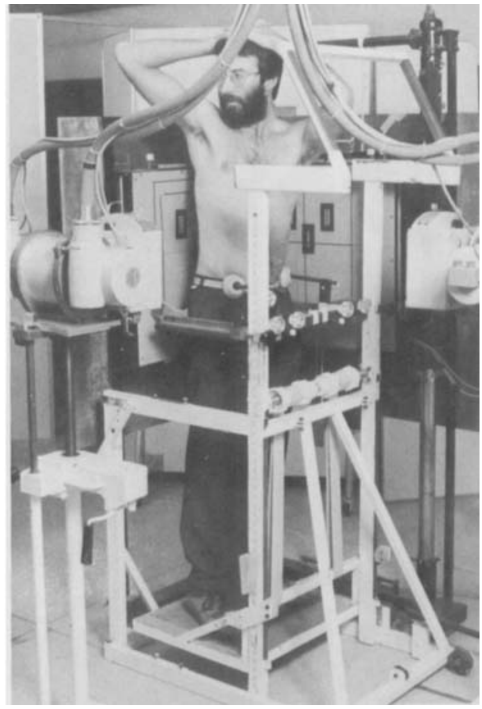




Figure 2(a) The posture adopted by an individual for the movements of flexion and extension.





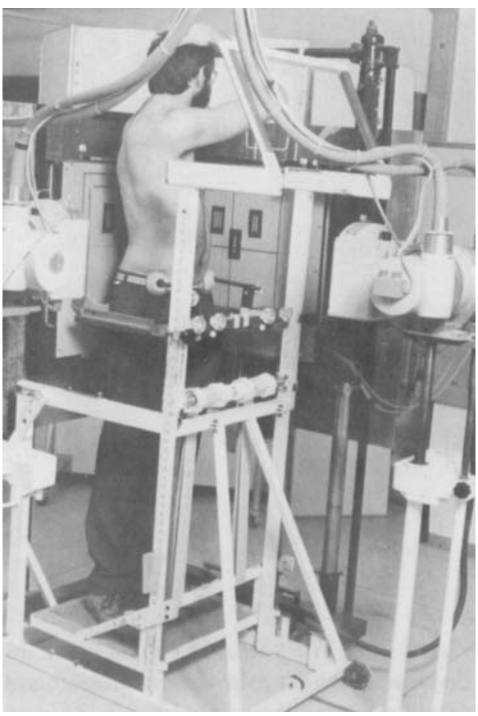


Figure 2(b) The posture adopted by an individual for the movements of twisting to the right and left.

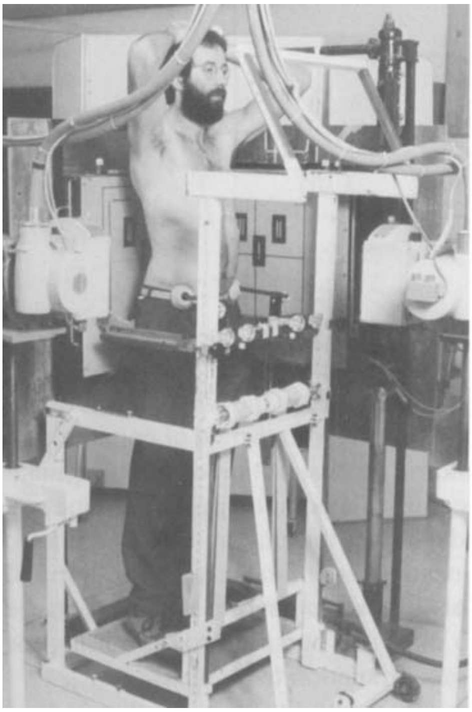
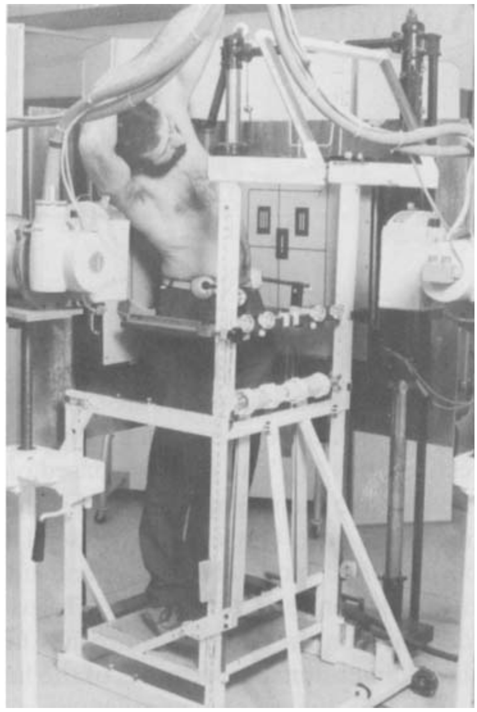
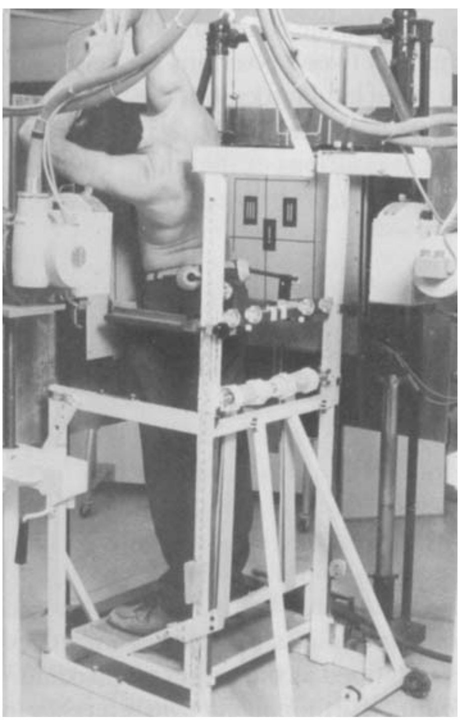




Figure 2(c) The posture adopted by an individual for the movements of bending sideways to the right and left.

Analysis

Nine anatomical landmarks are identified on each vertebra in the two biplanar radiographs for each position of the subject (Figures 3 and 4) with the aid of epipolar projection grids (8). The grids are based on geometric reconstruction of the equipment used to take the radiographs, giving the projection of a point on one film plane as a line on the other (Figure 5). The use of the grids enables the anatomical landmarks to be identified more accurately, and unequivocally discriminates between left and right sides on the lateral views. The use of this technique enables landmarks to be identified on the sacrum, which has hitherto not been possible, so permitting the three-dimensional movements of the lumbo-sacral junction to be measured.

The two-dimensional coordinates of the landmarks on the radiographs are then obtained using a digitising tablet and a Research Machines 380Z micro computer. The three-dimensional coordinates are computed using the technique descibed in the next section. Once the coordinates have been calculated an optimizing technique is used to adjust the positions of the landmarks to fulfil the constraint that each vertebra is a rigid body which does not change shape between positions of the patient (36). Three-dimensional analysis requires only three landmarks, but the use of nine permits the optimisation routine to produce a more accurate rigid body fit. Comparison of the coordinates between the three different positions of the subject then enables the intersegmental translations and rotations occuring between the positions to be calculated.

Three-Dimensional Calibration and Coordinate Calculation

Calibration of the biplanar radiographic system uses a form of direct linear transformation, in which a pair of linear equations is used to relate the two-dimensional coordinates of a point on the A-P and lateral radiographs to its position in three-dimensional space. Prior to using the system for subject studies, a Biplanar pair of radiographs is made of a calibration frame. If it is intended to take radiographs with the spine flexed a third film is taken with the A-P source lowered and inclined upwards as described previously. The calibration frame consists of nine steel spheres embedded in a rigid frame (Figure 6). One of the spheres is defined as the origin of the coordinate system, and the directions of the axes are defined orthogonally with reference to

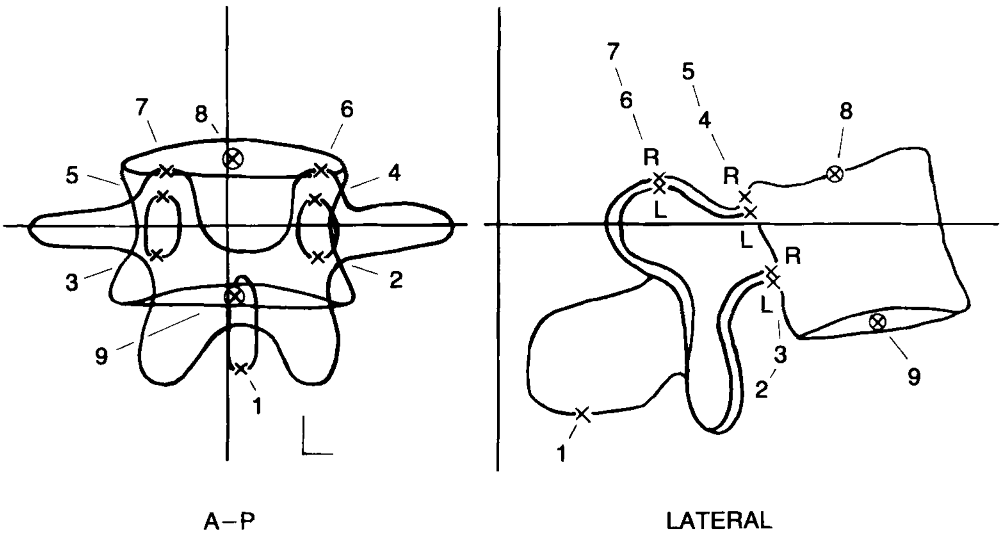


Figure 3 The nine anatomical landmarks (listed in Table 2).

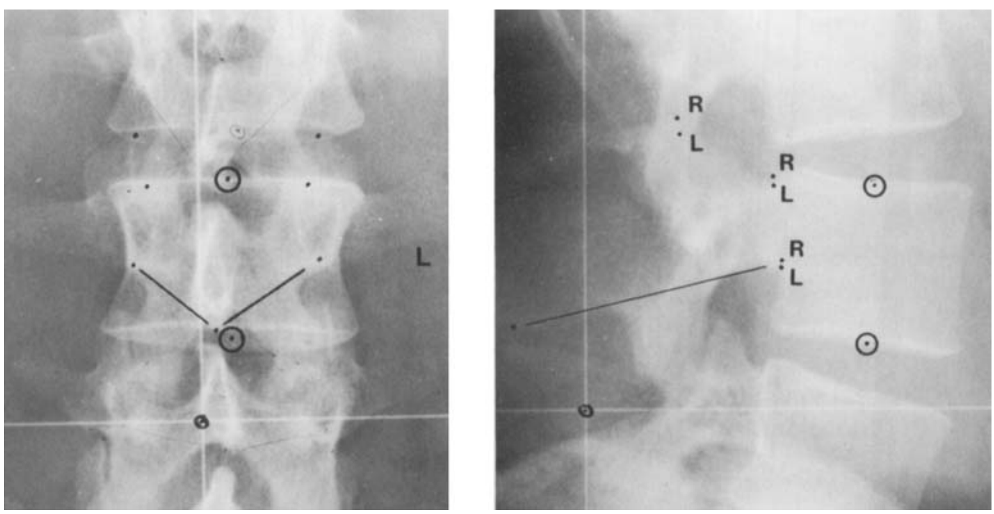


Figure 4 The nine landmarks shown on one of the vertebrae.

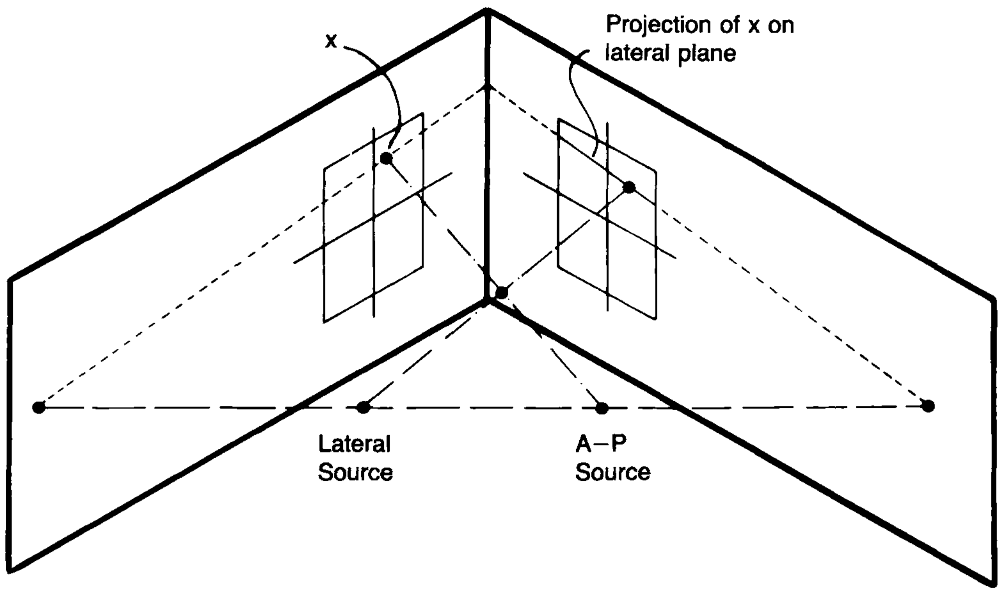


Figure 5 The epipolar projection of a point (X) on one plane into a line on the other.

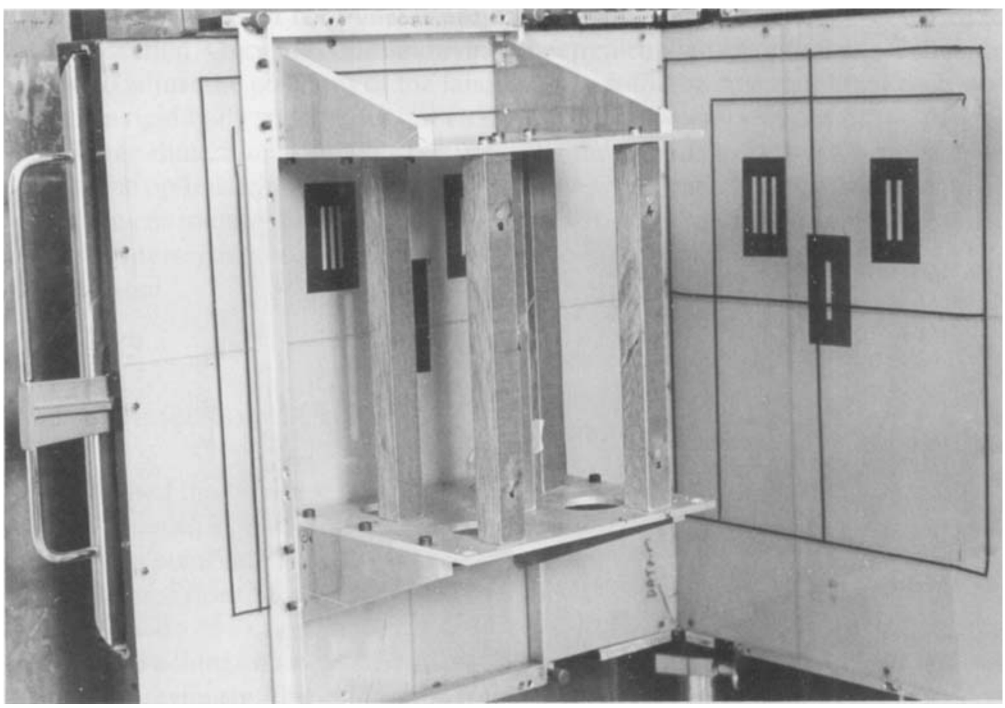


Figure 6 The calibration frame clamped to the film plates of the Biplanar rig.

the plane of the A-P radiographic plate to which the calibration frame is bolted. The A-P plane is defined as the X-Y plane with the Y axis vertical to the floor. The positions of the spheres in the frame were determined to an accuracy of 0.1 mm by precision measuring equipment.

The calibration procedure is a modification of that used with a stereoscopic television system for human locomotion analysis (43), and the mathematical basis is described in detail elsewhere (44). The first stage in the analysis is to determine, for each of the biplanar views, the location of the X-ray sources. These are determined from the perspective of the images of the calibration markers on the films. The calibration program then calculates the positions of the calibration markers from the viewpoint of the X-ray source, and compares the anticipated positions with the actual horizontal and vertical coordinates on the radiographic plates. A two-dimensional least squares linear regression produces the best fit between the anticipated and the actual marker positions for each of the Biplanar views. The resulting calibration factors are then used to estimate the coordinates of the markers in the horizontal plane, and the absolute errors in these estimates are determined. The procedure is repeated with incremental changes in the orientation in the horizontal plane of each radiographic plate relative to its source, until the errors are at a minimum. The procedure is then repeated for the orientation of the plates in the vertical plane, and again the positions giving the minimum errors are determined. The calibration factors, which are stored on computer disc, are the constants in the equations for the lines joining each of the sources to any given point on the radiographic image.

When analysing data from subjects, the two-dimensional coordinates of the landmarks on each pair of films are determined. The equations of the lines joining each X-ray source to the landmarks are then derived, using the calibration data. Where the lines from the A-P and lateral sources intersect is the three-dimensional location of the landmark, which is derived by solving the pair of simultaneous equations (Figure 7).

Intervertebral Movements

The anatomical and clinical descriptions of spinal movement (e.g. flexion/extension) imply the movement of each vertebra relative to its neighbour. To calculate the movements in this manner four of the 9 landmarks in each vertebra are used to define its individual coordinate system. The movement of one vertebra relative to its neighbour can then be calculated by transforming its landmark coordinates into the coordinate system of the neighbour, and looking at the changes in these coordinates between different positions of the subject.

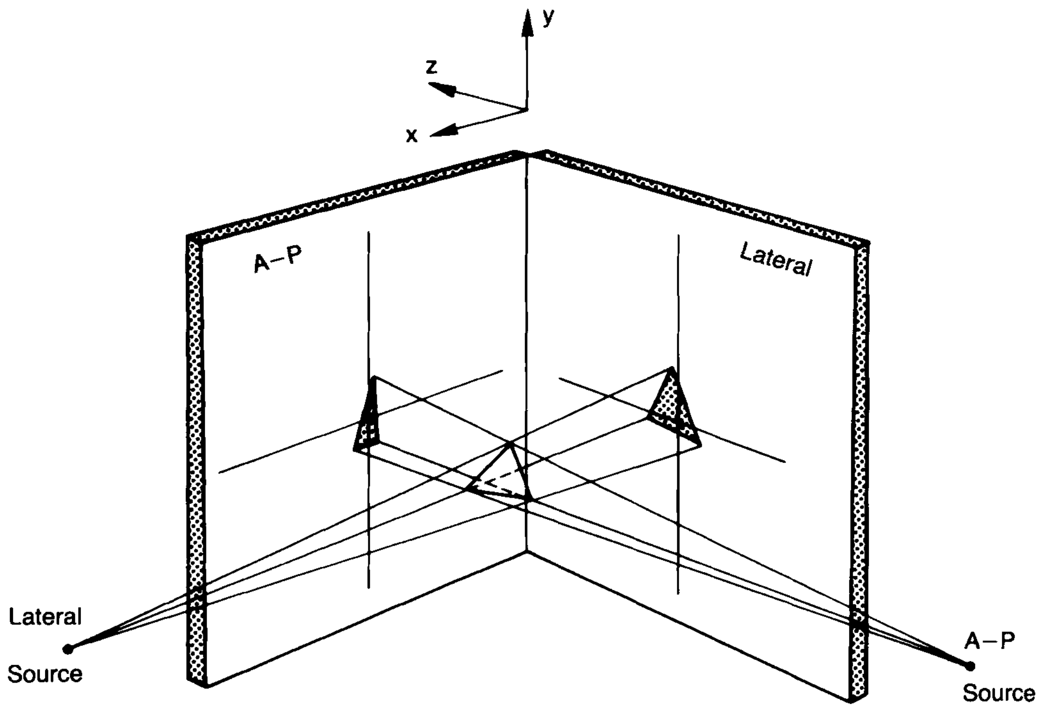


Figure 7 Geometric construction showing the method of calculation of the three-dimensional coordinates of points from their projection onto the two radiographic planes.

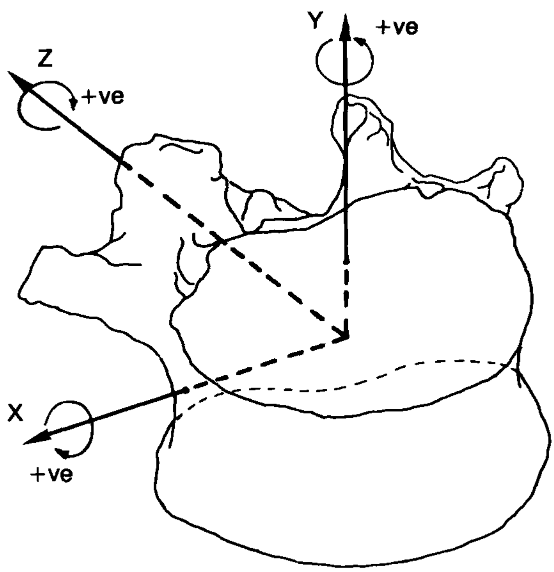


Figure 8 The system of orthogonal axes used for each vertebra showing the positive directions for the translations and rotations (rotation about the X axis is defined so that flexion is + ve). The positive directions for the axes are: X – axis, left to right; Y – axis, upwards; Z – axis, posteriorly.

Coordinate systems

The coordinate system for each vertebra is derived from the landmarks on the upper pedicles and the end-plates (Figure 3, Landmarks 4, 5, 8, 9), the origin being the centroid of these four points.

The direction of the vertical axis (Y in Figure 8) is defined by the two landmarks on the end-plates. A preliminary horizontal or lateral axis is similarly defined by the landmarks on the upper pedicles. However, these two axes are not necessarily at right angles, and the simplest transformation of coordinates from one system to another requires orthogonal axes (14). A third axis (Z) is therefore defined by taking the cross, or vector, product of the vectors defined by the first two axes, and the lateral axis (X) is then redefined by taking the cross product of the vertical and the Z axes.

Movements

The movements between vertebrae in three-dimensions are described by three translations and three rotations of each vertebra in the coordinate system of its inferior neighbour (Figures 8 and 9). Two of the translations involve anterior-posterior and lateral shear of the intervertebral disc, and the third involves approximation or distraction of the vertebral bodies. To indicate these movements, translations of the inferior end-plate of the superior vertebra are calculated in the coordinate system of the inferior vertebra, for the different positions of the subject.

Rotations about the three axes are determined by projecting lines related to the orientation of the upper vertebra onto the coordinate planes of the lower vertebra, and calculating the change in angle of these projected lines between different positions of the subject. For example, to measure flexion/extension, a line parallel to the vertical axis of the upper vertebra is transformed into the Y-Z plane of the lower vertebra, which approximates to the sagittal plane. The angles between the lines obtained for the neutral, flexed and extended spine are the angles of flexion and extension between the two vertebrae.

Accuracy of the Measurements

Three-dimensional coordinate calculations

To assess the accuracy of the three-dimensional coordinate calculations, the radiographs of the calibration frame, containing nine steel spheres, were redigitised for the two positions of the X-ray tubes used for the subject examinations, to give eighteen discrete measurements of sphere position. The errors of the calculated positions of the spheres from their known positions relative to the fixed origin in space were then calculated (Table 1).

Table 1 RMS and maximum errors in determining the absolute positions of the steel spheres (N=18).

AXIS	RMS ERROR mm	MAX ERROR mm
X	0.20	0.34
Y	0.31	0.70
Z	0.25	0.51
Combined	0.44	0.71

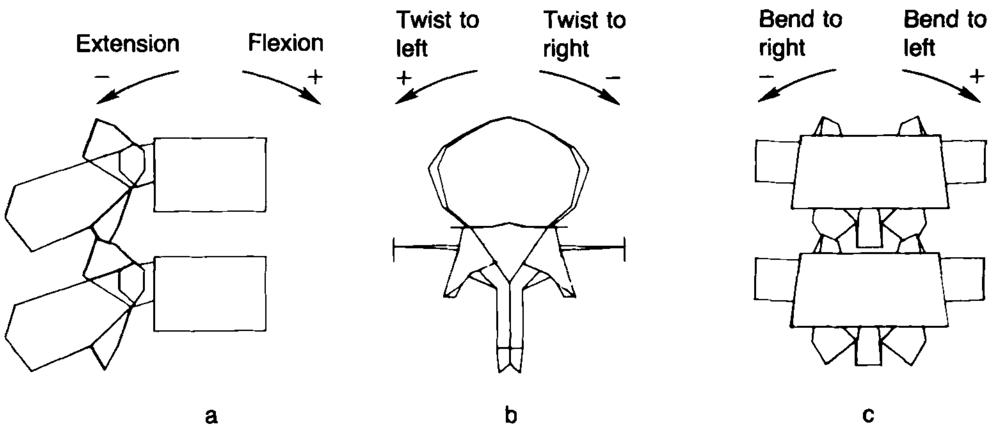


Figure 9 Diagrammatic sketches of an intervertebral joint showing the signs and directions of the rotations. (a) View from the right, flexion and extension; (b) view from above, axial rotation; (c) view from the front, lateral bending.

Repeatability of coordinate positions

The repeatability with which the positions of steel spheres and anatomical landmarks could be measured was investigated using an articulated model of a segment of the lumbar spine. The model consisted of two radiolucent cubes, each with four steel spheres embedded in it. The cubes were joined so that one could be rotated relative to the other about a single axis. A plastic cast of a vertebra was attached to each cube so that the relative orientation of the two vertebrae was the same as that of the cubes (Figure 10).

Five pairs of radiographs were made, with the model being straightened and then adjusted to represent five degrees of flexion between the vertebrae before each pair. The position of each steel sphere in the two cubes, and each landmark of the two vertebrae was measured for each of the five positions. The RMS error from the mean of the five measurements was determined for each point and the results for each sphere and landmark position were pooled to give overall values (Table 2). These results showed that the overall RMS error for the steel spheres was 0.09 mm, and for the landmarks was 0.40 mm. The end-plates had the smallest errors indicating them to be the most easily identified landmarks, as has been shown previously (32, 36). Combining the data for absolute accuracy (Table 1) with that for repeatability (Table 2), gave an RMS error of < 1 mm for determining the absolute locations of anatomical landmarks on the vertebrae.

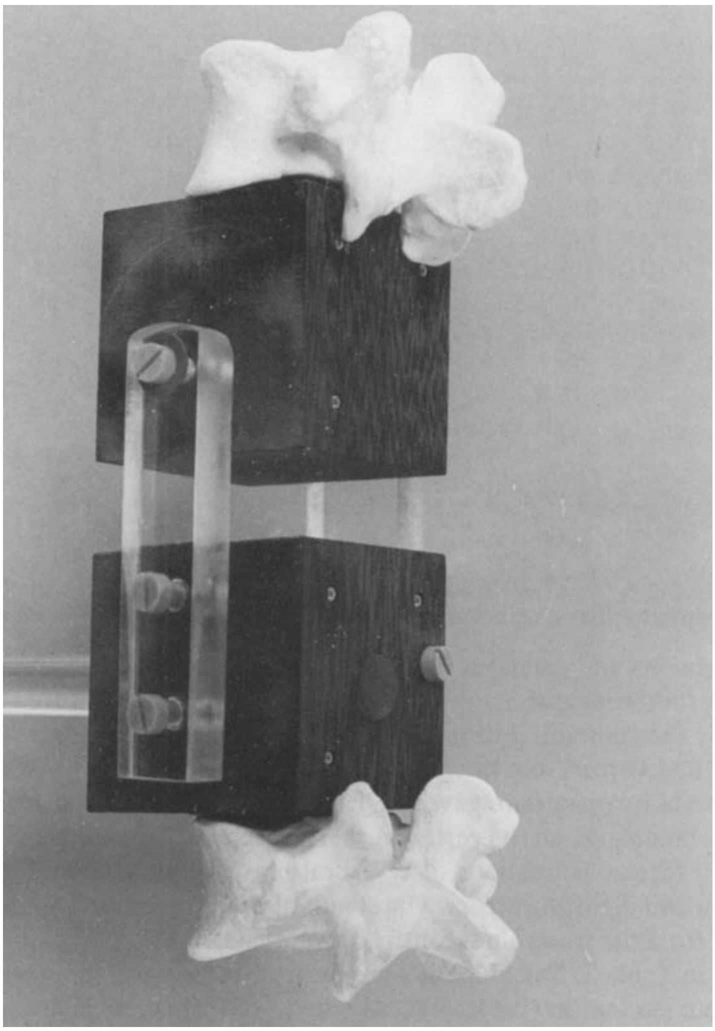


Figure 10 The model used to assess the accuracy of the biplanar radiographic measurements.

Table 2 RMS errors from the mean positions of the steel spheres and anatomical landmarks of the two assemblies of a cube and vertebra in the model spinal segment.

	UPPER ASSEMBLY RMS ERROR mm	LOWER ASSEMBLY RMS ERROR mm	COMBINED RMS ERROR mm
STEEL SPHERES	N=5	N=5	N=10
1	0.09	0.12	0.11
2	0.06	0.09	0.08
3	0.06	0.13	0.10
4	0.08	0.08	0.08
ALL SPHERES	N=20	N=20	N=40
	0.07	0.11	0.09
ANATOMICAL LANDMARKS	N=5	N=5	N=10
1 SPINOUS PROCESS	0.13	0.53	0.38
2 LEFT INFERIOR PEDICLE	0.42	0.42	0.42
3 RIGHT INFERIOR PEDICLE	0.38	0.56	0.48
4 LEFT SUPERIOR PEDICLE	0.73	0.38	0.58
5 RIGHT SUPERIOR PEDICLE	0.41	0.57	0.49
6 LEFT SUPERIOR FACET	0.31	0.29	0.30
7 RIGHT SUPERIOR FACET	0.30	0.43	0.37
8 SUPERIOR END-PLATE	0.30	0.20	0.25
9 INFERIOR END-PLATE	0.24	0.19	0.22
ALL LANDMARKS	N=45	N=45	N=90
	0.39	0.42	0.40

Movement repeatability and accuracy

The displacements and rotations of the model were used to asses the repeatability and accuracy for the measurement of vertebral movement. A measure of repeatability is given by the standard deviation about the mean value whilst accuracy is indicated by the RMS error from the true value.

The repeatability procedure gave five calculations of the movements of the steel spheres. The landmarks on the vertebrae were measured from the radiographs three times to give fifteen estimations of vertebral movements that included landmark identification and digitising errors. The standard deviations about the mean and the RMS errors from the true values for the movements of the cubes and the vertebrae are detailed in Table 3. Calculations were performed using all nine landmarks, and using only four landmarks (the least number required for the calculations). The technique was designed to be able to asses patients as well as normals and in some pathologies, such as fracture of the pars interarticularis or following laminectomy, the vertebrae cannot be considered to be rigid bodies. In these cases only landmarks on the anterior part of the vertebrae can be used and so it was necessary to know what effect using fewer landmarks had on the accuracy.

The results showed that the calculations from the steel spheres were approximately four times as accurate as for the anatomical landmarks on the vertebrae. The standard deviations and RMS errors were both larger when using four landmarks, showing that some accuracy is lost using less than nine landmarks. However, in general the displacements have an RMS error of <2 mm, and the rotations an RMS error of <1.5 degrees.

Table 3 Standard deviations about the mean (SD) and root mean square errors (RMS) from the true values for the translations (X, Y and Z) and rotations (F/E, flexion; LB, Lateral Bending; AR, Axial Rotation) of the cubes (4 steel spheres) and the vertebrae, based on 9 landmarks and 4 landmarks.

	X	Y mm	Z	F/E	LB Degrees	AR
STEEL SPHERES	N=5					
SD	0.21	0.11	0.11	0.29	0.11	0.13
RMS	0.19	0.16	0.23	0.26	0.12	0.30
9 LANDMARKS	N=15					
SD	1.06	0.15	0.89	0.46	0.71	0.54
RMS	1.16	0.17	0.86	0.83	0.69	1.36
4 LANDMARKS	N=15					
SD	1.92	0.29	1.43	0.79	0.76	0.68
RMS	2.07	0.33	1.38	0.78	1.21	0.97

Subjects

Volunteer Groups

The exposure of normal individuals to X-rays required approval of this study by the Central Oxford Research Ethics Committee. Approval was obtained for three small groups of normal male volunteers to be studied, one group in flexion and extension, one in axial rotation and one in lateral bending; no individual was permitted to be included in more than one group. None of the volunteers had ever suffered from back pain requiring time off work or medical treatment, nor had they suffered any back pain within the preceding twelve months.

The three groups of male volunteers investigated were as follows:

Flexion and Extension: 11 subjects of mean age 29 years (range 25 to 36 years).

Axial Rotation: 10 subjects of mean age 24 years (range 21 to 30 years).

Lateral Bending: 10 subjects of mean age 28 years (range 22 to 37 years).

Radiographic Abnormalities

Out of the 31 individuals examined 5 had obvious abnormalities visible on the radiographs.

In the group investigated in flexion and extension four had abnormalities:

1 case with an old unilateral fracture of the left pars interarticularis of L4.

1 case with a bilateral spondylolysis of L5 with a spondylolisthesis of less than grade 1.

1 case of spina bifida occulta of S1.

1 case of narrowing of the L5/S1 intervertebral disc.

The group investigated in axial rotation had only one individual with a radiographic abnormality which was spina bifida occulta of S1.

There were no abnormalities seen in the group investigated in lateral bending apart from one individual with a small lumbar scoliosis.

None of these individuals with radiographic abnormalities had movements significantly different from the rest of the group he was in.

Results

In the light of the accuracy of the technique presented above the rotations measured are given to the nearest degree and the translations to the nearest millimetre.

The data for each individual in the groups investigated in flexion and extension, axial rotation, and lateral bending are given in Appendices 1, 2 and 3 respectively.

Total Ranges of Movements

The primary rotations for the voluntary movements of flexion and extension, axial rotation, and lateral bending for the lumbar spine as a whole, and the total ranges at each intervertebral joint are given in Tables 4 and 5 respectively. The detailed results for each level including the accompanying rotations in the other two planes are given in Table 6 for voluntary flexion/extension, Table 7 for voluntary axial rotation, and Table 8 for voluntary lateral bending.

Primary Rotations

It was apparent that for the lumbar spine as a whole three quarters of the total range of flexion plus extension consisted of flexion from the upright position. The total range of flexion plus extension was similar for each intervertebral joint. However, the L4/5 level was significantly more mobile than the levels above (paired t-test $p < 0.05$), but not significantly more mobile than the L5/S1 level.

The standard deviations of the movements of flexion and extension of the L5/S1 level were larger than at the other levels. On inspection it was apparent that some subjects flexed more than they extended at L5/S1 whilst the others extended more than they flexed. This appearance indicated that the L5/S1 level did not demonstrate the consistent pattern of movement seen at the other levels, although the total range of flexion plus extension remained similar.

Flexion resulted in the anterior edges of the endplates coming closer together than the posterior in most subjects at the upper lumbar levels, and in several at L4/5

Table 4 Voluntary movements of the lumbar spine as a whole. Values given in degrees. Mean SD (range).

MOVEMENT	FLEXION/EXTENSION			AXIAL ROTATION			LATERAL BENDING		
Total	67	11	(55–83)	8	3	(4–15)	35	11	(15–48)
Flexion or To the Right	51	9	(40–62)	4	2	(1– 6)	17	5	(7–24)
Extension or To the Left	16	6	(9–21)	5	3	(1–11)	18	9	(1–28)

Table 5 Total voluntary movements at each intervertebral level. Values given in degrees. Mean SD (range).

LEVEL	FLEXION/EXTENSION			AXIAL ROTATION			LATERAL BENDING		
L1/2	13	5	(6–20)	2	1	(0–3)	10	2	(7–15)
L2/3	14	2	(10–16)	2	1	(1–3)	11	4	(7–18)
L3/4	13	2	(11–18)	3	1	(1–5)	10	2	(5–12)
L4/5	16	4	(9–19)	3	1	(1–5)	6	3	(1– 9)
L5/S1	14	5	(3–21)	2	1	(0–3)	3	2	(1– 6)

Table 6 Primary voluntary flexion and extension (F/E), plus the accompanying axial rotation (AR) and lateral bending (LB), and the translations along the three axes for each intervertebral level of the lumbar spine.
X, Y, Z values given in mm and F/E, AR, LB values in degrees.
Mean (SD) of 11 individuals (Appendix 1).

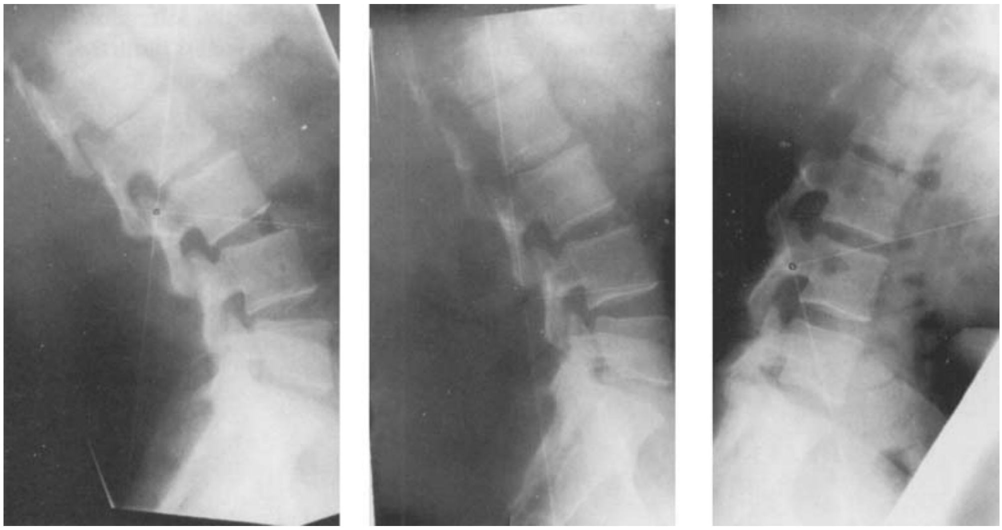
LEVEL	X	Y	Z	F/E	AR	LB
FLEXION						
L1/2	0 (0)	−1 (0)	−3 (1)	8 (5)	1 (1)	1 (1)
L2/3	0 (1)	0 (1)	−2 (1)	10 (2)	0 (1)	0 (1)
L3/4	0 (1)	0 (1)	−2 (1)	12 (1)	−1 (1)	1 (1)
L4/5	0 (1)	0 (1)	−2 (1)	13 (4)	0 (1)	0 (2)
L5/S1	0 (1)	−1 (1)	0 (1)	9 (6)	−1 (1)	0 (1)
EXTENSION						
L1/2	−1 (1)	0 (0)	1 (1)	−5 (2)	1 (1)	0 (1)
L2/3	0 (1)	0 (1)	1 (1)	−3 (2)	0 (1)	0 (1)
L3/4	0 (1)	0 (1)	0 (1)	−1 (1)	0 (1)	0 (1)
L4/5	0 (1)	0 (0)	1 (1)	−2 (1)	1 (1)	−1 (1)
L5/S1	−1 (1)	0 (0)	1 (1)	−5 (4)	1 (1)	0 (1)

Table 7 Primary voluntary axial rotation (AR) to the right and to the left, plus the accompanying flexion or extension (F/E) lateral bending (LB), and the translations along the three axes for each intervertebral level of the lumbar spine.
X, Y, Z values given in mm and F/E, AR, LB values in degrees.
Mean (SD) of 10 individuals (Appendix 2).

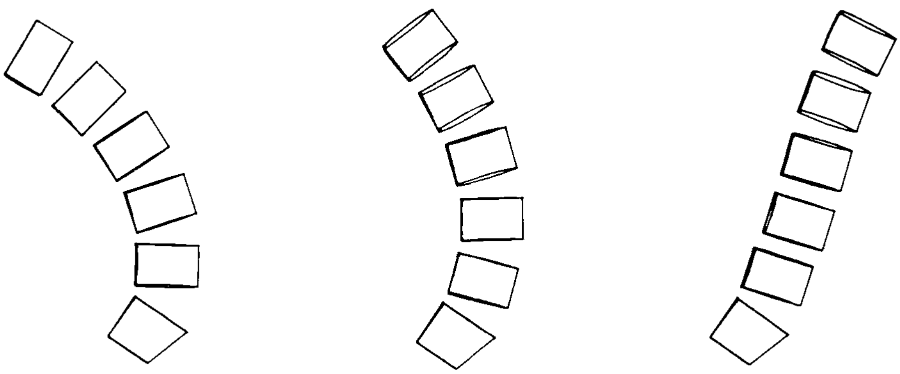
LEVEL	X	Y	Z	F/E	AR	LB
TWIST TO THE RIGHT						
L1/2	0 (1)	0 (1)	−1 (1)	0 (2)	−1 (1)	3 (2)
L2/3	−1 (2)	0 (1)	0 (1)	0 (2)	−1 (1)	4 (2)
L3/4	0 (1)	0 (1)	0 (1)	0 (1)	−1 (1)	3 (2)
L4/5	1 (1)	0 (1)	0 (1)	0 (4)	−1 (1)	1 (2)
L5/S1	0 (1)	0 (1)	0 (1)	0 (2)	−1 (1)	−2 (2)
TWIST TO THE LEFT						
L1/2	0 (1)	0 (1)	−1 (1)	0 (2)	1 (1)	−3 (2)
L2/3	0 (1)	0 (1)	0 (1)	0 (1)	1 (1)	−3 (2)
L3/4	−1 (1)	0 (1)	0 (1)	0 (2)	2 (1)	−3 (2)
L4/5	−1 (1)	0 (0)	0 (1)	0 (3)	2 (1)	−2 (2)
L5/S1	0 (1)	0 (1)	−1 (1)	0 (3)	0 (1)	1 (1)

Table 8 Primary voluntary lateral bending (LB) to the right and to the left, plus the accompanying flexion or extension (F/E) and axial rotation (AR), and the translations along the three axes for each intervertebral level of the lumbar spine.
X, Y, Z values in mm and F/E, AR, LB values in degrees.
Mean (SD) of 10 individuals (Appendix 3).

LEVEL	X	Y	Z	F/E	AR	LB
BEND TO THE RIGHT						
L1/2	0 (1)	0 (1)	0 (1)	−2 (2)	0 (2)	−5 (2)
L2/3	0 (1)	−1 (1)	0 (1)	−1 (1)	1 (1)	−5 (1)
L3/4	0 (1)	1 (1)	0 (1)	−1 (2)	1 (1)	−5 (3)
L4/5	0 (1)	0 (1)	0 (1)	0 (2)	1 (1)	−3 (2)
L5/S1	0 (1)	−1 (1)	0 (1)	2 (3)	0 (1)	0 (2)
BEND TO THE LEFT						
L1/2	0 (1)	0 (1)	0 (2)	−4 (3)	0 (2)	6 (2)
L2/3	0 (1)	1 (1)	1 (1)	−3 (1)	−1 (1)	6 (3)
L3/4	0 (1)	0 (1)	0 (1)	−2 (2)	−1 (2)	5 (3)
L4/5	0 (1)	0 (1)	0 (1)	−1 (2)	−1 (2)	2 (3)
L5/S1	1 (1)	0 (1)	0 (1)	0 (3)	−2 (1)	−2 (3)



a



b

Figure 11 Lateral views of the lumbar spine in extension, upright and in flexion showing the distraction and approximation of the anterior and posterior margins of the end-plates. (a) Radiographs, (b) Computer reconstruction of the same spine.

(Figure 11). This was not seen to occur at the L5/S1 level, due to its larger angle of lordosis, although in one case the endplates of L5/S1 did become parallel.

Neither in axial rotation nor in lateral bending were there statistically significant differences between movements to the right and to the left. In axial rotation there were also no significant differences between the individual levels, although there was a tendency for L3/4 and L4/5 to be slightly more mobile. In lateral bending the L4/5 and the L5/S1 levels were significantly less mobile than the upper three levels (paired t-test $p<0.01$).

In both axial rotation and lateral bending some individuals demonstrated movements in the opposite direction to the voluntary movement at individual intervertebral levels, most commonly at L4/5 and L5/S1. In lateral bending there was a general tendency for L5/S1 to bend in the opposite direction to the voluntary movement.

Accompanying Rotations

In voluntary flexion and extension there was generally very little accompanying axial rotation or lateral bending. In flexion one individual had an axial rotation of 3 degrees at L5/S1. Four subjects had lateral bends of 3 degrees; at L2/3 in one, at L3/4 in one and at L4/5 in three. One subject had a lateral bend of 4 degrees at L4/5. The appearance of lateral bending most commonly at L4/5 is reflected in Table 6 where the standard deviation for lateral bending has the value 2.

During both axial rotation and lateral bending there were large accompanying rotations in the other planes.

In axial rotation there was a consistent pattern of accompanying lateral bending. The relation between the two is shown in Figure 12. At the upper three levels axial rotation was accompanied by lateral bending in the opposite direction. That is, if the

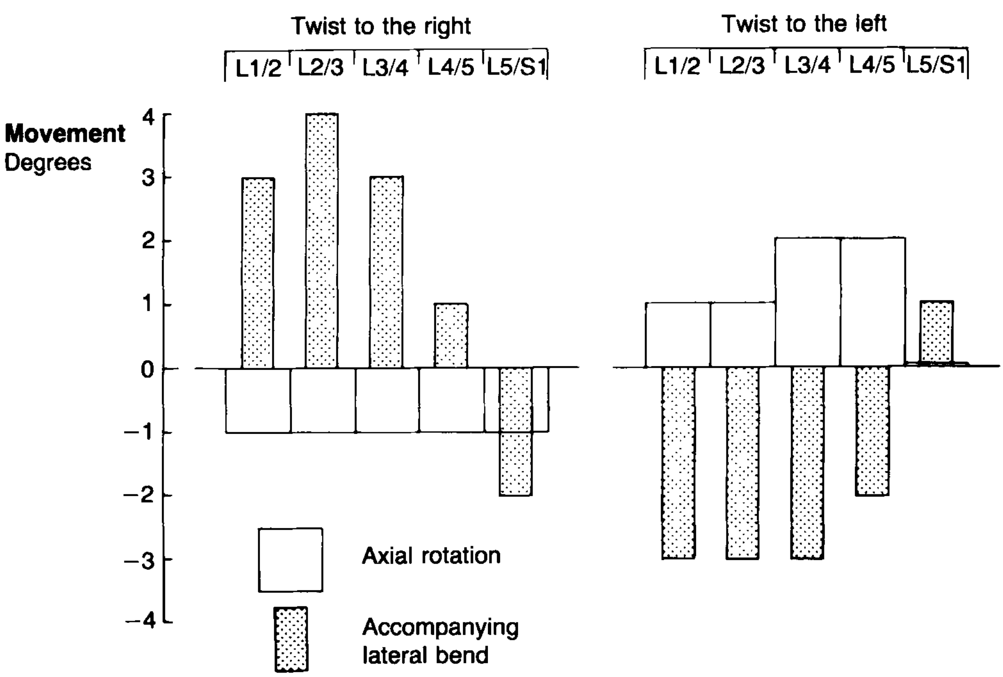


Figure 12 The mean angles of axial rotation and accompanying lateral bending at each level of the lumbar spine for voluntary axial rotation.

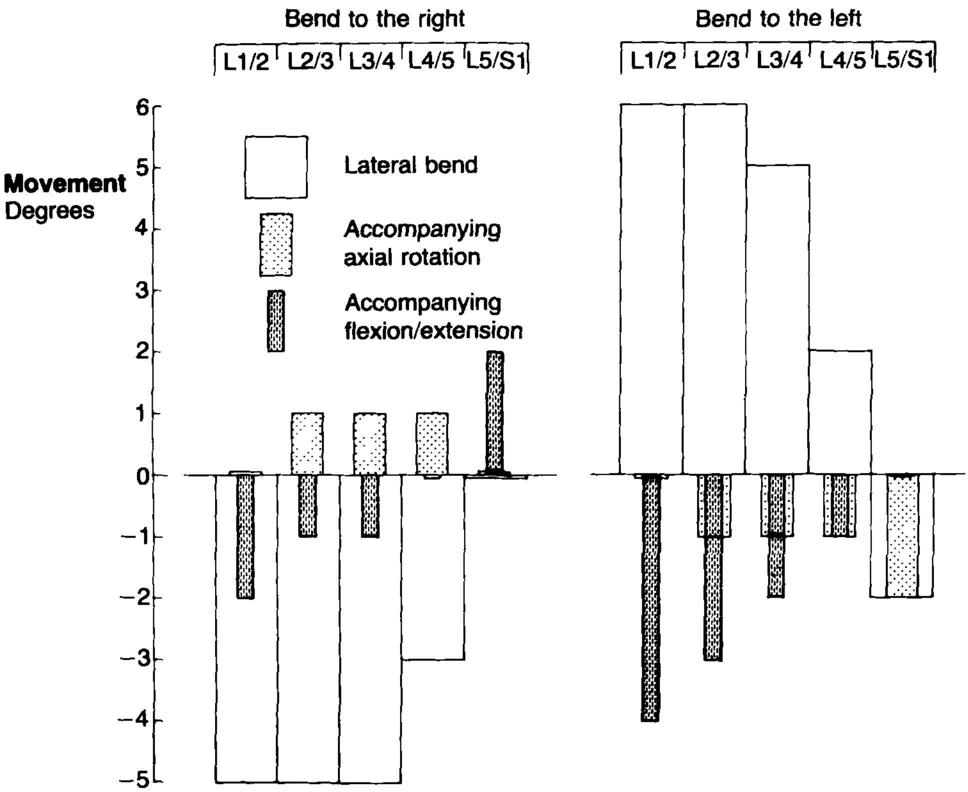


Figure 13 The mean angles of lateral bending and accompanying axial rotation and flexion or extension at each level of the lumbar spine for voluntary lateral bending.

voluntary axial rotation was to the right the accompanying lateral bend was to the left (Figure 9), and vice versa. At L4/5 some individuals exhibited lateral bending in the same direction as the axial rotation, and at L5/S1, if lateral bending occurred, it was always in the same direction as the axial rotation. No correlation was found at any level between the magnitudes of axial rotation and lateral bending. There was no consistent pattern of accompanying flexion or extension (the mean values were all 0 degrees), but some individuals did exhibit flexion or extension of up to 4° at the upper three levels, up to 9° at L4/5 and up to 5° at L5/S1.

In lateral bending there were consistent patterns of accompanying axial rotation and flexion/extension. The relation between the primary movement and the accompanying rotations in the other two planes is shown in Figure 13. Accompanying axial rotations tended to be in the opposite direction to the primary movement at the upper levels but in the same direction at L5/S1. During lateral bending to both right and left the upper levels consistently demonstrated extension. L4/5 generally extended but occasionally flexed and L5/S1 generally flexed. Again no correlation was found between the magnitudes of the primary and the accompanying movements.

Translations

During flexion and extension the only significant translations that occurred were forward displacements during flexion at the upper lumbar levels. These movements indicated that the axis of rotation for flexion lies centrally within the intervertebral disc for the upper levels, but closer to the inferior endplate of the upper vertebra at the lower levels.

During axial rotation and lateral bending the translations in all three axes were generally of the order of 1 mm to 2 mm and were considered to be of no significance.

Upright Spine Shape

The analysis of the relative positions of the vertebrae with the subjects standing upright, gave a measure of the upright spine shape. There was no statistically significant difference in these measures between the three groups of subjects and so they were all considered together to give the mean values shown in Table 9.

Some care is required in the interpretation of this Table. The translations refer to the displacement of the centre of the inferior endplate of the superior vertebra of a pair in relation to the axis system of the inferior vertebra. Where there is a large angle of lordosis such as is generally seen at L5/S1 the endplate will appear displaced posteriorly (Z axis), and this will also have a component in the vertical direction (Y axis), giving the appearance from this Table that the L5/S1 disc is narrower than those above. The angle of lordosis is calculated as an angle of extension by comparison of the vertical axes formed from the centres of the endplates (as described in the Movement Analysis section), and not from the anterior posterior wedging of the disc space. As the S1 vertebrae taper inferiorly the quoted angles of lordosis are generally larger than angles between the endplates on either side of the disc.

During voluntary flexion and extension the L5/S1 level was the only one to show an inconsistent pattern of movement between individuals. An explanation for this was sought in the lordosis of the subjects in the upright position. No correlation was found between the angle of lordosis at L5/S1 and the extent to which the joint flexed more than it extended. However, a significant correlation was found between the overall lumbar lordosis and the difference between flexion and extension at L5/S1, $p<0.05$ (Figure 14). This result indicated that those subjects whose L5/S1 level extended more than it flexed had larger angles of lordosis at all levels, except L5/S1 itself, than those whose L5/S1 levels flexed more than they extended.

Table 9 The relative positions of the vertebrae at each intervertebral level of the lumbar spine for the upright position.
(X – Lateral shift of superior vertebra of a pair, Y – Distance between inferior end-plates of the two vertebrae in a pair, Z – Posterior displacement of superior vertebra of pair; all these coordinates are relative to the axes of the inferior vertebra. Lordosis – angle of extension, AR – angle of rotation and LB – angle of lateral bend between the two vertebrae).
X, Y, Z values given in mm and Lordosis, AR, LB in degrees.
Mean (SD) of 31 subjects.

LEVEL	X	Y	Z	LORDOSIS	AR	LB
L1/2	0 (1)	34 (1)	2 (1)	−3 (4)	0 (1)	0 (2)
L2/3	0 (1)	35 (2)	4 (2)	−8 (4)	0 (1)	0 (3)
L3/4	0 (1)	35 (2)	5 (2)	−10 (3)	0 (1)	−1 (3)
L4/5	0 (1)	34 (2)	7 (2)	−16 (5)	0 (1)	0 (3)
L5/S1	0 (1)	29 (2)	15 (3)	−37 (6)	1 (1)	1 (2)

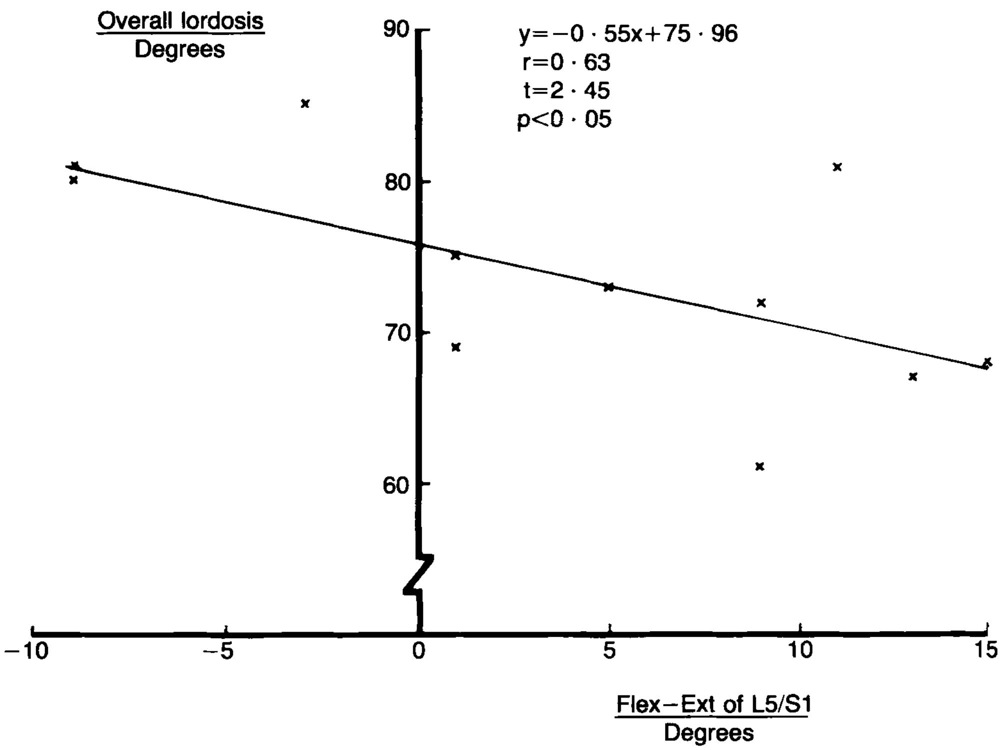


Figure 14 Regression of the overall lordosis on the angle of flexion minus extension at L5/S1.

Discussion

The ethical considerations of exposing normal subjects to ionising radiation limited these investigations to small groups of male volunteers. However, the movements of the subjects had sufficiently small variance within each group to validate their use as a base line for the comparison of movements in patients with low back pain. Mobility generally decreases with age (1, 39) and this should be taken into account when comparing patients of an older age group. Female subjects were not investigated due to the risk associated with irradiation of the gonads. There may be some differences in their movements in comparison with males, although in the patient groups investigated that have included older females no differences were found from the males with the same pathologies (24, 28).

Primary Rotations

Flexion and extension

Whilst all the intervertebral levels had similar overall ranges of flexion plus extension, there were some differences in the pattern of movement at each level. L1/2 showed slightly more flexion than extension whilst L2/3, L3/4 and L4/5 had very little extension, most of their movement being flexion from the upright position. L5/S1 had no discrete pattern, instead there would appear to be a continuum from those who flexed and had little extension to those who extended and had little flexion, the overall range of flexion plus extension remaining the same. The correlation between overall lumbar lordosis and the difference between the amount of flexion and extension at the L5/S1 level indicated that the shape and morphology of the lumbar spine may be responsible for this difference. However, the lordotic angle of the lumbosacral junction itself showed no correlation and so it would appear that the movement of this joint may be dictated by the way loads are imposed on it by the rest of the lumbar spine.

One subject (FE3, Appendix 1) had a total range of movement at L5/S1 of 3°. This lies outside two standard deviations from the mean of the group in which he is included. He also demonstrated the only coupled movement of 4°. It is not clear whether this individual represents the extreme of the normal range, or whether he has some undiagnosed spinal pathology.

One of the purposes of this study was to provide a base line of normal data to determine how abnormal movements relate to pathology in patients with back pain. With this in mind the presence of four cases of abnormal radiologic appearance in this group, but with normal movement, lend evidence to the hypothesis that abnormal movements are more likely to be related to symptoms than to pathology.

Axial rotation

This study showed agreement with previous studies in total range of axial rotation at all levels except L5/S1. Gregerson and Lucas (12) measured much larger movements at the lumbo-sacral junction but stated that their technique was unreliable at this level. Steinman pins were used in the spinous processes of each vertebra but not in the sacrum. Instead a sacral belt was used which was discovered to have considerable movement relative to the sacrum.

Lumsden and Morris (15) extended the work of Gregerson and Lucas by putting pins into the posterior superior iliac spines. Their measured average axial rotation at L5/S1 was 6°. The coordinate system they used was relative to the pelvis but initially set horizontal to the floor with the subjects standing. The coordinate system used in the present study for L5/S1 was relative to S1 with the vertical axis defined as the line joining the centre of its two end-plates. Owing to the inclination of the sacrum relative to the floor this coordinate system was angled forwards compared to that of Lumsden and Morris. This would result in rotations around the three axes having components in a plane parallel to the floor and would account in part for the differences seen. The measurements of Lumsden and Morris would also have included any movement of the sacro-iliac joints and may have given false high readings for axial rotation at L5/S1. It may be relevant to asses the rotations relative to a horizontal plane. However, a two-dimensional measure must be used with caution to estimate deformations of the intervertebral disc if the disc is not parallel to the plane of measurement. The present study indicated that there was very little axial rotation in the plane of the disc at L5/S1 suggesting that the disc itself was not strained to any extent by this movement.

Lateral bending

Previous radiographic studies of lateral bending have all reported similar ranges of lateral bending at the individual joints with only minor variations (2, 5, 16, 39). Miles and Sullivan (16) also found that the lowest two levels occasionally bent in the opposite direction to the voluntary movement, and they reported that accompanying axial rotation was seen generally in the opposite direction to the lateral bend. However, their technique would not have been able to discriminate the small movements at the lumbo-sacral junction. The recent study by Cosentino et al (5) examined subjects lying supine with hips and knees flexed to eliminate the lumbar lordosis, and it is interesting to note that with the spine flexed in this manner the L4/5 level was twice as mobile as found in the present study. However, six of their subjects were classical ballet dancers and might be expected to have a larger range of motion.

Lateral bending is not a manoeuvre that is generally performed in life as it is not easy to perform. These measurements showed that it was accompanied by extension as well as axial rotation which would make measurements of lateral bending taken from A-P radiographs alone liable to error and limit the use of such measurements.

Accompanying Rotations

In flexion and extension there were few accompanying rotations in the other planes. What there were suggests that during voluntary flexion and extension axial rotations of 3° or more lie outside the normal range; whilst lateral bends of 4° or more in flexion and 3° or more in extension should be considered abnormal.

Some previous cadaveric work has suggested that there is mechanical coupling of intervertebral joints such that axial rotation is always accompanied by a related amount of lateral bending (22), while others have found little consistency of coupling (33). This study has shown that the relation between axial rotation and lateral bending is not consistent at the different levels of the lumbar spine and that there is no simple correlation between the magnitudes of primary and accompanying rotations. At the three upper levels the accompanying rotation was in the opposite direction to the primary rotation, at L4/5 the two rotations were sometimes in opposite directions and sometimes in the same direction, and at L5/S1 axial rotation and lateral bending were generally in the same direction. Although some degree of mechanical coupling may be present it is more likely that the lordotic shape of the lumbar spine together with muscular control are the two principal factors affecting the accompanying rotations.

The magnitude of the accompanying axial rotations during lateral bending suggests that the lumbar spine is also twisted to its limit in the opposite direction during this manoeuvre. In voluntary axial rotation the accompanying lateral bends were generally one half to two thirds of the full range seen in voluntary lateral bending.

The L4/5 level was shown to be a transition point for the accompanying axial rotations and lateral bends. This together with the fact that the largest accompanying flexions or extensions were also seen at L4/5, lend evidence to the idea that this joint experiences higher stresses than the other levels, and gives a mechanical reason for L4/5 to have the highest incidence of intervertebral joint pathology (9).

Translations

The only translations greater than 2 mm were forward displacements during flexion at the upper levels of the lumbar spine. This indicated some forward shear of the discs, but the interpretation that appeared consistent with the radiographic appearence was a more inferior position of the axis of rotation at these levels compared to the lower levels.

In axial rotation and lateral bending there were few translations greater than 1 mm and only one greater than 2 mm. This indicated that no significant shear strains were imposed on the discs during these manoeuvres. In particular, it would appear that the L5/S1 disc is unlikely to be damaged by pure axial rotation.

Summary

The technique of Biplanar Radiography for the computer analysis of orthogonal radiographs of the human spine enables the calculation of three-dimensional coordinates for anatomical landmarks on the vertebrae. Three-dimensional intervertebral movements are deduced from the changes in the relative orientations of the vertebrae as a subject moves from one position to another. The three-dimensional coordinates of the anatomical landmarks on the vertebrae were found to have an RMS error of <1 mm. The RMS errors for translational movements were <2 mm and for rotations were $<1.5°$.

This study of normal subjects has defined the ranges of voluntary flexion and extension, axial rotation, and lateral bending in the lumbar spines of young males. The range of flexion plus extension at each lumbar intervertebral joint is approximately 14° with the L4/5 level being slightly more mobile than the others. There are approximately 2° of axial rotation at each joint with L3/4 and L4/5 being slightly more mobile. Lateral bending of approximately 10° occurs at the upper three levels while there is significantly less movement of 6° and 3° at L4/5 and L5/S1 respectively.

In flexion and extension accompanying axial rotation of 2° or more and lateral bending of 3° or more occurred rarely and any larger accompanying rotation at an intervertebral joint should be considered abnormal. During twisting and side bending axial rotation to the right is accompanied by lateral bending to the left and vice versa at the three upper levels. At L5/S1 axial rotation and lateral bending generally accompany each other in the same direction while L4/5 is a transitional level. During lateral bending there is also generally extension at the upper levels and flexion at L5/S1. The measurement in vivo of the accompanying rotations in the other planes has demonstrated that there is no simple mechanical coupling of the rotations.

Finally, this study has provided a base line of normal movements to which the movements seen in pathological conditions can be compared.

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References

(1) **Allbrook D.** Movements of the lumbar spinal column. J Bone Jt Surg 39B: 339–345, 1957.

(2) **Bakke S N.** Roentgenologische beobachtungen über die bewegungen der wirbelsaule. Acta Radiologica, Supplementum 13, Stockholm, 1931.

(3) **Benson D R, Schultz A B and DeWald R L.** Roentgenographic evaluation of vertebral rotation. J Bone Jt Surg 58A: 1125–1129, 1976.

(4) **Brown R H, Burstein A H, Nash C L and Schock C C.** Spinal analysis using a three-dimensional radiographic technique. J Biomech 9: 355–365, 1976

(5) **Cosentino R, Suarez A, Baccani S and Cosentino R V.** Etude radiologique de la mobilite du rachis dorso-lombaire. Revue de Chirurgie Orthopaedique 68: 91–95, 1982.

(6) **Cossette J W, Farfan H, Robertson G W and Wells R V.** The instantaneous centre of rotation of the third lumbar intervertebral joint. J Biomech 4: 149–153, 1971.

(7) **Dimnet J, Fischer L P, Gonon G and Carret J P.** Radiographic studies of lateral flexion in the lumbar spine. J Biomech 11: 143–150, 1978.

(8) **Drerup B, Frobin W and Haeusslar G.** Evaluation of biplane radiographs by epipolar ray correlation. Society for Photo-Optical Instumentation Engineers 166: 192–198, 1978.

(9) **Friberg S and Hirsch C.** Anatomical and clinical studies on lumbar disc degeneration. Acta Orthop Scand 19: 222–242, 1949.

(10) **Froning E C and Frohman B.** Motion of the lumbo-sacral spine after laminectomy and spine fusion. Correlation of motion with the result. J Bone Jt Surg 50A: 897–910, 1954.

(11) **Frymoyer J W, Frymoyer W W, Wilder D G and Pope M H.** The mechanical and kinematic analysis of the lumbar spine in normal living human subjects in vivo. J Biomech 12: 165–172, 1979.

(12) **Gregerson G G and Lucas D B.** An in vivo study of axial rotation of the human thoracolumbar spine. J Bone Jt Surg 49A: 247–262, 1967.

(13) **Hanley E N, Matteri R E and Frymoyer J W.** Accurate roentgenographic determination of lumbar flexion-extension. Clin Orth Rel Res 115: 145–148, 1976.

(14) **Kreysig E.** In Advanced Engineering Mathematics. Publ. John Wiley and Sons Inc., New York, USA, 1972, p 313–316.

(15) **Lumsden R M and Morris J M.** An in vivo study of axial rotation and immobilisation at the lumbosacral joint. J Bone Jt Surg 50A: 1591–1602, 1968.

(16) **Miles M and Sullivan W E.** Lateral bending at the lumbar and lumbosacral joints. Anat Rec 139: 387–398, 1961.

(17) **Nagel D A, Koogle T A, Piziali R L and Perkash I.** Stability of the upper lumbar spine following progressive disruption and the application of individual internal and external fixation devices. J Bone Jt Surg 63A: 62–70, 1981.

(18) **Olsson T H, Selvik G, Willner S.** Kinematic analysis of spinal fusions. Invest Radiol 11: 202–209, 1976.

(19) **Olsson T H, Selvik G, Willner S.** Mobility in the lumbosacral spine after fusion studied with the aid of roentgen stereophotogrammetry. Clin Orthop 129: 181–190, 1977.

(20) **Panjabi M M, Brand R A and White A A.** Three-dimensional flexibility and stiffness of the human thoracic spine. J Biomech 9: 185–192, 1976.

(21) **Panjabi M M.** Experimental determination of spinal motion segment behaviour. Orthop Clin N Amer 8: 169–180, 1977.

(22) **Panjabi M M, Krag M, White A A and Southwick W O.** Effects of preload on load displacement curves of the lumbar spine. Orthop Clin N Amer 8: 181–192, 1977.

(23) **Pearcy M J, Whittle M W.** Movements of the lumbar spine measured by three-dimensional X-ray analysis. J Biomed Eng 4: 107–112, 1982.

(24) **Pearcy M J, Burrough S J.** Assessment of bony union after interbody fusion of the lumbar spine using a biplanar radiographic technique. J Bone Jt Surg 64B: 228–232, 1982.

(25) **Pearcy M J, Portek I, Shepherd J E.** Three-dimensional X-ray analysis of normal movement in the lumbar spine. Spine 9: 294–297, 1984.

(26) **Pearcy M J, Tibrewal S B.** Axial rotation and lateral bending in the normal lumbar spine measured by three-dimensional radiography. Spine 9: 582–587, 1984.

(27) **Pearcy M J, Portek I, Shepherd J E.** The effect of low back pain on spinal movements measured by three-dimensional X-ray analysis. Spine (in press).

(28) **Pearcy M J, Shepherd J E.** Is there instability in spondylolisthesis? Spine 10:175–177, 1985.

(29) **Pearcy M J, Wordsworth B P, Portek I, Mowat A G.** Lumbar spinal movements in ankylosing spondylitis. The effect of treatment. Spine (in press).

(30) **Pennal G F, Conn G S, McDonald G, Dale G and Garside H.** Motion studies of the lumbar spine. J Bone Jt Surg 54B: 442–452, 1972.

(31) **Pope M H, Wilder D G, Buturla E, Matteri R, Frymoyer W W and Frymoyer J W.** Radiographic and biomechanical studies of the human spine. Report to the Air Force Office of Scientific Research (AFOSR), USAF, AFOSR-74-2738, 1977.

(32) **Rab G T and Chao E Y S.** Verification of roentgenographic landmarks in the lumbar spine. Spine 2: 287–293, 1977.

(33) **Schultz A B, Warwick D N, Berkson M H and Nachemson A L.** Mechanical properties of human lumbar spine motion segments. Part 1, Responses in flexion, extension, lateral bending and torsion. J Biomech Eng 101: 46–52, 1979.

(34) **Selvik G, Olsson T H and Willner S.** High accuracy analysis of movements of the spine with the aid of a roentgen stereophotogrammetric method. Biomechanics V-B. Edited by P V Komi, University Park Press, Baltimore, Maryland, USA, 1976, p 502–507.

(35) **Shepherd J E.** Investigation of the radiation dose received by a patient during a biplanar X-ray series. In, Report for Diploma in Professional Studies by J E Shepherd, 1982, Loughborough University of Technology.

(36) **Stokes I A F, Medlicott P A and Wilder D G.** Measurement of movement in painful intervertebral joints. Med Biol Eng Comp 18: 694–700, 1980.

(37) **Stokes I A F, Wilder D G, Frymoyer J W and Pope M H.** Assessment of patients with low back pain by biplanar radiographic measurement of intervertebral motion. Spine 6: 233–240, 1980.

(38) **Suzuki T, Pearcy M J, Tibrewal S B, Wilson D and Duthie R B.** Posterior intertransverse fusion assessed clinically and with biplanar radiography. International Orthopaedics (in press).

(39) **Tanz S.** Motion of the lumbar spine. A roentgenologic study. Amer J Roentgenology 69: 399–412, 1953.

(40) **Tibrewal S B, Pearcy M J, Portek I, Spivey J.** A prospective study of lumbar spinal movements before and after discectomy using biplanar radiography – correlation of clinical and radiologic findings. Spine (in press).

(41) **Weitz E M.** The lateral bending sign. Spine 6: 388–397, 1981.

(42) **White A A and Panjabi M M.** Clinical biomechanics of the spine. J B Lipincott Co, Philadelphia, 1978.

(43) **Whittle M W.** Calibration of the three-dimensional television system. Annual Report No. 7, 1980, Oxford Orthopaedic Engineering Centre.

(44) **Whittle M W.** Calibration and performance of a three-dimensional television system for kinematic analysis. J Biomech 15: 185–196, 1982.

(45) **Wordsworth B P, Pearcy M J, Mowat A G.** In-patient regime for the treatment of Ankylosing Spondylitis: an appraisal of improvement in spinal mobility and the effects of corticotrophin. Brit J Rheum 23: 39–43, 1984.

APPENDICES

CODED DATA FOR THE INTERVERTEBRAL MOVEMENTS AND SPINAL SHAPE FOR EACH INDIVIDUAL

KEY TO DATA.

All values for X, Y and Z are in mm.
All values for F, AR, LB and L are in degrees.

MOVEMENTS

X Translation in X direction (+ve left to right).
Y Translation in Y direction (+ve inferior to superior).
Z Translation in Z direction (+ve anterior to posterior).

F Flexion and Extension (+ve values indicate flexion, -ve values extension).
AR Axial Rotation (+ve values indicate rotation to the left, Figure 9).
LB Lateral Bending (+ve values indicate bending to the left, Figure 9).

UPRIGHT SPINE SHAPE

X Displacement in X direction.
Y Displacement in Y direction.
Z Displacement in Z direction.

L Angle of Lordosis.
AR Angle of Axial Rotation.
LB Angle of Lateral Bend.

RADIOGRAPHIC ABNORMALITIES

¥ Fracture of pars interarticularis.
\+ Bilateral pars interarticularis
defects and grade 1 Spondylolisthesis.
£ Spina bifida occulta.
= Narrowing of the disc space.
~ Lumbar scoliosis, approx 25 degrees.

Appendix 1 The Data for the 11 Individuals who were Examined in FLEXION AND EXTENSION.

			FLEXION						EXTENSION						UPRIGHT SHAPE					
SUBJECT	AGE	LEVEL	X	Y	Z	F	AR	LB	X	Y	Z	F	AR	LB	X	Y	Z	L	AR	LB
FE1	29	L1/2	0	-1	-3	17	1	1	-1	0	1	-3	-1	0	0	36	6	-11	0	0
		L2/3	2	1	-2	15	-1	0	0	0	1	-1	0	1	-1	35	6	-11	0	-2
		L3/4	1	0	-2	12	-1	0	1	1	0	-1	-2	2	-1	35	6	-14	1	-3
		L4/5	0	-1	-2	15	0	2	-1	0	1	-4	0	0	0	33	9	-25	0	1
		L5/S1	0	-1	0	3	1	-2	0	0	2	-12	1	0	0	31	11	-30	0	1
FE2	33	L1/2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		L2/3	-1	-1	-2	11	1	2	-1	1	1	-4	1	1	1	38	3	-4	-1	1
		L3/4	-1	-1	-4	13	0	1	-1	0	-1	-1	0	0	0	37	7	-13	0	-1
		L4/5	0	0	-2	14	0	0	-1	0	1	-2	1	1	1	36	6	-14	-1	0
		L5/S1	0	0	0	7	0	2	0	1	0	-6	0	0	-1	29	17	-38	2	0
FE3	27	L1/2	0	0	-3	9	2	2	0	0	1	-7	1	1	-1	35	2	-2	0	1
		L2/3	0	-1	-3	12	0	2	0	-1	0	-1	0	0	0	36	6	-13	-1	2
		L3/4	1	0	-3	11	-1	2	1	0	0	-2	0	0	1	37	5	-7	0	0
		L4/5	1	-1	-2	9	0	-4	1	0	0	-1	0	-1	-1	36	6	-16	0	1
		L5/S1	-1	0	1	-1	0	0	-1	0	0	2	1	1	1	31	15	-39	2	2
FE4	27	L1/2	0	-1	-2	3	-1	1	0	0	0	-3	1	0	0	35	-1	6	-1	-1
		L2/3	0	1	-1	8	-1	0	0	2	3	-7	0	1	0	36	2	-1	1	-2
		L3/4	1	-1	-3	14	0	-1	0	1	0	-4	0	1	-1	36	7	-8	0	2
		L4/5	1	0	-3	16	-1	1	0	0	1	-1	1	-1	-2	34	9	-18	-1	5
		L5/S1	0	0	-1	18	-2	-1	-1	0	1	-3	2	0	1	28	17	-41	2	2
FE5	29	L1/2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		L2/3	0	-1	-4	10	0	1	0	0	0	-1	-1	1	1	38	7	-8	0	0
		L3/4	-1	0	-1	12	0	-1	-1	1	1	-2	0	-1	-1	36	8	-14	0	2
		x L4/5	0	0	-3	16	1	0	-1	1	0	-3	1	-2	0	37	3	-12	-1	0
		L5/S1	1	0	-3	16	-1	1	-1	0	1	-3	-1	2	0	31	16	-33	2	2
FE6	27	L1/2	-1	-1	-2	7	1	-1	-1	0	1	-7	1	-1	0	37	2	-2	0	-1
		L2/3	0	0	-2	12	1	1	0	0	0	-1	0	0	1	36	6	-13	0	-2
		L3/4	-1	0	-2	12	0	0	-1	-1	0	0	0	1	2	36	6	-12	1	-6
		L4/5	0	0	-2	11	0	-2	0	0	1	-3	1	-1	0	34	8	-18	0	0
		L5/S1	0	-1	0	5	-1	0	0	0	1	-8	0	-1	-1	28	16	-42	-1	1
FE7	33	L1/2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		L2/3	-1	-1	-2	12	2	1	-1	0	0	-4	1	0	1	37	4	-5	0	-3
		L3/4	-2	0	0	13	-2	3	0	0	1	1	-1	-1	1	36	5	-12	1	-2
		L4/5	0	1	-2	19	1	-1	0	0	-1	-1	2	-1	0	31	12	-25	1	1
		+ L5/S1	0	-1	3	14	0	-1	-1	0	0	-5	0	0	0	34	8	-30	1	0
FE8	25	L1/2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		L2/3	0	-1	-3	7	0	-3	-1	0	1	-3	0	0	0	37	4	-5	0	2
		L3/4	1	0	-1	9	-1	0	0	0	0	-2	1	-1	-1	35	8	-15	0	1
		L4/5	0	0	-1	6	-1	3	0	0	1	-3	0	-1	0	33	10	-23	1	-2
		£ L5/S1	1	-1	1	3	-1	1	-1	0	2	-12	1	0	2	29	15	-38	2	-2
FE9	29	L1/2	0	-1	-2	7	0	2	0	0	-1	-2	0	0	1	35	2	-3	1	-1
		L2/3	-1	0	-1	9	0	-1	0	1	1	-4	1	0	-1	35	5	-8	-2	2
		L3/4	0	0	-2	11	-1	1	0	0	1	-1	0	1	0	35	4	-10	1	-3
		L4/5	0	-1	-3	16	0	1	0	0	1	-2	1	-1	0	35	7	-15	0	1
		L5/S1	0	-1	0	8	-1	0	0	0	0	-3	1	-1	0	27	17	-40	1	1
FE10	30	L1/2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		L2/3	0	-1	-4	7	0	0	-1	0	1	-6	0	1	0	38	3	-3	0	2
		L3/4	-1	-1	-3	13	0	2	0	0	1	-2	0	-2	1	39	5	-9	1	-3
		L4/5	1	0	-2	15	-2	3	0	1	1	-1	0	1	1	35	8	-17	2	-3
		L5/S1	0	-1	-1	14	-1	-1	-1	0	-1	-3	1	1	1	26	20	-52	1	0
FE11	36	L1/2	0	-1	-3	4	0	-1	-1	0	1	-6	1	0	-1	36	2	-2	-2	1
		L2/3	1	0	-3	10	-1	1	1	0	2	-4	-2	0	-1	36	5	-8	1	0
		L3/4	-1	-1	-2	11	-1	-1	-1	0	-1	0	0	-2	0	37	5	-12	-1	2
		L4/5	1	-1	-2	10	0	-3	1	1	2	-3	0	-2	0	38	3	-8	0	0
		= L5/S1	0	0	0	10	-3	2	-1	0	2	-1	0	2	1	30	13	-33	4	-2

Appendix 2 The Data for the 10 Individuals who were Examined in AXIAL ROTATION.

			TWIST TO RIGHT						TWIST TO LEFT						UPRIGHT SHAPE					
SUBJECT	AGE	LEVEL	X	Y	Z	F	AR	LB	X	Y	Z	F	AR	LB	X	Y	Z	L	AR	LB
AR1	21	L1/2	0	-1	-1	0	0	2	0	-1	0	0	1	-2	-1	32	3	-6	-1	1
		L2/3	-1	0	0	-1	-1	3	0	0	0	-2	-1	-4	-2	33	2	-5	0	3
		L3/4	0	0	1	-1	0	3	0	0	0	1	3	-3	-2	33	4	-9	-5	5
		L4/5	1	-2	-1	5	-2	1	-1	0	-1	2	2	-2	1	31	8	-18	1	1
		£ L5/S1	2	2	-1	1	-1	-2	1	0	0	-5	-2	0	0	28	9	-25	2	2
AR2	25	L1/2	1	1	-2	-1	-2	2	1	1	0	-1	-1	-3	0	35	3	-3	2	-3
		L2/3	-1	0	0	1	0	4	1	-1	0	1	2	-5	0	37	4	-9	-2	-2
		L3/4	0	1	1	0	0	2	-1	1	0	1	1	-2	-1	37	3	-7	-1	-2
		L4/5	2	0	1	1	-2	2	0	0	1	-1	3	-5	-1	37	6	-11	1	0
		L5/S1	1	-1	0	3	-1	-1	0	-1	-1	3	0	0	0	23	20	-54	2	0
AR3	26	L1/2	0	0	0	-1	-2	3	-1	0	-1	-2	1	-1	-1	34	3	-5	0	2
		L2/3	0	0	1	-2	-1	5	-1	0	0	-2	2	-3	-1	36	4	-7	0	-1
		L3/4	-2	-1	-1	1	0	2	-1	0	0	0	3	-2	0	37	2	-4	-1	-1
		L4/5	1	-1	-1	2	0	-1	-1	0	0	1	3	2	-1	33	8	-18	0	0
		L5/S1	2	1	0	-2	-1	-7	0	0	0	1	2	0	-1	32	12	-27	1	2
AR4	26	L1/2	0	0	-1	2	0	4	1	1	1	2	0	-1	1	33	2	-4	0	-3
		L2/3	-1	-1	-2	2	-1	3	1	-1	0	0	0	0	1	35	4	-6	1	-3
		L3/4	-1	2	1	-2	0	6	-1	0	1	0	2	0	2	35	3	-6	1	-4
		L4/5	0	-1	0	0	-1	3	-1	0	0	0	2	-5	-1	35	7	-16	1	1
		L5/S1	-1	0	0	-1	0	0	0	1	1	-2	1	1	0	27	14	-37	0	3
AR5	22	L1/2	0	-1	1	-3	0	3	1	-1	0	-4	1	-7	0	33	1	1	-1	1
		L2/3	1	0	0	1	-1	6	1	-1	-1	1	0	-4	0	33	6	-11	-1	-2
		L3/4	0	0	0	2	-1	4	0	0	0	2	4	-5	2	32	6	-15	0	-4
		L4/5	0	0	0	1	1	-3	0	0	0	1	0	1	-1	31	8	-19	0	0
		L5/S1	0	-1	-1	2	-1	-1	0	0	-1	2	-2	0	-1	26	16	-37	1	2
AR6	22	L1/2	0	0	0	3	1	4	0	1	-1	0	2	-3	-2	34	3	-6	-2	2
		L2/3	1	0	0	0	-2	1	0	0	-1	1	-1	-1	-1	36	4	-9	0	4
		L3/4	0	0	0	0	-1	3	-1	0	0	0	2	-1	0	36	3	-6	-1	2
		L4/5	-1	0	1	0	-1	-1	-1	0	0	1	0	0	2	34	8	-21	1	-1
		L5/S1	-1	0	0	0	0	0	0	-1	-1	5	-2	2	0	27	15	-40	3	-4
AR7	22	L1/2	-1	2	-2	0	0	5	0	0	-2	4	1	-1	0	33	3	-5	-1	3
		L2/3	1	0	1	2	-1	4	0	-1	-1	1	2	-1	-1	35	5	-12	0	0
		L3/4	0	0	1	-1	0	1	0	1	1	-3	1	-5	-2	35	5	-12	-1	5
		L4/5	0	0	2	-9	0	2	0	0	2	-7	3	-2	0	37	2	-6	2	1
		L5/S1	-1	0	0	-2	0	-2	-1	0	0	-3	-1	1	1	29	16	-35	2	0
AR8	23	L1/2	0	1	1	1	-1	5	-1	0	-1	1	0	-2	2	35	1	-3	0	-6
		L2/3	-2	1	2	-1	0	9	-1	0	1	0	1	-4	1	36	0	-2	-1	-5
		L3/4	0	0	1	-1	-3	4	0	-1	-1	2	0	-6	1	37	4	-8	0	-2
		L4/5	1	1	0	-5	-1	-2	-1	1	1	-3	1	0	0	35	6	-14	1	-1
		L5/S1	1	0	0	-1	-1	0	1	0	-1	0	0	0	0	27	17	-38	3	1
AR9	30	L1/2	-1	-1	-2	2	0	4	0	1	1	1	1	-4	0	33	4	-6	2	2
		L2/3	-1	1	1	1	1	5	0	0	0	1	2	-3	0	33	4	-8	-2	1
		L3/4	1	0	0	1	-3	1	-1	0	0	0	2	-5	-1	34	5	-10	-1	1
		L4/5	1	0	0	0	-2	3	-2	-1	0	1	2	-3	-1	32	8	-20	1	-1
		L5/S1	0	1	1	-5	0	-2	-1	2	-1	-5	0	2	0	26	15	-38	1	0
AR10	25	L1/2	0	-1	-1	0	-2	-1	-1	-2	-3	0	1	-1	0	35	3	-3	0	-2
		L2/3	0	0	-2	-2	0	2	0	0	0	-1	1	-5	-1	36	5	-6	0	4
		L3/4	0	0	0	0	0	2	0	0	-1	-1	2	-5	-2	36	6	-11	-3	5
		L4/5	0	0	0	1	0	2	0	0	-1	2	1	-3	0	37	7	-14	0	2
		L5/S1	0	1	-1	2	-2	-1	0	1	-1	3	0	0	2	27	19	-42	2	2

Appendix 3 The Data for the 10 Individuals who were Examined in LATERAL BENDING.

				BEND TO RIGHT						BEND TO LEFT						UPRIGHT SHAPE					
SUBJECT	AGE		LEVEL	X	Y	Z	F	AR	LB	X	Y	Z	F	AR	LB	X	Y	Z	L	AR	LB
LB1	26		L1/2	0	1	-1	-2	2	-6	1	0	-1	-4	0	4	-1	33	2	-3	0	-3
			L2/3	1	0	1	-1	1	-4	0	0	2	-3	1	3	0	34	5	-10	0	-2
			L3/4	0	1	0	-3	-1	2	0	0	0	-2	0	5	0	33	3	-4	1	-3
			L4/5	-1	-1	1	0	1	1	0	0	-1	2	-1	0	0	32	7	-17	2	-3
			L5/S1	1	0	0	3	-1	0	1	0	-1	0	-1	-4	-1	28	13	-37	0	2
LB2	37	"	L1/2	0	-1	-1	-2	0	-3	0	0	-1	-9	-2	8	1	31	4	-8	1	-3
		"	L2/3	-1	1	1	-1	4	-4	-1	0	2	-2	0	5	1	29	7	-22	-1	-4
		"	L3/4	-1	0	0	1	3	-11	2	0	-2	3	-1	-3	-2	30	7	-19	0	5
		"	L4/5	0	-1	-1	4	1	-3	2	0	1	0	-1	-3	-4	32	4	-12	-2	9
		"	L5/S1	0	0	1	3	0	-1	3	0	2	5	-2	-6	0	30	8	-27	0	3
LB3	30		L1/2	0	0	0	-4	1	-8	-1	1	0	-7	2	7	-1	35	1	1	0	3
			L2/3	1	0	0	-3	1	-8	0	0	1	-4	-3	2	-2	35	3	-6	1	7
			L3/4	1	0	-1	-2	1	-5	0	0	0	-3	0	7	0	35	5	-9	-1	0
			L4/5	-1	0	-1	-1	3	-1	0	0	0	-3	-1	3	0	35	3	-6	0	-3
			L5/S1	-1	0	-1	5	0	2	1	-1	-1	-1	-2	-4	1	27	17	-38	0	0
LB4	27		L1/2	1	-1	0	1	-1	-6	0	-1	0	0	-2	4	-1	35	2	-6	0	2
			L2/3	0	1	0	1	2	-5	-2	1	1	-3	0	10	2	35	5	-11	-1	-3
			L3/4	0	0	0	1	0	-4	0	1	1	0	-3	8	2	36	5	-13	2	-4
			L4/5	1	1	-1	0	0	-3	2	1	-1	0	-4	6	0	34	8	-16	2	-4
			L5/S1	0	-1	2	0	1	-2	2	0	2	-3	-3	0	-2	32	12	-32	2	-1
LB5	37		L1/2	1	0	1	-3	0	-3	1	0	-1	-4	-1	4	0	36	4	-5	0	0
			L2/3	0	-1	0	0	2	-4	0	0	1	-2	-1	3	0	37	4	-8	0	0
			L3/4	0	1	0	-1	2	-7	0	0	0	-2	1	2	1	37	5	-9	-2	-1
			L4/5	-1	0	1	-1	1	-1	-1	0	0	-1	-2	2	0	36	8	-19	1	-1
			L5/S1	0	-1	0	1	0	0	1	-1	0	-5	-2	-2	-2	33	15	-32	1	3
LB6	25		L1/2	1	-1	-2	-2	-1	-5	0	0	-1	-1	0	4	-1	35	0	3	0	0
			L2/3	1	-1	-1	-3	-1	-5	0	0	-1	-4	-1	6	0	36	3	-4	1	-1
			L3/4	0	0	-1	0	1	-5	0	0	1	-3	0	5	1	35	5	-9	0	-1
			L4/5	-1	0	-1	-1	2	-5	1	0	0	-4	-2	4	1	35	8	-17	0	-3
			L5/S1	1	-1	0	-3	0	-2	0	0	0	-2	-3	1	-1	30	16	-41	3	-2
LB7	22		L1/2	1	0	-2	0	-3	-7	0	0	-3	-3	0	4	-1	35	3	-5	-1	1
			L2/3	0	0	0	-1	0	-7	0	1	1	-4	-1	8	-1	36	3	-5	-1	1
			L3/4	-1	2	1	-3	2	-5	-1	1	0	-4	0	6	0	35	3	-7	-2	1
			L4/5	0	0	0	1	1	-5	0	1	0	-2	-2	4	0	34	8	-18	2	0
			L5/S1	-1	-1	-1	8	2	0	1	-1	-1	3	-3	1	0	31	12	-39	0	1
LB8	23		L1/2	-1	0	0	-5	-1	-3	-1	1	-1	-5	2	6	1	34	2	-1	-1	0
			L2/3	1	-1	0	-2	0	-6	-1	0	-1	-3	0	5	2	35	5	-8	1	-4
			L3/4	2	0	1	-1	0	-3	0	1	1	-2	-1	7	0	33	6	-12	1	-4
			L4/5	-1	0	0	0	2	-3	-1	1	-2	1	-1	5	-2	34	9	-18	-1	-1
			L5/S1	-1	-1	0	-1	-1	3	-1	0	0	1	-2	1	-1	25	17	-43	-1	2
LB9	23		L1/2	0	0	1	-2	2	-2	-1	0	2	-3	2	10	2	33	0	1	-2	-3
			L2/3	0	0	1	-1	1	-6	1	0	2	-3	-3	12	1	33	5	-12	2	-5
			L3/4	-1	0	0	0	1	-5	0	0	0	-1	-4	7	0	33	6	-12	1	-1
			L4/5	0	-1	0	-1	2	-5	0	-1	1	-1	3	-1	-4	31	5	-15	-3	7
			L5/S1	0	0	-1	3	1	0	0	1	1	1	0	-4	-1	28	15	-38	-2	4
LB10	28		L1/2	0	1	1	0	-1	-2	-1	2	2	-4	1	6	1	34	2	-4	1	-3
			L2/3	1	-1	0	0	0	-4	0	-1	1	-1	0	4	1	35	4	-9	0	-3
			L3/4	-1	1	-1	-1	2	-4	-1	0	0	-1	0	8	2	35	7	-13	0	-7
			L4/5	0	0	0	0	0	-3	0	1	0	-3	-1	3	-2	33	8	-20	0	3
			L5/S1	-1	0	0	1	1	0	0	-1	0	1	-1	-1	0	30	14	-35	-1	3