Modeling Spine Shape for the Seated Posture

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ABSTRACT

Regression models were developed for predicting spine curvature for a given posture based on the position of the chest and pelvis. The first type of model is highly individualistic, requiring measurement of the subject in several seated postures in order to determine the regression equations between chest position and lumbar spine curvature (most subjects have $r^2 > 0.8$). The second type is a general model based on a large sample of 102 subjects (50 males and 52 females). This regression model is less accurate ($r^2 = 0.62$) but is simple to implement.

I Introduction

A. Background

Knowledge of the shape of the spine in the seated posture is of primary importance to the automotive seat designer. The spine consists of three sections: cervical, thoracic and lumbar (Figure 1). The cervical spine (neck) supports the head during driving, the thoracic spine is the portion of that supports the rib cage and the lumbar spine is the low back area between the rib cage and the pelvis.

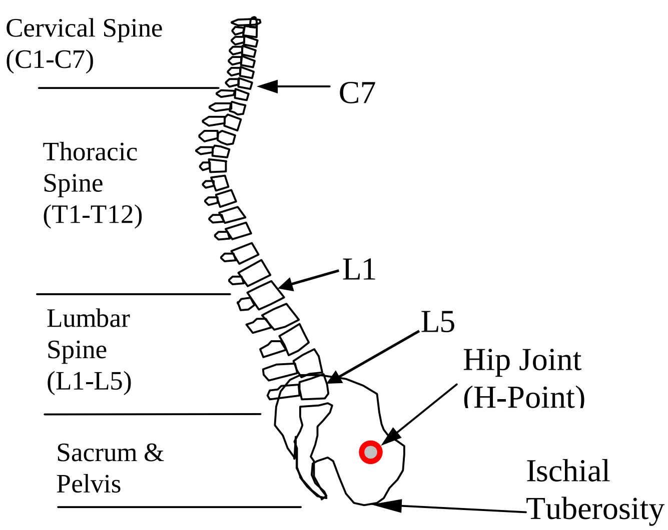


Figure 1. Spinal column and Pelvis.

In this report the terms position and posture are fequently used. We define position of a rigid body to be a description of the location of that body in three-dimensional space. Posture is defined as an internal body state that is dependent on the position of one body part relative to another. For example, an erect posture occurs when the chest is positioned relative to the pelvis such that the lumbar spine is extended (lordotic, i.e. concavity to the posterior).

Due to the rib cage, the thoracic spine is far more rigid than the cervical or lumbar areas. The overall shape of the thoracics is relatively constant for different postures compared to the cervical and lumbar sections of the spine. The lumbar spine shape changes remarkably for different postures. If seated erect, the lumbar spine is lordotic and if seated in a slouched posture the lumbar spine is kyphotic (concavity to the anterior). The goal of this research is to provide a model that accurately predicts the shape of the lumbar spine based on the position of the chest and pelvis.

We assume the rib cage to be a rigid body connected to the pelvis via the lumbar spine and that the shape of the lumbar spine is a function of the position of the chest relative to the pelvis. Anatomically, the lumbar spine consists of five vertebrae (L1 - L5); however, in this research we are most interested in the geometry of the spine, not necessarily the position of the vertebral levels. Thus, for this research, the spinous processes provide landmarks for identifying the shape of the back.

Since the nineteenth century a healthy seated posture has been considered to be when the lumbar spine has some degree of extension (lordosis), and a poor posture is when the lumbar spine is kyphotic (slumped) [1]. However, it is difficult to determine the posture of the spine without x-rays, unless the seat is modified [2]. Although modifications of this sort are acceptable for research, such changes in the seat structure affect the mechanics of the seat and therefore may affect the posture of the individual. In addition, such modifications cannot be implemented to measure posture in an existing automobile seat during on-road testing. Such a modification interferes with comfort evaluations as well as poses potential safety problems. Thus it is important that a model be developed that can reliably predict spinal posture of the seated driver occupant using non-invasive measurement techniques.

Reed, *et al* [3] mapped the shape of the back of standing subjects to estimate the shape of the back with the subject seated. They rotated the standing back shape so that the relative sternal positions were comparable, but concluded that such a mapping is very inaccurate. Monheit and Badler [4] developed a kinematic model of the human torso as an improvement to "Jack", a computer model of the human figure. Although their model has the look and feel of a human torso in motion, all movements are based on a compilation of information available in the literature, not on actual measurements.

One important aspect of any model for predicting spine shape is the need for robustness. A major shortcoming of most measurements on the human body is measurement error as well as palpation error for determining the location of a bony landmark. Palpation errors are estimated to be on the order of 5mm, but the error is probably sensitive to the landmark being palpated as well as individual variations and the amount of tissue overlying the landmark. Measurement errors for the electro-goniometer were less than 0.5mm and the maximum error for the video system was 5.5mm [5-7]. Thus, it is very important that any model for predicting spine shape be very robust.

B. Research Outline

The overall goal was to develop a model for predicting spinal posture based on non-invasive measurements of a subject seated in an existing automobile seat without modifying the structure of the seat. We have developed a method for measuring anatomical landmarks in a moving automobile using a video camera system and an on-board computer [5,7]. Thus, we can determine the position of the chest using video cameras. The pelvis position is determined using pressure mat data to locate the ischial tuberosities and video cameras to locate the ASIS [5-7]. The purpose of this project was to develop a means for predicting the shape of the spine given the position of the chest and pelvis. In order to achieve this goal, we divided the project into four stages:

i) Measure data on a large number of subjects positioned in several seated postures.
ii) Normalize the data, investigate the relationship between spine shape and chest-pelvis position and develop a model for predicting spine shape.
iii) Test the model using a seat buck to simulate drive conditions but yet allow independent measurement of the back shape for comparison to the predicted shape.
iv) Test the model on a separate group of subjects.

A large number of subjects (102) were recruited for data collection. For each subject, measurements were made to determine the location of the pelvis, chest and spinous processes in five seated postures. Subject posture was controlled using the spine anthropometry seat (SAS). Anatomical landmarks were measured using an electro-goniometer (FARO Technologies, Lake Mary, FL) and the location of the ischial tuberosities were determined using a pressure mat system (Tekscan, Boston, MA).

The same subjects were also measured in a seat buck, with the subjects seated in a modified production seat. The seat was modified to allow measurement of spine contour as well as pressure in the seat pan. In addition, the three-dimensional location of retro-reflective targets on the chest, arms, legs and pelvis were measured using four video cameras as described in [5, 7]. The position of the pelvis was determined using a combination of video and pressure data, as described in [5] and [6].

In the second stage, the data was normalized and regression equations were used to predict spinal contour based on pelvis and chest position. Spinal shape was described using curvature theory. Postures were analyzed and classified into erect (lordotic), neutral (straight) and slumped (kyphotic) lumbar spine positions based on the average curvature of the lumbar spine. The robustness of the regression models were analyzed to determine the effects of measurement errors.

The chest and pelvis data from the seat buck were used to estimate the lumbar spine shape and the results were compared to the spine contours measured in the seat buck. This provided a test of the accuracey with which the lumbar spine shape can be predicted from the video and pressure data.

In the final stage, the model was tested using existing data which had been collected for a different study. Twenty six male subjects were measured in different postures, with the location of the chest, pelvis and spine determined using the electro-goniometer and pressure mats. The model was then tested against this data to determine the errors between model predictions of subject posture and the measured posture of the subject. This provided an independent test of our spine model on a separate group of subjects.

II Methods

A. Equipment

1) Pressure Mat System

Tekscan (Boston, MA) pressure mats were used to locate the contact area and measure the centroid of the high-pressure peaks under the ischial tuberosities of a seated subject. Two 112mm X 112mm mats (with 1.2mm X 1.2mm sensors on 2.5mm centers, 10psi max pressure) were used (Figure 2).

2) Electro-goniometer

The CCM (FARO Technologies, Lake Mary, FL) is a six degree of freedom electro-goniometer [5] capable of measuring the three-dimensional position of a point with an error less than 0.5 mm. It was used to measure the location of the anatomical landmarks listed in Tables 1, 2 and 3.

3) Spine Anthropometry Seat (SAS)

The spine anthropometry seat [5,6] was used to take anthropometric measurements and for collecting spine and pelvis data for this study. The SAS is illustrated in Figure 2. In this report we will describe the use of this seat as it relates to spine and posture measurements. The seat was designed to support a subject in five seated postures; upright, erect, and three slumped postures (three postures with the lumbar spine in flexion). The seat had four major controls for adjusting/controlling posture:

a) Adjustable Height. The height of the seat was adjustable in order to control knee angle. The knee angle was held constant at 105^o to reduce the effect of the hamstring muscles on pelvic orientation.

b) Pelvic Stabilization. A seat belt was combined with the pelvic plate shown in Figure 2 to hold the subject's pelvis in a single fixed posture. In a previous report we investigated the extent to which we were able to hold the pelvis in one position [6]. The average motion of the Ischial tuberosity was less than 1.0 cm.

c) Back Rests. Backrests could be adjusted vertically and horizontally and were designed to support the chest as the subject leaned rearward to create an extended lumbar posture.

d) Chest Support. For the three flexion postures, the subject leaned forward to generate a flexed lumbar spine. The position of the chest and the changes in chest position from one posture to the next were controlled via the position of the chest support. The chest support is illustrated in Figure 2. The position of the chest support was measured using linear optical encoders (ANILAM, Inc), to measure the X (horizontal) and Z (vertical) positions.

Coordinate System. Since the electro-goniometer was moved between two measurement stations (i.e. seat buck and SAS) for each subject's laboratory session, the coordinate system had to be quickly and accurately redefined. For the SAS, the origin was 14.5 cm behind the seat back and lying approximately in the mid-sagittal plane as shown in Figure 2.

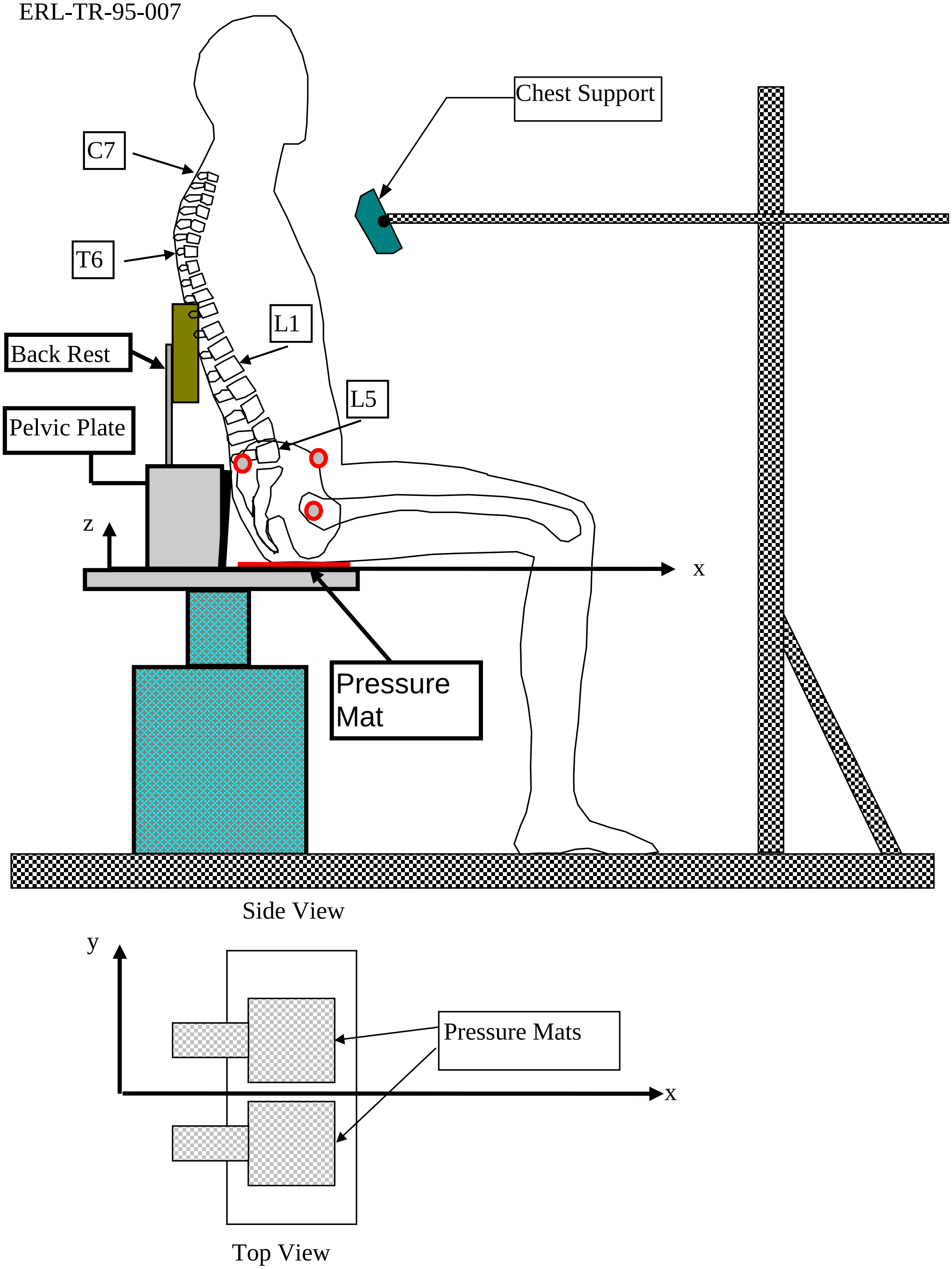


Figure 2. Position of the subject, location of pressure mats and illustration of the landmarks measured for this research.

The +Z axis was directed upward, perpendicular to the horizontal seat surface of the SAS. +X was defined in a forward direction and +Y was defined in the left lateral direction. Thus, a right-handed, orthogonal axis system was defined that corresponded to the axes of the cardinal anatomical planes of the body (i.e. sagittal, frontal, and transverse).

4) Seat Buck

A 1992 Pontiac 6000 was modified so that the engine compartment forward of the fire-wall and the rear of the car from just behind the B-pillar were cut and removed. The remaining interior with roof, windshield and front doors still operable were mounted on a platform. The cut surfaces were cleaned and all edges were finished for appearance and safety. The passenger seat was removed.

The seat that was placed in the seat buck was a six-way adjustable AM6 W seat with a power seat back recliner; however, the subjects were allowed to make adjustments in only the fore/aft and the up/down directions. Three different displacements were measured using linear potentiometers: (1) fore/aft displacement, (2) front riser height, and (3) rear riser height.

Four CCD video cameras were installed as previously described [5]. The seat back was modified with a series of spine displacement transducers (see [5] for further details) and the cushion upholstery had a zipper installed around the outer edge of the seat foam so that a pressure mat could be inserted between the upholstery and foam (see Figure 4).

Location of the pressure mat was measured with a calibration structure that was placed on the seat cushion so that pressure cells were mapped to the seat coordinate system (seat coordinate system is described below). Points on the calibration structure were measured with an electro-goniometer (CCM) to define the unloaded seat surface contour in 3-D space.

Coordinate System. Since the electro-goniometer (CCM) had to be moved to different stations during a laboratory measurement session, the coordinate system in the seat buck had to be re-established before every measurement session. All data were measured with respect to a coordinate system defined relative to the seat attachments to the seat buck floor as shown in Figure 3.

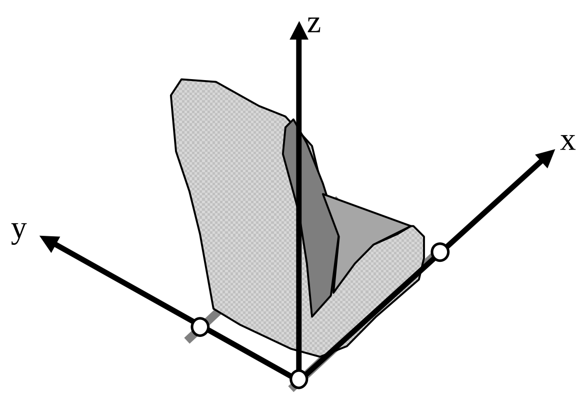


Figure 3. Coordinate system in seat buck and vehicle laboratory.

Spine Displacement Transducers. The seat back in the seat buck was modified so that we could measure the contour of a subject's spine. Steel rods were placed inside a plastic sleeve with a spring attached so that the rods were forced forward by a spring (Figure 4). A series of these were placed in the center line of the seat back so that they contacted the spine of a subject sitting in the seat (see Figure 4), allowing us to measure spinal contour.

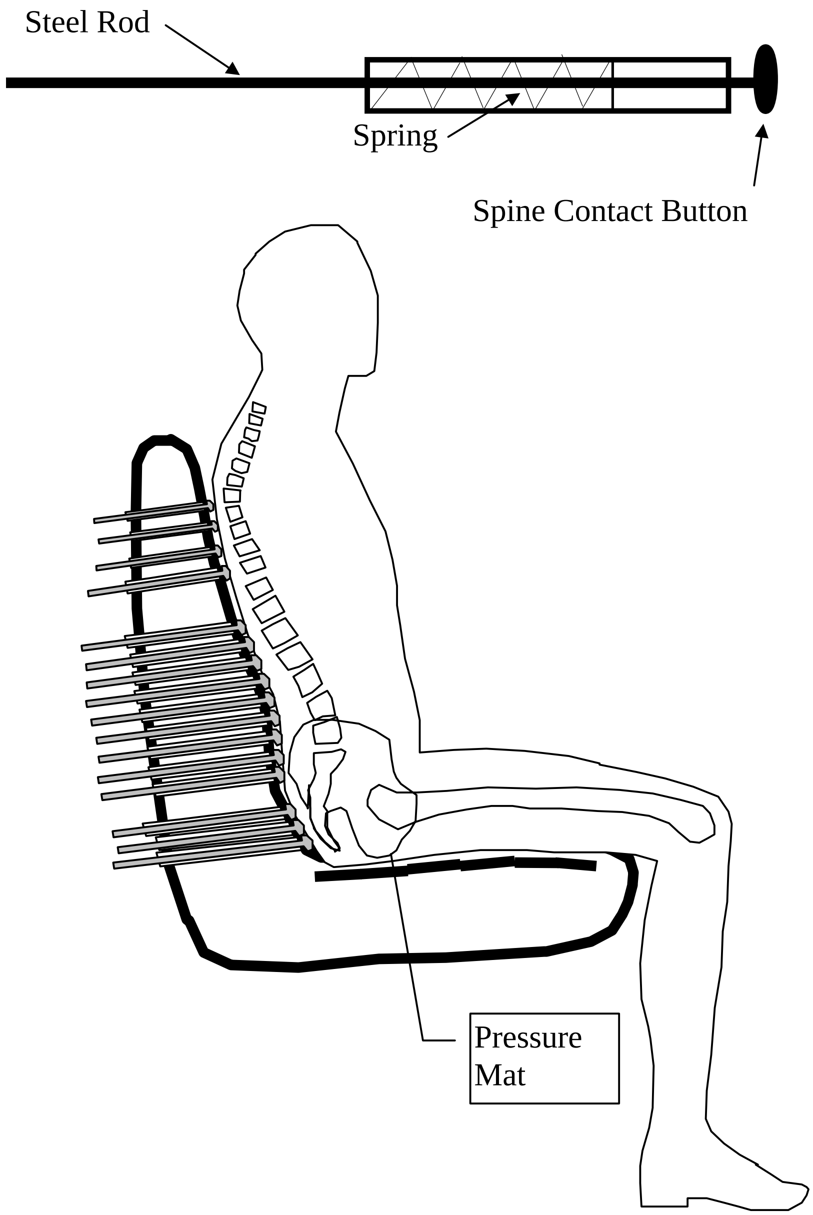


Figure 4. Measuring Spine Contour using Spine Displacement Transducers (SDT).

5) Drive Posture Measurement Station (DPMS)

Data from a previous study was used to independently test our spine curvature prediction models. Twenty-six subjects had previously been measured on our drive posture measurement station (DPMS). The DPMS is designed to simulate an automobile environment, but still allow precise anthropometric measurements. It consists of a hard seat, foot rest and steering wheel, all positioned according to the specifications from a mid-size car drawing. The seat pan angle was 8^o from horizontal and the seat back 19^o from vertical (101^o from the seat pan). Linear rails and bearings mounted on either side of the seat pan support the seat back and allow it to slide fore and aft (see Figure 3). The seat back fore/aft position could be positioned in 1cm increments. A slot in the seat back allowed access to the subjects' spinal region for measurement of spinal landmarks in any seated postures.

Pressure mats were located immediately below the ischial tuberosities of the subjects, representing the location of D-point. The seat was mounted to the platform and its height fixed so that the center of the pressure mat system was 160mm above the heel point. This height was within the range for that of the D-point to heel point heights from a mid-size car package drawing.

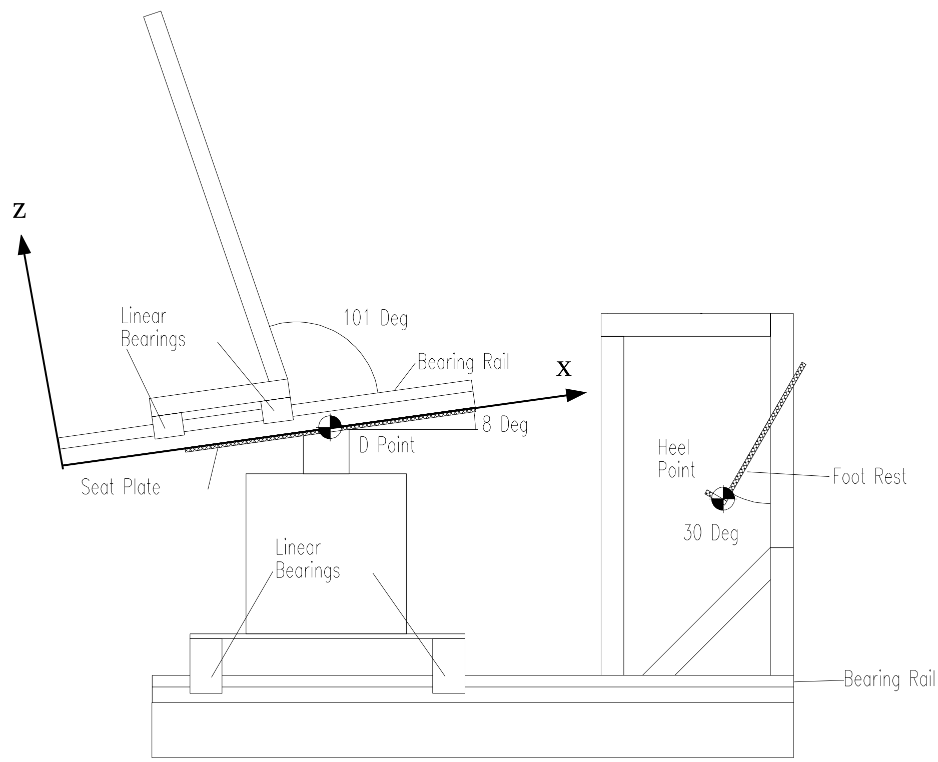


Figure 5. Simulated drive posture measurement station.

Coordinate System. The electro-goniometer coordinate system was defined relative to the frame of the seat as shown in Figure 5. As a result, the X axis (running from posterior to anterior) was tilted 8^o from the horizontal and the Z axis (running from inferior to superior) was tilted 8^o from the vertical. The Y axis was positive going from right to left.

B. Subjects

For the spine anthropometry seat (SAS) and the seat buck measurements, one hundred and two subjects were recruited with ages ranging from 25 to 76 as described in a previous report [5]. There were an equal number of males and females. After a subject arrived, the purpose and procedures of the experiment were explained and the subject signed an informed consent form approved by the MSU UCRIHS committee. In a previous study, twenty six male subjects were recruited from the student population at Michigan State University for measurements on the drive posture measurement station (DPMS). Data from this study was used to further test our spinal regression models.

For all subjects, file folders with the protocol, consent form, data collection forms, and subject reimbursement forms were placed in the conference room where the subject was informed of the goals of the project. Upon arrival, the goals of the study were outlined and the data collection methods were described. Throughout this description the subject was encouraged to ask questions. After the subject signed the human use consent form, they changed their clothing to bike shorts and a tank top. For the SAS and DPMS measurements, subjects were asked to remove their shoes and all data was collected with subjects either bare foot or in socks.

C. Data Collection Procedures

1) Spine Anthropometry Seat

Clothing All subjects were provided biking shorts and a tank top. Shoes were removed for the pelvic and spine data collection phase of the study.

Equipment Setup The CCM was moved to a preset position and the coordinate system was defined as described previously and illustrated in Figure 2. The pressure mats were positioned as shown in Figure 2 and the pressure mat handles were attached. The seat height was lowered to its lowest setting and the pelvic plate was positioned to the upright position.

Subject Position The subject was asked to sit in a position such that two clearly defined pressure peaks were visible on the pressure mats (Figure 2). The output of each pressure mat was shown in real time on a computer monitor, allowing the adjustment of the subject's position until the high pressure areas created by the ischial tuberosities were centered on the pressure mats. For some subjects the pressure readings were saturated beyond the range of the mat, so a foam pad was placed over the pressure mats to reduce any potential for damage to the mats.

Once the subject was positioned so that reliable pressure data were measured for their seated position, a seat belt was secured across their pelvis. The pelvic plate was adjusted forward (Figure 2) to insure the pelvis was held fixed. The subject’s feet were placed so that the tibia was perpendicular to the floor. The seat height was adjusted so that the knee angle was at 105^{o}. Subjects were measured in five postures:

1. Upright, lumbar spine either neutral or slightly lordotic
2. Extension, lumbar spine having a significant lordosis
3. Slumped 1, the lumbar spine neutral or slightly kyphotic
4. Slumped 2, lumbar spine having a moderate kyphosis
5. Slumped 3, lumbar spine having a greater kyphosis than in 4

These postures represent the full range of positions for a subject in a driving posture. The three-dimensional coordinates were measured for points on the thigh, pelvis, chest and spine for each of the five postures. The order of the posture measurements was the same for all subjects.

Upright Posture

After positioning the pelvis, thigh and legs as described above, the subject was asked to sit in an upright posture, with the lumbar spine either straight or slightly lordotic. A shoulder support was placed in front of the subject's shoulders so that the support touched the shoulder. The subject was asked to maintain their posture without resting any weight on the support. The shoulder support was instrumented so that the X and Z position of the shoulder pads were known. The initial position of the subject's shoulders was recorded. Subsequent positioning of the subject was defined relative to the position of the shoulders in the upright posture. Once positioned, the locations of anatomical landmarks were measured using the CCM, except for the ischial tuberosities, which were measured using the pressure mat system. Data collection methods are explained in more detail below.

Extended Posture

The seat back rest positions (see Figure 2) were adjusted so that they were near the level of the lower-thoracic spine and at least one inch posterior to the back of the person while they were sitting in the upright posture. The person was asked to lean back against the backrests. Since the pelvis was fixed in an upright posture, leaning the chest backward generated a lordotic lumbar curvature. The shoulder support was positioned so that it touched the subject's shoulder. The position of the shoulder support was recorded. For all subjects, the minimum motion of the shoulder was 10 cm posterior. Data collection methods were the same as for the upright posture.

Slump Postures 1-3

For the first slumped posture, the chest supports were adjusted to translate a specified X (≈10cm forward) and Z (≈10cm inferior) distance from the original position from posture 1. The subject was then asked to bend forward so that the upper chest and/or shoulders were resting against the chest support. For the slump 2 and slump 3 postures, the subject was asked to sit up while the chest support was translated a specified X (≈5cm further forward) and Z (≈5cm further down) distance from the previous posture. The subject was asked to lean forward to rest their chest at the new position. Data collection methods were the same as for the upright posture.

Data Collection

The following data was collected for each of the postures described above. Pressure mat data was recorded first. The electro-goniometer was used to measure the three-dimensional position of all other landmarks. Landmarks on the spine, pelvis, and legs were measured (see Table 1). The position of the chest support was also recorded.

1. Right lumbar support
2. Left lumbar support
3. Floor
4. Knee
5. Hip
6. R ASIS
7. Shoulder
8. Suprasternale
9. Sternum 2
10. C7

11. T2	18. L2
12. T4	19. L3
13. T6	20. L4
14. T8	21. L5
15. T10	22. S1
16. T12	23. R PSIS
17. L1	

Table 1. Landmarks measured on subject when seated on the SAS.

2) Seat Buck

All subjects measured at the SAS measurement station were also measured in the seat buck. The seat was placed in the rear-most and most inferior position. After the subject was seated, they were asked to adjust the seat until they were in a comfortable driving position. Retro-reflective targets were placed on the subject over the landmarks listed in Table 2.

Seat position data was recorded electronically using an A/D board to digitize the voltage of the linear potentiometers. Video images from four video cameras (see [5] for further details) were captured using a video capture board and saved to disk. The positions of the retro-reflective targets were determined using 3DAQ software (described in [6,7]). Two points on each of the SDT's were recorded using the electro-goniometer. The electro-goniometer was also used to measure the sternum landmarks, and ASIS. This provided an independent measurement of these landmarks for comparison to the video anthropometry measurements. The position of C7 was also recorded using the electro-goniometer, providing a spinal landmark for mapping the location of the spinous process (details are described in section II.D.3) and thus locate the lumbar spine.

1. Suprasternale	6. Knee
2. Sternum 2	7. Ankle
3. Neck	8. Elbow
4. Shoulder	9. Wrist
5. R ASIS	

Table 2. Placement of Retroreflective Targets for Subjects Seated in the Seat Buck.

3) Drive Posture Measurement Station

In the DPMS, a total of twenty-six subjects were measured. Ten were measured in three postures; sixteen were measured in four postures. Each of the postures is defined below.

Initial Posture. The subject sat so that his ischial tuberosities were on the pressure mats and his feet rested on the footrest (see Figure 3). The fore/aft position of the seat was adjusted to obtain a 125^{o} knee angle. The subject was asked to sit with his back resting against the seat back and his gluteal muscles touching the seat back. This position straightened his lumbar spine region.

The pressure mat output was checked to insure that the ischial tuberosities were located on the mats and to insure the equipment was functioning properly. The CCM was positioned so that the ball tip could reach the upper body landmarks. The coordinate system was defined and the three-dimensional coordinates of the required data points were recorded using the electro-goniometer. A list of the data collection points is described in Table 3.

Extended Posture. Once the initial posture data was collected, the subject was asked to extend his back and lean forward. This movement tilted his pelvis forward. The seat-back was moved forward from 10-30mm until it contacted the back of the pelvis. The subject was instructed to lean back without letting his pelvis slide forward. This position extended his lumbar spine into a lordotic, erect posture.

The subject was asked to relax his lumbar musculature to insure that the lordosis was not maintained by muscle contraction. We reasoned that it was important for the subject to maintain a lordosis without appreciable muscle contraction since the muscles might relax and result in a change in his posture during the data collection process. The lumbar spine was palpated to determine if a lordotic posture had been achieved and to determine if the lumbar musculature was being actively contracted. If we were not satisfied with the extent of the lumbar lordosis, the procedure was repeated by moving the seat-back posterior, having the subject resume the initial posture and repeating the steps described above to achieve a lordotic lumbar curve. Data collection followed the same procedure outlined for the initial posture.

1. C7		14. L1
2. T1		15. L2
3. T2		16. L3
4. T3		17. L4
5. T4		18. L5
6. T5		19. S1
7. T6		20. S2
8. T7		21. RPSIS
9. T8		22. LPSIS
10. T9		23. Suprasternale
11. T10		24. Sternum 2
12. T11	Simultaneously record pressure mat data ←	25. R. ASIS
13. T12		

Table 3 Data collected for the DPMS.

Slouched Posture 1 (Intermediate Slouched Posture). The first ten subjects were not measured in this posture. This posture was added after a preliminary analysis of the first ten subjects indicated that the originally defined slouched posture may be excessive and not representative of an automobile driver's posture. The intermediate slouched posture followed the extended posture. The subject was asked to lean forward while the seat back was moved 5cm posterior relative to the position it had been in for the neutral posture. The subject was asked to "unroll" his back until his chest was leaning comfortably against the seat back. The subject was specifically instructed to keep his pelvis from sliding forward or backward. Data collection followed the same procedure outlined for the initial posture.

Slouched Posture 2 (Maximum Slouched Posture). The maximum slouched posture followed the extended posture for the first ten subjects. For the remaining 16, this posture was recorded after the intermediate posture had been recorded. The subject leaned forward and the seat back was moved rearward 10cm posterior to the neutral posture position. The subject “unrolled” his back until his chest was leaning comfortably against the seat back. The subject was again instructed to keep his pelvis from sliding forward or backward. Data collection followed the same procedure outlined for the neutral posture.

D. Data Analysis

1) H-Point and D-Point

Pressure mat data was used to estimate the locations of the ischial tuberosities as previously described [6]. To briefly summarize, the pressure mat positions were known with respect to the coordinate system defined by the electro-goniometer; thus each cell within the pressure mat was mapped to the same coordinate system used to measure the remaining landmarks. Assuming that the ischial tuberosities were at the point of peak pressure, the position of the ischial tuberosities was determined relative to the measurement coordinate system. However, in most cases, there was no distinct pressure peak; thus, the pressure data was analyzed as follows. The pressure data was smoothed using a Gaussian mask to remove the effects of isolated high pressure points. All data below a threshold of 50% of the scale maximum was removed. Of the remaining pressure data there were several connected components, the largest component was assumed to be under the ischial tuberosity; thus the centroid of the largest connected component was used to define the location of the ischial tuberosity. Once the ischial tuberosity location was determined, the hip joint center (H-point) was estimated for each subject using the method described in [6].

2) Pelvic Coordinate System, Chest Angle and Data Normalization

We assume that lumbar curvature for the seated posture is completely defined by the position of the chest with respect to the pelvis. Thus, all relevant data was converted to a coordinate system oriented in the pelvis, with the ischial tuberosity as the origin and the line from ischial tuberosity to ASIS forming the z-axis (see Figure 6). This was a convenient coordinate system since the only pelvic data available in the seat buck and drives were these two points [5].

The rib cage is a relatively rigid object; although it does have some flexibility, this is often assumed to be negligible. The sternum is a rigid body that can be used to define the chest angle. We defined the angle between the sternum and z_{pelvis} to be the chest angle, using the two sternum targets to define a line parallel to the sternum. The angle shown in Figure 6 illustrates the chest-pelvis angle. It must be noted that the angles in Figure 6 use the right hand rule about the y-axis (into the page). Using the angles illustrated in Figure 6, the chest angle and the chest-pelvis angle are both negative while the pelvis angle illustrated is a positive angle. It is also important to note that a zero degree chest-pelvis angle does not necessarily correspond to a neutral lumbar posture.

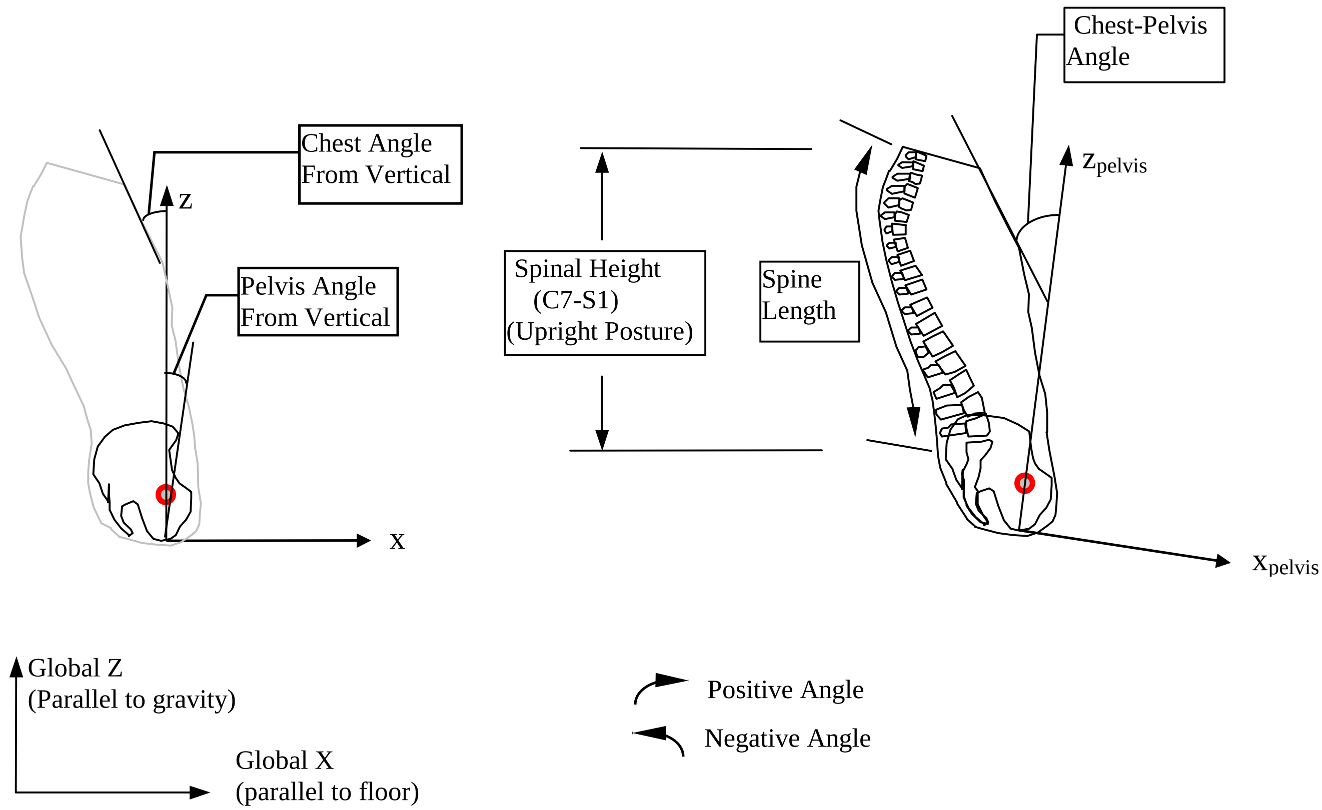


Figure 6 Pelvic coordinate system, chest angle, spinal height and spinal length.

There was a wide range in the stature of subjects in this study; thus, in order to develop a model, the effect of body size needs to be removed as a variable. Since the goal of this research is to understand the geometry of the spine, we used spine height as the normalizing variable. Spine height was defined as the vertical height from C7 to S1 relative to a line parallel to the direction of gravity (see Figure 4) as measured in the upright posture. The upright posture was used since it is equivalent to the standard anthropometric measurement posture.

3) Locating the Lumbar Spine in the Seat Buck

As described previously, the location of two points were recorded on each of the 16 SDT's: the back of the pin (see Figure 4) and a second point at the back of the plastic sleeve. A unit vector describing the direction of the pin was determined relative to the seat buck coordinate system (Figure 3). The position of the front of the pin (the contact point with the back) was determined by multiplying the unit vector with the known length of the rod. Thus, the position of 16 points along the spine were determined from the SDT measurements and measuring the position of C7 (for a total of 17points) provided a reference for mapping the location of the remaining spinous processes. The details of this procedure are described below.

A third order polynomial was fit to the 17 spine points measured in the seat buck . A third order polynomial was used since it has been shown to fit spine data to a high degree of accuracy [13].

From the SAS data, the distance between spinal landmarks were known for the five measurement postures. We assumed that the seat buck posture would be similar to the upright posture from the SAS data. The Euclidean distances between each landmark was determined from the upright posture, so that the distance along the spine from C7 to each landmark was known. For example, to locate T4 on a given subject, first determine the length from C7 to T4 using the data from the upright SAS posture, where the C7-T4 length is defined as the Euclidean distance from C7 to T2 plus the Euclidean distance from T2 to T4. Then, using C7 as the reference point, T4 is defined as the length along the cubic polynomial that corresponds to the measured length from C7 to T4. The lumbar spine was defined as the region along the 3rd order polynomial that lies between the estimated positions of T12 and S1. The curvature of the lumbar spine was then determined using the procedure defined below, in Section II.D.4.

4) Spinal Curvature

The spine data was divided into thoracic and lumbar data segments. The lumbar curvature was defined as the curve connecting the points from T12 to S1. The lumbar spine data was fit with a second order polynomial of the form:

$$x = Az^2 + Bz + C \qquad (1)$$

where A, B and C are constants, z is the vertical height of a given point along the lumbar curve and x is the horizontal position of the point. The variables A, B and C were found using a least-squares estimate of the best-fit line for the data for each posture of each subject.

The curvature (k) can then determined for any point along the lumbar segment, where:

$$k = \frac{(d^2x/dz^2)}{[1 + (dx/dz)^2]^{3/2}} = \frac{2A}{[1 + (2Az + B)^2]^{3/2}} \qquad (2)$$

Curvature can be determined at each point, from T12 to S1. An average curvature was determined for each lumbar data segment for each posture by averaging the curvature over the entire length of the data segment:

$$K_{ave} = \frac{\int_{H_1}^{H_2} k\,dz}{\int_{S_1}^{S_2} ds} \approx \frac{\int_{H_1}^{H_2} k\,dz}{\int_{H_1}^{H_2} dz} \qquad (3)$$

where S is the length of the curve, ds is the differential of the length and H_1 and H_2 are the points corresponding to the beginning and end of the lumbar spine along the z axis. Solving the integrals for a curve of the type in equation (1) results in an average curvature of:

$$K_{ave} = \frac{2AH_2 + B}{H((2AH_2 + B)^2 + 1)^{1/2}} - \frac{2AH_1 + B}{H((2AH_1 + B)^2 + 1)^{1/2}} \qquad (4)$$

where $H = (H_2 - H_1)$. This process provides a better fit of the data than can be achieved by a curve with a single fixed radius. The radius at any point on the curve can be determined by simply inverting the curvature at that point (i.e. $R = 1/k$, where k is found using equation (2)). The units of curvature are radians/unit length. Thus, for the normalized data, the curvature is in radians/spine height (rad/SH).

Using the coordinate system illustrated in Figure 4, the curvatures calculated using equation (2) and/or (4) have a negative value for curves corresponding to an extended (lordotic) lumbar spine. That is, the center of curvature would be located posterior to the subject. Positive curvatures correlate with flexion (kyphosis) of the lumbar spine.

For the seat buck data, the entire spine is modeled as a third order polynomial of the form $x = Az^3 + Bz^2 + Cz + D$; thus, in order to determine the curvature, equation (2) becomes:

$$k = \frac{6Az + 2B}{[1 + (3Az^2 + 2Bz + C)^2]^{3/2}} \qquad (5)$$

The average curvature of the lumbar spine for the seat buck data was determined numerically, by averaging a large number of points in the lumbar spine area.

5) Lumbar Curvature Model

The basic assumption of this research is that the shape of the lumbar spine is a function of the position of the chest relative to the pelvis. In addition, we are investigating only flexion/extension, thus we model the motion as planar motion. Planar motion has three degrees of freedom: horizontal translation, vertical translation and rotation of the body. Thus there are a maximum of three linearly independent variables that can describe the position of the chest relative to the pelvis. Due to the link nature of the lumbar spine, it is expected that translation of the chest is highly dependent on the angle of the chest orientation. If the chest rotated about one point on the pelvis, then all chest motions could be fully explained by the chest-pelvis angle. Similarly, if the lumbar spine were a linkage system with fixed centers of rotation, then, again, all chest motions could be explained by the chest-pelvis angle. However, the lumbar spine does not have fixed centers of rotation; there is considerable translation allowed between the vertebral bodies [8].

In addition to the general mechanics of the function between the chest, lumbar spine and pelvis, there is the individual variation that must be accounted for. For example, slight differences in pelvis and chest anatomy will give a different chest-pelvis angle for two individuals, even though they have the same lumbar curvature. Even after adjusting for differences between chest and pelvis anatomical variation, there is individual variation in the lumbar spine itself. Even the number and shape of the vertebra are highly variable [9]. Thus, it would be expected that an accurate model for predicting spinal curvature must be individualistic, requiring measurements of a subject in a number of postures to insure accuracy.

In light of the above discussion, the data will be analyzed in two ways. In the initial analysis we will investigate the relationship between the chest, pelvis and lumbar spine curvature for each individual subject and generate a model for predicting the lumbar spine geometry for each subject. In the second analysis we will investigate the same relationships in general, including all subjects. The result will be a general model for predicting lumbar shape based on chest-pelvis position.

Given that the shape of the lumbar spine follows a second order curve, the variables A and B in equation (1) can be found if the tangents of the curve at T12 and S1 are known (see Figure 7). Denoting the tangent at T12 as θ_T and the tangent at S1 as θ_s the variables A and B can be determined as a function of the height (H) of the lumbar spine. Differentiating equation (1) gives: $dx/dz = 2Az + B$

It can be shown that $dx/dz = \theta(z)$, thus, at $z = H_1$ and $z = H_2$ we have:

$$\theta_s = \theta(H_1) = 2AH_1 + B$$
$$\theta_T = \theta(H_2) = 2AH_2 + B \qquad (6)$$

Solving for A and B gives:

$$A = \theta_T/2H \qquad B = -\theta_T H_1 /H \qquad (7)$$

Using these values to solve for K_{ave} in equation (4) gives:

$$K_{ave} = \frac{\theta_T}{H(\theta_T^2 + 1)^{1/2}} - \frac{\theta_s}{H(\theta_s^2 + 1)^{1/2}} \qquad (8)$$

Thus, the average curvature can be determined if the tangents at T12 and S1 are known.

In this research we will explore the extent to which the tangent angles are a function of the position of the chest relative to the pelvis. It is expected that θ_T will be highly dependent on the chest angle and that the range of θ_s will be limited to small values. If this is true, then the first term in equation (8) will dominate. The equation $\theta_T / (H(\theta_T^2 + 1)^{1/2})$ has the general shape shown in Figure 8. There is a significant portion of the equation that can be approximated by a straight line and the slope of the linear portion is approximately 1/H, assuming H is constant. However, for different postures, the height of the lumbar spine is expected to be variable. To linearize the relationship, the angle must be normalized by the lumbar spine height. The extent to which the lumbar spine height affects the relationship between θ_T and spine curvature will be investigated. The above model indicates that the relationship between lumbar curvature and chest position is likely to be linear, thus we will examine the effectiveness of linear regression as a means for developing a model for predicting lumbar curvature based on chest position.

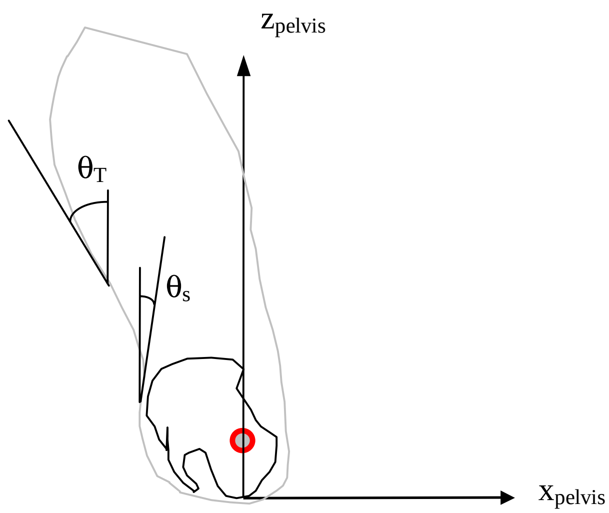


Figure 7. Tangents of the lumbar spine at T12 and S1. θ_T is the tangent of the lumbar curve at T12, θ_s is the tangent of the lumbar curve at S1.

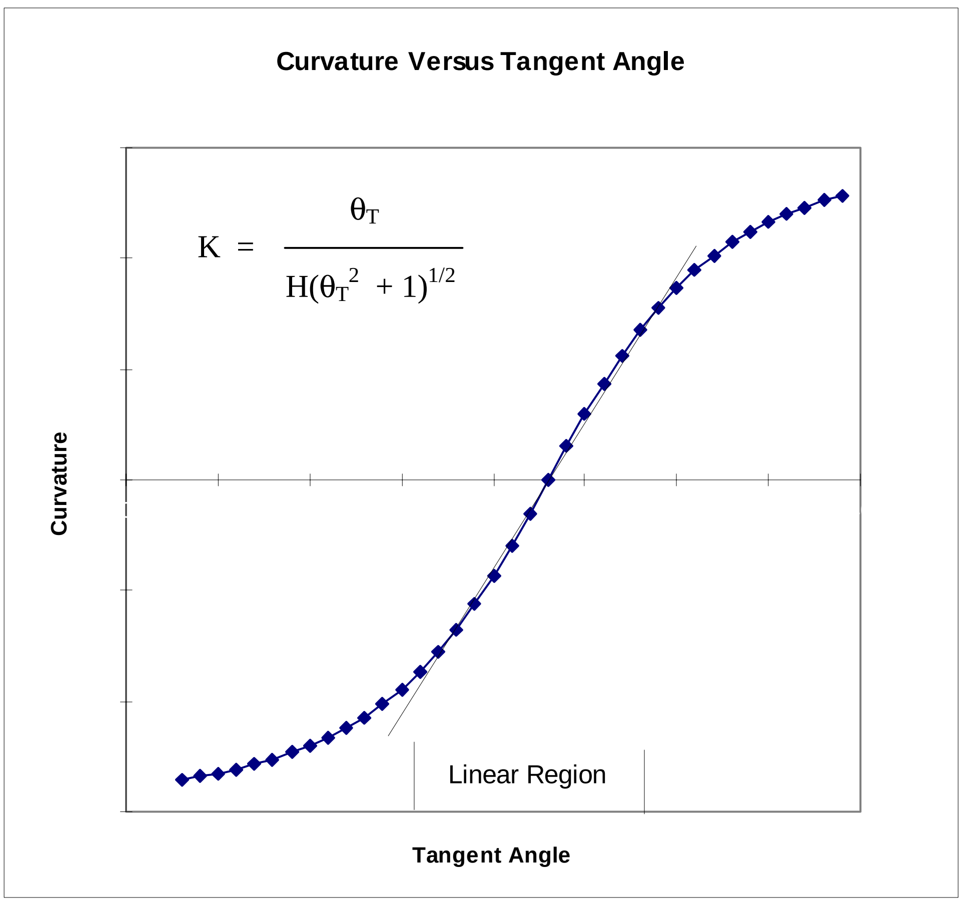


Figure 8. Curvature versus tangent angle. The relationship is linear within a range around zero, thus the relationship between chest angle and lumbar curvature is expected to be linear.

III Results

A. Spine Anthropometry

1) Spine Height and Length

The average cervicale sitting height (height from seat surface to C7 in the upright posture) for females was 608.0mm (±23.3) (standard deviation) and 658.5mm (±26.2) for males. These are low compared to the 1988 anthropometric survey of army personnel [12], which reports 628.5mm for females and 676.6mm for males. If subjects below the 10th percentile are dropped, then the averages for our subjects are 622.5mm for females and 668.8mm for males. These are at the 45th and 40th percentile for females and males, respectively when compared to reference [12].

We were concerned that subjects with short torso heights may be anthropometrically different than those with taller torso heights, and that this may affect the biomechanics of the spine. Since all data were normalized for each subject using spinal height (SH) in the upright posture (see Figure 6), the effect of size was removed. However, spine biomechanics are sensitive to the vertebrae height to spine height ratio. Thus, we needed to determine if vertebra:spine ratios were independent of subject height. The vertical distance between each spinous process in the upright posture was divided by spine height (SH) (vertical distance from C7 to S1) to provide the vertebra:spine ratio for each lumbar spine motor unit. Male and female subjects were classified into four stature categories:

Short (≤25th percentile)
Medium 1 (between 25th and 50th percentile)
Medium 2 (between 50th and 75th percentile)
Tall (≥75th percentile)

Subjects were placed into each category depending on their stature, using the percentiles given in reference [12]. An ANOVA test showed there were no significant correlations between the vertebra-spine ratios and stature classification (females $p = 0.431$, males $p = 0.687$). Thus, normalizing by spine height removes the effect of stature on spine anthropometry. We assume that this normalization also removes the effect of stature on spine biomechanics.

The average spine height (C7 to S1as shown in Figure 6) in the seated, upright posture was 430.2 mm (±26.8) for females and 483.8mm (±25.7) for males. The height of each spinal landmark is given as a proportion of the spine height (SH) in Table 4a. The small standard deviations indicate that this provides a reliable method for predicting the position of spinal landmarks if the height from S1 to C7 is known. In addition, the heights of the thoracic (C7-T12) and lumbar (L1-L5) areas are also summarized in Table 4a for males and females.

The standard anthropometric measurement for sitting posture is the cervicale sitting height. Being able to predict the approximate location of spinal landmarks from this anthropometric measurement may have future value; thus, we report the height of each spinal landmark (C7 to S1) as a proportion of the C7 sitting height (C7Ht) in Table 4b. The relatively small stadard deviations indicate these proportions are relatively constant across subjects. The results of the ANOVA described above indicate that these proportions are independent of stature, and thus can be applied to any subject, regardless of their body size.

The angle of the chest and pelvis relative to vertical (see Figure 6) are summarized in Table 4c. There is a difference in the chest-pelvis angle between males and females; however, the difference may be due to slight differences in a subject's position. Females had an average lumbar radius of 374mm in the posture compared to 576mm for males that was likely caused by the larger chest-pelvis angle the females had. Thus, in spite of our attempts to obtain an equivalent position for all subjects, there were differences between males and females.

	F Ave	F Std	F Ave (mm)	M Ave	M Std	M Ave (mm)
C7	1.000	0.000	430.2	1.000	0.000	483.8
T2	0.901	0.018	387.6	0.906	0.016	438.2
T4	0.778	0.037	334.5	0.790	0.028	382.4
T6	0.649	0.045	279.0	0.662	0.036	320.4
T8	0.534	0.041	229.8	0.539	0.038	260.8
T10	0.449	0.031	193.3	0.437	0.035	211.3
T12	0.364	0.032	156.7	0.345	0.030	167.0
L1	0.304	0.032	130.7	0.286	0.030	138.1
L2	0.235	0.034	101.0	0.219	0.030	106.0
L3	0.167	0.033	72.0	0.155	0.028	74.9
L4	0.100	0.025	43.0	0.096	0.026	46.4
L5	0.046	0.016	19.7	0.042	0.015	20.5
S1	0.000	0.000	0.0	0.000	0.000	0.0
T Spine Ht (C7-T12)	0.637	0.033	274.0	0.655	0.030	316.8
L Spine Ht (L1-L5)	0.257	0.033	110.7	0.243	0.028	117.7

Table 4a. Vertical Position of Spinal Landmarks relative to S1. Units are in proportion to the upright spine height (SH) (C7 to S1).

	F Ave	F Std	F Ave (mm)	M Ave	M Std	M Ave (mm)
C7	1.000	0.000	608.0	1.000	0.000	658.5
T2	0.930	0.013	565.6	0.931	0.013	613.4
T4	0.843	0.027	512.5	0.847	0.025	558.0
T6	0.752	0.032	457.1	0.753	0.030	495.9
T8	0.671	0.030	408.0	0.662	0.032	436.2
T10	0.611	0.023	371.2	0.587	0.028	386.4
T12	0.549	0.025	334.1	0.519	0.025	341.8
L1	0.507	0.025	308.1	0.475	0.027	312.7
L2	0.458	0.028	278.4	0.426	0.029	280.6
L3	0.411	0.030	249.6	0.379	0.030	249.3
L4	0.362	0.029	220.4	0.333	0.029	219.6
L5	0.324	0.027	197.3	0.296	0.029	194.9
S1	0.292	0.021	177.7	0.265	0.024	174.3

Table 4b. Sitting Height of Each Vertebra (C7 to Seat Surface). All measurements are in SH units unless noted otherwise.

	Chest Angle	Pelvis Angle	Chest-Pelvis Angle	Lumbar Radius
F Ave	-29.2	19.8	49.0	374 mm
F Std	6.3	4.2	7.9	
M Ave	-27.2	17.2	44.3	576 mm
M Std	6.4	5.1	8.2	

Table 4c. Angle of the Chest and Pelvis and Radius of the Lumbar Spine in the Upright Posture. All angles are in degrees.

The distances between spinal landmarks are summarized in Table 5a. These are the Euclidean distances between each landmark and are given in SH units. In Table 5b, the length from S1 to each spinous process is given, and in Table 5c, the length from C7 to each spinous process is given (see Figure 6). All distances are normalized to the upright sitting height and are in SH units. The purpose of these tables is to provide a tool for estimating spinal landmarks as a function of length along the back instead of the vertical position along the back. Note that the lengths Due to the fact that the back contour does not significantly change the is minimal in the upright posture, the proportions listed in Table 4a and 5b are almost identical.

	F Ave	F St Dev	M Ave	M St Dev
|C7-T2|	0.110	0.018	0.109	0.017
|T2-T4|	0.130	0.024	0.124	0.018
|T4-T6|	0.131	0.014	0.133	0.018
|T6-T8|	0.115	0.023	0.124	0.014
|T8-T10|	0.087	0.022	0.104	0.020
|T10-T12|	0.089	0.026	0.094	0.027
|T12-L1|	0.062	0.012	0.061	0.016
|L1-L2|	0.070	0.014	0.067	0.009
|L2-L3|	0.068	0.017	0.066	0.015
|L3-L4|	0.069	0.021	0.060	0.013
|L4-L5|	0.057	0.018	0.055	0.020
|L5-S1|	0.048	0.016	0.044	0.015
T Length (C7-T12)	0.663	0.039	0.687	0.037
L Length (L1-L5)	0.261	0.037	0.245	0.032

Table 5a. Length Between Spinous Processes and Length of Thoracic and Lumbar Areas in the Upright Posture. All distances are in SH units.

	F Ave	F St Dev	M Ave	M St Dev
S1-L5	0.048	0.016	0.044	0.015
S1-L4	0.103	0.024	0.097	0.026
S1-L3	0.170	0.034	0.155	0.030
S1-L2	0.238	0.037	0.221	0.033
S1-L1	0.308	0.035	0.288	0.033
S1-T12	0.369	0.034	0.349	0.033
S1-T10	0.459	0.031	0.443	0.037
S1-T8	0.546	0.041	0.547	0.041
S1-T6	0.661	0.046	0.671	0.041
S1-T4	0.792	0.040	0.804	0.037
S1-T2	0.922	0.027	0.927	0.028
S1-C7	1.032	0.021	1.036	0.022

Table 5b. Length from S1 to each Spinous Process. All distances are in SH units.

	F Ave	F St Dev	M Ave	M St Dev
C7-T2	0.110	0.018	0.109	0.017
C7-T4	0.241	0.035	0.233	0.029
C7-T6	0.372	0.042	0.365	0.036
C7-T8	0.487	0.041	0.490	0.038
C7-T10	0.574	0.034	0.593	0.038
C7-T12	0.663	0.039	0.687	0.037
C7-L1	0.725	0.038	0.748	0.039
C7-L2	0.795	0.040	0.816	0.038
C7-L3	0.863	0.039	0.881	0.035
C7-L4	0.930	0.033	0.940	0.034
C7-L5	0.986	0.029	0.994	0.029
C7-S1	1.032	0.021	1.036	0.022

Table 5c. Length from C7 to each Spinous Process. All distances are in SH units.

2) Spinal Length Changes With Posture

The thoracic and lumbar spine lengths are summarized for each posture in Table 6. All lengths are given in terms of SH. For convenience, the average spinal lengths for each posture are given in terms of both SH and in millimeters. The spine increases in length an average of about 11% between the fully extended posture and the third slumped posture. In the thoracic spine, the increase averages only about 1% between extended and the third slumped postures. The lumbar spine has the greatest change in length, increasing on average 31% for females and 26% for males between the extended and third slumped posture. Thus, as would be expected, most of the change in spinal length is due to the change in shape of the lumbar spine. The lumbar spine length is plotted as a function of the chest-pelvis angle in Figure 9, including the linear regression.

Spine		Females			Males		
Segment	Posture	Ave (SH)	St Dev (SH)	Ave(mm)	Ave (SH)	St Dev (SH)	Ave (mm)
Full Spine	Extension	1.004	0.034	431.9	1.016	0.040	491.5
	Upright	1.034	0.018	444.8	1.038	0.021	502.2
	Slump 1	1.083	0.039	465.9	1.088	0.041	526.4
	Slump 2	1.100	0.049	473.2	1.103	0.051	533.6
	Slump 3	1.121	0.058	482.2	1.118	0.056	540.9
Thoracic	Extension	0.649	0.041	279.1	0.665	0.034	321.7
	Upright	0.663	0.039	285.2	0.687	0.037	332.4
	Slump 1	0.662	0.043	284.8	0.684	0.046	330.9
	Slump 2	0.664	0.041	285.7	0.678	0.053	328.0
	Slump 3	0.657	0.045	282.6	0.674	0.052	326.1
Lumbar	Extension	0.355	0.039	152.7	0.351	0.034	169.8
	Upright	0.371	0.032	159.6	0.351	0.031	169.7
	Slump 1	0.421	0.041	181.1	0.404	0.031	195.4
	Slump 2	0.436	0.042	187.6	0.425	0.038	205.6
	Slump 3	0.464	0.050	199.6	0.444	0.044	214.8

Table 6. Average spinal, lumbar and thoracic length for each posture. All data normalized with respect to upright spinal sitting height (SH), unless otherwise noted.

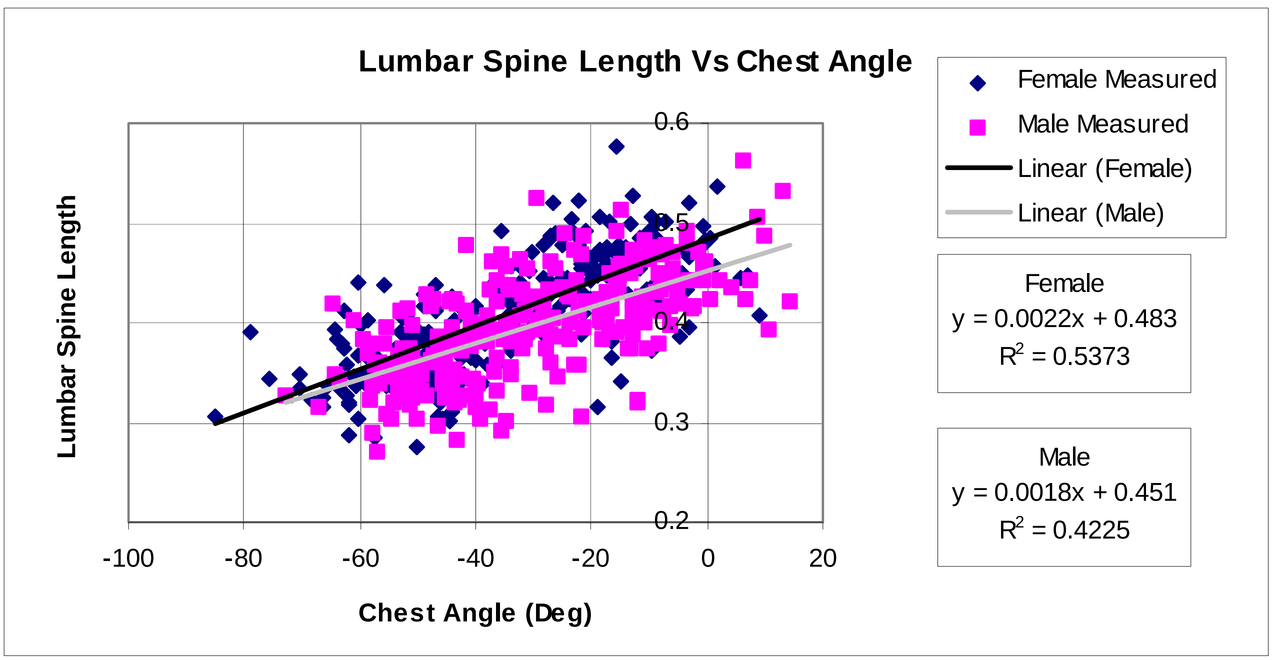


Figure 9. Lumbar spine length versus chest-pelvis angle. Units are in SH.

B. Lumbar Spine Shape

1) Lumbar Curvature

For each posture, a second order polynomial was fit to the lumbar spine data as described in the methods section (II.D.4). The average lumbar curvatures were calculated using equation (4). The units of the curvature are radians/SH, unless otherwise noted. The goodness of fit of the second order polynomial was tested using an F-test and the correlation coefficient (r^2) was determined for each posture for every subject. Out of 510 measurements, only 9 were not statistically significant ($p > 0.05$): for the extended posture, $r^2 > 0.95$ for all subjects; for the neutral posture, $r^2 > 0.84$, for all subjects. Out of the 510 polynomial curves there were only 11 that had $r^2 < 0.8$ (see Table 7).

The average lumbar curvatures are listed in Table 8. The average curvature for the extension posture was -1.77 radians/SH for females and -1.42 radians/SH for males. The radius corresponding to these curvatures can be calculated by inverting the curvature (1/k). For convenience, the radius of the curvature is also given in millimeters. For the extension posture, females had a radius of 243mm and males a radius of 341mm.

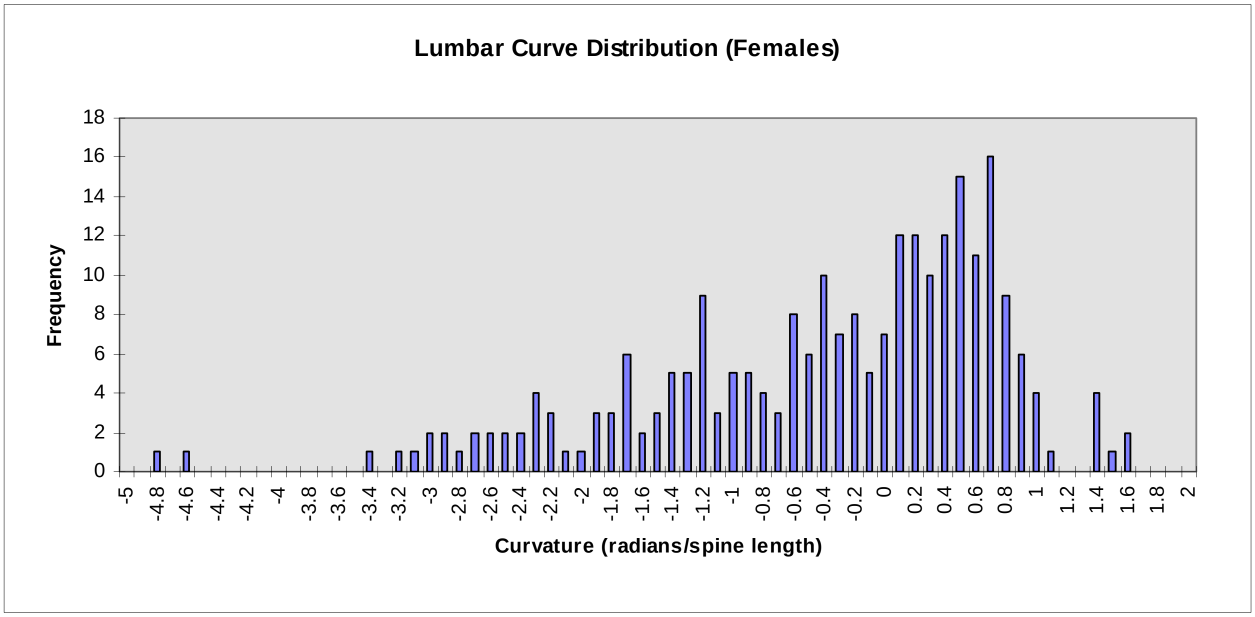
	Extended	Neutral	Slump 1	Slump 2	Slump 3
Average r^2	0.99	0.99	0.98	0.97	0.97
Minimum r^2 or number with r^2<0.8	0.95 (minimum r^2)	0.84 (minimum r^2)	1	5	6
Number with $p > 0.05$	0	0	1	4	5

Table 7. Goodness of fit for polynomial regressions of lumbar spine data.

Females	**Extension**	**Upright**	**Slump 1**	**Slump 2**	**Slump 3**
Average rad/SH (radians/mm) [Radius in mm]	-1.77 (-0.0041) [243]	-1.15 (-0.0027) [374]	-0.01 (-0.00002) [43020]	0.28 (0.00065) [1536]	0.45 (0.00104) [956]
St Dev	1.09	0.89	0.60	0.55	0.51
Max	0.38	0.91	1.52	1.46	1.55
Min	-4.85	-3.25	-1.71	-1.07	-1.26
Males					
Average rad/SH (radians/mm) [Radius in mm]	-1.42 (-0.0029) [341]	-0.84 (-0.0017) [576]	0.11 (0.00023) [4398]	0.30 (0.00062) [1613]	0.46 (0.00095) [1052]
St Dev	0.85	0.77	0.67	0.64	0.56
Max	-0.14	0.90	1.20	1.48	1.39
Min	-3.33	-2.77	-1.83	-2.11	-1.54

Table 8. Summary of lumbar curvatures (K_{ave}) for each measurement posture. Curvature units are radians/SH, unless otherwise noted.

Figure 10 illustrates the frequency of occurrence of lumbar curvatures for the 510 measurements. Curvatures less than zero indicate extension (lordosis), curvatures greater than zero indicate lumbar flexion (kyphosis). More extension measurements were made than flexion measurements. In the next section, the postures are reclassified according to measured lumbar spine curvature instead of the posture classification at the time of data collection.



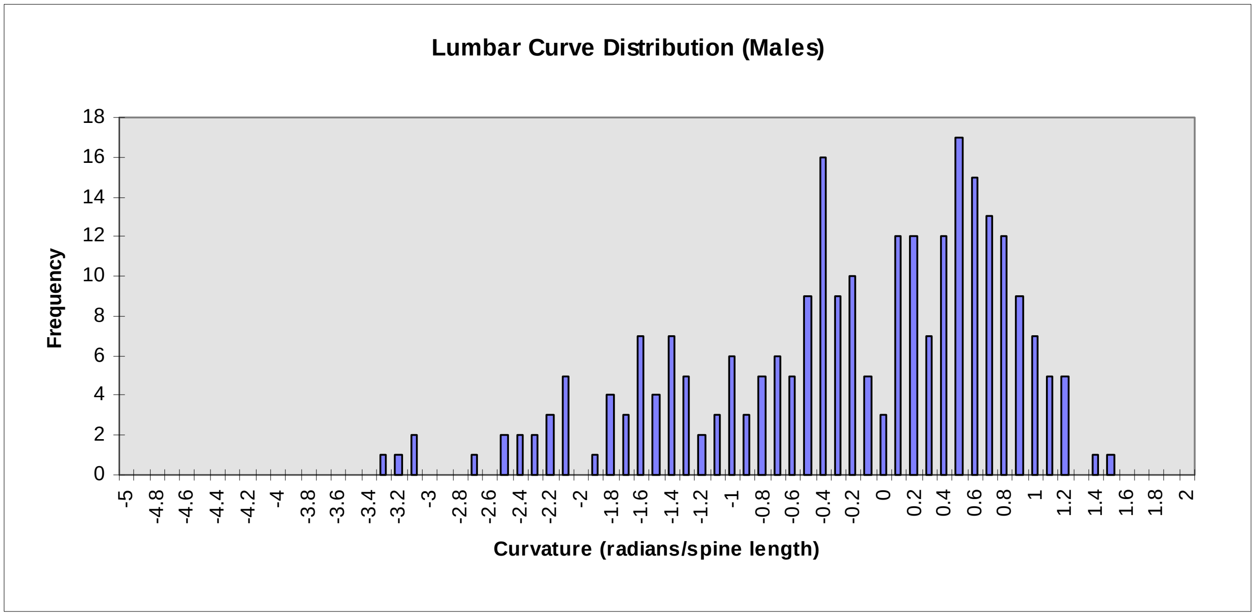


Figure 10. Frequency of lumbar curvature measurements. Females (top) and Males (bottom).

2) Posture Reclassification

Defining posture is a difficult, subjective task. We defined the seated posture as a function of lumbar spine curvature. The purpose for this procedure was to analyze spine data for comparable spine postures. For example, a subject may have been placed in a neutral posture, but his/her actual lumbar spine may have been in an erect (lordotic) posture. Thus, in order to maintain consistency, subject postures were re-defined using the following criteria. The neutral posture was defined as that having a minimal lumbar curvature (i.e., $k \approx 0$). Based on the data illustrated in Figure 10, a curvature of $-0.6 \geq k \leq 0.6$ radians/SH was used to define a neutral lumbar curvature. In addition, if a subject had two or more postures within this category, the posture that corresponded to the most neutral (closest to zero) was selected to represent the neutral posture for that subject.

The curvatures within the neutral range ($-0.6 \geq k \leq 0.6$) correspond to a radius of 717mm or greater for females and a radius of 806mm or greater for males. These are relatively large radii and thus correspond to lumbar curvatures that are very near to being a straight line. Using this definition, there were 47 females and 48 males having neutral lumbar curvatures (see Table 9).

The extension posture was defined by curvatures with $-2.0 \geq k < -0.6$ radians/SH. Thus, excessive lumbar curvatures (those less than -2.0 radians/spine length) were excluded. If a subject had two or more lumbar curvatures within this range, then the smaller (absolute) lumbar curvature was selected. There were 39 females and 42 males having lumbar curvatures using these criteria.

The slumped posture was defined by curvatures with $k > 0.6$ radians/SH. If subjects had two or more measurements within this category, the larger curvature was selected. There were 25 females and 25 males having curvatures within this category.

Females	**Ext (n=39)**	**Neut (n=47)**	**Slump (n=25)**
Ave radians/SH	-1.33	0.06	0.73
(Ave in radians/mm)	-0.00310	0.00014	0.00171
Ave Radius (mm)	-322.71	7116.59	586.08
St Dev radians/SH	0.40	0.22	0.16
Min	-1.95	-0.45	0.61
Max	-0.60	0.59	1.36
Males	**Ext (n=42)**	**Neut (n=48)**	**Slump (n=25)**
Ave radians/SH	-1.33	-0.01	0.77
(Ave in radians/mm)	-0.00274	-0.00002	0.00158
Ave Radius (mm)	-364.38	-49563.24	631.28
St Dev radians/SH	0.39	0.28	0.12
Min	-1.94	-0.57	0.61
Max	-0.62	0.56	1.12

Table 9. Lumbar curvatures based on data reclassification. All data is in radians/SH unless otherwise noted.

C. Lumbar Geometric Descriptors as a Function of Chest Position

1) Chest Motion Relative to the Pelvis

As discussed in Section II.D.5, the position of the chest with respect to the pelvis can be described by the position of one point on the chest (i.e., the (x, z) position of Suprasternale) and the angle of the chest. In this section we examine these three variables (Suprasternale x & z, and chest angle) to determine the extent to which they are important descriptors of chest position relative to the pelvis.

The chest angle averages, standard deviations, minimum and maximums are summarized in Table 10 for each of the measured postures. For the extended posture the chest angle for females was -57.28^o (±9.63^o) and -51.37^o (±8.70^o) for males. For the most slumped posture (slump 3) the average chest angle for females was -13.98^o (±12.82^o) and -11.38^o (±14.35^o) for males. The range of motion of the chest relative to the pelvis is summarized in Table 11. Females had a slightly larger range of motion (average 43.58^o) than males (average 39.9^o), probably due to the fact that females have a smaller trunk stature and therefore needed to move their torso through a larger range to assume the measurement postures.

The relationship between Suprasternale x and z as a function of chest angle is illustrated in Figure 12. There is a strong linear correlation between the x position of the Suprasternale and the chest angle; however, the correlation for the z position is very weak.

All Subjects	**Average** (degrees)	**St Dev** (degrees)	**Maximum** (degrees)	**Minimum** (degrees)
Extended	-54.27	9.59	-31.30	-85.11
Neutral	-46.65	8.37	-25.91	-66.28
Slump 1	-27.53	12.06	0.40	-62.28
Slump 2	-21.08	11.97	8.54	-48.64
Slump 3	-12.91	13.60	14.41	-45.37
Females	**Average**	**St Dev**	**Maximum**	**Minimum**
Extended	-57.28	9.63	-37.09	-85.11
Neutral	-49.04	7.99	-28.28	-66.28
Slump 1	-28.63	12.28	-8.58	-62.28
Slump 2	-22.21	11.05	-0.32	-46.25
Slump 3	-13.98	12.82	9.21	-45.37
Males	**Average**	**St Dev**	**Maximum**	**Minimum**
Extended	-51.37	8.70	-31.30	-72.71
Neutral	-44.34	8.15	-25.91	-59.28
Slump 1	-26.47	11.87	0.40	-47.30
Slump 2	-19.99	12.82	8.54	-48.64
Slump 3	-11.88	14.35	14.41	-40.75

Table 10. Chest Angle for each posture.

	Average	St Dev	Max	Min
All	41.70	10.79	68.08	9.79
Females	43.58	9.98	68.08	23.66
Males	39.90	11.31	57.49	9.79

Table 11. Range of motion of the chest relative to the pelvis. All data are in degrees.

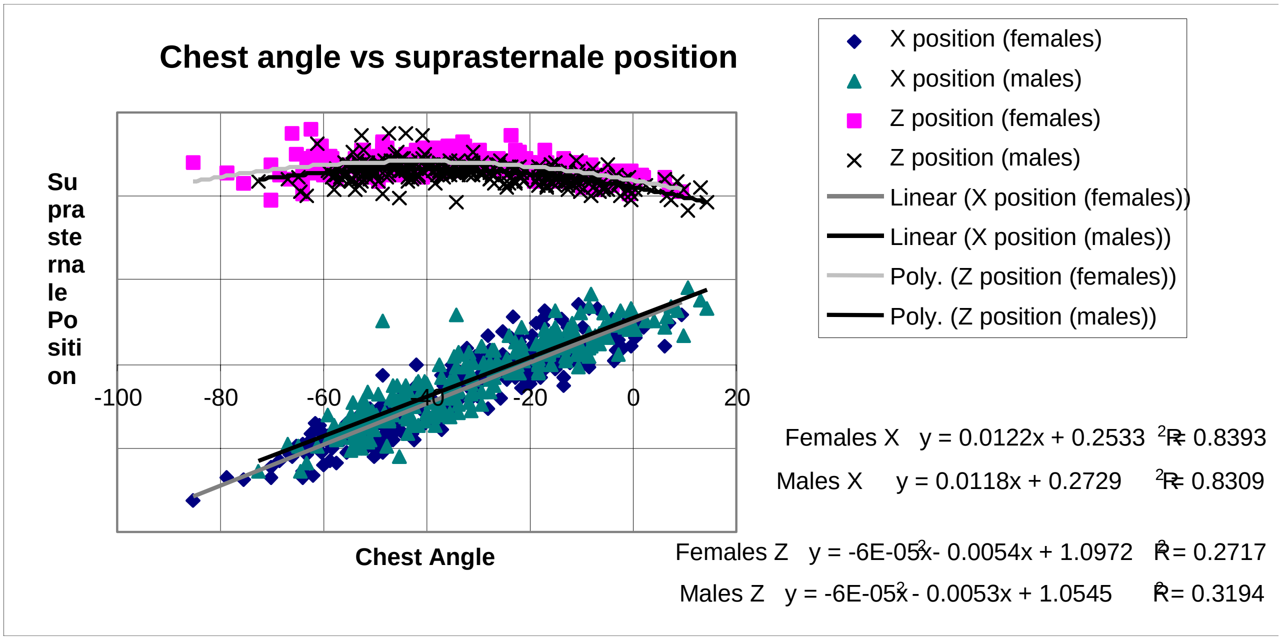


Figure 11. Suprasternale X and Z Position (SH) versus Chest Angle (deg).

2) Lumbar Spine Height and Lumbar Curve Tangents as Functions of Chest Position

For the model described in Section II.D.5, the curvature depends on lumbar spine height (H) and the tangents to the lumbar curve at T12 (θ_T) and at S1 (θ_s). In this section we describe the relationship of lumbar spine height and the tangents (θ_T and θ_s) to chest angle and chest x-position.

The relationship between lumbar spine height and chest angle is illustrated in Figure 12. The r^2 value is 0.61, indicating a moderate linear correlation between lumbar spine height and chest angle. When investigated on an individual basis, the correlation is much stronger; 92% of the subjects had an r^2 value greater than 0.70, indicating that lumbar spine height is very strongly correlated to chest angle for each subject. Thus, as would be expected, individual anatomical differences is one source for the variability.

The tangent to the lumbar curve at T12 (θ_T) and at S1 (θ_s) were determined by evaluating the first derivative of equation (1), (where $dx/dz = \theta(z) = 2Az + B$) at T12 and S1, respectively. A regression analysis reveals that θ_T has a strong linear correlation to the chest angle ($r^2 = 0.7$), while θ_s has a very poor correlation with chest angle ($r^2 = 0.037$) (see Figure 13).

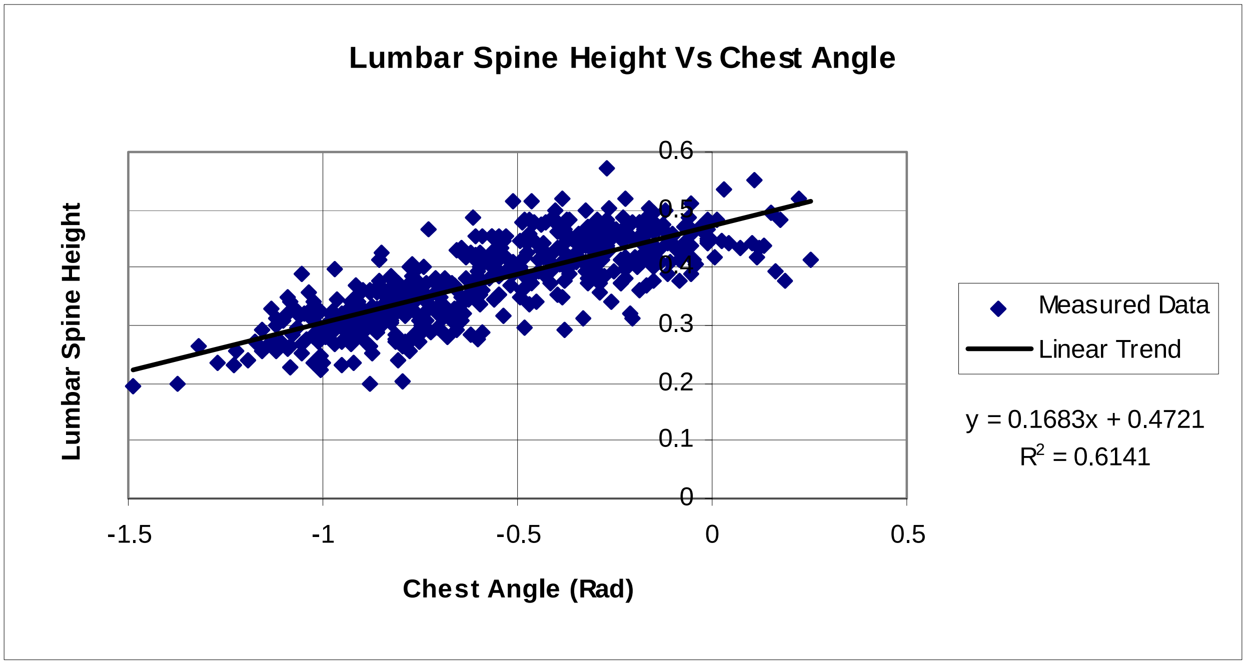


Figure 12. Lumbar Spine Height Versus Chest Angle. Lumbar spine height is in SH.

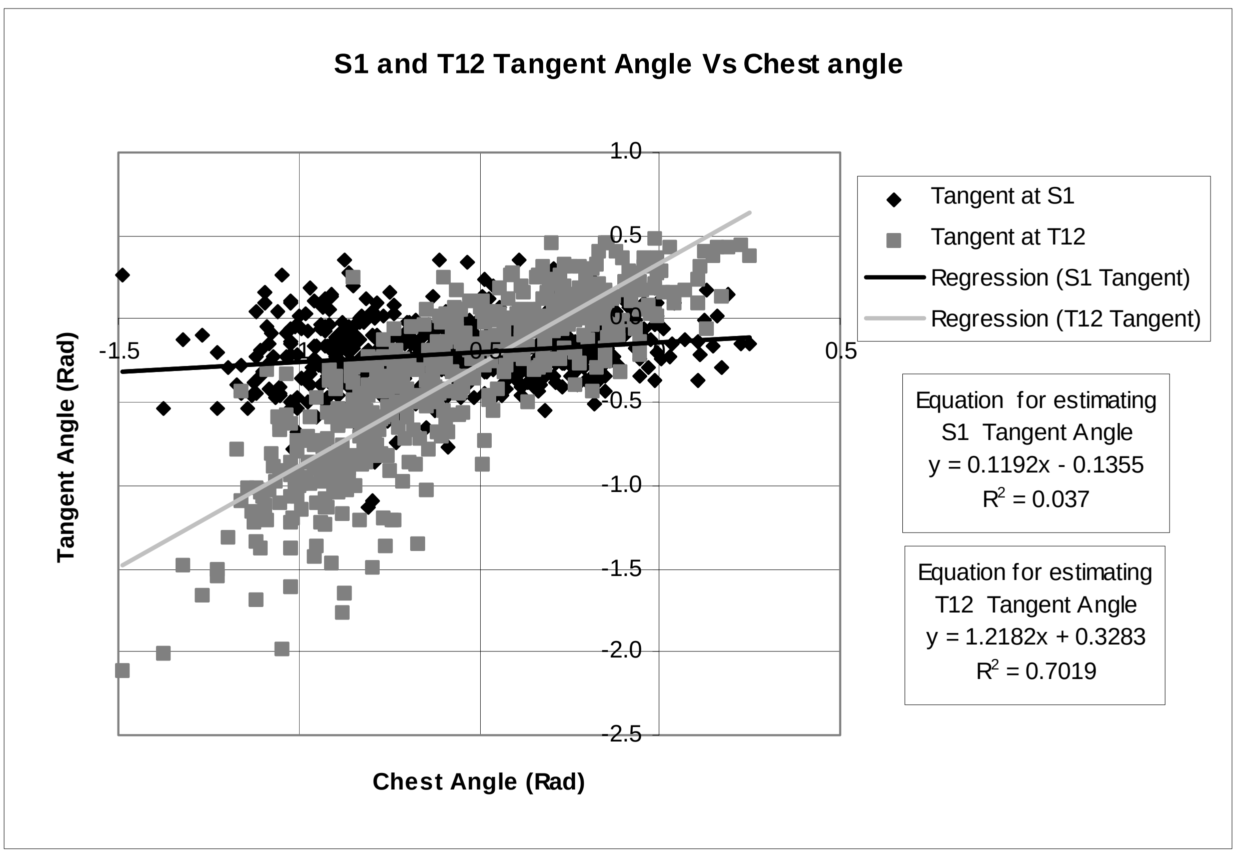


Figure 13. Tangent angles at S1 and T12 versus chest angle.

The correlation between θ_T and chest angle is relatively strong and this correlation increased when we examined the regression for θ_T and chest angle for each individual subject. We found 99% of the subjects had $r^2 > 0.7$ and 95% had $r^2 > 0.8$.

We also examined the range of "motion" (i.e., the angle change) in the θ_T angle from full extension to the most slumped posture for each subject. Since this is a tangent angle and not a true joint, the range is not intended to give the joint angle change between T12 and L1, but to provide a comparison for the change in the tangent angles at T12 and S1. For all subjects, the average range of "motion" for the T12 tangent angle was 1.15 ± 0.30 radians ($65.9^o \pm 17.2^o$). This is larger than the average range of motion of the chest relative to the pelvis (Table 11).

The correlation between θ_s and chest angle is very weak, but improves if we examine the relationship for each individual subject. When this is done, 25.5% of the subjects had $r^2 > 0.7$ and 44% had $r^2 > 0.5$. Thus, predicting the sacral tangent from chest angle will not result in a reliable prediction.

As discussed in Section II.D.5, if the angle, θ_s has a small range of "motion" over different postures and if the average value for θ_s is small, then its contribution to the curvature will be negligible. The average tangent angle of the lumbar curve at the sacrum was $\theta_s = -0.20 \pm 0.21$ radians ($11.5^o \pm 12.0^o$) for all subjects. For females the averages were $-0.18 \pm .22$ and for males, $-0.22 \pm .19$ radians.

The range of "motion" of the sacral tangent angle from full extension to full slumped averaged $0.28 \pm .14$ radians ($16.0^o \pm 8.0^o$). For females and males the range for θ_s was $0.30 \pm .16$ and $0.27 \pm .12$ radians, respectively. The range for the tangent angle at S1 is 24.3% of the range for the tangent angle at T12. This indicates that the sacral angle is an important component of the lumbar curve that cannot be considered negligible. The fact that it changes with posture but the change is not well correlated with chest angle indicates that it will be a complicating factor in predicting curvature.

The lumbar spine height and the tangent angles are shown as a function of Suprasternale x-position (chest x-position) in Figure 14. The T12 tangent angle (θ_T) has the strongest linear correlation to the chest x position ($r^2 = 0.84$). S1 tangent angle (θ_s) has the weakest correlation ($r^2 = 0.08$). The correlation for the lumbar spine height is moderate ($r^2 = 0.66$). These results indicate that θ_T and lumbar spine height can be estimated from either chest angle or chest x position, but that θ_s cannot be accurately estimated as a function of chest motion.

Lumbar angle is defined as the difference between the T12 and S1 tangents ($\theta_T - \theta_s$). The relationship between lumbar angle and lumbar curvature is important to investigate, since it provides an indication as to the effectiveness a linear model will have for estimating lumbar curvature. As illustrated in Figure 15, the lumbar curvature has a very strong linear correlation to the lumbar angle ($r^2 = 0.97$). This result indicates that the lumbar curvature is in the linear range of the function illustrated in Figure 8. This means that the relationship between curvature and chest angle is linear. However, due to the fact that θ_s cannot be accurately estimated from chest position and that θ_s has a significant range and cannot be ignored, the linear behavior is likely to be highly individual, and the scatter of the general data is likely to be high.

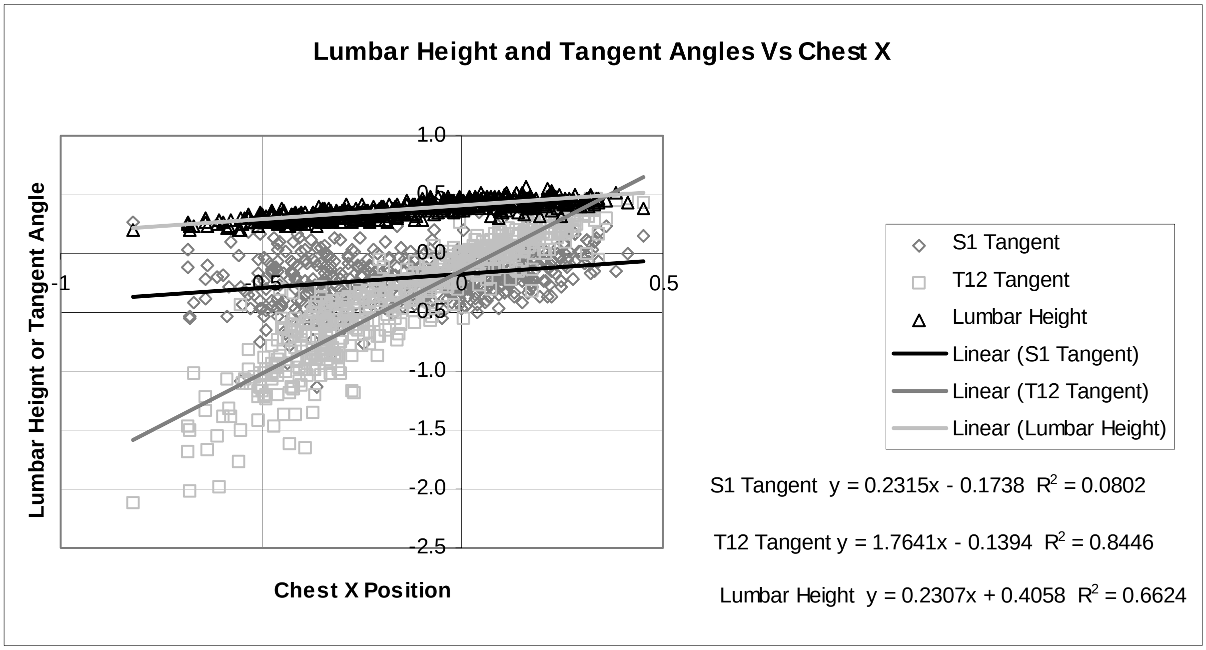


Figure 14. Lumbar Height and Tangent Angles versus Suprasternale X-position. Suprasternale X-position and lumbar height are in SH, angles are in radians.

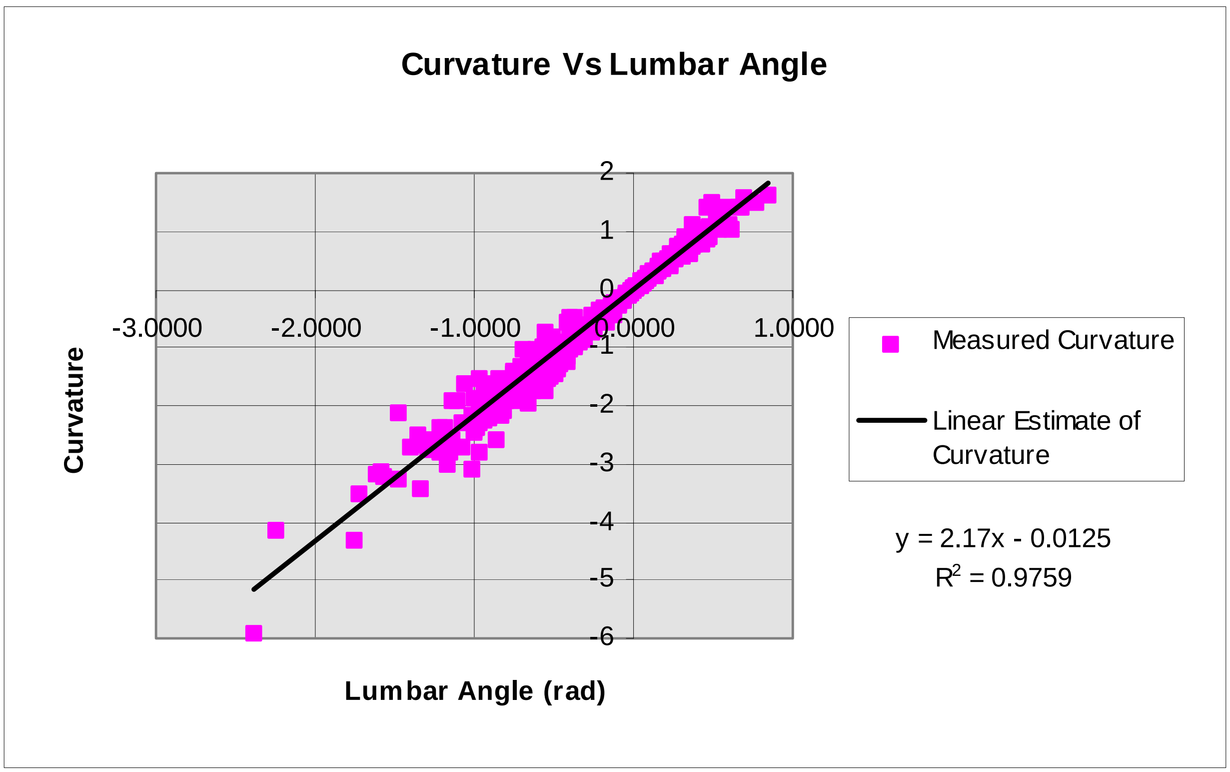


Figure 15. Curvature Versus Lumbar Angle. Lumbar angle = $\theta_T - \theta_s$, curvature is in radians/SH.

D. Predicting Lumbar Curvature From Chest Position

We examined two approaches for modeling lumbar spine curvature. Data can be collected from a large number of subjects and a general equation relating chest position to lumbar spine curvature can be developed or information from each subject can be used to develop an equation that is specific to that individual. In the following sections we investigate both of these approaches.

1) General Regression Equations for Lumbar Curvature Versus Chest Position

The results summarized above (Section III.C) support the hypothesis that lumbar curvature is a linear function of chest position. In this section we examine the linear relationship between lumbar curvature as a function of chest angle as well as a function of the chest x-position. We assume that the curvature can be expressed as:

$k = A\theta + B$ and $k = Cx + D$

where k is the average curvature of the lumbar spine, θ is the chest-pelvis angle, x is the Suprasternale x-position and A,B,C,D are fixed values. We will first describe the general regression equations, using data from all subjects to determine the above relationships.

The relationship between chest angle and lumbar curvature is illustrated in Figure 16a. The linear correlation is moderate ($r^2 = 0.52$), but an examination of the raw data indicates that the relationship may not be entirely linear. However, when lumbar curvature is plotted against chest angle normalized by lumbar spine height, the raw data looks more linear and the r^2 value increases to 0.58. Regression equations and r^2 values for males and females are given on the figures. The curvature as a function of chest x-position is illustrated in Figure 17a. There is a stronger linear correlation ($r^2 = 0.57$) than that for curvature versus chest angle. The correlation improves to ($r^2 = 0.60$) when chest x-position is normalized by lumbar height (Figure 17b). The regression equations and r^2 values for males and females are given on each figure.

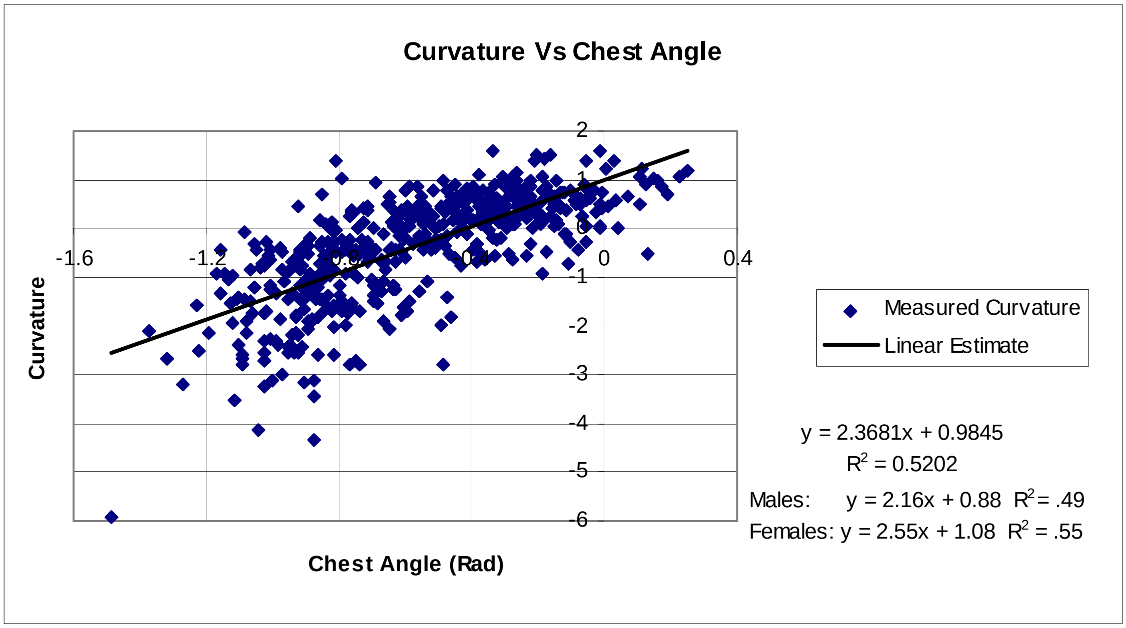


Figure 16a Curvature Versus Chest Angle. Curvature is in radians/spine height.

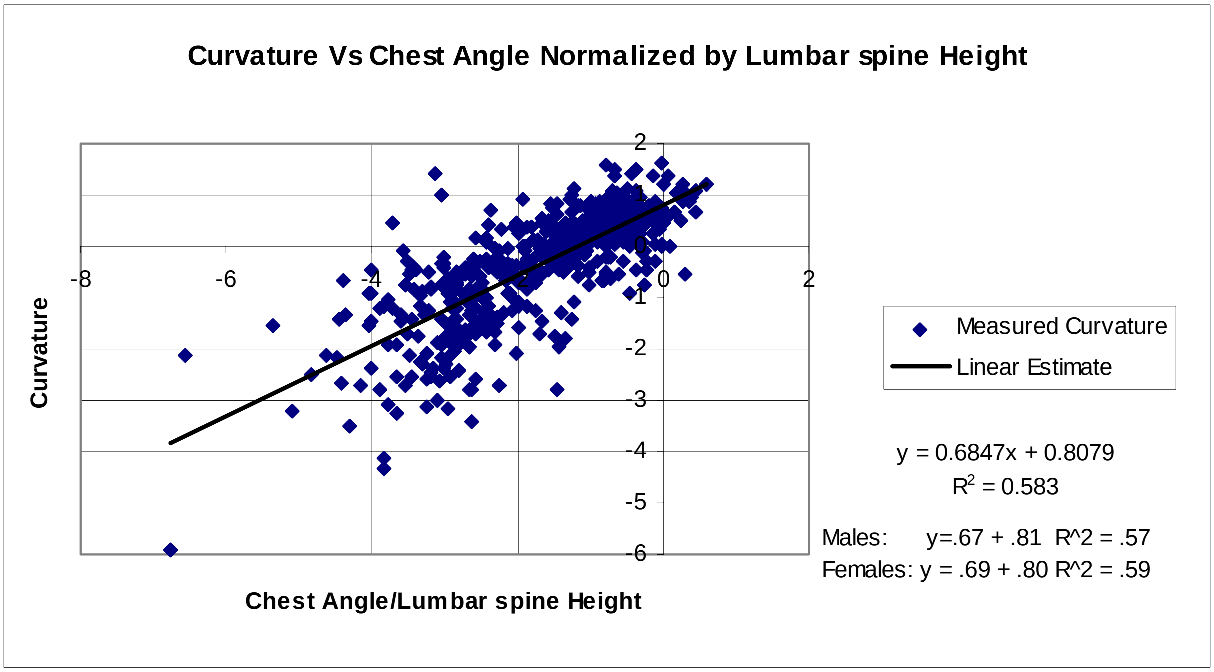


Figure 16b Curvature Versus Chest Angle Normalized by Lumbar Height. Units are radians/spinal height and radians/lumbar spine height, respectively.

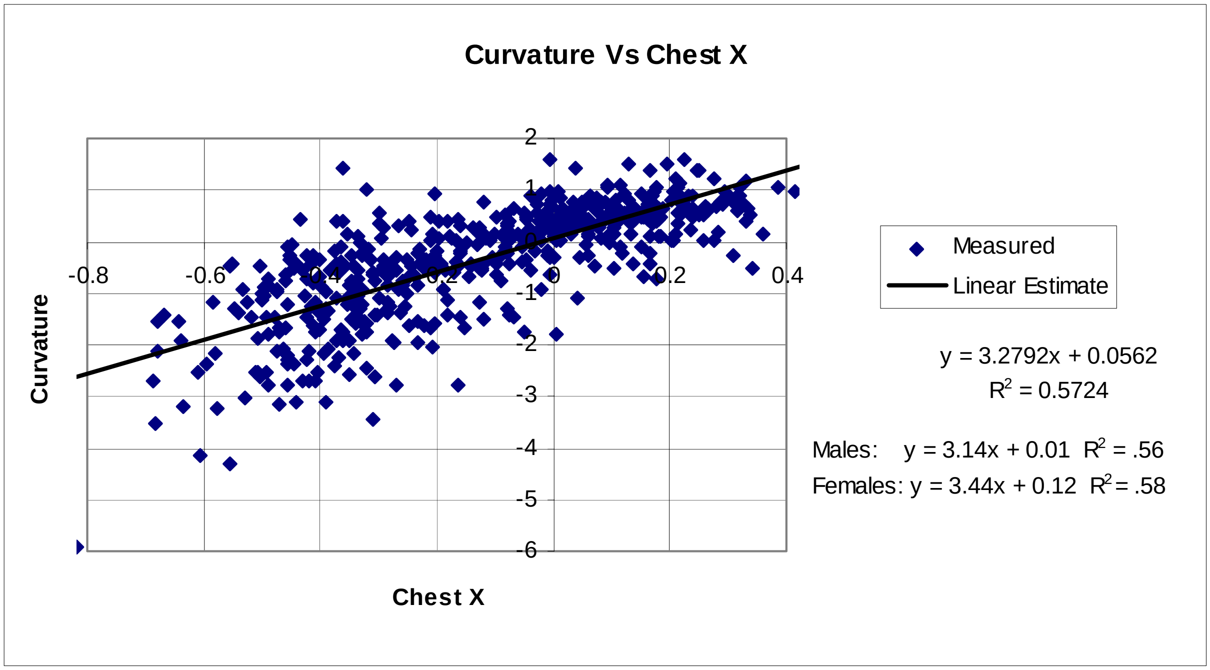


Figure 17a. Curvature Versus Chest X Position.

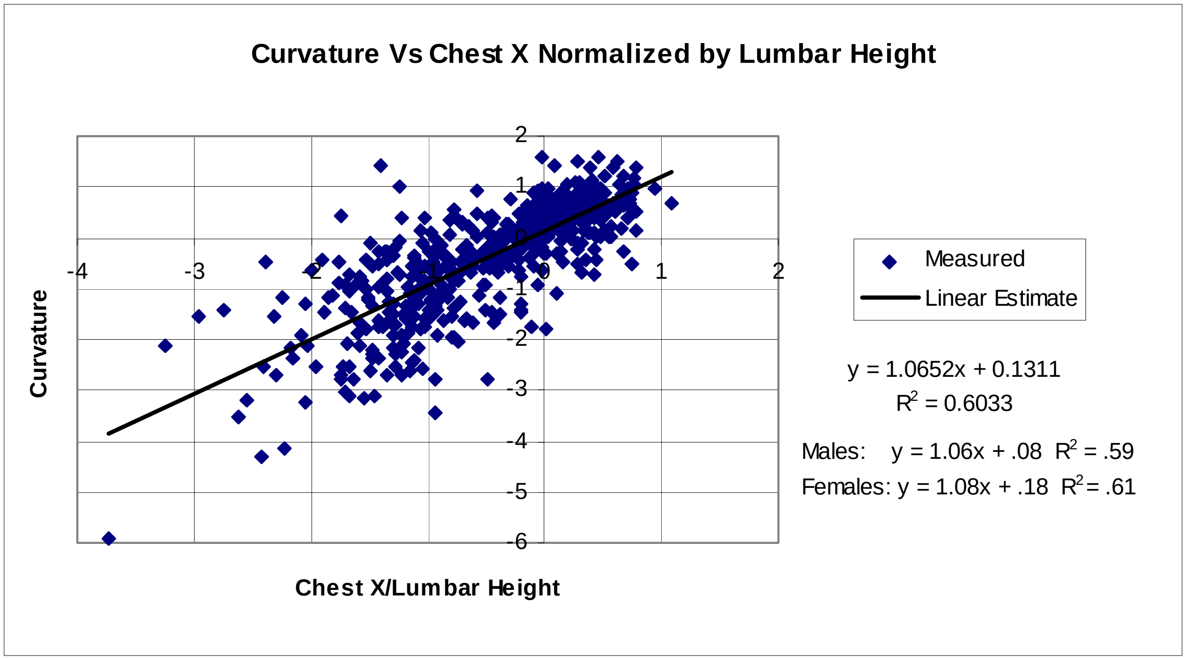


Figure 17b. Curvature Versus Chest X Normalized by Lumbar Height.

2) Individual Regression Equations for Lumbar Curvature Versus Chest Position

The linear correlations for curvature versus chest angle and chest x-position improve when investigated for each individual subject. An example of the linear fit for curvature versus chest angle is shown for one subject in Figure 18. The goodness of fit data is summarized in Table 12. For each subject, the linear fit is very strong with 78% of the subjects having $r^2 > 0.8$ and an average absolute error in the estimated curvature of 0.229 radians/spine height.

The linear relationship between curvature and sternum x-position is illustrated in Figure 19 for the same subject as in Figure 18. The goodness of fit statistics are summarized in Table 13. There is a strong linear correlation for individual subjects, with an average r^2 of 0.87 and with 87% of the subjects having $r^2 > 0.8$.

	Ave r^2 (SD)	Min r^2	# subjects with $r^2 > 0.80$	# subjects with $p < 0.05$
Females n=51	0.88 (.11)	0.50	41	44
Males n=51	0.86 (.12)	0.57	39	40
Ave Abs Error for all subjects 0.229 (±.208)				

Table 12. Goodness of Fit Summary for a Linear Regression of Curvature Versus Chest-Pelvis Angle.

	Ave r^2 (SD)	Min r^2	# subjects with $r^2 > 0.80$	# subjects with $p < .05$
Female n=51	0.89 (0.10)	0.50	44	46
Male n=51	0.88 (0.13)	0.36	45	46
Ave Abs Err for all subjects 0.211 (±0.194)				

Table 13. Goodness of Fit Summary for a Linear Regression of Curvature Versus Chest X-Position.

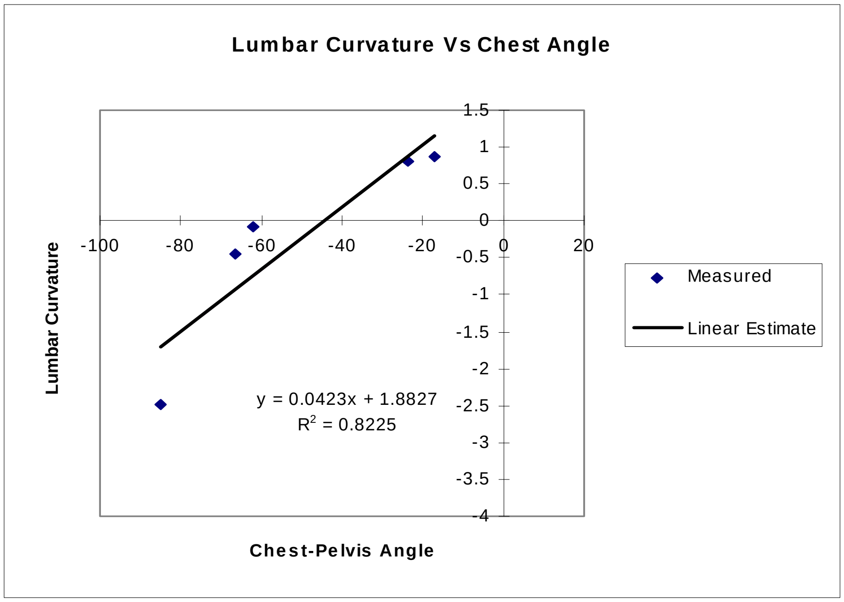


Figure 18. Linear regression for the lumbar curvature versus the chest-pelvis angle. This figure illustrates the raw data and linear regression for a representative subject.

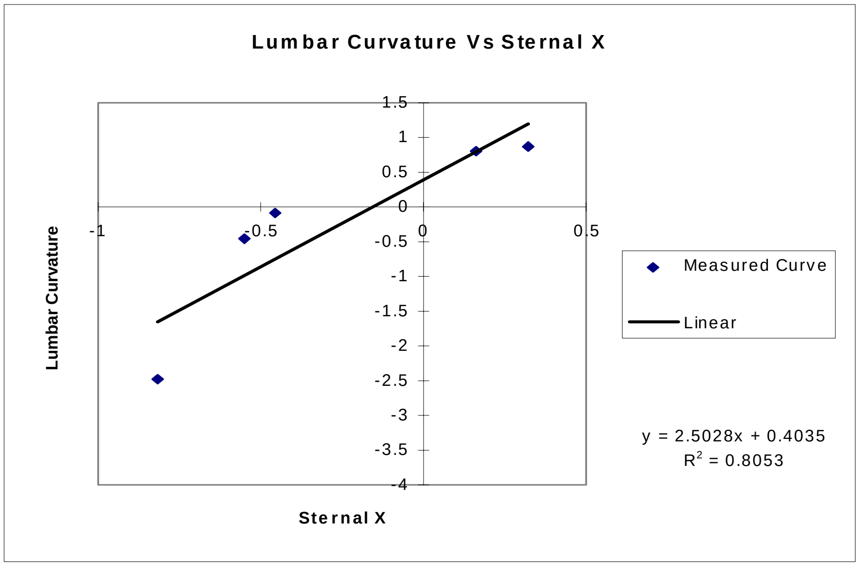


Figure 19. Curvature Versus Sternal X Position.

3) Error Analysis of Individual Regression Equations for Predicting Curvature

The primary issue reported in this section is the errors associated with using the individual regression equations for predicting the shape of the lumbar spine. Since curvature of the back is a linear function of chest angle as well as chest x-position, errors in measuring the chest angle and/or chest x-position will lead to an error in the estimated curvature of the lumbar spine. We describe the effect of measurement errors on the estimated curvature of the lumbar spine.

Errors ranging from $\pm 5^o$ to $\pm 15^o$ were added to the measured chest-pelvis angle to determine the effect such an error has on the estimated curvature. The errors were described in terms of the absolute error between estimated and measured curvature. Similarly, errors ranging from ±12.1 mm to ±72.6mm were added to the measured x-position of Suprasternale and the absolute error between the estimated and measured curvature was determined for each subject.

In addition to describing the absolute error we also described the effect of errors on accurately predicting a subjects' posture. Subjects' postures were classified into five categories:

Extended	$k < -0.6$radians/spine height
Neutral	$-0.6 \le k \ge 0.6$ radians/spine height
Slumped	$0.6 < k$ radians/spine height
EXTENDED	$k \le 0$ radians/spine height
SLUMPED	$k \ge 0$ radians/spine height

The effect of measurement error on classifying posture was determined by comparing the subjects' posture from the estimated lumbar curvature to the posture from the measured lumbar curvature.

The effect of errors in chest angle is summarized in Table 14. Errors that result in the chest having a more negative (extended) angle have a larger effect on the classification of the individuals posture. A -5^o error reduces the ability to accurately determine a Slumped posture to 53% and a SLUMPED posture to 72%. However, the same error increases the reliability in estimating an extended posture. A positive error (an error that results in estimating the chest to be further in flexion) has less effect on the extended posture. It requires more than $+10^o$ to result in errors in posture classification of less than 60%.

Estimating curvature from chest x-position is far more robust (see Table 15). Errors need to exceed 2.5% of the spine height (approximately 11.4mm) before there is an appreciable error in posture classification. An error of -11.4mm is 72% accurate for estimating a Slumped posture and 82% accurate for estimating a SLUMPED posture. At -22.8mm, the accuracy decreases to 59% and 76%, respectively. Errors must exceed 34.2mm before the absolute error in lumbar curvature is equivalent to that of a 10^o error in chest angle.

Error In Chest Angle (Deg)	Est Ext k<-.6	Est Neut -.6<k<.6	Est Slump .6<k	Est EXT k<0	Est SLUMP 0<k	Absolute Error Ave	Std
-15.00	1.00	0.41	0.18	1.00	0.33	0.77	0.43
-10.00	1.00	0.60	0.27	1.00	0.51	0.53	0.35
-5.00	0.99	0.76	0.53	1.00	0.72	0.32	0.26
0.00	0.96	0.80	0.82	0.98	0.87	0.23	0.21
5.00	0.81	0.75	0.95	0.90	0.95	0.32	0.26
10.00	0.69	0.58	0.98	0.78	0.99	0.53	0.35
15.00	0.51	0.39	0.99	0.67	1.00	0.77	0.43

Table 14. Errors in Curvature as a Function of Errors in Chest angle.

Error (mm)	Error (%spine height)	Est Ext k<-.6	Est Neut -.6≤k≤.6	Est Slump 0.6<k	Est EXT k≤0	Est SLUMP k≥0	Absolute Error Ave	Std
-68.40	-0.15	1.00	0.57	0.21	1.00	0.48	0.56	0.34
-45.60	-0.10	0.99	0.69	0.40	1.00	0.64	0.40	0.28
-34.20	-0.075	0.98	0.74	0.49	1.00	0.72	0.32	0.25
-22.80	-0.05	0.98	0.78	0.59	1.00	0.76	0.27	0.22
-11.40	-0.025	0.98	0.80	0.72	0.99	0.82	0.23	0.20
0.00	0.00	0.95	0.83	0.83	0.97	0.88	0.21	0.19
11.40	0.025	0.95	0.81	0.93	0.95	0.93	0.22	0.21
22.80	0.05	0.88	0.78	0.94	0.93	0.97	0.24	0.22
34.20	0.075	0.84	0.75	0.97	0.90	0.98	0.32	0.26
45.60	0.10	0.78	0.67	0.99	0.86	0.98	0.39	0.29
68.40	0.15	0.67	0.54	1.00	0.78	1.00	0.56	0.34

Table 15. Errors in Curvature as a Function of Errors in Chest X Position.

E. Comparing Estimated Lumbar Curvatures To Measured Curvatures.

1) Seat Buck Results

The seat buck results were analyzed for forty subjects that were involved in the drives, as described in [5]. For the first ten drive subjects the C7 landmark was not recorded during the seat buck measurement session, thus were could not estimate the location of the lumbar spine and thus these subjects were dropped from this portion of the analysis. An additional five subjects were dropped due to missing video anthropometry data. Four were missing measurements of the sternum retro-reflective targets and one was missing the measurement of the ASIS target. Thus, a total of 25 subjects were involved in this portion of the project.

a) Determining Lumbar Curvature from STD Measurements

The curvature of the lumbar spine was measured using the SDT's as described in Section II.D.3. These curvature results were compared to the estimated curvature determined using the chest and pelvis positions calculated from the video images and pressure mat data.

The raw STD measurements for a typical subject are illustrated in Figure 20. The diamonds in the figure are the calculated positions of the SDT's in contact with the subjects back. The top diamond in the figure is the location of the C7 landmark for that subject. The light gray line is a cubic polynomial fit of the data, of the form $x = Az^3 + Bz^2 + Cz + D$ as described in Section II.D.3. The dark gray region is the estimated location of the lumbar spine, using the methods described in Section II.D.3. The average curvature for the lumbar region was obtained numerically by averaging the curvatures from a number of points in the lumbar region, which were calculated using equation (5).

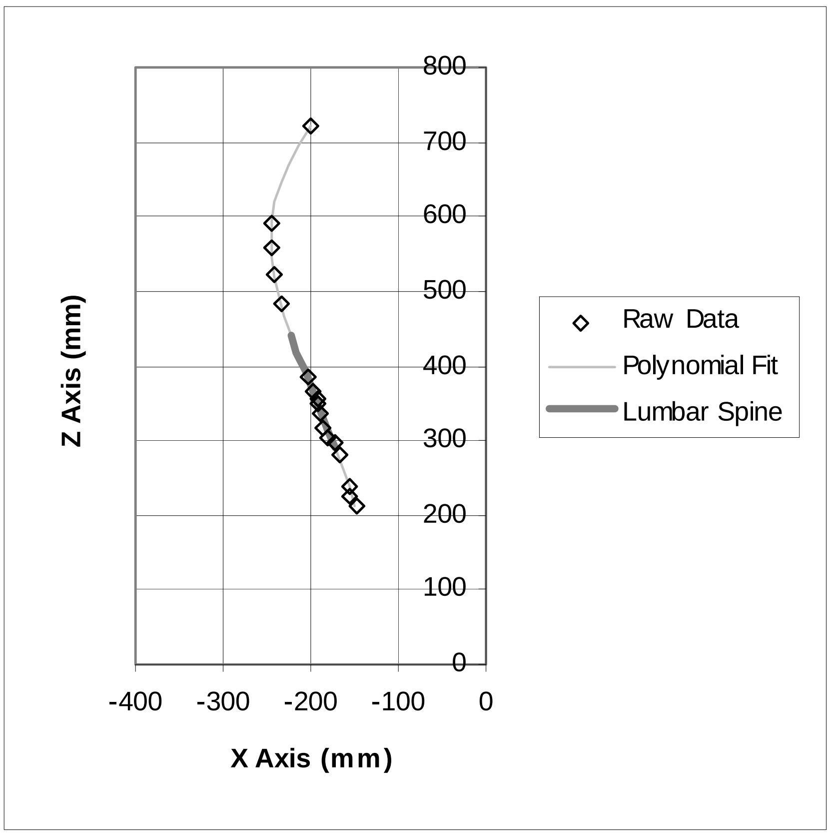


Figure 20. Representative Results for One Subject from the Seat Buck Data.

b) Estimating Lumbar Curvature Using Chest and Pelvis Position Data.

The position of the pelvis for the 25 subjects was calculated using the methods described in Section II.D.1. The position of the chest was determined from the two sternum landmarks. The lumbar curvature was estimated using the individual regression equations for curvature versus chest-pelvis angle and curvature versus sternum x-position. Three of the 25 subjects were missing one of the sternum landmarks due to poor video images, thus the lumbar curvature for these subjects could only be determined using the individual regression equation for curvature versus sternum x-position.

The results for these 25 subjects are summarized in Table 16.

Sub	Chest-Pelvis Angle (deg)	Sternum-X (SH)	K_θ (Est) Using C-P Angle (rad/SH)	K_x (Est) Using Sternum -X (rad/SH)	Average (K_θ & K_x) rad/SH	K Measured (rad/SH)	K_θ Error rad/SH	K_x Error rad/SH	K_{Ave} Error rad/SH
034	-33.00	-0.05	0.1230	0.2128	0.1679	-0.0458	0.1687	0.2586	0.2136
055	-34.81	-0.21	-0.5111	-0.4447	-0.4779	-0.3737	0.1374	0.0710	0.1042
121		0.17		0.1918	0.1918	0.3498		0.1580	0.1580
195	-29.18	-0.15	-0.1143	-0.4814	-0.2979	0.1521	0.2665	0.6336	0.4500
306	-22.24	-0.13	-0.0694	-0.2456	-0.1575	-0.0024	0.0669	0.2432	0.1551
359	-27.11	-0.26	1.7248	-0.2271	0.7489	0.2325	1.4923	0.4596	0.5163
405	-36.95	-0.18	0.1453	0.0326	0.0889	-0.0391	0.1844	0.0716	0.1280
426	-11.60	0.10	-1.2017	-1.2766	-1.2392	-0.5727	0.6291	0.7039	0.6665
433	-28.03	-0.04	0.4960	0.6565	0.5762	0.5736	0.0777	0.0828	0.0026
526	-28.59	-0.19	0.0426	-0.1164	-0.0369	0.9015	0.8589	1.0180	0.9384
545	-10.80	-0.06	0.2403	-0.3047	-0.0322	0.4219	0.1816	0.7265	0.4540
579	-18.19	-0.02	0.2606	0.2052	0.2329	0.1802	0.0804	0.0250	0.0527
611	-30.19	-0.13	0.4456	-0.0407	0.2024	0.1936	0.2519	0.2343	0.0088
704	-29.06	-0.37	-0.1217	-1.1840	-0.6529	0.0669	0.1887	1.2509	0.7198
735	-25.84	0.00	0.0332	0.1260	0.0796	0.0943	0.0611	0.0317	0.0147
779	-43.35	-0.35	-0.1074	-0.2498	-0.1786	0.2782	0.3856	0.5280	0.4568
796	-19.41	-0.09	-0.0421	-0.4643	-0.2532	-0.1726	0.1304	0.2917	0.0806
805	-22.46	0.08	-0.0870	0.2218	0.0674	-0.1091	0.0221	0.3309	0.1765
810	-22.50	0.06	1.3284	-0.1156	0.6064	0.2247	1.1038	0.3402	0.3818
820		0.10		0.1408	0.1408	-0.2247		0.3655	0.3655
831	-33.52	-0.18	-0.3922	-0.7231	-0.5577	-0.1570	0.2352	0.5661	0.4006
833	-32.45	-0.29	-0.3177	-0.4229	-0.3703	0.0602	0.3779	0.4831	0.4305
835		-0.21		-0.7530	-0.7530	-0.5132		0.2398	0.2398
836	-36.54	-0.22	-1.4455	-1.5642	-1.5048	-0.0992	1.3463	1.4651	1.4057
838	-4.72	0.17	0.5596	0.5946	0.5771	0.3667	0.1930	0.2280	0.2105
Ave	-26.39	-0.10	0.04	-0.25	-0.11	0.07	0.38	0.43	0.35
Std	9.35	0.15	0.68	0.55	0.55	0.33	0.43	0.37	0.33

Table 16. Estimated and Measured Curvatures and Absolute Errors.

2) Applying the General Equations for Estimating Curvature to New Subjects

The goal of this section is to examine the general regressions equations when used to estimate the lumbar curvature on a separate population. These regression equations are given in Figures 14a and 15a. Although normalizing chest angle and chest x-position with lumbar spine height results in a stronger linear relationship (i.e., a larger r^2 value), such an equation is not as easy to apply as the equations that require only chest angle or chest x-position.

The 26 male subjects from the simulated drive portion of the experiment were used. None of the data from these subjects was used to derive the linear regression equations and none of the 26 simulated drive subjects were a part of the SAS database. In addition, the mechanics of achieving lumbar spine lordosis and kyphosis were very different between the two experiments.

In the SAS experiment, the pelvis was fixed and the chest was moved to generate the desired lumbar spine shape. In the simulated drive experiment, both the chest and pelvis were allowed to move. Thus, using the simulated drive data to test the general regression equations provides an independent test on a second group of subjects as well as testing the assumptions made regarding the mechanics that control the lumbar spine shape.

From Figure 16a and 17a, the regression equations for lumbar curvature as a function of chest angle are:

$k = 2.16\theta + 0.88$ (males) (9a)

$k = 2.55\theta + 1.08$ (females) (9b)

Where θ is the angle of the chest relative to the pelvis as defined in Figure 6 and k is in radians/SH. The regression equations for lumbar curvature as a function of chest x-position (Suprasternale x-position) are:

$k = 3.14x + 0.01$ (males) (10a)

$k = 3.44x + 0.12$ (females) (10b)

where x is the x-position of the Suprasternale relative to the pelvis, using the coordinate system defined in Figure 6 and expressed in SH units, and k is in radians/SH.

The male regression equations were used to estimate the lumbar curvature of the simulated drive subjects and the results were compared to the measured curvature. The scatter of the measured curvature versus chest angle is illustrated in Figure 20a. The estimated curvatures using equation (9a) are shown in light gray. The estimated curvature lies on a line that is very close to the linear trend of the simulated drive measured curvature data (black line). The linear trend of the simulated drive curvature data is:

$k = 1.52\theta + .696$ (11a)

The intercept is close to that of equation (9a), but there is a definite difference in the slope. However, the difference in the slope is negligible if we normalize the chest angle with lumbar spine height (see Figure 20b). This normalization results in a nearly perfect fit between the regression equations for the two experiments, even though the data were collected on two different populations and the chest-pelvis mechanics were very different. However, as mentioned above, such normalization makes the equations difficult to apply to other subjects without a great deal of difficulty, requiring several measurements of each subject.

Figure 21a illustrates the scatter of the measured curvature versus chest x-position with the estimated curvatures using equation (10a) shown in light gray. The estimated curvatures lie almost completely on top of the linear trend of the simulated drive data (black line). The linear trend for the simulated drive data is:

$k = 3.29x + 0.01$ (11b)

which is very close to the regression equation for the SAS data (equation 10). When the chest x-position is normalized by lumbar spine height, the regression equation is slightly different between the two data sets (see equation on Figure 21b). This indicates that lumbar spine height has less effect on predicting curvature when using sternum x-position.

The error was estimated by averaging the absolute value of the difference between the estimated and measured curvatures. In addition, the subject's postures were classified into EXTENDED ($k < 0$) and SLUMPED ($k > 0$) postures. The percent agreement for these classifications was used to determine the extent to which the regression equations could accurately predict the posture of the subject. Using the equations for chest x-position resulted in slightly less error than using chest angle as a predictor of curvature. In addition, using chest x-position had greater accuracy for predicting the slumped posture (85.7% versus 77.8%). Both methods underestimated the extended posture (see Table 16).

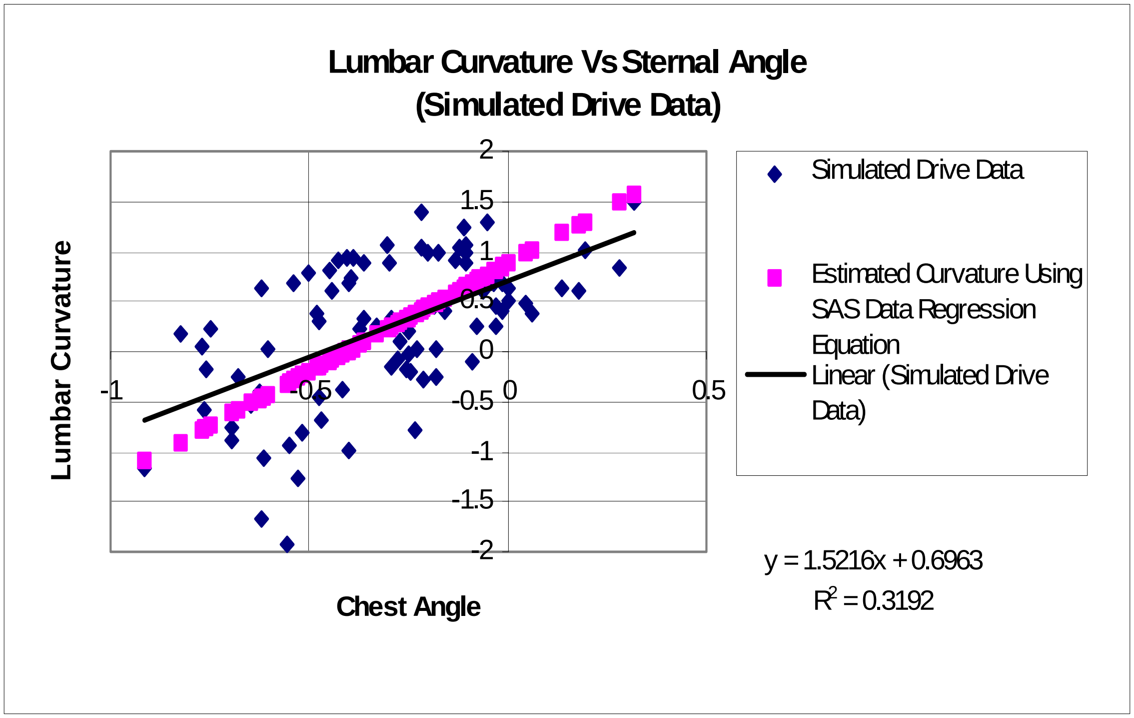


Figure 20a. Lumbar Curvature Versus Chest Angle.

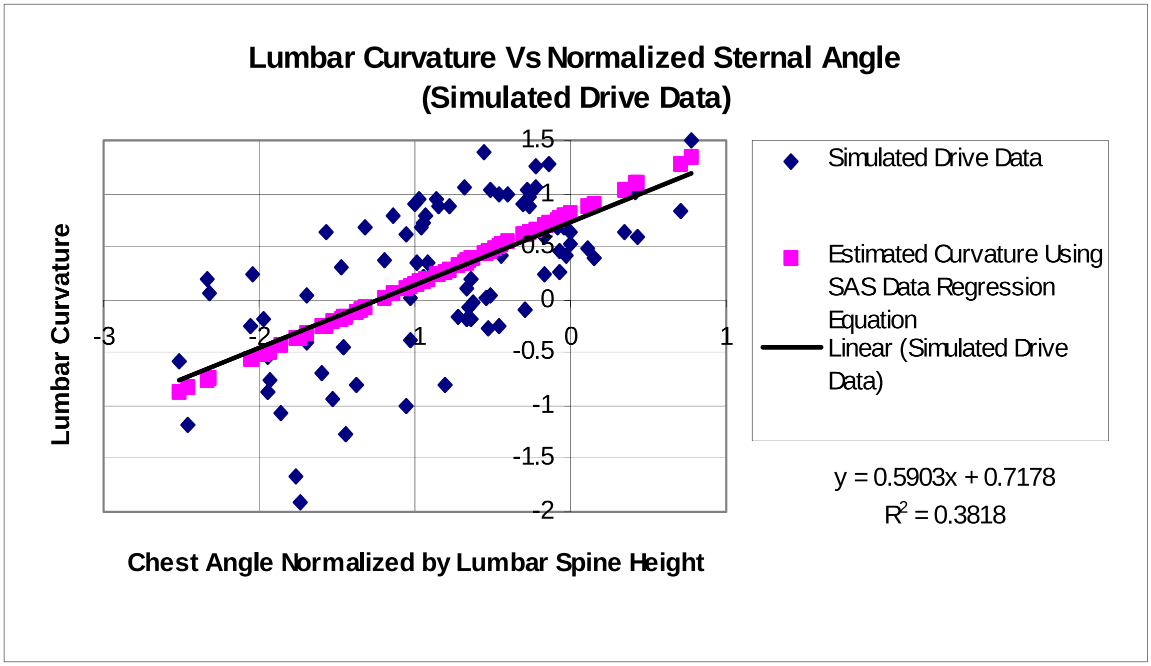


Figure 20b Lumbar Curvature Versus Chest Angle Normalized by Lumbar Height.

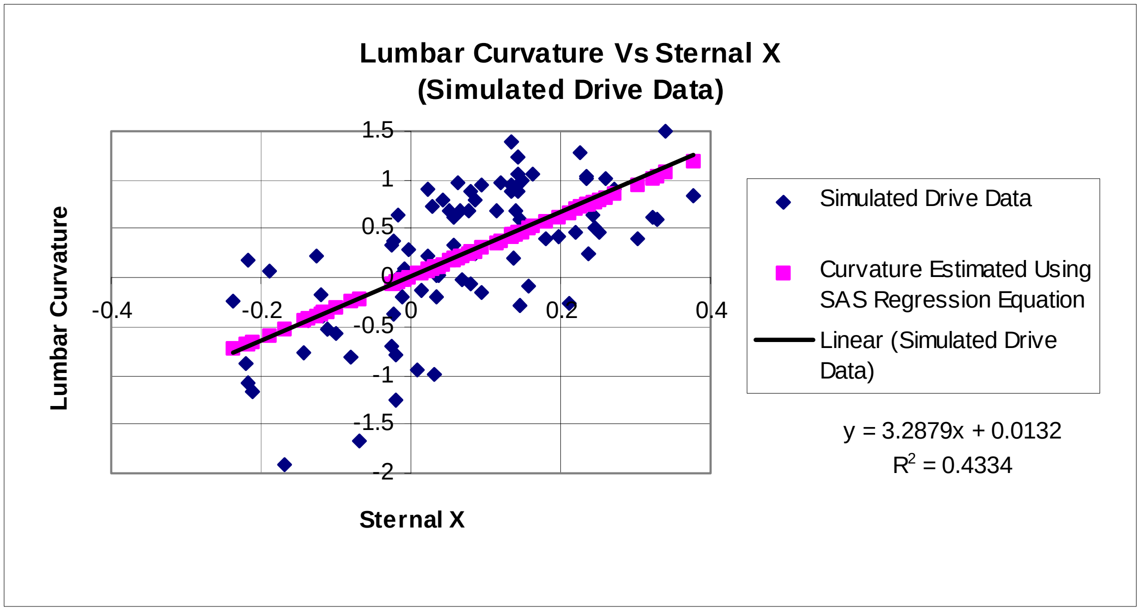


Figure 21a. Lumbar Curvature Versus Chest X-Position.

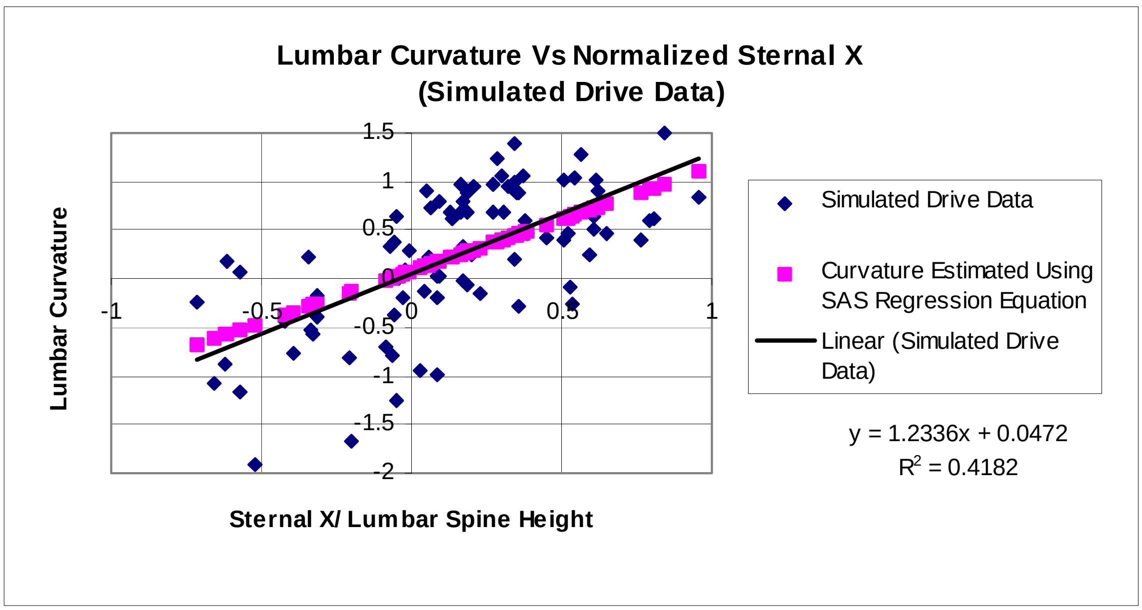


Figure 21b. Lumbar Curvature Versus Normalized Chest X-Position.

	EXTENSION % Agreement	SLUMP % Agreement	Abs Err (rad/spine ht)
Chest X-position regression equation	64.5	85.7	0.462
Chest Angle regression equation	67.7	77.8	0.500

Table 16. Percent Agreement for Estimating Posture and Error for Estimating Curvature Using General Regression Equations.

6) Modified General Equations for Estimating Lumbar Curvature

The general regression equations can be adapted to suit each individual if we assume that for a given lumbar curvature there are anatomical differences in chest angle and/or chest x-position that are responsible for the differences between a subject's measured lumbar curvature and that estimated by the general regression equation. Assume that for a given individual with chest angle θ_1 and chest x-position, x_1 there is a lumbar curvature, k_1. In addition, assume that using the general equation results in estimated curvatures k_θ and k_x such that:

$$k_\theta = m\theta_1 + b \tag{12}$$

$$k_x = nx_1 + c \tag{13}$$

where k_θ, m and b are the estimated curvature, the slope and intercept from equation (9a) or (9b), depending on the gender of the subject. Similarly, k_x, n and c are the estimate curvature, the slope and intercept from equation (10a) or (10b). Assume that there is a difference in the anatomy of the subject so that obtaining the measured curvature, k_1, requires there must be an adjustment to the chest angle of ϕ and an adjustment to the chest x-position of u. Then, for that individual, the general equation for estimating curvature from chest angle is modified to:

$$\begin{aligned} k_1 &= m(\theta_1 + \phi) + b \\ &= m\theta_1 + b + m\phi \\ &= k_\theta + m\phi \\ &= k_\theta + k_{\theta s} \end{aligned} \tag{14}$$

Where $k_{\theta s} = m\phi$ is the curvature correction for that subject. If the curvature, k_1 is known for any posture of a subject, then the curvature correction can be made:

$$k_{\theta s} = k_1 - k_\theta \tag{15}$$

where k_θ is determined from equation (12). Thus, the general equation can be modified for a given subject if we know the curvature of that subject in one posture:

$$k = m\theta + b + k_{\theta s} \tag{16}$$

where m and b are the slope and intercept from equation (9) and $k_{\theta s}$ is determined by taking measurements of the subject in one posture.

Similarly, the general equation for chest x-position can be modified to:

$$\begin{aligned} k_1 &= n(x_1 + u) + c \\ &= nx_1 + c + nu \\ &= k_x + nu \\ &= k_x + k_{xs} \end{aligned} \tag{17}$$

Where k_{xs} = nu is the curvature correction for that subject if chest x-position is used to estimate lumbar spine shape. Again, if the curvature, k_1, is known for a given posture, then the curvature modification can be made:

$$k_{xz} = k_1 - k_x \tag{18}$$

where k_x is determined from equation (13). Thus, the general equation for estimating curvature from chest x-position can be modified for a given subject if we know the curvature of that subject in one posture:

$$k = nx + c + k_{xs} \tag{19}$$

where n and c are the slope and intercept from equation (10) and k_{xs} is determined from equation (18) by taking measurements of the subject in one posture.

The procedure described above was tested using the simulated drive subjects. The curvature of each subject in the neutral posture was used to derive the curvature correction factors, $k_{\theta s}$ and k_{xs}. The curvature was then estimated for each subject in the other postures. The errors were estimated by averaging the absolute error in curvature. In addition, the estimated curvatures were classified into EXTENDED ($k < 0$) and SLUMPED ($k > 0$) and the percent agreement with the measured classification was determined. The absolute error decreased and the ability to accurately predict posture classification increased (Table 17).

	EXTENSION % Agreement	SLUMP % Agreement	Abs Err
Chest X-position with Modified Intercept	81.5	83.7	0.368
Chest Angle with Modified Intercept	85.2	83.7	0.335

Table 17. Percent Agreement for Estimating Posture and Error for Estimating Curvature Using Modified General Regression Equations.

IV Discussion

A. Spine Anthropometry

The vertical locations of spinal landmarks are given as a percent of cervicale (C7) sitting height (C7Ht) in Table 3a. There are slight differences between males and females, especially in the lumbar and lower thoracic spine, where male spinal landmarks are slightly lower in proportion to the C7Ht. An examination of the cervicale sitting height reveals that our averages are smaller than those given in the 1988 U.S. Army anthropometric survey. Dropping subjects having sitting height below the 10th percentile increases the average of our cervicale sitting height to the 45th percentile for females and 40th percentile for males.

B. Lumbar Spine Shape

Using a second order polynomial to fit the lumbar spine shape provides a means of smoothing the data as well as a means of using the polynomial to describe lumbar curvature. Although it is convenient to try to fit spine data to the arc of a circle, a polynomial is more likely to fit the measured data than an arc of fixed radius. The correlation coefficient, r^2, exceeded 0.8 for all but 12 out of 510 of the measurements and only 9 out of 510 measurements had $p < 0.05$ (see Table 6). This indicates that a second order polynomial fits the data very well. The radius of spine segments have been estimated by others using a least-squares fit to force the data to fit an arc of fixed radius, or using arc length and arc depth to estimate the radius [10, 11]. The advantage of the method outlined in this report is that the data is not forced to fit a curve of fixed radius, but yet a single value for describing the curvature of the back can still be estimated.

We elected to use the curvature as a descriptor of the lumbar spine since it is continuous throughout the range of motion of the lumbar spine, whereas the radius becomes infinite when the lumbar spine is straight.

The average curvatures for each of the measurement postures are summarized in Table 7. The average radii for each posture range from 243mm for the extended posture to a nearly infinite radius (i.e., the lumbar spine was essentially a straight line) in the slump 1 posture. For women, the average curvature was -1.77 radians/spine height compared to -1.42 radians/spine height for men. These correspond to relatively small radii (243mm for females, 341mm for males) and probably exceed the lumbar curve desired for a comfortable seat. However, there were subjects placed in the extended posture for which we were not able to obtain a lumbar lordosis. Likewise, there were subjects placed in a position intended to create a slouched posture, but which resulted in the measurement of a lordosis rather than a kyphosis.

In general, the pelves of most subjects were rotated forward in order to place the ischial tuberosities over the pressure mat. The large amount of forward rotation resulted in a lordotic lumbar spine in the upright posture and, for some subjects; the lordosis could not be reduced by chest flexion within the constraints of the SAS equipment. However, for most subjects, the lumbar spine was lordotic in the upright and extended posture and was neutral or kyphotic in the slumped postures.

One problem with posture description is the anatomical variation of subjects. For example, two subjects may have the same chest-pelvis angle, but due to anatomical differences, the lumbar curvature may be very different. Thus we chose to use the lumbar curvature to define the posture rather than the chest and pelvis position.

Neutral was defined as zero or near zero curvature. The range of curvatures $-0.6 \le k \le 0.6$ radians/spine height was used as the boundary for the neutral posture since such a curvature corresponds to a relatively large radius. Using this method, the average curvature was essentially zero for both the male and female neutral postures.

The range of acceptable curvatures for defining a lordotic lumbar spine was based on the curvature distributions of Figure 8 and the assumption that an excessive lordosis is not comfortable. There is a "clumping" of data in Figure 8, where $k = -2.0$ appears to be a natural break, in addition, this curvature corresponds to a radius of half the upright spine height, which we subjectively decided was the limit of a comfortable lordosis. Thus, the curvatures for defining a lumbar lordosis were $-2.0 \le k \le -0.6$ resulting in an average curvature of -1.33 radians/SH for both females and males. The corresponding radius for females is 323mm and for males, 364mm.

Defining a slumped posture was based on curvatures $k \ge 0.6$, since we did not have curvatures exceeding 1.6 radians/spine height, we did not set an upper bound. However, due to the mechanics of the lumbar spine, the curvature of the most slumped posture will be smaller than the curvature of the most extended posture (see Figure 20).

These postures were used to define the shape of the back for the seat design template, ERL. Further discussion on this topic will be given in a separate report.

C. Lumbar Geometric Descriptors as a Function of Chest Position

Modeling lumbar spine shape as a function of chest-pelvis motion requires that we understand which variables are important descriptors of chest motion. For many joints, the angle is the only variable needed to describe joint position. However, the lumbar spine is relatively complex and there can be translation of the chest without a change in the chest-pelvis angle. The data in Figure 9 indicate that the most important variables for describing chest position relative to the pelvis are the angle of the chest and the x-position of the Suprasternale. The z-position of the Suprasternale does not change significantly. If the chest were pinned to a single point relative to the pelvis, then chest position would be completely described by the chest-pelvis angle and the chest x-position would be a sinusoidal function of chest angle. There are significant portions of a sine curve that can be approximated by a straight line; this explains why the regression of chest x-position illustrated in Figure 9 has a strong linear correlation ($r^2 = .83$) with the chest angle. However, the scatter of the data about the regression line indicates that there is translation of the chest x-position that is independent of chest angle. Since the data has been normalized for spine height, the scatter is not likely to be due to differences in stature. Thus, we concluded that lumbar geometric descriptors are most likely to be functions of chest angle and chest x-position (Suprasternale x-position) and that chest z-position could be ignored.

The height of the lumbar spine (z-height in the pelvis coordinate system) has a moderate correlation with both chest angle and chest x-position (see Figures 10 and 12). If examined on an individual basis, the lumbar spine height has a very strong correlation with chest angle and chest x-position, with $r^2 > 0.7$ for 92% of the subjects. The general mechanics of the lumbar spine indicate that the height must have a correlation with chest angle and chest x-position (see Figure 20).

The tangent to the lumbar spine at T12 (θ_T), has a very strong correlation with chest angle and chest x-position (see Figures 11 and 12), with $r^2 = 0.7$ for the chest angle and $r^2 = 0.84$ for the chest x-position. This correlation is even stronger when analyzed on an individual basis. The T12 tangent has a correlation of $r^2 > 0.8$ for 95% of the subjects when using chest angle as the independent variable. The high linear dependence of the T12 tangent on chest angle is not surprising since, mechanically, the location of T12 and L1 are obviously highly dependent on chest position. However, the range of motion for the tangent exceeded that of the chest-pelvis angle. The average range for the T12 tangent angle was 65.9^o ($\pm$17.2^o), exceeding the average range of motion of the chest by 24.2^o. Since the relationship between the tangent of the curve at T12 and the motion at T12-L1 is not known, we do not know if this indicates that there is significant motion taking place at the upper lumbar and lower thoracic spine. This is not likely since the motion in the upper lumbar and lower thoracic spine is limited to about 12^o compared to 20^o for L5-S1 [8].

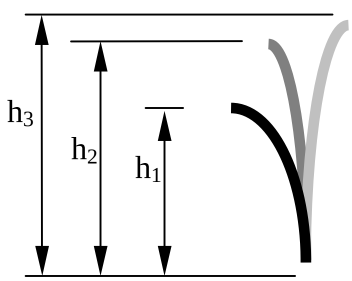


Figure 20. Lumbar Spine Height in Lordosis, Neutral and Kyphotic Postures.

The tangent at S1 (θ_s) was shown to have a very weak linear correlation to the chest angle and chest x-position (see Figures 11 and 12). In addition, the S1 tangent angle had a fairly wide range so that for each subject the S1 tangent angle changed an average of 16.0^o ($\pm$ 8.0^o). Since this is 38.4% of the T12 tangent angle average range, the tangent at S1 cannot be ignored when estimating the shape of the lumbar curvature. Unfortunately we have no means of predicting this variable, due to the poor correlation. The linear correlation does increase when evaluated on an individual basis (25.5% of the subjects had $r^2 > 0.7$ and 44% had $r^2 > 0.5$). However, we concluded that using chest angle or chest x-position to predict the S1 tangent is not reliable.

We defined an additional variable, lumbar angle, to be (θ_T - θ_s). Plotting lumbar curvature against the lumbar angle (see Figure 13) has a very strong linear correlation ($r^2 = 0.98$). This is an important finding since the basis of our model assumes that the relationship between curvature and tangent angle will be in the linear range, as illustrated in Figure 6. This finding indicates that the relationship between lumbar curvature and chest angle is also likely to be linear.

Lumbar curvature versus chest angle has a moderate linear correlation ($r^2 = 0.52$), with a slightly stronger correlation for females ($r^2 = 0.55$) than males ($r^2 = 0.49$) (see Figure 14a). The linear correlation increases when the chest angle is normalized by lumbar spine height (Figure

14b). When normalized, the correlation increases ($r^2 = 0.58$), again with females ($r^2 = 0.59$) having a slightly stronger correlation than males ($r^2 = 0.57$). These results further support the model described in Section II.4.d. This indicates that the slight curve evident in Figure 14a is due to the fact that the lumbar spine heights are not equivalent for all subjects. However, after normalizing, the linearity of the data becomes more evident (Figure 14b), even if the scatter is still significant.

The scatter in Figure 14b can at least be partially explained by anatomical variation among subjects. When a linear regression of lumbar curvature versus normalized chest angle is done for each individual subject, the variability in the slopes of the regression equations are all very close, while there is more variability in the intercepts. This means that the change in curvature is the same for a change in chest angle, but due to anatomical variation between subjects, the lines have different intercepts. The relevance of this finding is discussed in the next section.

Curvature as a function of chest x-position is illustrated in Figure 15a. The linear correlation ($r^2 = 0.57$) is slightly stronger than that for the chest angle and slightly stronger for females ($r^2 = 0.58$) than for males ($r^2 = 0.56$). Normalizing for lumbar spine height results in a slightly higher correlation coefficient ($r^2 = 0.60$), with females ($r^2 = 0.61$) having a slightly higher correlation than males ($r^2 = 0.59$). These results strengthen the argument that lumbar spine height plays a role in understanding the relationship between curvature and chest position.

Individual regressions of curvature versus chest angle or chest x-position are illustrated for one subject in Figure 16 and 17. In general, the linear regressions had very high correlation coefficients, with $r^2 > 0.8$ for 78% of the subjects and $p < 0.05$ for 82% of the subjects for curvature versus chest angle. For curvature versus chest x-position, $r^2 > 0.8$ for 87% of the subjects and $p < 0.05$ for 90% of the subjects. This indicates that for each individual, a linear regression equation can be determined for predicting the curvature of the lumbar spine. In the following section we discuss the robustness of this approach.

D. Predicting Lumbar Curvature From Chest Position

As discussed above, a regression equation for each individual has a strong linear correlation with the curvature of the lumbar spine. The error in the individual regression equations was determined by the absolute value of the difference between the measured and the estimated curvature. Using chest angle, the average absolute error was 0.229 (±.208) radians/SH; using the chest x-position regression equation, the average absolute error was 0.211 (±.194) radians/SH. These errors are relatively small, corresponding to about 3% of the full range of the lumbar curvatures measured and about 6% of the range of curvatures used to define the Erect, Neutral and Slumped postures for the seat design template, ERL. The chest x-position provides a better estimate of the curvature than chest angle (see Tables 11-14), a result that was not expected.

Predicting the posture of the subject was investigated using the categories described in III.4.a where the subjects were divided into one of three categories: Extended ($k \leq -0.6$ rad/SH), Neutral ($-0.6 < k < 0.6$ rad/SH) or Slumped ($k \geq 0.6$ rad/SH), as well as placing them in one of two categories: EXTENDED ($k < 0$) and SLUMPED ($k > 0$). Using chest angle, the subjects' curvatures were correctly categorized into the Extended posture 96%, Neutral posture 80%, and the Slump posture 82% of the time. Using the chest x-position, the categories were correct 95% Extended, 83% Neutral and 83% Slumped. If the curvatures were only divided into one of two categories, then, using the chest angle, subjects were correctly classified into the EXTENDED posture 98% of the time and into the SLUMPED posture 87% of the time. Using chest x-position, the results were 97% EXTENDED and 88% SLUMPED. Thus, predicting the correct posture of a subject using the linear regression equations is very accurate.

The curvature estimates using chest angle were less robust than those using chest x-position. Errors of 5^o increased the absolute error (0.32 rad/SH) and decreased the Slumped categorization accuracy to 53% and the SLUMPED to 72% (Table 13). In order to reach the same level of inaccuracy in the absolute error, the chest x-position error had to exceed 34mm and for the equivalent errors in categorization the error had to exceed 22mm (Table 14). Thus, chest x-position is far more robust, providing smaller absolute error as well as fewer classification errors.

The general regression equations can be accurately applied to a separate group of subjects (Table 15). The absolute error is smaller using the chest x-position. The errors in categorization are slightly better if the chest angle is used to predict EXTENSION and for chest x-position for predicting SLUMPED.

These errors are greatly reduced if the general equations are adapted for individual subjects using the curvature correction described in III.4.c. The absolute errors are reduced compared to the general regression absolute error (Table 16). In addition, the ability to classify subject posture exceeds 80% for both EXTENDED and SLUMPED postures.

The individual regression equations using chest angle and chest x-position are a relatively robust means for predicting lumbar spine curvature, with chest x-position having slightly greater accuracy and slightly more robustness than chest angle. The general equations by themselves are better than chance for predicting posture, but the accuracy can exceed 80% if the subject's curvature is known for at least one posture.

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