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Average Male in Seated Postures

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has been accepted towards fulfillment
of the requirements for

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GEOMETRIC MODEL AND SPINAL MOTIONS OF THE AVERAGE MALE IN SEATED POSTURES

By

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ABSTRACT

GEOMETRIC MODEL AND SPINAL MOTIONS OF THE AVERAGE MALE IN SEATED POSTURES

By

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The position of the pelvis relative to the thorax in the seated posture and the distribution of mid-sagittal bending in the lumbar spine are not well understood. In this study, a computer graphics model and a mid-sagittal bending motion program were created. Initial seated postures were formed and, through the use of a motion program which utilized different distributions of lumbar motion, several published studies were simulated to evaluate the relative positions of the pelvis and thorax. The published studies were best simulated by equally distributing the rotation in the mid-sagittal plane among the L5/S1 interspace through the T12/L1 interspace and using the initial postures.

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1. INTRODUCTION

The need for a representation of human seated posture is apparent in the current practice of automobile seat design. The current practice in the automotive seating industry is to layout the interior of the automobile and the seats using the SAE 2-D drawing templates, Figure 1, and other SAE accommodation tools (SAE is an abbreviation of Society of Automotive Engineers). This seating layout is followed by the development of a prototype automobile seat which is tested using the three-dimensional (3-D) H-point machine, Figure 2. The 2-D drawing template and the 3-D H-point machine provide a location in the automobile seat of the H-point and the seatback angle. The H-point is a point defined by the SAE which represents the center of rotation of the hip joint relative to the pelvis. The seatback angle is defined as the angle from vertical to a line on the torso of the 2-D drawing template and the 3-D H-point machine. Both the position of the H-point and the seatback angle are often specified prior to the construction of the automobile seat. The contours of the 2-D template and the 3-D H-point machine are flat in the lumbar region and curve forward at the shoulders. This is the posture which has been typical in American automobile seats for many years.

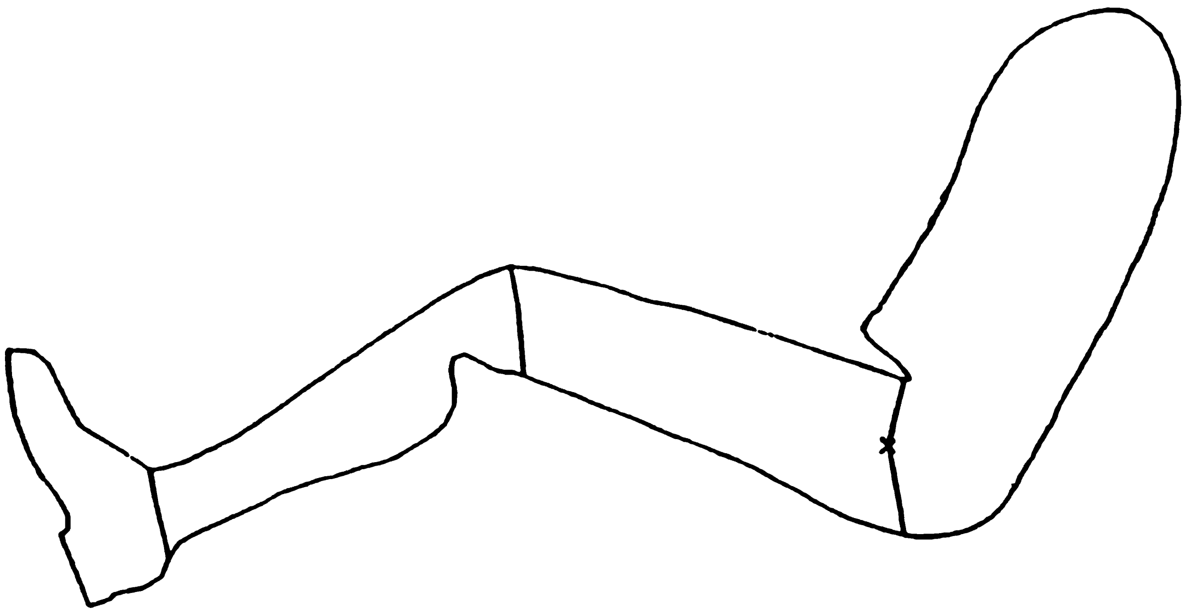


Figure 1 - 2-Dimensional drawing template

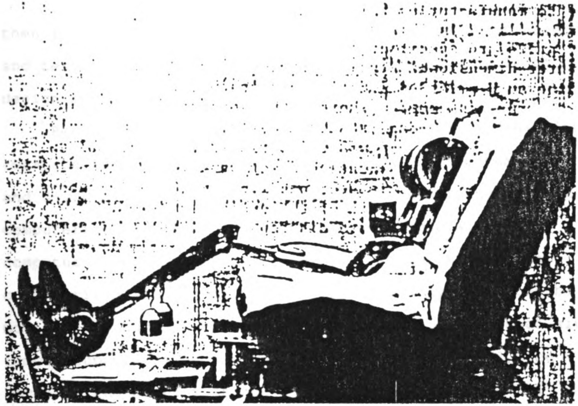


Figure 2 - 3-Dimensional H-Point machine

There has been a problem since the introduction of highly contoured seats and lumbar support in the automobile seats. The contours and the lumbar support cause the 2-D template and the 3-D H-point machine to rotate forward in the seat. This results in the automobile seat failing to meet the required specified H-point location and seatback angle.

Another problem with the 3-D H-point machine is that it can only be used on a previously constructed automobile seat. If an automobile seat fails to meet specifications, then it must be redesigned and a new prototype constructed and tested. This often results in an expensive cycle of design and redesign.

Because of the inability to meet the specified H-point location and seatback angle with the 2-D drawing template and 3-D H-point machine, a new seating model is needed. A computerized seating model could be developed with a computer aided design (CAD) package. To be useful, the computerized seating model must realistically simulate the motion of a human. When considering an automobile seat with lumbar support using the computerized seating model, the torso of the model must not rotate forward in the seat. Instead the seating model must represent the lordosis of the spine as it would occur naturally.

Limited information is available which quantitatively describes the motion of the lower spine. Most of the literature does not describe the motion at the individual joint centers. Some literature is available which does quantitatively describe the motion of the lower spine and the position of the pelvis.

The most recent and extensive study of human posture in automobile seats comes from the University of Michigan Transportation Institute (UMTRI)[1]. Included among the data from UMTRI[1] is a set of full scale drawings which show the skeletal position of the seated occupant along with a table of coordinate locations of important landmarks. The positions which UMTRI[1] described are representative of the 5th percentile female and the 50th and 95th percentile male in the then current automobile seats. The data were gathered through seating occupants in a hard seat which was representative of a typical automobile seat. After placing markers on important external landmarks, photographs were taken and measured providing data on the position of external landmarks in a seated posture. Generally, the skeletal placement was based on estimates from external landmarks based on the Link System of the Human Torso by Chaffin et. al.(Link Study)[2]. An apparent problem with the skeletal drawing and the skeletal data is the position of the pelvis in the body. There is 46mm of tissue between the bottom of the pelvis and the surface of the buttocks. This appears to be too much tissue for a person in the seated posture.

In another important publication, Andersson et. al.[3] measured radiographs of seated occupants to describe the positions of their pelves relative to their lumbar spines in both the standing posture and in a variety of seated postures.

A report by Reynolds and Robbins, "Position and Mobility of Skeletal Landmarks of the 50th Percentile Male in an Automotive Seating Posture"[4], is also significant. This publication provides the positions of several vertebral interspaces and the position of the pelvis for a single seated posture. Fortunately, the posture studied by Reynolds and Robbins was different from the posture used by UMTRI[1]. This allowed for a comparison between the two postures.

A study by Nyquist and Patrick, "Lumbar and Pelvic Orientations of the Vehicle Seated Volunteer"[5], contained data concerning the positions of the pelvis and lumbar region for two seated male volunteers obtained through the use of radiographs.

Data for the distribution of spinal motion among the vertebral interspaces in the spine are from two sources. The first source, "Kinematics of Human Spine" by Panjabi and White[6], quantitatively describes the proportion of movement for each spinal interspace. The second source for lumbar motion distribution is by Allbrook, "Movements of the Lumbar Spinal Column"[7].

Data for the representation of the skeletal pelvis were obtained from a study by Reynolds, et. al., "Spatial Geometry of the Human Pelvis"[8]. They measured many skeletal pelves utilizing a digitizing technique then divided the pelves into three size categories, including the 50th percentile male.

Data for the creation of the skull for a computer model were furnished by Hubbard[9]. In this publication, Hubbard extensively described the dimensions and the creation of a 50th percentile male skull model.

The present research to model and study the spinal motions of an average adult male consists of several parts:

1. Construction of two-dimensional representations of the thorax, skull, and pelvis.
2. Selection of a nominal position of the skeletal model.
3. Development of a motion algorithm and computer model for the lumbar region of the spine.
4. Testing of various motion models of the lumbar spine to determine their effect on the relative positions of the thorax and the pelvis.
5. Verification of the model created in step 2 by comparison to available data.
6. Recommendations for the use of the model in the design of automobile seating.

2. METHODS

2.1 Introduction to Methods

To represent the 50th percentile male pelvis, skull, and ribcage, geometric models were formed based on available literature. The pelvis and skull were first modeled as three-dimensional objects. Then, two-dimensional representations of the skull and the pelvis were formed based upon the three-dimensional models. For this study, three-dimensional representations were not necessary. Only 2-D mid-sagittal motion is studied so two-dimensional representations were used. Also, at the beginning of this study, a three-dimensional representation of the thorax was not available.

Positions of the head relative to the thorax have also been predicted by the model. The user can place the head of the model on any angle from the horizontal. The model will then automatically distribute evenly the motion needed to obtain this angle throughout the cervical region. No further research has been done for the cervical region since the lumbar region, not the cervical region, is the focus of this study.

2.2 Computer System and Software

The computer system used to develop and study the skeletal motion model was the SUN SYSTEM 3/60 utilizing the SDRC IDEAS 3.8 GEOMOD[10] Solid Modeling package.

2.3. Skull Modeling

2.3.1 3-D Skull

The 3-D skull was created using data supplied by Hubbard[9]. This publication contained data on the three-dimensional locations of various skeletal landmarks representing the skull of the 50th percentile male. This skull geometry described by Hubbard[9] is the basis for the head of the Hybrid III crash test dummy. Portions of the lower jaw and eye socket region could not be adequately constructed from the data supplied by Hubbard[9]. Figure 3 is a 3-D wireframe representation of the skull.

The origin of the coordinate system for the skull was at the Nasion which is at the bridge of the nose. The X-Y plane was defined as the Frankfort plane, which was the plane formed by the porions and the orbitales skull landmarks. The positive X axis was in the forward direction, and the positive Y axis was to the left of the body. The Z plane was perpendicular to the Frankfort plane with the positive Z in the superior direction.

The cranial portion of the skull was created through the merging of two spheres as used in modeling the skull by Khalil and Hubbard[11]. The first and larger sphere which described the posterior section of the cranium measured 71mm in radius. The second and smaller sphere which described the frontal section of the cranium measured 60mm in radius. The centers of the spheres were positioned 46mm apart as specified by Khalil and Hubbard[11]. A conical segment of length 43.2mm was placed between the two spheres. Once the spheres and the cone were positioned, they were joined together forming the major segment of the superior portion of the skull.

Next, using landmark locations specified by Hubbard[9], the remainder of the skull was formed. Those areas of the skull, mainly the lower part of the jaw, which needed a more detailed description than that supplied by Hubbard[9], were described through measurements of a typical skull.

The sockets for the eyes were created as follows. First, two spheres of 18mm radius and a third sphere of 17mm radius were formed. The two initial spheres were cut with the third sphere resulting in was hollow spheres. Next, the spheres were cut in half and the centers of the cut surfaces of the spheres were placed at the skull coordinates -7.6mm,$\pm$31.0mm,-12.7mm. The final step in the creation of the skull was the placement of two small spheres in the eye sockets to represent pupils using data obtained through the measurement of an average skull.

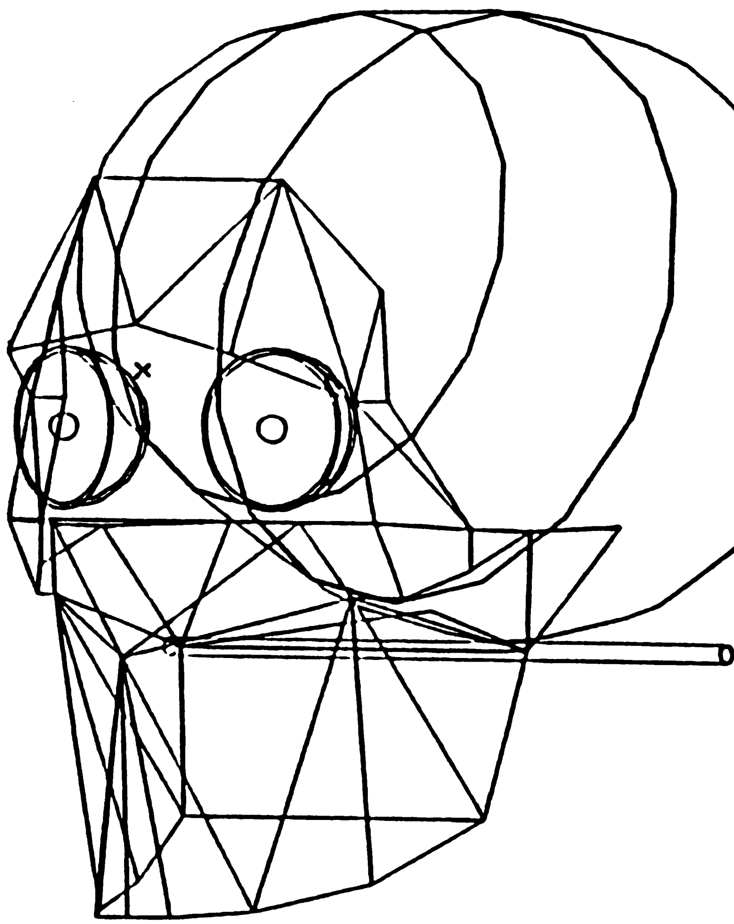


Figure 3 - 3-Dimensional wireframe skull

2.3.2. 2-D Skull

The two-dimensional skull was created by cutting a 1mm wide portion of the 3-D solid model of the skull about the mid-sagittal plane. This can be seen in Figure 4.

2.4 Pelvis

2.4.1 3-D Pelvis

The pelvis for the model was created using the data contained in a report by Reynolds, et al.[8] The publication contained data on inside and outside skeletal landmarks of the pelvis. Three types of pelves were described, the 50th and 95th percentile male and the 5th percentile female. These pelvic data were gathered for use in future crash test dummies.

The data used to create a model of the 50th percentile male pelvis is given in Appendix 1 and a wireframe picture of the pelvis can be seen in Figure 5. First the coordinates of the points to form the pelvis were entered into the computer utilizing the sequence of commands. As each point was entered using pelvic coordinates, the computer program assigned to each set of coordinates a label which became its new name. The points and their corresponding labels are listed in Appendix 1. After each

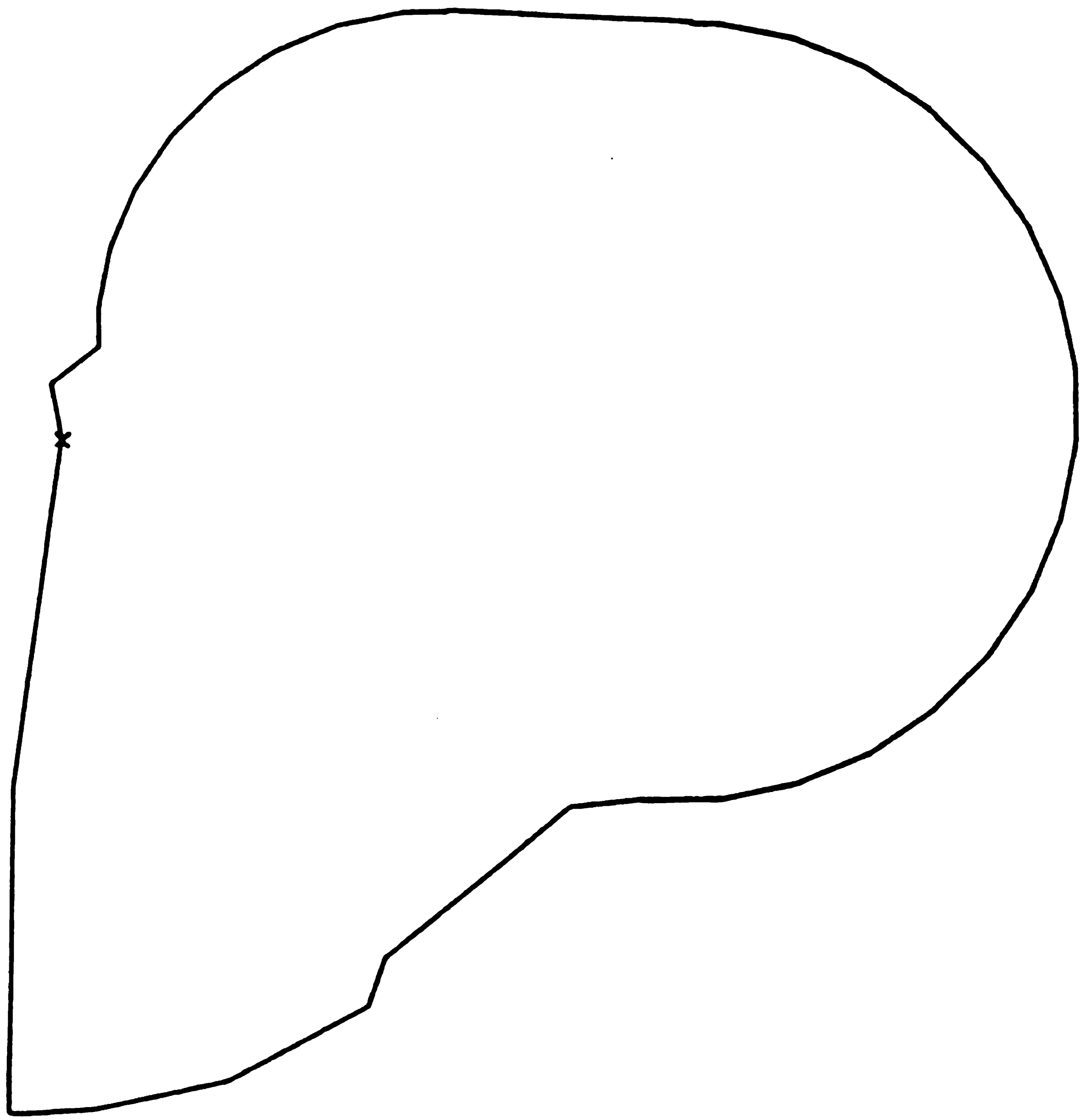


Figure 4 - 2-Dimensional skull

point was entered and assigned a label, the points had to be assembled into facets. The computer program asked for the points, using the labels, needed to assemble facet 1. After entering the point labels for facet 1, each subsequent facet was formed until the left half of the pelvis was completed. Then, the mirror image of the left half of the pelvis was created and the two halves were simultaneously fused together.

2.4.2 2-D Pelvis

The two-dimensional pelvis was simply a facet formed using all the points which described the outer surface of the pelvis projected onto the mid-sagittal plane as seen from the left lateral view. Appendix 2 contains these data. The two-dimensional pelvis was then stored as a separate object, named 2DPELVIS, Figure 6.

2.5 Thorax

The first of two thorax representations was developed from measurements of diagrams supplied by the University of Michigan Transportation Research Institute (UMTRI)[1]. This initial thorax was two-dimensional and was used in the process to create and debug the spinal motion computer program. Appendix 3 contains the data for this thorax also shown in Figure 7. These data include the skeletal

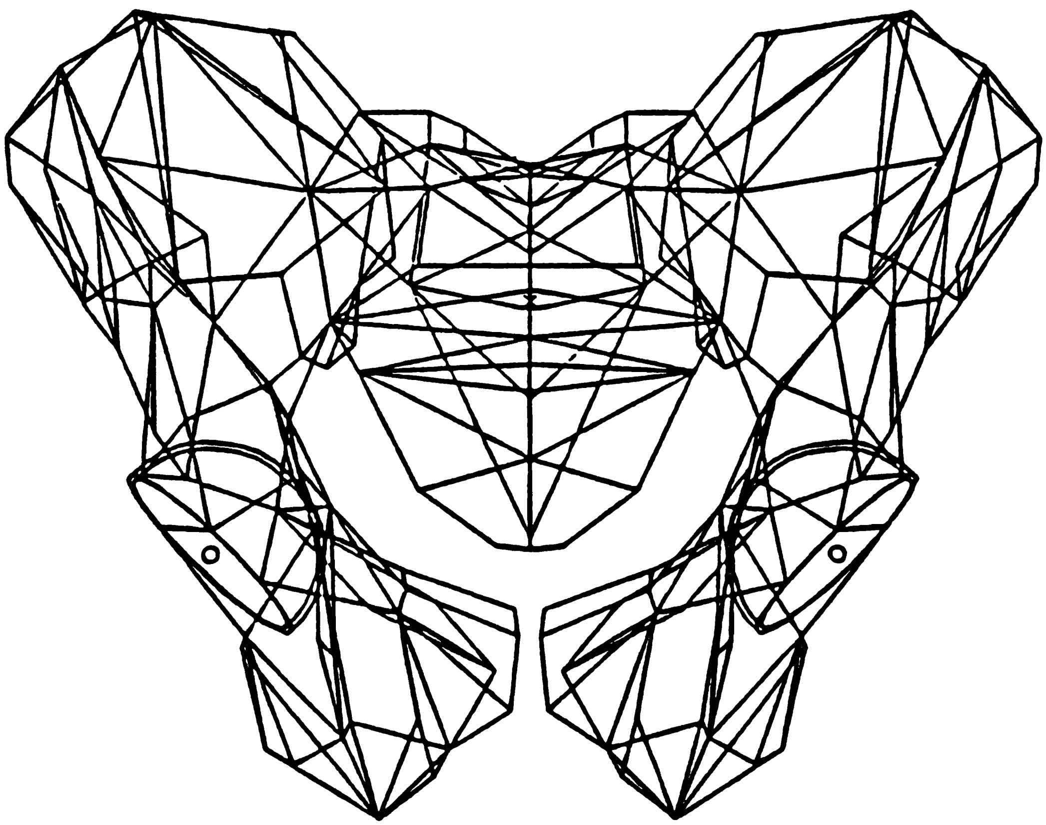


Figure 5 - 3-Dimensional wireframe pelvis

positions of the twelve thoracic spinous processes, three points on the sternum and one point to represent the lowest margin on the 10th rib.

A three-dimensional thorax was created using measurements of a typical thorax. The coordinates of the points measured on the thorax were entered into the computer to create facets in the same manner as for the 3-D pelvis.

Even though a three-dimensional thorax, Figure 8, was created, it was not used in this motion study. The two-dimensional model based upon the UMTRI[1] drawing was used because the 3-D thorax did not have any spinous processes. It was thought that the lack of spinous processes would cause problems when trying to fit the model into a seatback. Figure 9 shows the differences between the two thorax models. Furthermore, the three-dimensional thorax was not needed because this is a planar motion study.

2.6 Creation of The Nominal Posture

2.6.1 Placement of 2-D Body Segments

The placement of the pelvis, rib cage, and skull to represent a 50th percentile male was derived from the diagrams and data supplied by UMTRI[1], Appendix 4. This initial posture was the basis for the JOHN1 model. The model was assembled using the SYSTEM ASSEMBLER option offered by the IDEAS GEOMOD[10] package. The SYSTEM

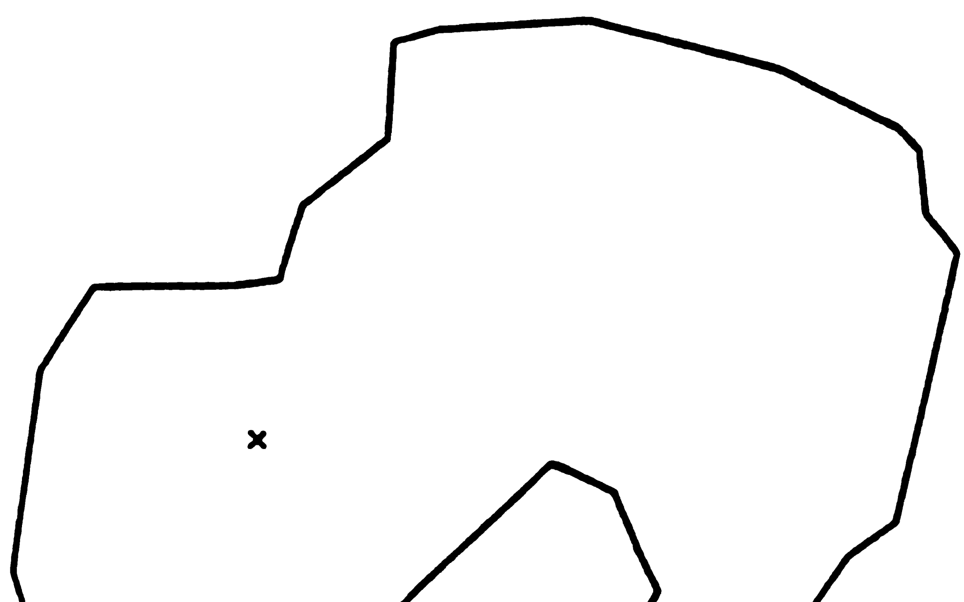


Figure 6 - 2-Dimensional pelvis

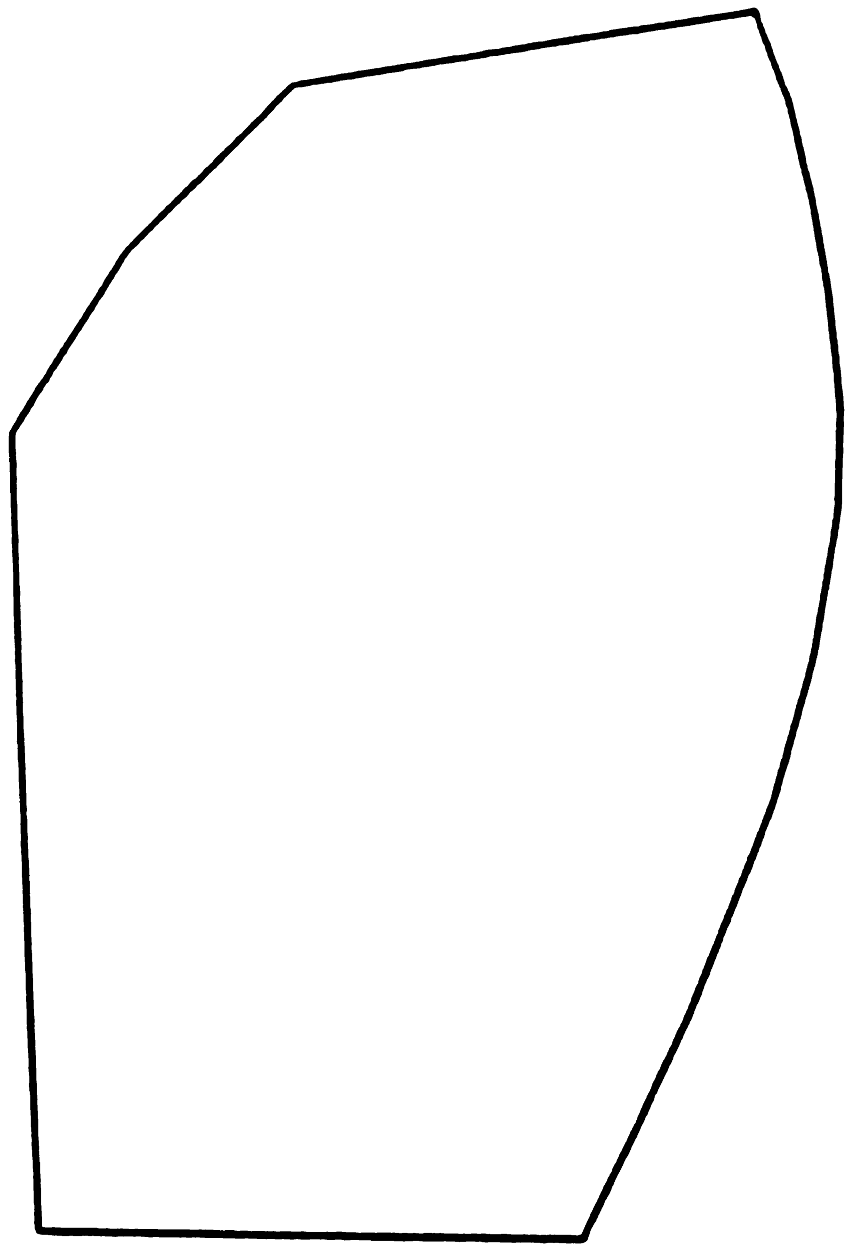


Figure 7 - 2-Dimensional thorax

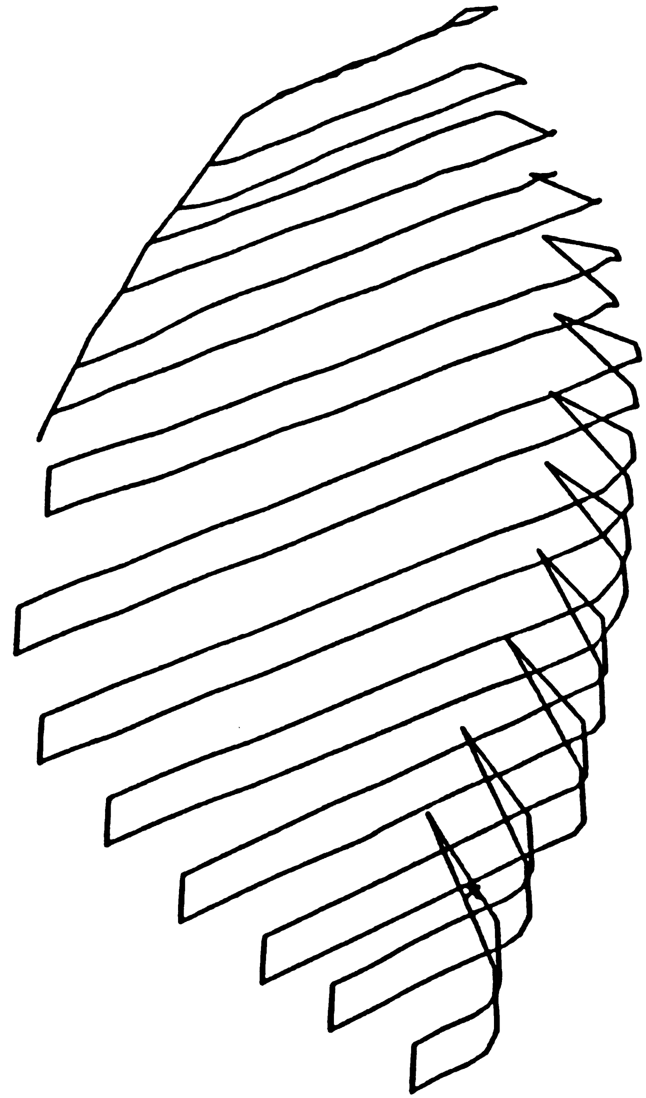


Figure 8 - 3-Dimensional ribcage

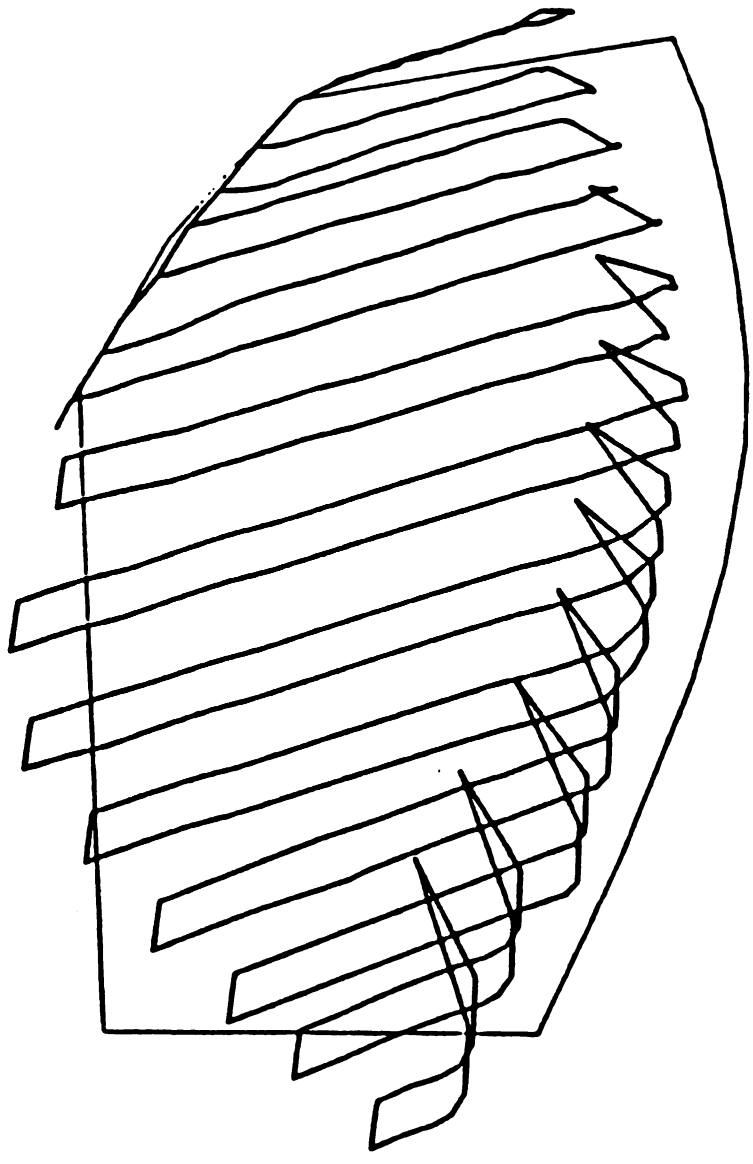


Figure 9 - 2-D thorax/3-D ribcage overlay

ASSEMBLER package is arranged so that each component to be assembled was called onto the computer screen individually in the position designated by the components coordinate system. As an example, when the two-dimensional skull was called onto the screen, the nasion was at the origin of the SYSTEM ASSEMBLER coordinate system.

To complete the body, each component was called onto the screen then placed in reference to the SYSTEM ASSEMBLER coordinate system. The SYSTEM ASSEMBLER coordinate system and subsequently the whole body coordinate system was designated so that the X axis was parallel to the floor and positive forward (toward the left of the viewer in all diagrams). The positive Y axis was lateral to the body in the left hand direction of the model (pointing out of the page for all diagrams) and also parallel to the floor. The Z axis was perpendicular to the floor, with the upward direction to be positive.

First, the 2-D pelvis was called onto the screen. When it appeared on the screen, the midpoint of the anterior superior iliac spines (ASIS) was at the origin. To place the pelvis in the orientation specified by UMTRI[1], the pelvis was first translated to place the midpoint of the hip joint centers of the pelvis at the origin of the whole body coordinate system (0mm,0mm,0mm). The pelvis was then rotated negative -54.07 degrees about the positive Y axis as specified by UMTRI[1].

Second, the 2-D skull was called onto the screen. As stated earlier the Nasion was at the origin, with the Frankfort plane aligned with the SYSTEM ASSEMBLER coordinate system. To move the skull into the position of whole body coordinates the mid-point of the porions originally at -86.36mm, 0mm,-33.02mm was translated to -185mm,0mm,614mm. This corresponds with the position as designated by UMTRI[1]. The skull in the UMTRI[1] drawing and their literature does not have a level Frankfort plane. Instead, the skull in the UMTRI[1] literature, and hence the 2-D skull model was rotated -3.9 degrees about the positive Y axis with the mid-point of the porions as the center of rotation.

The third component called onto the computer screen was the thorax. Since the whole body coordinates as assigned by UMTRI[1] were used to create the thorax, the thorax was in the proper position when it was called onto the computer screen.

2.6.2 Spinal Linkage

The first step in the process of creating the spinal linkage was to decide how the spine would be modeled. For the sake of simplicity, the spine was modeled as a chain of links which would have fixed length. This meant that the joint centers of rotation were fixed with respect to the vertebra. White and Panjabi[6] described the regions of the joint centers for flexion and extension. Their conclusion was that the joint centers moved rearward, especially at the end of the facet joint range of motion. Although not documented in the traditional academic manner, Jones[12] described lumbar motion as a chain of links with joint centers at the disc centers for the first 36 degrees of extension from a straight lumbar spine. After this, the facet spinous process impacted and the joint centers moved rearward. In future studies, the effects of motions of the spinal joint centers should be investigated.

The second step in creating the spinal linkage was the designation of centers of rotation for the motion model. Initial data were needed for the positions of the centers of rotation for the spinal discs. The UMTRI[1] study, which is based on the study by Chaffin et. al.[2], was used to supply the initial joint centers of motion. The centers of rotation for the lumbar spine which UMTRI[1] supplied were the joint center between the twelfth thoracic vertebra and the first lumbar vertebra (T12/L1), the joint center between the second lumbar vertebra and the third lumbar vertebra (L2/L3), and the joint center between the fifth lumbar vertebra and the first sacral vertebra (L5/S1). To get the other centers of rotation, a line was drawn along the three known centers of rotation on the drawing, and the remainder of the centers of rotation were chosen to be at the midpoint of the interspaces along this line. For the thoracic centers of rotation, UMTRI[1] supplied the center of rotation between the seventh cervical vertebra and the first thoracic vertebra (C7/T1), the T4/T5, and the T8/T9 joint centers. The remainder of the centers of rotation were estimated to create a smooth curve. A similar method was used for the cervical centers of rotation. For the cervical region, UMTRI[1] supplied the C7/T1 and the C1/skull centers of rotation. The remainder of the centers of rotation were estimated through the use of a smooth curve. The coordinates for the joint centers are contained in Appendices 5-7.

At this point an initial posture for the model had been created, the JOHN1 model, Figure 10. Since the choices for the centers of rotation were not necessarily correct a method was devised by which the centers of rotation could easily be changed, if a superior set of data would become available. The computer motion program accessed separate external data sets which contained the coordinates of the centers of rotation. These data sets could then easily be changed without changing the motion program.

The bottom of the pelvis on the UMTRI[1] drawing was 46mm from the surface of the buttocks. This seemed to be too large a distance. The external surface of the body was measured in the UMTRI[1] study and the position of the skeleton was estimated from the location of external body landmarks. Furthermore, the lengths of the lumbar vertebrae

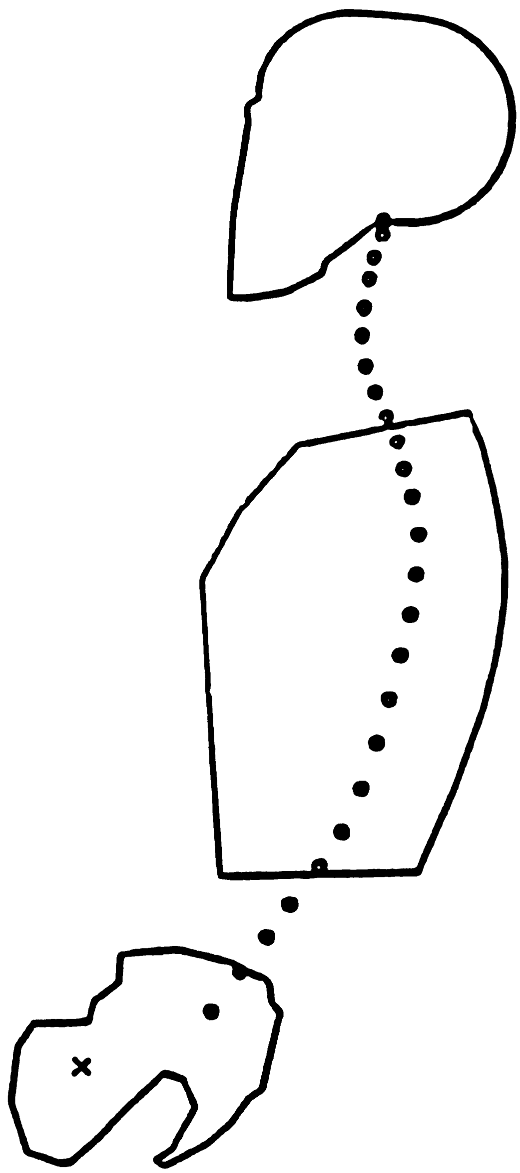


Figure 10 - JOHN1 model in nominal position

in the UMTRI[1] study were shorter than the lengths of the lumbar vertebrae in the Link Study[2]. Because the Link Study[2] provided a lumbar spine which was 29.6mm longer, the data from it might provide a superior position of the pelvis.

To create the new lumbar region of the spine with the Link Study[2] data the same angles for the spine and the body as used by UMTRI[1] were used again. The only aspect which changed was the length of the lumbar vertebrae. To position the pelvis with the longer lumbar spine the top of the head was kept in the UMTRI[1] position. Since the top of the head was an external landmark this position was known by UMTRI[1] with relatively good accuracy. Because the UMTRI[1] data for everything except for the length of the lumbar spine and the position of the pelvis were maintained, the position of the T12/L1 interspace was the same for both models. This model is named the JOHN2 model, Figure 11. Appendices 8-10 contain the coordinates of the joint centers used for the JOHN2 model.

2.7 Spinal Motion

2.7.1 Important Seating Variables

Once an initial posture had been created, the motion program for the model was written. Since the motion program

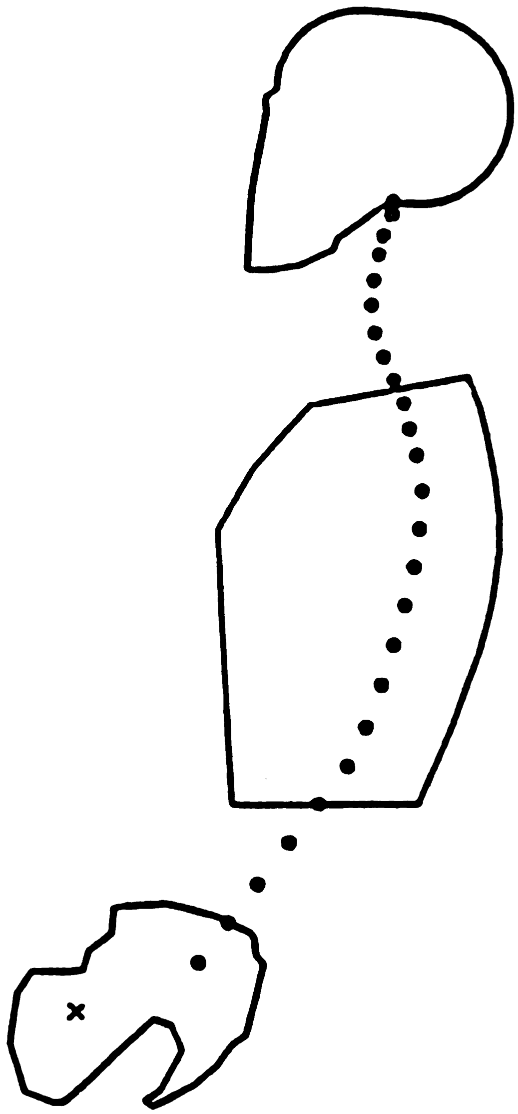


Figure 11 - JOHN2 model at initial position

will eventually be used by people with little knowledge of biomechanics the program must be user friendly. The input which is required to operate the program must be kept as simple as possible.

Several meetings with seating engineers of Johnson Controls Inc., The Society of Automotive Engineers, and General Motors Chevrolet-Pontiac Canada were arranged to decide the important variables for the spinal motion program. These meetings supported the decision that the three most important variables for the computer program would be:

1. Hip joint center location.
2. The curvature of the spine.
3. The seatback angle.

2.7.2 Hip Joint Center Location

The common practice of placing the hip joint center at the origin of the coordinate system was used in the computer program. An additional capability of the computer program is that the operator can move the hip joint center of the model into any desired position.

2.7.3 Spinal Rotation Distribution

The spinal rotation distribution portion of the program is the portion where the user decides what proportion of total rotation will occur at each of the vertebral interspace joints. For example if an even distribution of rotation is chosen, each joint center would rotate through the same range of motion. An important aspect of studying the curvature of the spine is to find if there are differences due to various spinal rotation distributions. This will be discussed further in Section 2.7.5.

A decision was made that there would be no sacral motion. By altering the data sets for the centers of rotation and the program slightly, sacral motion could be added.

The relative proportion of L5/S1 vertebral rotation was defined as 1.0 All the input for the spinal motion distribution was relative to L5/S1 rotation. If, for example, the L4/L5 joint center rotated through twice the range of motion the L5/S1 joint center did, then the proportion of rotation for L4/L5 was 2.0.

2.7.4 Total Lumbar Curvature (TLC)

After a lengthy literature search, no standard definition for spinal curvature was found. Therefore, a definition for spinal curvature was created, Total Lumbar Curvature (TLC). TLC is defined as:

TLC = (pelvic rotation) - (thoracic rotation)

Pelvic and thoracic rotations are about an axis parallel to the Y-axis and are positive according to the right hand rule, i.e. counterclockwise is positive when viewed from the left hand side of the model.

2.7.4.1 Rigid Thorax

If the thorax is assumed to be rigid, the resulting model has 6 mobile lumbar joint centers. The joint centers are at the interspaces of L5/S1, L4/L5, L3/L4, L2/L3, L1/L2, and T12/L1. For a TLC of 30 degrees, the T12 vertebra and the entire thorax would be rotated through an angle of 30 degrees relative to the pelvis. For an even distribution of rotation relative to the L5/S1 interspace, each lumbar joint center would have the same proportion of total rotation. The L4/L5 joint center has the same rotation as the L5/S1 joint center. The L3/L4 joint center has the same rotation as the L4/L5 joint center and the L5/S1 joint center, etc... Since the proportion of rotation for L5/S1 is defined as 1 the total of the proportions is 6, 1 for each of the mobile joint centers. The rotation at each joint center is calculated by dividing the TLC by the total of the proportions and multiplying this number by the proportion at each joint center. In equation form:

$$\text{Rotation at a joint center} = \frac{(\text{TLC}) \times (\text{Joint center proportion})}{\text{Total of all proportions}}$$

As an example in the case of 30 degrees TLC and even distribution, each joint center would have a rotation of five degrees. The five degrees rotation was calculated by dividing the TLC (30 degrees) by the total of the proportions (6). Then, this number (30 degrees/6) is multiplied by the proportion at each joint center. Since the distribution is even, each proportion is 1. Therefore, the L5/S1 joint center would have a rotation of (30 degrees/6)*1=5 degrees. The T12/L1 joint center would also rotate through 5 degrees. Therefore the total rotation of the L5 vertebra would be 5 degrees. The L4 vertebra would have rotated 5 degrees relative to the L5 vertebra (5 degrees rotation at the L4/L5 joint center). Therefore, the total rotation for the L4 vertebra would be 10 degrees. At the T12 vertebra, the total rotation would be 30 degrees.

For an uneven distribution of rotation, each proportion will not be equal to 1. If the L4/L5 joint center has half the mobility of the L5/S1 joint center, the proportion for the L4/L5 joint center would be 0.5. An example is a model for which all joint centers other than L5/S1 have half the mobility of the L5/S1 joint center. This would result in one joint center with a proportion of 1 and five joint centers with proportions of 0.5. The total of the proportions would be 1+(5x0.5)= 3.5. For a TLC of 35 degrees, the L5/S1 joint center would have a rotation of (35 degrees/3.5)x1= 10 degrees. The L4/L5 joint center would have a rotation of (35 degrees/3.5)x0.5= 5 degrees rotation. The remaining mobile joint centers would have the same rotation as the L4/L5 joint center. The total rotation of the L5 vertebra would be 10 degrees. The rotation of the L4 vertebra would be 5 degrees relative to the L5 vertebra (5 degrees rotation at L4/L5). Therefore, the total rotation of the L4 vertebra would be 15 degrees. The total rotation of the T12 vertebra would be 35 degrees.

2.7.4.2 Non-Rigid Thorax

It was decided that thoracic bending in the mid-sagittal plane might be significant enough to warrant the inclusion of thoracic motion. For a model for which the motion attributed to lower back motion stops at the T9 vertebra, the first immobile vertebra is the T9 vertebra. This results in 6 mobile lumbar joint centers, as is the case for a model with a rigid thorax, and 3 additional mobile thoracic joint centers with the remainder of the thorax modeled as rigid. For an even distribution of rotation there would be 9 proportions. For a TLC of 30 degrees and even distribution of rotation, each joint center would rotate through 3.33 degrees (30 degrees/9)x1. Therefore, the L5 vertebra would rotate through 3.33 degree and the L4 vertebra would rotate through 6.66 degree. The T10 vertebra would rotate through 26.77 degrees and the portion of the thorax which is modeled as rigid, the T9 vertebra and above, would rotate through 30 degrees.

For a model with an uneven distribution of rotation the same procedure would be used as for the case of the rigid thorax with uneven distribution. The only difference would be the greater number of joint centers.

2.7.5 Effect of Spinal Rotation Distributions

To investigate the various distributions of motion, a multiple image screen containing 5 images was used. The nominal position was with a TLC of zero degrees and, therefore, a straight lumbar spine. The other positions were for different values of TLC and the images of these positions were superimposed by the nominal position. The motion algorithm moved the JOHN1 model to different images with a TLC of 10 degrees flexion, 10, 20, and 30 degrees extension. This range of motion was chosen as representative of possible ranges of motion for a person seated in an automobile seat. Robbins and Reynolds[4] studied a TLC of 9 degrees extension and Nyquist and Patrick[5] studied a TLC of 17 degrees extension. A TLC of 10 degrees flexion and up to 30 degrees extension was used to ensure that a sufficiently large range of motion was encompassed.

While studying the rotation distributions each pelvis remained locked in place and superimposed. By doing this only the movement of the thorax and the spine due to the TLC was studied. Then by entering various distributions of motion, the resultant positions of the lumbar interspaces and the thorax were compared for each distribution of motion. The distributions which were investigated are listed in Table 1.

Distribution One is the case with even distribution of rotation, relative to the L5/S1 interspace, and a rigid thorax. This case will be the distribution which all the other distributions will be compared with.

Distribution Two is a slightly modified version of Distribution One. The only change for this case is the presence of greater rotation at the top of the lumbar spine.

TABLE 1
Rotation Distributions

DIST. NO.	L5 S1	L4 L5	L3 L4	L2 L3	L1 L2	T12 L1	T11 T12	T10 T11	T9 T10	T8 T9	T7 T8	T6 T7
1	1	1	1	1	1	1	------RIGID THORAX-----					
2	1	1	1	2	2	1	------RIGID THORAX-----					
3	1	1	1	.5	.5	1	------RIGID THORAX-----					
4	1	1	1	.5	.5	.5	------RIGID THORAX-----					
5	1	.85	.75	.7	.6	1	------RIGID THORAX-----					
6	1	1.12	.77	.47	.35	1	------RIGID THORAX-----					
7	1	.85	.75	.7	.6	.6	.6	.45	.3	.3	------	
8	1	.85	.75	.7	.6	.6	.6	.45	.3	.3	.3	.25
9	1	.85	.75	.7	.6	.6	------RIGID THORAX-----					
10	1	1.12	.77	.47	.35	.35	------RIGID THORAX-----					

Distribution Three is the opposite of Distribution Two. This case is where there is less rotation at the top of the lumbar spine than at the bottom.

Distribution Four is the same as Distribution Three except for the modification that not only is there less rotation present at the top of the lumbar spine but there is also less rotation for the rigid thorax.

Distribution Five is the distribution of rotation described by White and Panjabi[6] except for the rotation of the rigid thorax. The rotation at T12/L1 for the rigid thorax rotation was modeled as equivalent to that of L5/S1 because no data were available from White and Panjabi[6] for the modeling of a rigid thorax.

Distribution Six is the distribution described by Allbrook[7]. Once again, a rigid thorax was modeled and assigned a rotation proportion value of one at T12/L1, since Allbrook did not research thoracic rotations.

Distribution Seven is the distribution listed by White and Panjabi[6]. For this case, a non-rigid thorax was modeled. This distribution has motion up to the T8/T9 interspace.

Distribution Eight is also data from White and Panjabi[6]. For this case the thorax was modeled as non-rigid with motion up to the T6/T7 interspace.

Distribution Nine is the same as Distribution Five except for this case the rigid thorax was assigned the relative rotation of the T12/L1 interspace as described by White and Panjabi[6].

Distribution Ten was the same as Distribution Six except that the rigid thorax rotation was set equal to the relative rotation of the L1/L2 interspace.

The ten distributions were compared with each other to investigate how the various distributions effected the positions of the spinal interspaces, and the thorax.

2.7.6 Seatback Angle

In the automobile seating industry, the seatback angle is defined as the angle from the vertical of a line on the torso of the 2-D drawing template and the 3-D H-point machine. The seatback angle is measured with the 3-D H-point machine after it has settled into an automobile seat. Since the new seating model is a computer model and cannot settle into an automobile seat, a problem for this project is how to define the seatback angle without knowledge of the force-deflection characteristics of the human body in automobile seats. To use the computer seating model, a method must be developed by which the torso of the model can be rotated into a seatback.

The first method used to rotate the torso into a seatback was to define a tangent line to the body. The line was defined as the tangent from the most rearward point of the pelvis to the most rearward point of the torso. The seatback angle was defined as the angle from the vertical of this tangent line. The user would input a value for this seatback angle and the computer would then rotate the model about the H-point into this position. This attempt to define the seatback angle did not work for any seatback except for a straight hard seatback. Since the model was eventually to be used to develop automobile seats, this method to define the seatback had to be discarded.

The next method to rotate the torso of the model into a seatback was to utilize a torso angle. The torso angle is the angle from vertical between two points defined in the published literature described below. By modifying the motion program any angle on the torso could be used by the computer operator. The user could define the angle from the vertical of any line on the torso. The computer would then rotate the model about the H-point so that the defined line on the torso would be on the defined angle from the vertical.

2.7.7 Comparison of Model with Literature

For comparison of postures between the model and published literature, the published results were simulated. First, the TLC used in the published study was entered into the computer motion program. If the study did not supply the TLC, then it was estimated from the published diagrams or tables. Second, the model was rotated into the torso angle specified in the literature. Third, the resultant pelvic angles of the model were compared with the pelvic angles found in the literature.

2.8 Published Data

2.8.1 Robbins and Reynolds[4]

Robbins and Reynolds[4] supplied the positions of several vertebral interspaces. The angle from the vertical of a line between the T4/T5 interspace and the T8/T9 interspace was 0 degrees. This angle was estimated from a diagram supplied by Robbins and Reynolds[4] and was the torso angle used to rotate the torso of the computer model. Figure 12 is the diagram from the Robbins and Reynolds[4].

The TLC for the posture studied by Robbins and Reynolds[4] was not given in their study. To calculate the TLC for this posture, their diagram was used. Lines were drawn between the given lumbar interspaces. The angle from the vertical of the line between the L5/S1 interspace and the L4/L5 interspace was 23 degrees. The angle from the vertical of the line between the L4/L5 interspace and the L3/L4 interspace was 28 degrees, and the angle from the vertical of the line between the L3/L4 interspace and the L2/L3 interspace was 26 degrees. The next given interspace was T12/L1. Therefore, the TLC of the Robbins and Reynolds[4] posture had to be estimated using the three measured angles since the position of the L1/L2 interspace was not known. Even though the angles did not progress in a smooth manner, the TLC was estimated using the overall change of 3 degrees (23-26). The three degree change

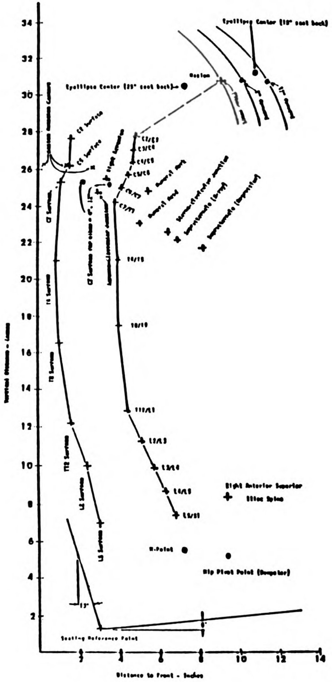


Figure 12 - Robbins and Reynolds[4] seated posture

occurred at the L4/L5 and the L3/L4 interspaces. TLC is the change at all mobile interspaces, not just the L4/L5 and the L3/L4 interspaces, and the 3 degrees change was only a portion of the entire TLC. The rotations at the remainder of the mobile interspaces were still not known. If the model has a rigid thorax and all the interspaces have a rotation proportion of 1, then the rotation proportions for the L4/L5 and L3/L4 interspaces are both 1. This results in 6 mobile joint centers each with a rotation proportion of 1 and a total of the rotation proportions equal to 6. The rotation at the L4/L5 and the L3/L4 interspaces is only 2/6 of the TLC. The total change of 3 degrees is 2/6 the TLC, therefore the TLC is (6/2)x(3 degrees)=9 degrees. To calculate the TLC for the Robbins and Reynolds[4] study, divide the total of all the rotation proportions by the total of the rotation proportions for the L4/L5 and the L3/L4 interspaces and multiply by 3 degrees. In equation form this is:

$$\text{TLC}=\frac{(\text{total of proportions})\times(3\text{ degrees})}{(\text{L4/L5 proportion}+\text{L3/L4 proportion})}$$

Table 2 contains the calculated TLC of the Robbins and Reynolds[4] study for each of the 10 different rotation distributions.

The last piece of data given by Robbins and Reynolds[4] was the pelvic angle. They listed the rotation of the pelvis as 42 degrees from the standing position. Since the JOHN1 posture has a pelvic rotation of 54 degrees from the standing position, the difference is 12 degrees. Therefore, the pelvic rotation from the nominal JOHN1 computer model position is 12 degrees.

TABLE 2
TLC For Robbins and Reynolds[4]

DISTRIBUTION NUMBER	TLC (DEGREES)
1	9.0
2	12.0
3	7.5
4	6.8
5	9.2
6	7.5
7	11.5
8	12.6
9	8.4
10	6.5

2.8.2 Nyquist and Patrick[5]

Nyquist and Patrick[5] defined and measured the spine line angle as the angle from the vertical of the line between the T12/L1 and the L5/S1 vertebral interspace centers. To match the position of the computer model with the position of the Nyquist and Patrick[5] data, the spine line of the computer model was matched to the spine line found in their data.

The TLC of the Nyquist and Patrick[5] postures was estimated by measuring the diagrams provided by Nyquist and Patrick, Figures 13 and 14, in their publication. Lines were drawn between the lumbar joint centers depicted on the diagram. The angular change of the L1 vertebra relative to the L5 vertebra was 7 degrees for the first subject, CJM.

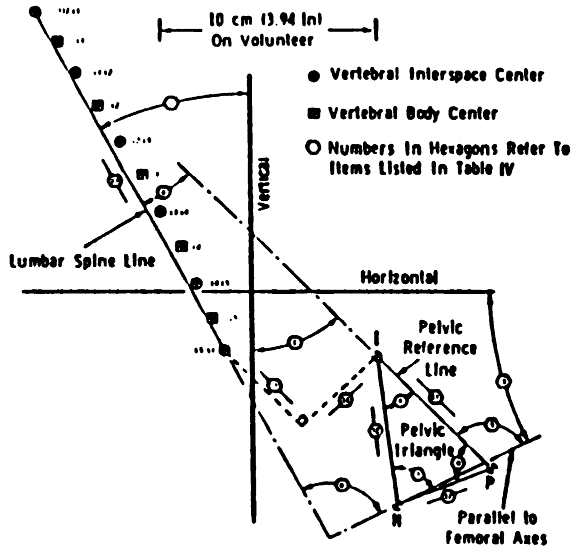


Figure 13 - Figure of data from subject CJM from Nyquist and Patrick[5]

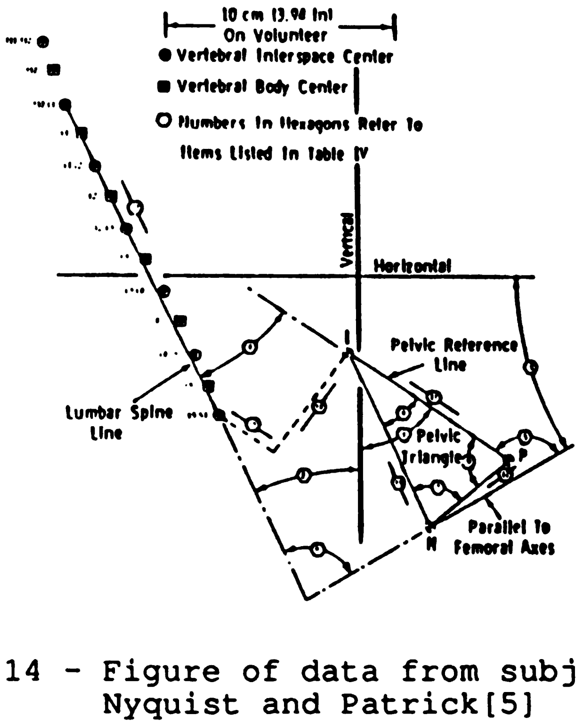


Figure 14 - Figure of data from subject LMP from Nyquist and Patrick[5]

The angular change of the L1 lumbar vertebra relative to the L5 vertebra was approximately 5 degrees for the second subject, LMP. These angular changes only measure the rotations at the L1/L2 through L4/L5 lumbar joint centers. Since TLC is the total rotation at all the mobile joint centers, the rotations measured from the Nyquist and Patrick[5] diagrams are only a portion of the TLC. If the model has a rigid thorax and all rotation proportions are 1, then the rotations at the L1/L2, L2/L3, L3/L4, and the L4/L5 interspaces measured on the diagrams are only 4/6 of the TLC. Therefore, the angular change equals (4/6)xTLC. The TLC equals (6/4)x(angular change).

The TLC for the Nyquist and Patrick postures was calculated by dividing the total of all the rotation proportions by the total of the rotation proportions of the L1/L2, L2/L3, L3/L4, and L4/L5 interspaces then multiplying by the angular change. In equation form, this is:

$$\text{TLC} = \frac{\text{(total of all proportions)x(angular change)}}{\text{(total of proportions for L1/L2, L2/L3, L3/L4, L4/L5)}}$$

Table 3 contains the calculated TLC for the two male subjects and the pelvic rotations from the JOHN1 position.

TABLE 3
TLC for Nyquist and Patrick[5]

DISTRIBUTION NUMBER	TLC (DEGREES) FOR SUBJECT CJM	LMP
1	10.5	7.5
2	9.3	6.6
3	11.7	8.4
4	10.5	7.5
5	11.8	8.4
6	12.1	8.6
7	14.8	10.6
8	16.2	11.6
9	10.9	7.8
10	10.2	7.3

2.8.3 Andersson et. al.[3]

Andersson et. al.[3] provided data for the position of the pelvis and the relative position of the lumbar region. He defined and measured the total lumbar angle, the sacral-horizontal angle, the sacral-pelvic angle, and the pelvic-horizontal angle, Figure 15. The total lumbar angle is defined as

> '...the angle between perpendiculars from a line drawn along the superior surface of L1 and a second line drawn along the sacral endplate.'[3]

The sacral-horizontal angle is defined as:

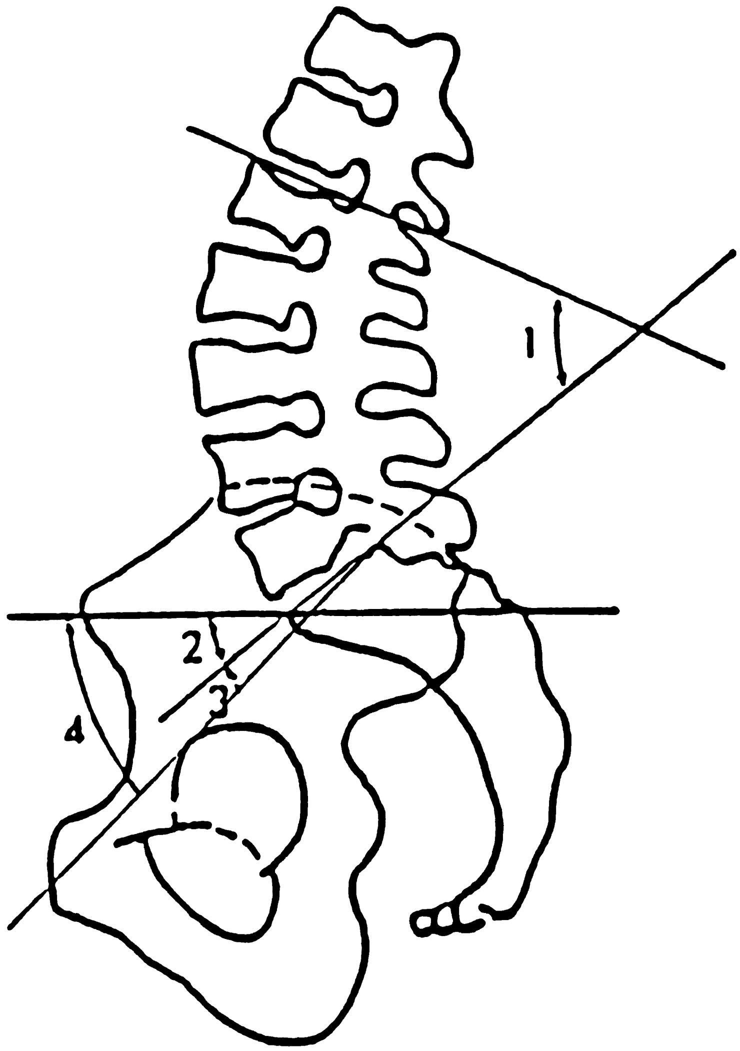
> '...the angle between the sacral endplate and a horizontal line intersecting the top of the sacrum at the posterior corner.'[3]

The sacral-pelvic angle is defined as:

> '...the angle between the line along the sacral end-plate and a second line which intersects the line of the sacral end-plate at the posterior corner of the sacrum, and is drawn to the most superior point of the acetabulum.'[3]

The pelvic-horizontal angle is defined as:

> '...the angle between a line drawn from the superior corner of the sacrum to the uppermost point on the



Angles measured from the radiographs of subjects in the study: 1 - total lumbar angle. 2 = sacral-horizontal angle. 3 - sacral-pelvic angle. 4 - pelvic-horizontal angle.

Figure 15 - Pelvic angle definitions from Andersson et. al.[3]

> acetabulum and the horizontal line passing through the superior-posterior corner of the sacrum.'[3]

A change in the pelvic horizontal angle is the rotation of the pelvis.

A change in the total lumbar angle is related to a change in TLC. The change in total lumbar angle and the change in TLC are not identical because of a discrepancy in the number of mobile joint centers. Total lumbar angle as described by Andersson et. al.[3] measures only the rotation due to the L5/S1 through L1/L2 lumbar joint centers. TLC measures the rotation of all the lumbar joint centers and the mobile thoracic joint centers. Due to the difference in the number of mobile joint centers, the change in the total lumbar angle measured must be multiplied by an appropriate factor to obtain TLC. For the case of even distribution of motion and a rigid thorax, the total lumbar angle must be multiplied by 6/5 to obtain TLC. For the case of non-even distribution of rotation and a rigid thorax, the total of all proportions must be added together and divided by the proportions for the L5/S1 through L1/L2 lumbar joint centers. For the case of a non-rigid thorax, the proportions of rotation for each joint center must be added together then divided by the total of the L5/S1 through L1/L2 proportions. In equation form, this is:

$$\text{Multiplication factor} = \frac{\text{Total of all proportions}}{\text{Total of L1/L2, L2/L3, L3/L4, L5/S1 proportions}}$$

For this study, TLC is calculated by multiplying the total lumbar angle by the multiplication factor. Table 4 contains the multiplication factors.

Andersson[3] measured the pelvic horizontal angle, the total lumbar angle, and the sacral-horizontal angle in one standing and three seated postures, Table 5. For each posture, Andersson had the participants sit in a vertical seatback chair. The chair was equipped with a variable position lumbar support which could be varied to either be in back of the seatback, or in front of the seatback. For the -2 posture, the lumbar support was positioned 2 cm to the rear of the straight seatback. For the +2 posture, the lumbar support was positioned 2 cm forward of the straight seatback. For the +4 posture, the lumbar support was positioned 4 cm forward of the straight seatback.

TABLE 4
Multiplication Factors

DISTRIBUTION NUMBER	MULTIPLICATION FACTOR
1	6/5
2	8/7
3	5/4
4	4.5/4
5	4.9/3.9
6	4.7/3.7
7	6.2/3.9
8	6.7/3.9
9	4.5/3.9
10	4.1/3.7

Andersson[3] also measured a 0 posture. For this posture the lumbar support was flush to the seatback. This posture was not used for this research because for this posture there was apparent sacral movement. There was little difference between the sacral-pelvic angles for the -2, +2, and the +4 postures. But the sacral-pelvic angle was different for the 0 posture. This indicated that there was sacral motion. Since the computer model used in this research did not incorporate sacral movement, the 0 posture could not be used.

TABLE 5
Data from Andersson et. al.[3]

POSTURE	PELVIC HORIZONTAL ANGLE	TOTAL LUMBAR ANGLE	SACRAL HORIZONTAL ANGLE
STANDING	63.8 degrees	59.8 degrees	38.0 degrees
-2 cm	34.3	9.7	27.5
+2 cm	47.5	29.9	28.8
+4 cm	54.7	46.8	28.3

Andersson et. al.[3] supplied no data on the position of the thorax in his study. Therefore, to simulate the of the Andersson et. al.[3] study, the pelvic horizontal angle and the TLC for each posture was recreated. The resulting posture was examined to find if it simulated a reasonable posture of a human in a vertical seatback. The criteria used for examining the resultant postures was to look at the postures and see if the thorax was rotated unrealistically rearward or forward to simulate a vertical seatback.

2.9 Method for Comparison of JOHN1 Model with Published Data

The method for comparing the model with the results found in literature was a four step process.

1. Chose one or more representative rotation distributions.
2. Using the rotation distribution(s) chosen in Step 1, model the data from Robbins and Reynolds[4].
3. Using the rotation distribution(s) chosen in Step 1, model the data from Nyquist and Patrick[5].
4. Using the rotation distribution(s) chosen in Step 1, model the data from Andersson et. al.[3].

2.9.1 Step 1: Method for Selection of Representative Rotation Distribution(s)

To choose between the rotation distributions, the joint centers for each distribution were compared to the corresponding joint centers of the first distribution. If the distance between the compared joint centers was 12.7 millimeters or less, then the distributions were considered essentially equivalent. The distance of 12.7 millimeters (0.5 inch) was chosen because in the automobile seating environment the position of the seated occupant is not precisely defined, and a 12.7 millimeter difference is negligible.

If the difference between the corresponding joint centers was 12.7 millimeters or greater then the two distributions were considered to be different. All distributions which were found to be different from distribution one were then used for Steps 2, 3, and 4.

2.9.2 Step 2: Method for Modeling Robbins and Reynolds Study[4]

To model the Robbins and Reynolds[4] study, the distributions chosen in Step 1 were used and the procedure to obtain TLC outlined in section 2.8.1 was followed. To rotate the torso into the seat, the angle between the T4/T5 interspace and the T8/T9 interspace was used. This line was measured to be vertical on the diagram supplied by Robbins and Reynolds[4]. The computer model was rotated about the H-point until the line between the T4/T5 interspace and T8/T9 interspace of the computer model was vertical. The angle which the torso and the pelvis was rotated through was called the pelvic rotation.

2.9.3 Step 3: Method for Modeling Nyquist and Patrick Study[5]

To model the Nyquist and Patrick[5] study, the rotation distributions chosen in Step 1 were used following the procedure to obtain TLC found in Section 2.8.2. To rotate the torso into the seat, the spineline angle was used. The value for this angle was given in the Nyquist and Patrick[5] publication for both male subjects. The angle which the torso and the pelvis was rotated through was called the pelvic rotation.

2.9.4 Step 4: Method for Modeling Andersson et. al. Study[3]

To model the Andersson et. al.[3] study, the distributions chosen in Step 1 were used following the procedure to obtain TLC as outlined in Section 2.8.3. To rotate the torso into the seat, the pelvic angle was used. Andersson et. al.[3] supplied the pelvic-horizontal angle. The resultant postures were then viewed to see if they were reasonable for a person in a vertical seatback.

A decision was then made if any of the distributions could be eliminated on the basis of the resultant postures or the pelvic rotations. The chosen distribution was the distribution for which the pelvic rotations of Steps 2 and 3 were closest to the values given in the published data, and the resultant postures were reasonable for a person in a vertical seatback.

2.10 Method of Comparison of JOHN2 Model with Published Data

This part of the verification process involved using the Link Study[2] data for the lumbar region. To verify the position of the pelvis relative to the thorax for the JOHN2 model, the same evaluation procedure which was used for the JOHN1 model was used again.

2.11 Review of Methods

The questions addressed in this research are:

1. The effect of various rotation distributions on the position of the thorax.
2. The position of the thorax relative to the pelvis, e.g. the angular position of the pelvis and the choice of the JOHN1 or the JOHN2 model.
3. Placement of a computer human postural model into a seat.

To find the answer to question 1, ten different rotation distributions were tested for differences in the positions of the vertebral joint centers. These differences were considered significant if they were greater than 12.7mm between the positions of the interspaces for a distribution when compared to the positions of the same interspaces of distribution one. Then using any rotation distributions which were considered different, the data found in Robbins and Reynolds[4] and Nyquist and Patrick[5] were simulated with the JOHN1 and JOHN2 models. The TLC calculated for the published studies in Sections 2.8.1 and 2.8.2 was used as input. Then the spine of the computer model was placed in the same position as the spine in the literature. The position of the pelvis of the computer model was then compared to the position of the pelvis in the literature.

Data from Andersson[3] was simulated, using as input the position of the pelvis and the TLC. The resultant posture was then reviewed to examine if the posture could be the posture of a person in a vertical seatback. This procedure was first done for the JOHN1 computer model, then for the JOHN2 computer model.

To place the computer model into the posture found in the literature, three methods were used. The first method for Robbins and Reynolds[4] was to use as input TLC and a thoracic body angle. The second method for Nyquist and Patrick[5] was to use as input TLC and a lumbar spine angle. The third method for Andersson[3] was to use as input TLC and a pelvic angle.

The recommended method to place the computer model into the seatback was chosen from these three methods. This recommended method was the method which supplied results which were closest to the results of the literature.

3. RESULTS AND DISCUSSION

3.1 Evaluation of the Rotation Distributions for the JOHN1 Model

The distance criteria used for deciding whether the difference between two positions was significant was 12.7 millimeters. If the position of the same interspace was different by a distance of 12.7mm or less for two different rotation distributions, then the rotation distributions were considered to be not significantly different.

Figure 16 is a representative multi-screen figure of the rotation distribution evaluations for the JOHN1 model.

Appendices 11-14 contain the differences between the joint centers of distribution one and all other distributions. The distances between the joint centers is calculated as indicated in Figure 17. A negative difference for the x coordinates indicates that the joint center for that distribution is posterior to the same joint center for distribution one. A negative difference for the z indicates that the joint center for that distribution is below the same joint center for distribution one.

Table 6 and Figure 18 contain the results of the rotation distribution evaluations for 10 degrees flexion. This table lists the distances for all interspaces from the

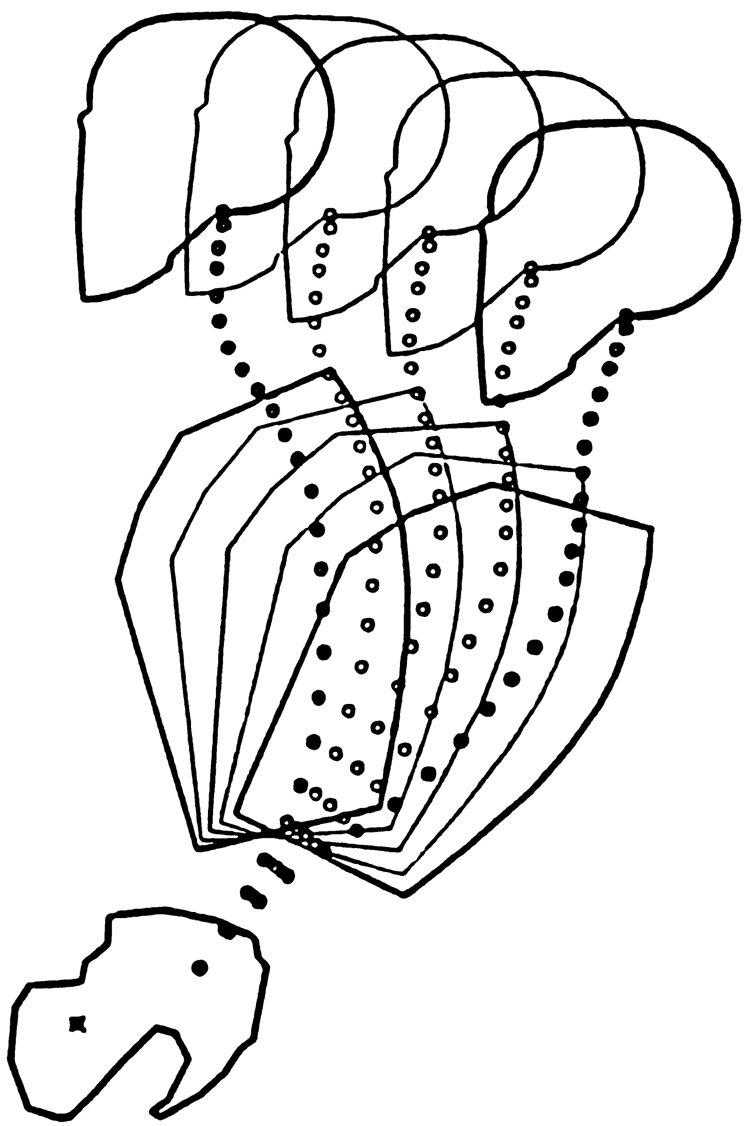
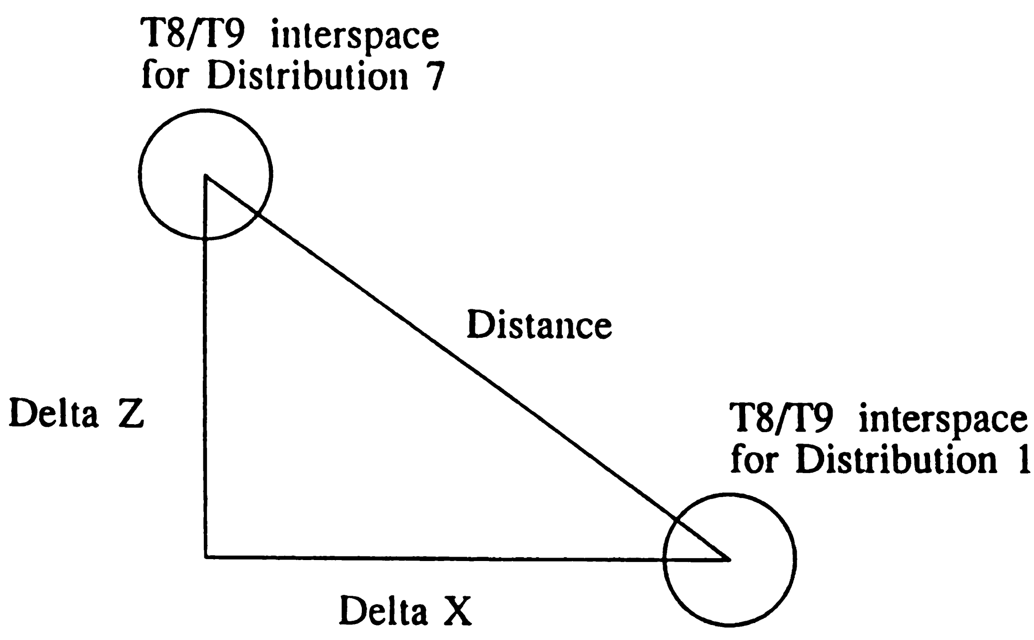


Figure 16 - Multi-screen model of distribution one for the JOHN1 model



$$\text{Distance} = \sqrt{(\text{Delta X})^2 + (\text{Delta Z})^2}$$

Figure 17 - Calculation of distances between interspaces

TABLE 6
Distances (mm) Between Interspaces
for the JOHN1 Model
10 Degrees Flexion

INTER-SPACE	DISTRIBUTION NUMBER 2	3	4	5	6	7	8	9	10
T5/T6	1.39	1.03	2.64	0.36	1.39	5.57	8.54	1.61	3.76
T6/T7	1.30	1.08	2.64	0.50	1.44	5.57	8.54	1.66	3.81
T7/T8	1.30	1.08	2.64	0.50	1.44	5.57	8.35	1.66	3.81
T8/T9	1.30	1.08	2.64	0.50	1.53	5.57	7.97	1.70	3.81
T9/T10	1.30	1.08	2.64	0.50	1.53	5.28	7.27	1.73	3.81
T10/T11	1.30	1.08	2.64	0.50	1.44	4.78	6.39	1.66	3.81
T11/T12	1.44	1.03	2.64	0.36	1.39	3.81	5.02	1.61	3.76
T12/L1	1.44	1.03	2.56	0.36	1.39	2.37	3.22	1.61	3.76
L1/L2	1.58	1.25	2.37	0.67	1.70	1.30	1.94	1.48	3.45
L2/L3	1.30	1.03	1.75	0.58	1.39	0.58	1.03	1.08	0.42
L3/L4	0.72	0.58	0.94	0.45	0.94	0.22	0.36	0.72	1.53
L4/L5	0.28	0.28	0.36	0.22	0.22	0.00	0.14	0.36	0.45
L5/S1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

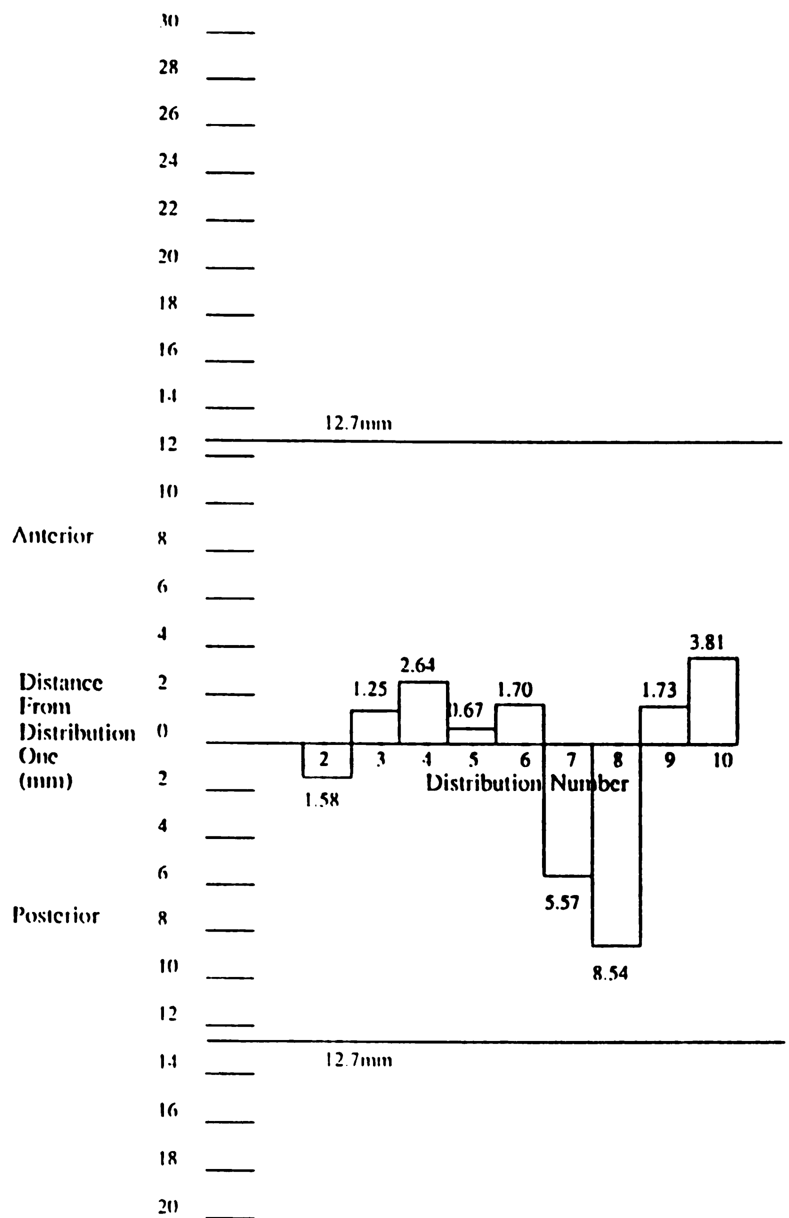


Figure 18 - 10 degrees flexion for the JOHN1 model

T5/T6 interspace down. The higher interspaces were not listed because the distances are the same as the distance for the T5/T6 interspace. The differences listed are comparisons between the first rotation distribution with equal rotations at each interspace in the lumbar spine and each of the other nine rotation distributions. The largest differences occurred between the first distribution and the eighth distribution. This was expected since the eighth rotation distribution was the distribution with the greatest amount of thoracic mobility. Since none of the distances exceeded 12.7mm the conclusion was that for 10 degrees flexion, all the spinal rotation distributions were judged to be equivalent.

Table 7 and Figure 19 contain the results of the spinal rotation distribution evaluations for 10 degrees extension. Once again the largest differences occurred for the eighth rotation distribution. The largest difference occurred at the T5/T6 interspace with a value of 8.58mm. Since this value is less than the 12.7mm limit, the conclusion was that, for 10 degrees extension, no difference existed between the spinal rotation distributions.

Table 8 and Figure 20 contain the results of the spinal rotation distribution evaluations for 20 degrees extension. The only rotation distribution pattern which had distance values greater than 12.7mm was distribution eight. This rotation distribution involved thoracic mobility. For all other rotation distribution patterns, there existed no

TABLE 7
Distances (mm) Between Interspaces
for the JOHN1 Model
10 Degrees Extension

INTER-SPACE	DISTRIBUTION NUMBER 2	3	4	5	6	7	8	9	10
T5/T6	1.35	1.00	2.62	0.45	1.50	5.55	8.58	1.64	3.76
T6/T7	1.42	1.00	2.62	0.42	1.42	5.63	8.58	1.64	3.76
T7/T8	1.25	1.06	2.62	0.42	1.49	5.63	8.44	1.63	3.75
T8/T9	1.36	1.06	2.69	0.50	1.49	5.58	8.05	1.70	3.83
T9/T10	2.10	1.00	2.62	0.42	1.42	5.33	7.43	1.64	3.76
T10/T11	1.28	1.06	2.62	0.50	1.49	4.74	6.41	1.70	3.83
T11/T12	1.28	1.06	2.62	0.50	1.49	3.78	5.00	1.70	3.83
T12/L1	1.36	1.06	2.62	0.42	1.42	2.34	3.20	1.70	3.83
L1/L2	1.56	1.20	2.34	0.64	1.70	1.35	1.98	1.42	3.33
L2/L3	1.28	1.00	1.70	0.58	1.42	0.64	1.00	1.14	2.48
L3/L4	0.64	0.58	1.00	0.50	0.86	0.14	0.42	0.72	1.50
L4/L5	0.28	0.22	0.36	0.22	1.22	0.40	0.14	0.36	0.50
L5/S1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

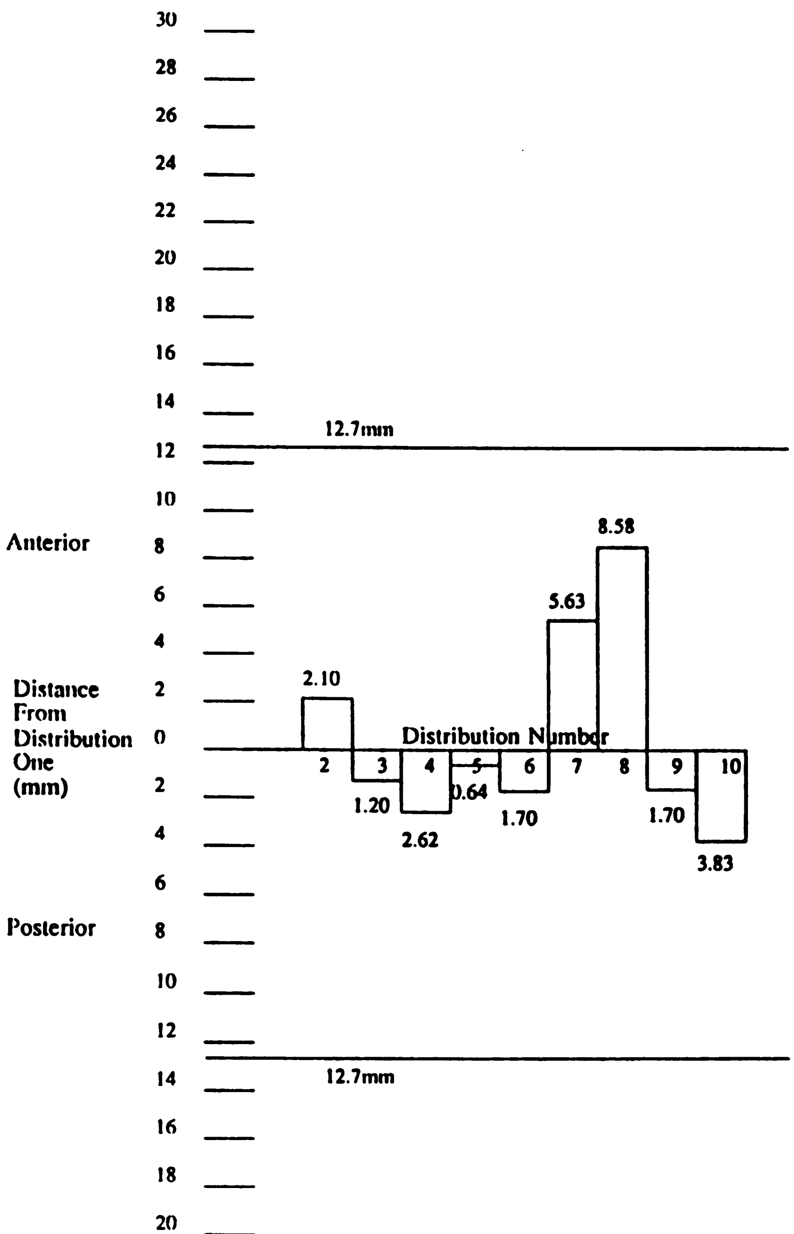


Figure 19 - 10 degrees extension for the JOHN1 model

TABLE 8
Distances (mm) Between Interspaces
for the JOHN1 Model
20 Degrees Extension

INTER-SPACE	DISTRIBUTION NUMBER 2	3	4	5	6	7	8	9	10
T5/T6	2.69	2.13	5.30	0.92	2.90	11.19	17.20	3.32	7.57
T6/T7	2.69	2.05	5.23	0.86	2.90	11.19	17.26	3.32	7.57
T7/T8	2.62	2.12	5.30	0.92	2.97	11.19	16.84	3.39	7.57
T8/T9	2.69	2.12	5.23	0.92	2.90	11.19	16.04	3.32	7.57
T9/T10	2.62	2.12	5.23	0.92	2.97	10.70	14.68	3.32	7.57
T10/T11	2.62	2.12	5.23	0.92	2.97	9.56	12.82	3.32	7.64
T11/T12	2.69	2.19	5.30	0.92	2.97	7.57	10.11	3.39	7.23
T12/L1	2.62	2.12	5.23	0.92	2.97	4.60	6.36	3.32	7.57
L1/L2	3.05	2.48	4.74	1.35	3.39	2.62	3.82	2.97	6.79
L2/L3	2.55	2.13	3.54	1.28	2.97	1.06	1.84	2.27	5.02
L3/L4	1.42	1.06	1.84	0.92	1.77	0.42	0.85	1.49	2.97
L4/L5	0.50	0.42	0.64	0.42	0.57	0.00	0.22	0.64	0.92
L5/S1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

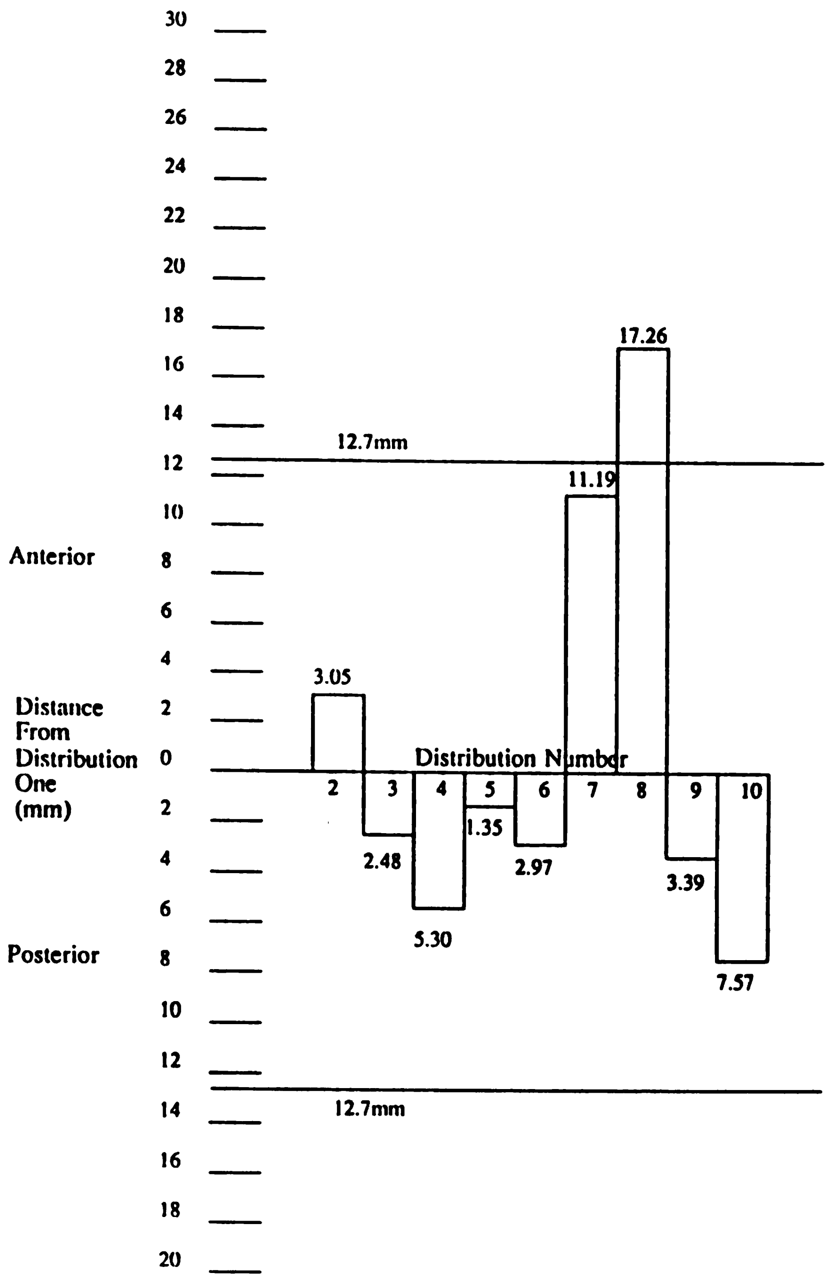


Figure 20 - 20 degrees extension for the JOHN1 model

significant differences between the rotation distribution patterns.

Table 9 and Figure 21 contain the results of the spinal rotation distribution evaluations for 30 degrees extension. Figures 22-30 are the comparisons at 30 degrees extension TLC between distribution one and each of distribution two through ten, respectively. As with 20 degrees extension, the rotation distribution which included thoracic mobility, distribution eight, had distances much greater than 12.7mm. The only other rotation distribution which had distances that exceeded 12.7mm was rotation distribution seven. This rotation distribution also had thoracic mobility. Therefore, all spinal rotation distributions which had a rigid thorax were considered equivalent.

The evaluation of the spinal rotation distribution revealed that all spinal motion distributions which did not involve thoracic mobility can be considered to be essentially equivalent. Distribution one was chosen as the representative rotation pattern for rigid thorax models because of its simplicity, assuming even distribution of rotation. The only spinal rotation patterns which exceeded the 12.7 mm criteria were the two rotation distributions which involved thoracic mobility.

At this point in the research work, it was not determined whether the preferred motion pattern for the JOHN1 model would be distribution one, distribution seven, or distribution eight. For lumbar mobility only, there

TABLE 9
Distances (mm) Between Interspaces
for the JOHN1 Model
30 Degrees Extension

INTER-SPACE	DISTRIBUTION NUMBER 2	3	4	5	6	7	8	9	10
T5/T6	4.03	3.32	7.90	1.35	5.11	16.80	25.89	4.97	11.34
T6/T7	3.96	3.18	7.82	1.42	4.39	16.80	25.97	4.97	11.32
T7/T8	3.96	3.26	7.90	1.42	4.46	16.80	25.33	4.97	11.40
T8/T9	3.93	3.21	7.86	1.45	4.42	16.77	24.11	5.00	11.35
T9/T10	3.96	3.26	7.90	1.49	4.46	16.03	22.10	5.04	11.40
T10/T11	3.96	3.26	7.90	1.42	4.46	14.40	19.28	4.97	11.40
T11/T12	4.03	3.19	7.90	1.41	4.39	11.45	15.12	5.04	11.34
T12/L1	3.96	3.19	7.90	1.35	4.46	6.92	9.46	4.97	11.40
L1/L2	4.60	3.69	7.04	1.91	5.11	3.98	5.81	4.47	10.18
L2/L3	3.89	3.11	5.17	1.84	4.32	1.70	2.83	3.32	7.44
L3/L4	2.05	1.70	2.83	1.41	2.76	0.57	1.20	2.26	4.53
L4/L5	0.67	0.57	0.99	0.71	0.85	0.10	0.36	0.99	1.41
L5/S1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

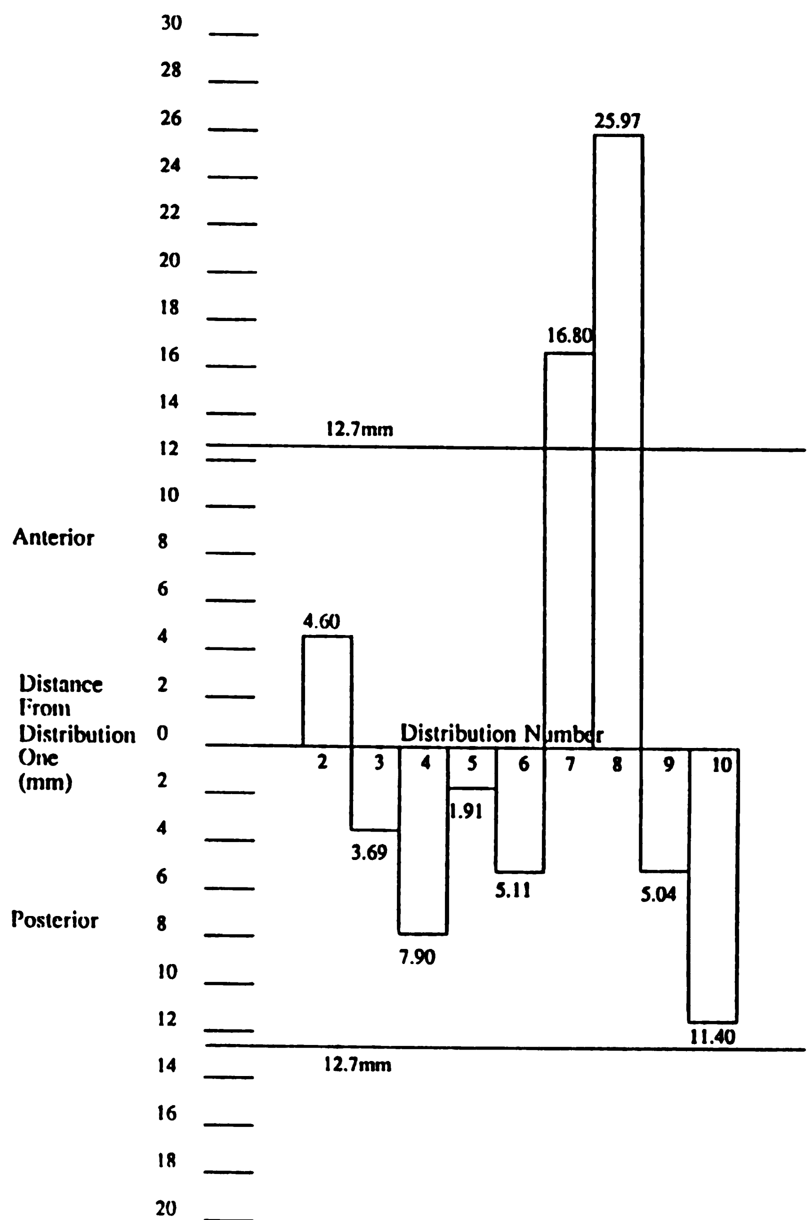


Figure 21 - 30 degrees extension for the JOHN1 model

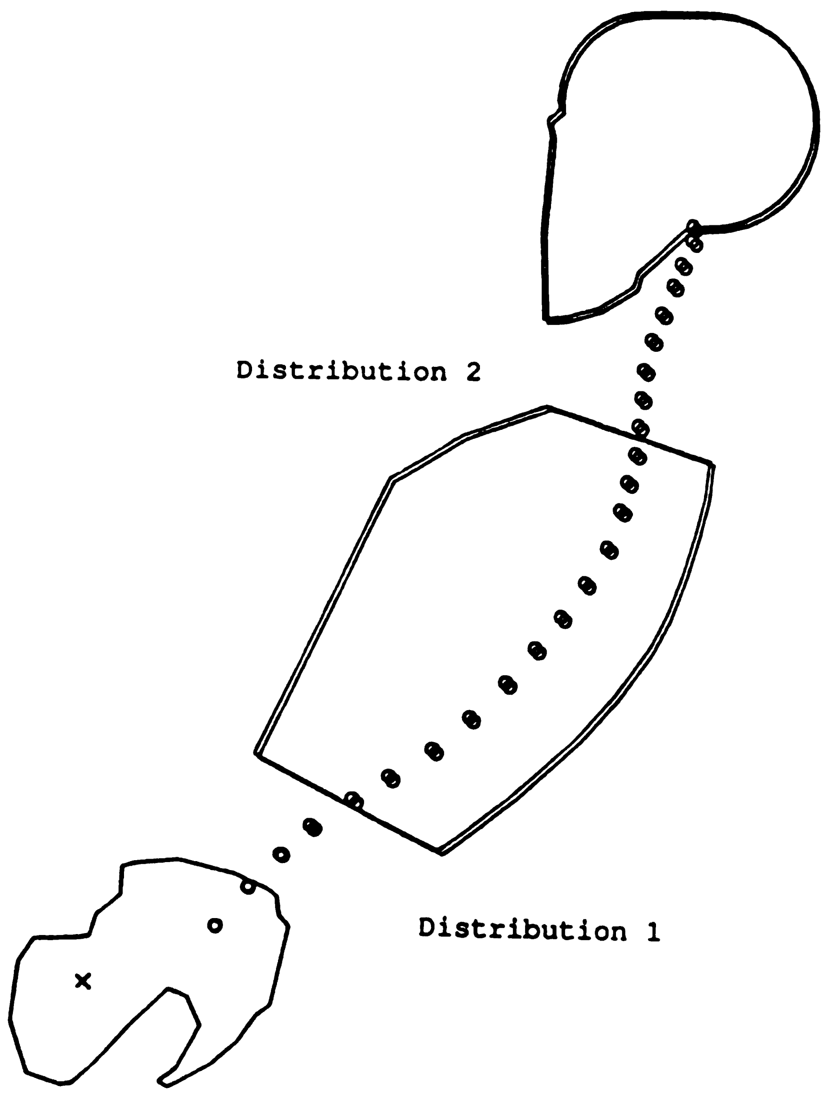


Figure 22 - Comparison of distribution one and distribution two at 30 degrees extension for the JOHN1 model

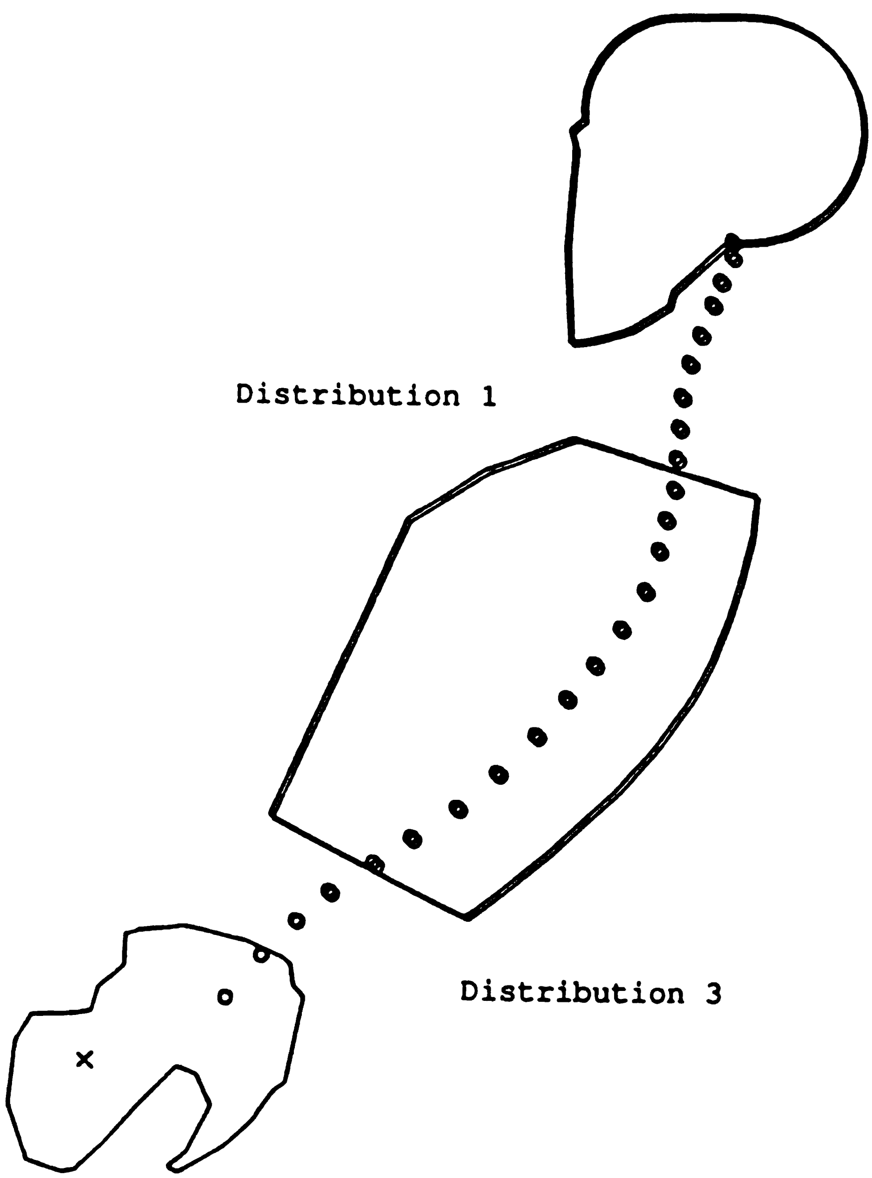


Figure 23 - Comparison of distribution one and distribution three at 30 degrees extension for the JOHN1 model

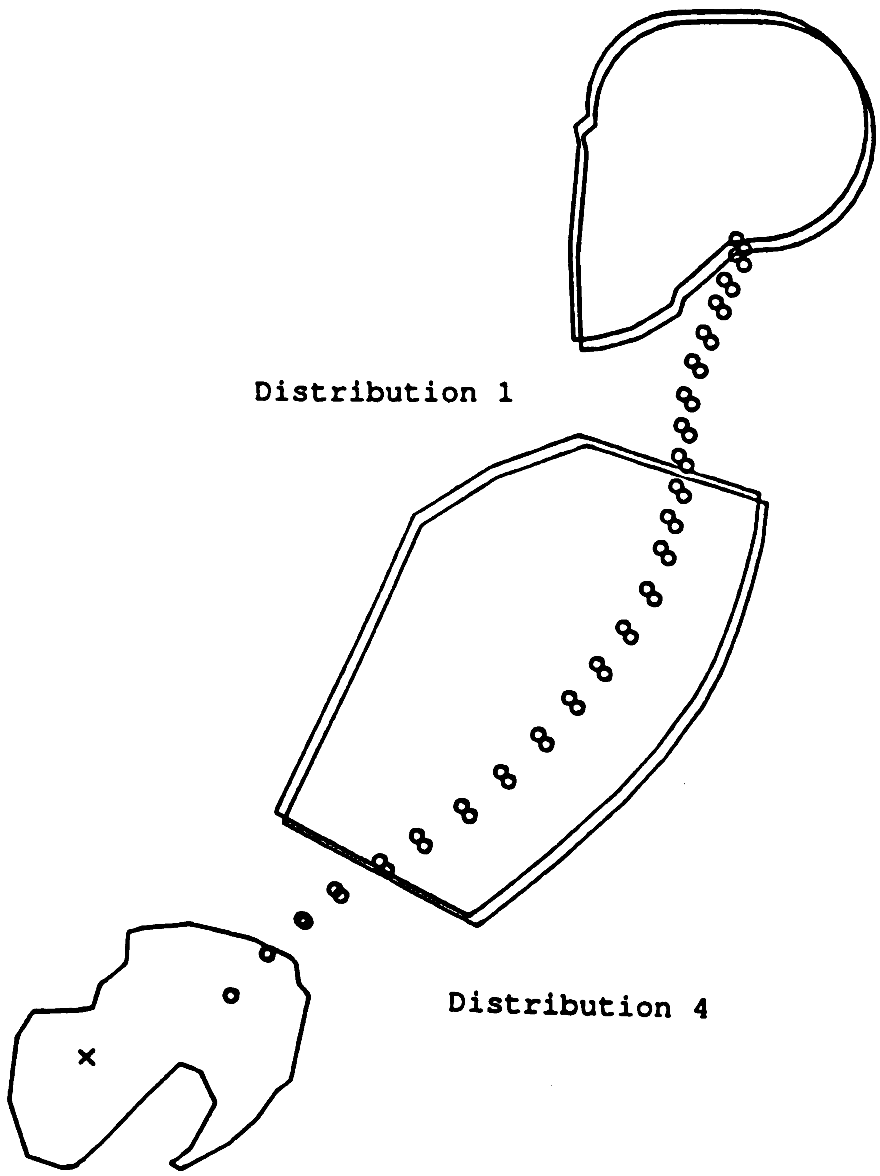


Figure 24 - Comparison of distribution one and distribution four at 30 degrees extension for the JOHN1 model

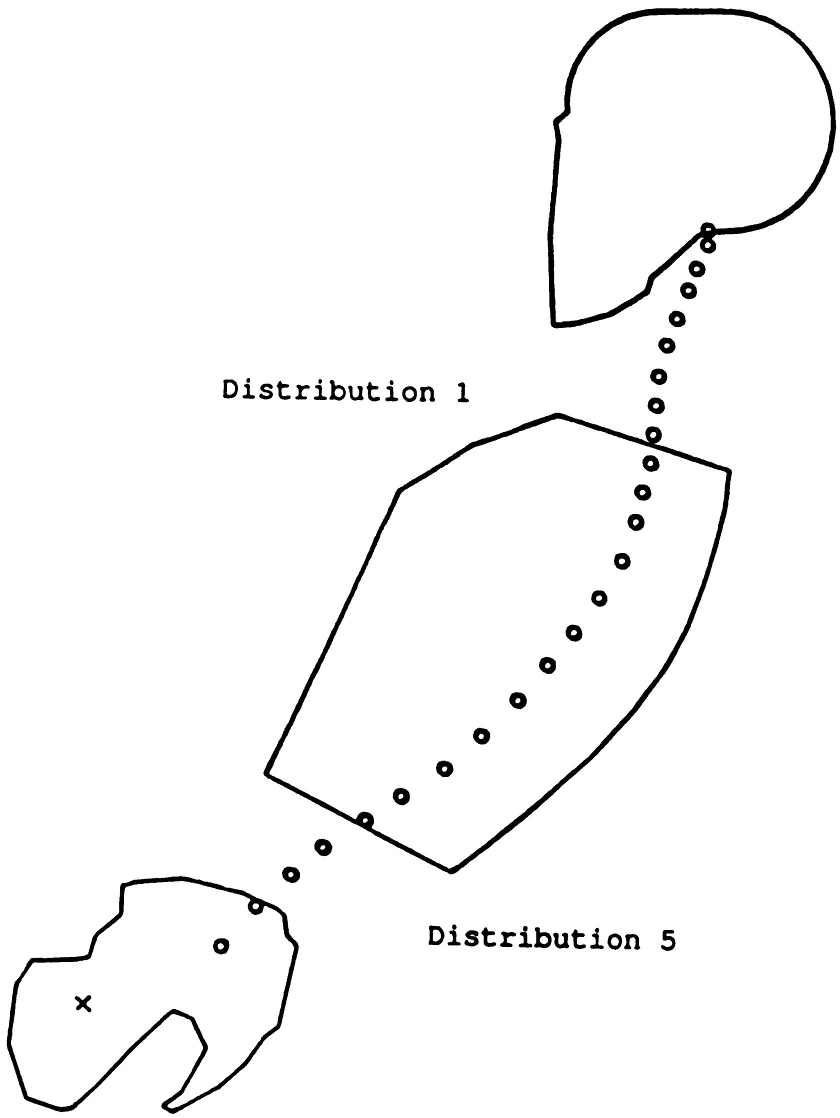


Figure 25 - Comparison of distribution one and distribution five at 30 degrees extension for the JOHN1 model

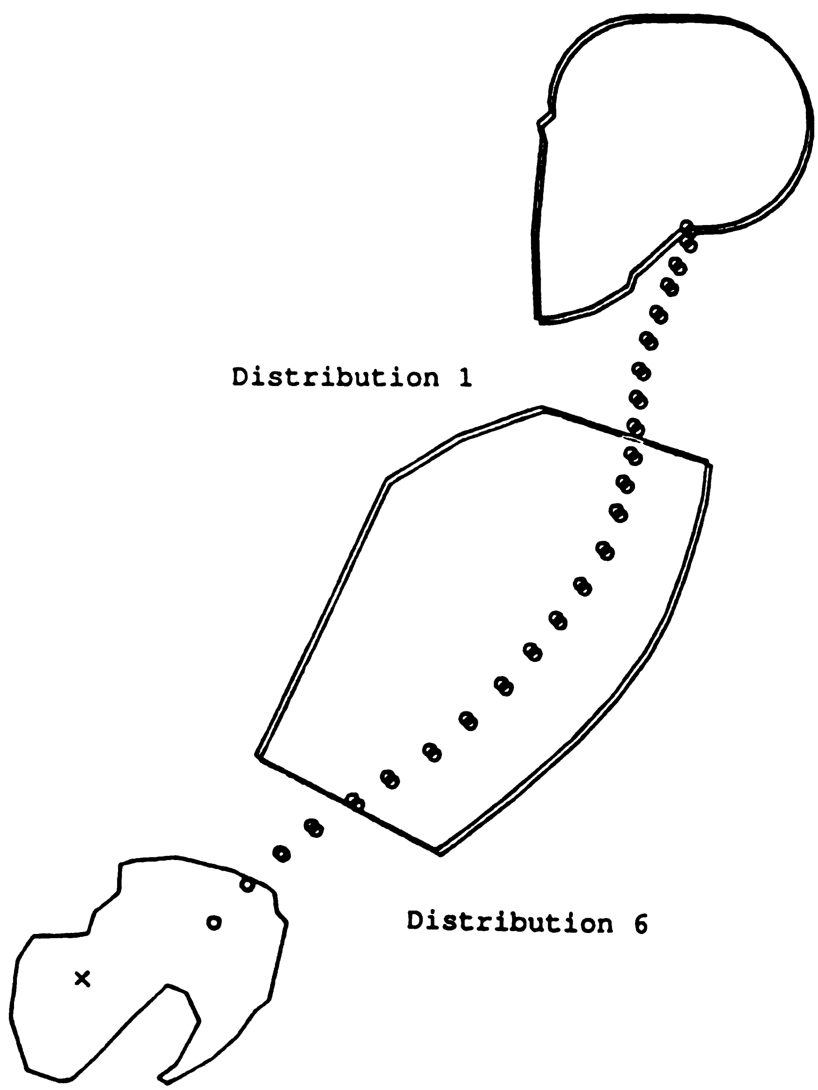


Figure 26 - Comparison of distribution one and distribution six at 30 degrees extension for the JOHN1 model

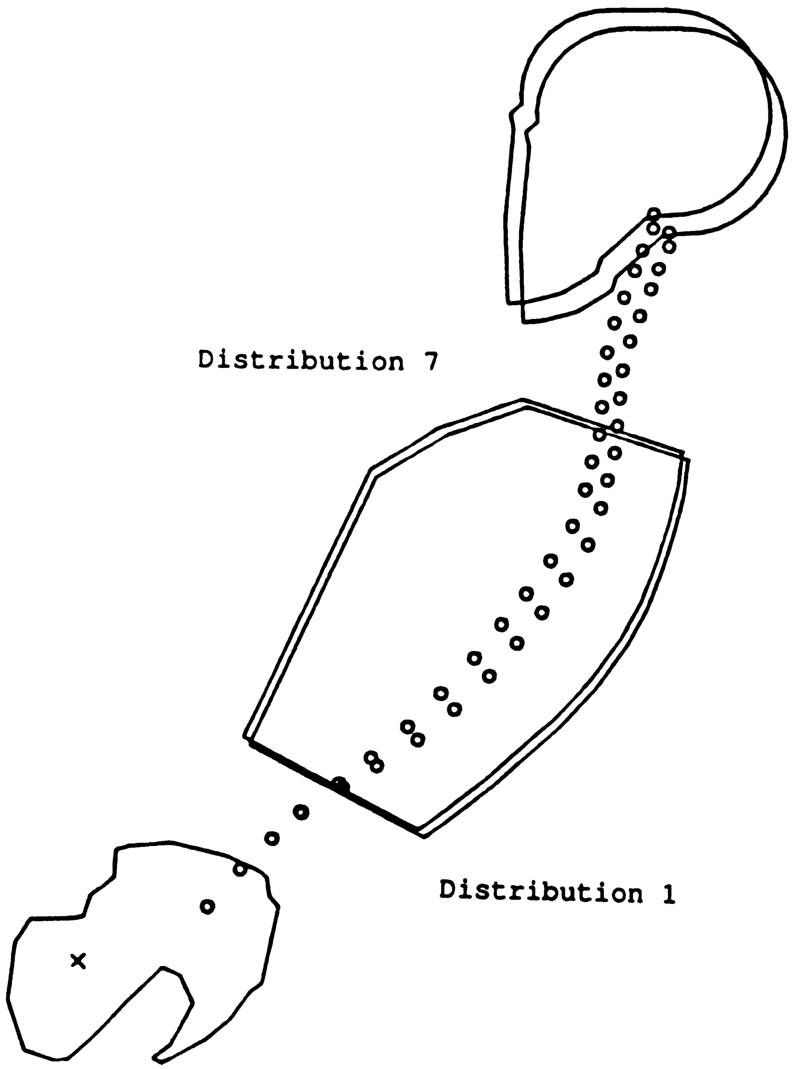


Figure 27 - Comparison of distribution one and distribution seven at 30 degrees extension for the JOHN1 model

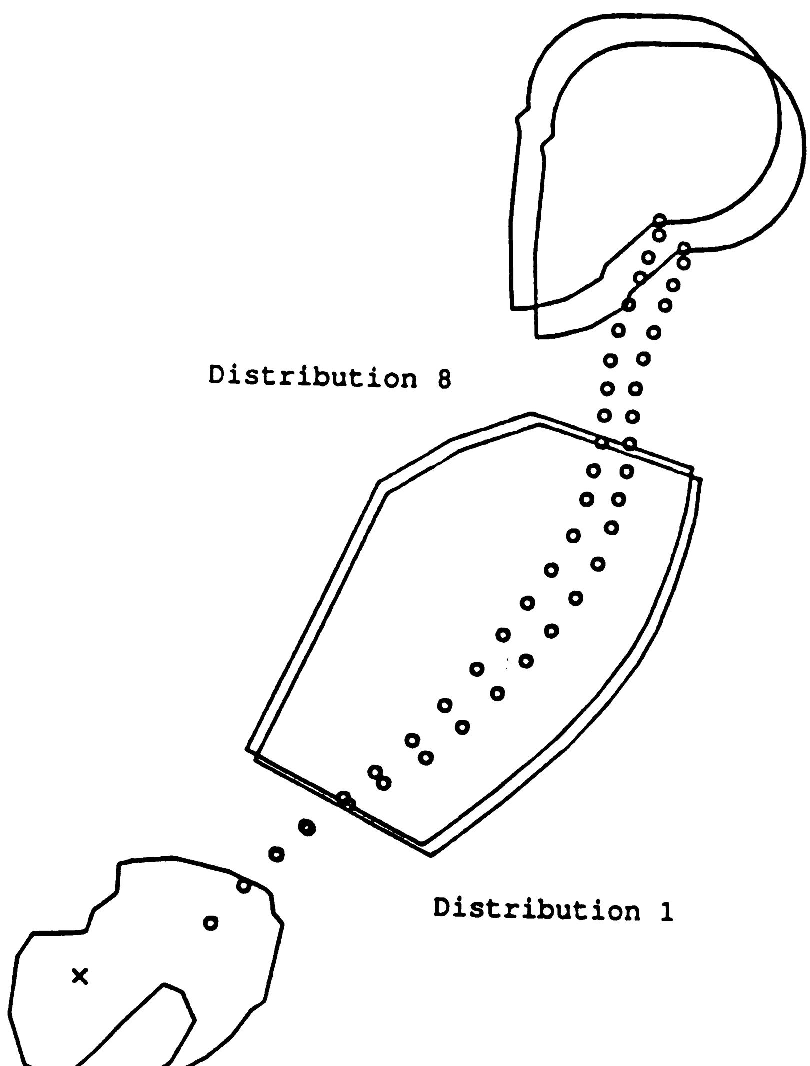


Figure 28 - Comparison of distribution one and distribution eight at 30 degrees extension for the JOHN1 model

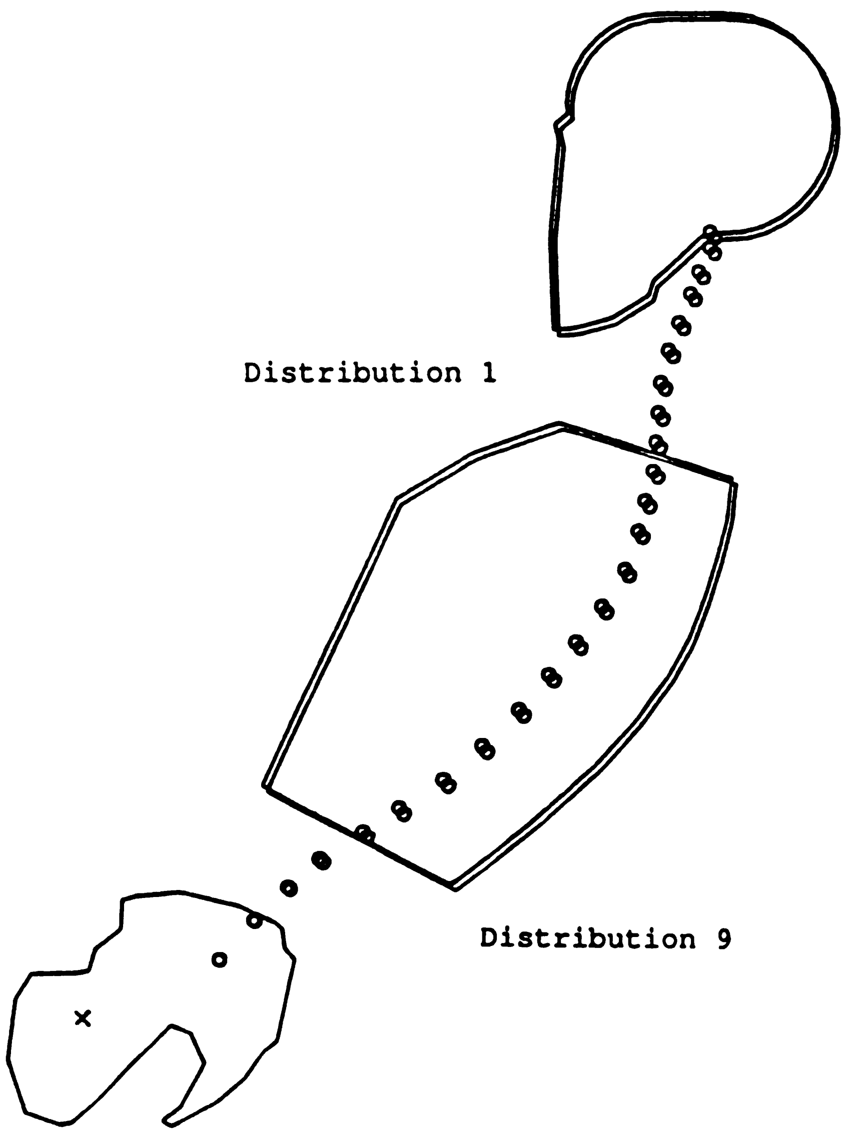


Figure 29 - Comparison of distribution one and distribution nine at 30 degrees extension for the JOHN1 model

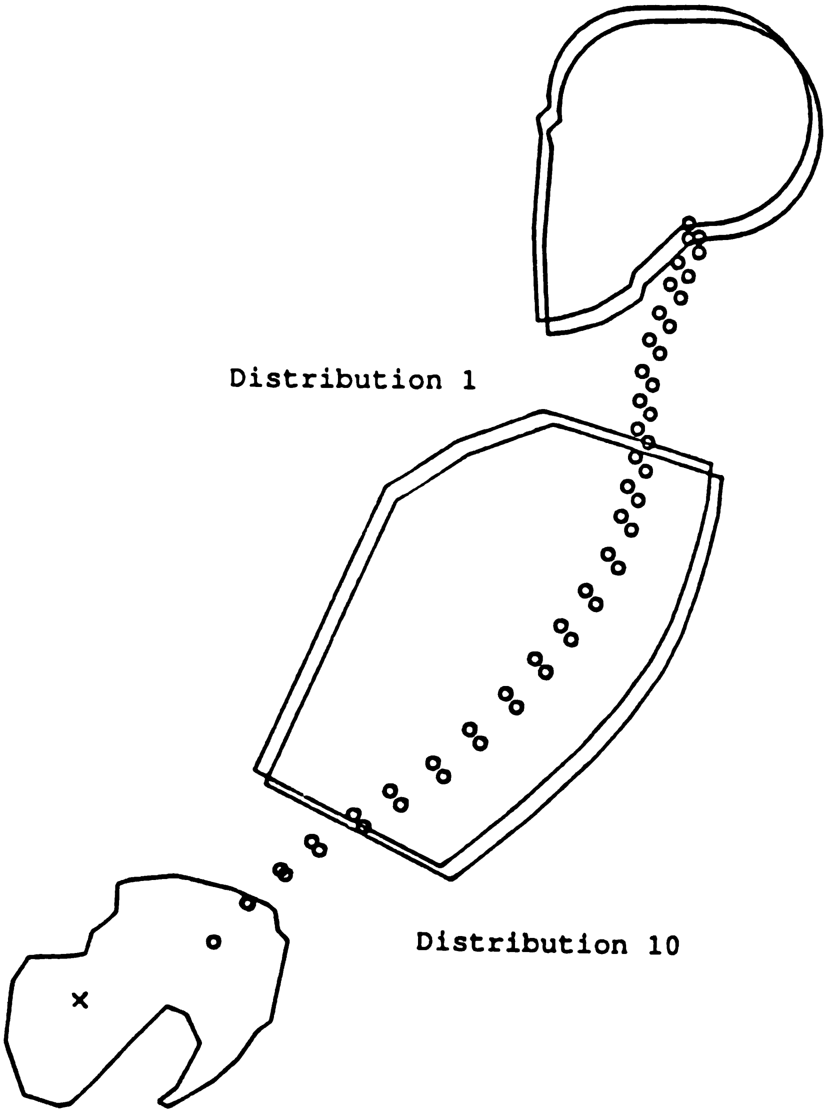


Figure 30 - Comparison of distribution one and distribution ten at 30 degrees extension for the JOHN1 model

existed no differences between the rotation distributions. A non-rigid thorax distribution resulted in significant differences from the distributions with lumbar mobility only. It was still unknown if the final rotation distribution should have a rigid or a non-rigid thorax. To discover which of the patterns best simulated human motion, each of the three remaining distributions were used in attempting to duplicate the results found in the literature.

3.2 Simulation of Robbins and Reynolds[4] for the JOHN1 Model

To model the results found in Robbins and Reynolds[4], the procedure in Section 2.9.2 was followed. Table 2 contains the calculated values of TLC from Robbins and Reynolds[4] for each of the rotation distributions. Table 10 contains the results from the testing of the three different motion distributions chosen in Section 3.1.

TABLE 10
Results of the Simulation of
Robbins and Reynolds[4]
for the JOHN1 Model

DISTRIBUTION NUMBER	TLC (DEGREES)	PELVIC ROTATION (DEGREES)
1	9.0	11.6
7	11.5	14.1
8	12.6	14.8

As noted in Section 2.8.1, the rotation of the pelvis from the JOHN1 position for the Robbins and Reynolds[4] study is 12 degrees. Therefore, the computer model should ideally give an indicated pelvic rotation of 12 degrees. The pelvic rotation which was closest to the desired rotation of 12 degrees was the 11.6 degree rotation for distribution one. But the indicated pelvic rotations for all of the three distributions were close to the desired 12 degree rotation. Furthermore, since the TLC and the positions of the T4/T5 and the T8/T9 interspaces from the Robbins and Reynolds[4] study were not precisely known, it remained undetermined which of the rotation distributions best modeled this study. However, all of the three motion distributions resulted in a good agreement with the Robbins and Reynolds[4] study. This reinforced the belief that the original position of the pelvis in the UMTRI[1] position was representative of human posture.

3.3 Simulation of Nyquist and Patrick[5] for the JOHN1 Model

The second test was to compare the computer model results to those of Nyquist and Patrick[5] following the procedure outlined in Section 2.9.3. Nyquist and Patrick[5] measured the angle from the vertical of the line between the hip joint center and the ASIS. For the first subject, CJM, this angle was -7 degrees. For the second subject, LMP, this angle was -23.5 degrees. In the standing posture as defined by Reynolds et al.[8], the line between the hip joint center and the ASIS are is 36 degrees from the vertical. Therefore the pelvic rotation from the standing posture to the seated posture was -7-36=-43 degrees for CJM and -23.5-36=-59.5 degrees for LMP. The pelvic rotation from standing for JOHN1 was -54 degrees. Thus, the pelvis of subject LMP was rotated 11 degrees from the JOHN1 posture. The pelvis of subject CJM was rotated -5.5 degrees from the JOHN1 posture. This posed a problem for subject LMP. The pelvis was rotated rearward from the JOHN1 posture. Furthermore, the TLC for LMP was approximately 5 degrees. Even if the TLC was 0 degrees, this posture cannot be obtained from the JOHN1 posture. The decision was made to ignore the results of subject LMP. If the original position of the pelvis in the JOHN1 posture was found to be incorrect in subsequent study, then this position of the pelvis for LMP would be further explored.

Table 11 is the results of the computer evaluation of subject CJM for each of the three distributions. Distribution one resulted in the pelvic rotation value closet to the 11 degrees pelvic rotation found by Nyquist and Patrick[5]. However, all values of the rotation were close to the desired rotation of 11 degrees. Since the TLC was not accurately known and the rotations were all similar, a choice of the best distribution to describe human motion was still not possible. These results also reinforced the belief that the original position of the pelvis in the JOHN1 posture was representative of human posture.

TABLE 11
Results of the Simulation of
Nyquist and Patrick[5]
for the JOHN1 Model

DISTRIBUTION NUMBER	TLC (DEGREES)	PELVIC ROTATION (DEGREES)
1	10.5	13.0
7	14.8	13.9
8	16.2	13.9

3.4 Simulation of Andersson et. al[3] for the JOHN1 Model

The third test to discriminate between the rotation distributions was to model the Andersson et al.[3] data which is in Table 5. The first step was to determine if the position of the pelvis in the JOHN1 posture was similar to the position of the pelvis in any of the three Andersson postures.

For the UMTRI[1] pelvis in the standing posture as defined by Reynolds, et al.[8] the sacral horizontal angle is 46.4 degrees. This is the angle from the horizontal of a line drawn along the top of the sacrum, Figure 15. In the standing posture for Andersson et. al.[3], the sacral horizontal angle measured 38 degrees. This was a discrepancy of 8.4 degrees. Since the standing posture may differ between the Andersson et. al.[3] study and the Reynolds et. al.[8] study, this 8.4 degrees discrepancy was considered to be a constant which must be carried through the calculations. When the UMTRI[1] pelvis was rotated into the UMTRI[1] posture, the sacral horizontal angle became 46.4-54.07= -7.67 degrees. From the UMTRI[1] drawing, the measured angle from the horizontal of the superior surface of the L1 vertebra was 28 degrees. The drawing was used for this measurement because no better data were available. This information was used to calculate the total lumbar angle. Andersson et. al.[3] defined the total lumbar angle as the angle between the superior surface of the L1 vertebra and the superior surface of the sacrum. In the UMTRI[1] posture, this total lumbar angle was calculated as 28-7.64= 20.33 degrees. Assuming the 8.4 degrees discrepancy due to sacral position was a constant, the total lumbar angle as defined by Andersson et. al.[3] was 20.33-8.4= 11.9 degrees. This value compared extremely well with the value of 9.7 for the total lumbar angle as found by Andersson et. al.[3] for the case of the -2 lumbar support. The 2.2 degree difference can be caused by differences between subjects or errors in the UMTRI[1] diagram or its measurement.

At this point in the research, the position of the pelvis relative to the spine is well supported by available data. A good correlation was found between the position of the pelvis relative to the lumbar spine in the UMTRI[1] posture and the position of the pelvis relative to the lumbar spine in the -2 posture found in Andersson et. al.[3]. Also, the position of the pelvis for the JOHN1 model correlated well with the data of Robbins and Reynolds[4] and Nyquist and Patrick[5] by using the computer motion program.

A single representative rotation distribution still had not been found. Three distributions (1,7, and 8) remained as possibilities. The last step to decide between the distributions was to model the -2, +2, and +4 Andersson et. al.[3] postures following the procedure in Section 2.8.4

Since the position of the pelvis relative to the lumbar spine in the UMTRI[1] original position and the -2 lumbar support case of Andersson match well, the next step was to consider the entire body rigid and rotate about the H-point to place the torso into the -2 lumbar support posture. For Andersson[3], the pelvic-horizontal angle is 63.8 degrees in the standing posture and 34.3 degrees in the -2 lumbar support posture. Therefore, from the standing posture to the -2 lumbar support posture the pelvis was rotated 63.8-34.3= 29.5 degrees. For the original UMTRI[1] position the pelvis was rotated 54.07 degrees from the standing position to the seated position. So to achieve the -2 lumbar support posture, the pelvis, and therefore the body of the computer model must be rotated 54.07-29.5= 24.07 degrees forward, which is the difference between the two pelvic rotations from the standing posture. Since no data was given for the position of the thorax or the lumbar spine, the only way to match the Andersson et. al.[3] -2 posture was to rotate the body through the 24.07 degrees to find if the resulting position was representative of a 50th percentile man in a vertical seatback. Figure 31 is the resulting posture. Upon inspection the posture appears to be a representation

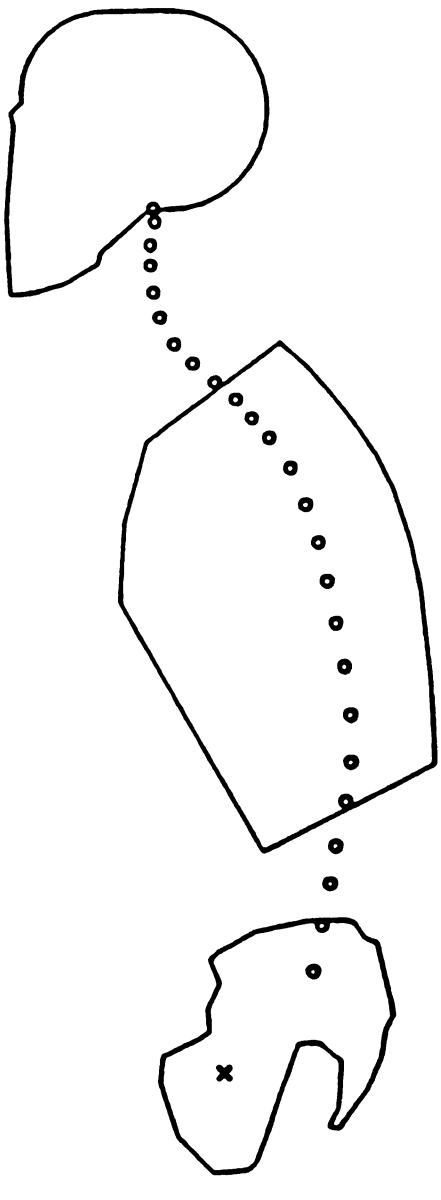


Figure 31 - Andersson -2 posture for the JOHN1 model

of a 50th percentile man in a vertical seatback posture. The bottom of the torso of the model appears to be in a position approximately directly above the posterior of the pelvis. This is what should happen in a vertical seatback. This posture will be the same for all rotation distributions since the torso was rotated about the H-point with no change in TLC.

The pelvic-horizontal angle is 47.5 degrees in the +2 lumbar support posture. Therefore, from the standing posture to the +2 lumbar support posture of Andersson et. al.[3], the pelvis was rotated 63.8-47.5= 16.3 degrees rearward. So from the nominal JOHN1 model seated posture, with the pelvis rotated 54.07 degrees from the standing posture, to the +2 posture the computer model must be rotated 54.07-16.3= 37.77 degrees forward. For the +2 lumbar support posture, the total lumbar angle is 20.2 degrees.

The pelvic-horizontal angle is 54.7 degrees in the +4 lumbar support posture. Therefore, from the standing posture to the +4 lumbar support posture of Andersson et. al.[3], the pelvis was rotated 63.8-54.7= 9.1 degrees rearward. So from the nominal UMTRI[1] seated posture to the +4 posture the computer model must be rotated 54.07-9.1= 44.52 degrees. For the +4 lumbar support posture, the total lumbar angle is 46.8-9.7= 37.1 degrees.

TLC is calculated by multiplying the total lumbar angle by the multiplication factor, calculated in Section 2.8.3.

Table 12 shows the values of the calculated TLC for each posture and rotation distribution. Figures 32-37 show the resulting postures. Figure 38 is a composite picture of the three distributions in the +2 posture. For the +2 cm position, the resultant postures for all three distributions appear to be representative of a person in a vertical seatback. Figure 39 is a composite picture of the three distributions in the +4 posture. By viewing the +4 postures, it can be seen that only distribution one resulted in a posture representative of a person in a vertical seatback. For distributions 7 and 8 the top of the thorax is rotated too far rearward to represent a person in a vertical seatback.

It was concluded that the preferred rotation distribution is distribution one, the case of even distribution of rotation with a rigid thorax. Distribution one resulted in superior postures for simulating the Andersson et. al.[3] study and in superior pelvic rotations for simulating Robbins and Reynolds[4] and Nyquist and Patrick[5].

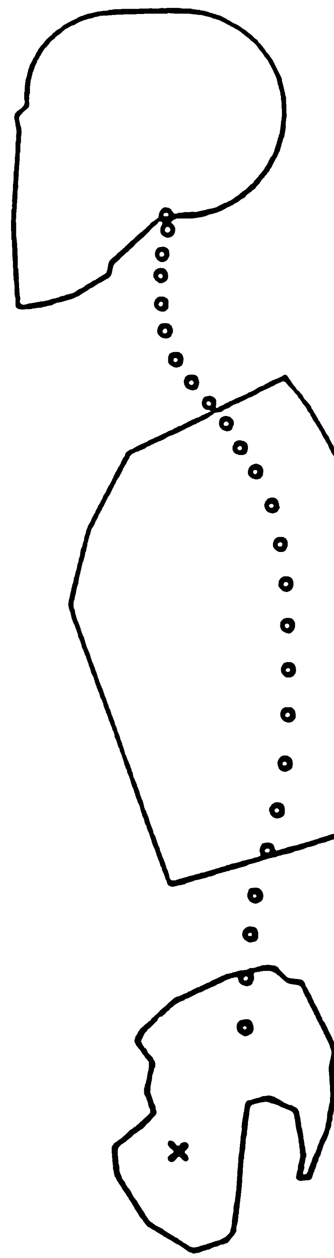


Figure 32 - Andersson +2 posture for the JOHN1 model with distribution one

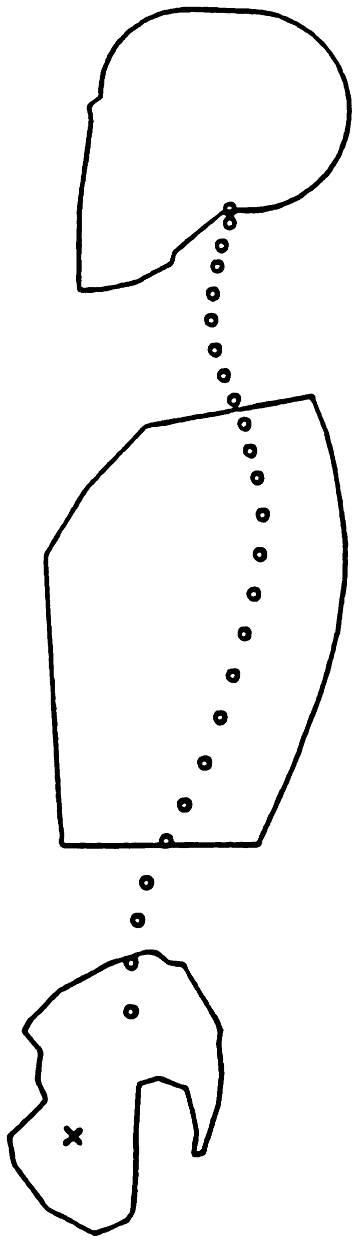


Figure 33 - Andersson +4 posture for the JOHN1 model with distribution one

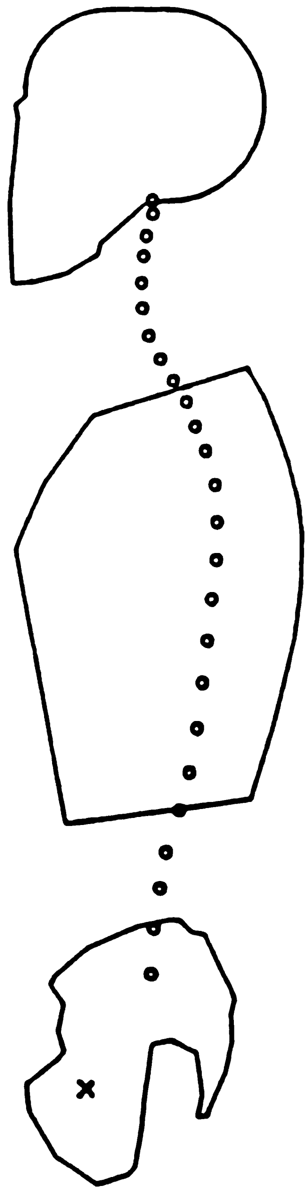


Figure 34 - Andersson +2 posture for the JOHN1 model with distribution seven

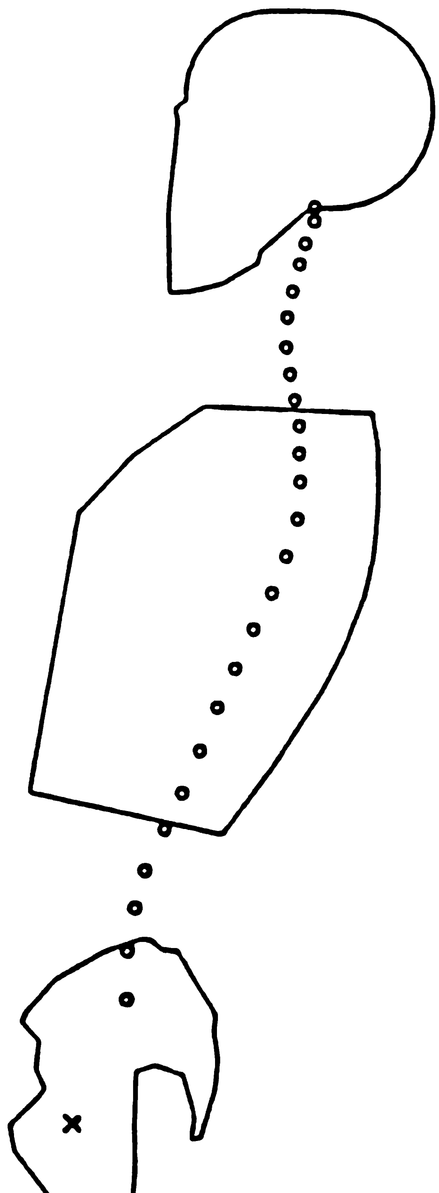


Figure 35 - Andersson +4 posture for the JOHN1 model
with distribution seven

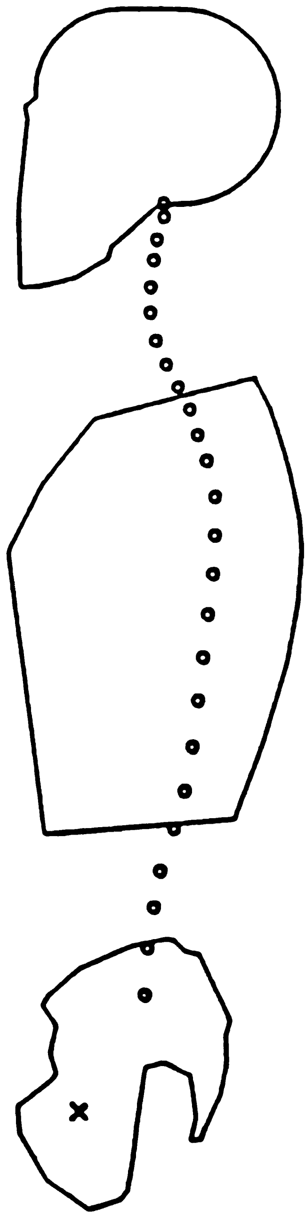


Figure 36 - Andersson +2 posture for the JOHN1 model
with distribution eight

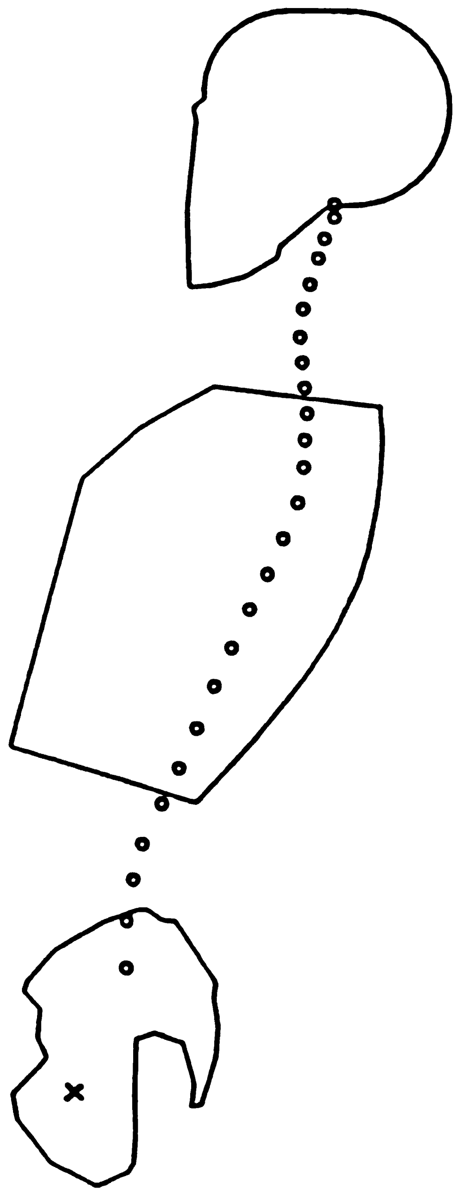


Figure 37 - Andersson +4 posture for the JOHN1 model with distribution eight

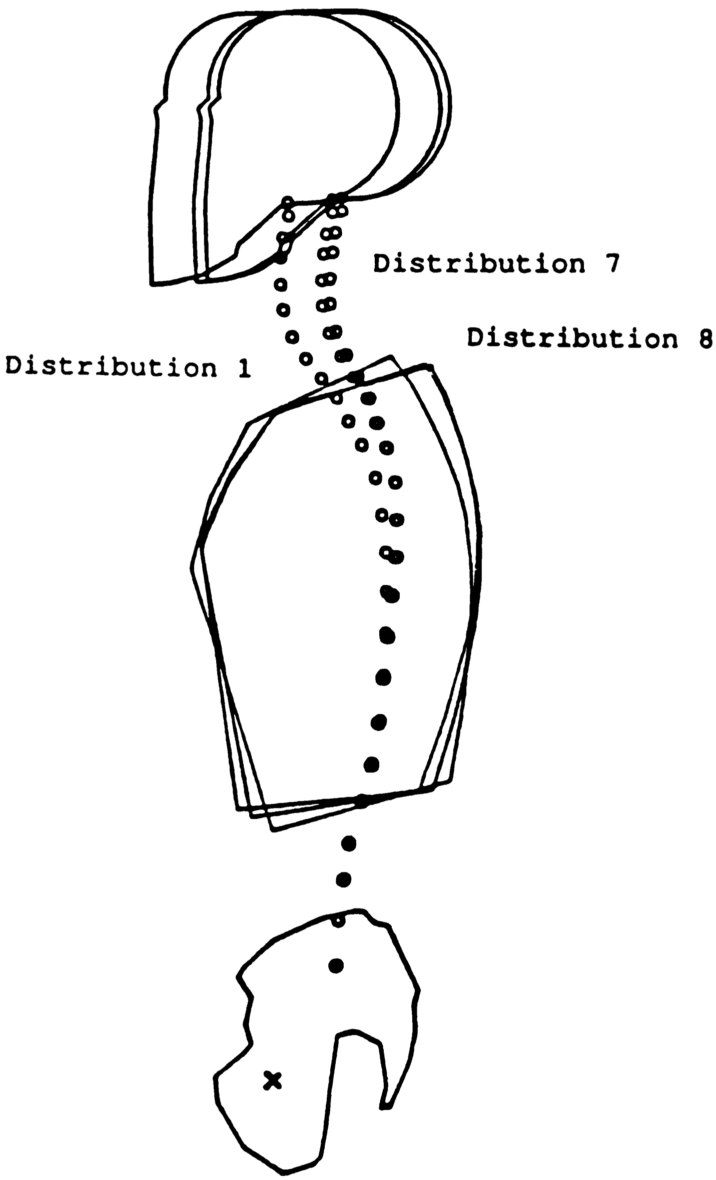


Figure 38 - Composite figure of Andersson +2 posture for the JOHN1 model for distributions one, seven, and eight

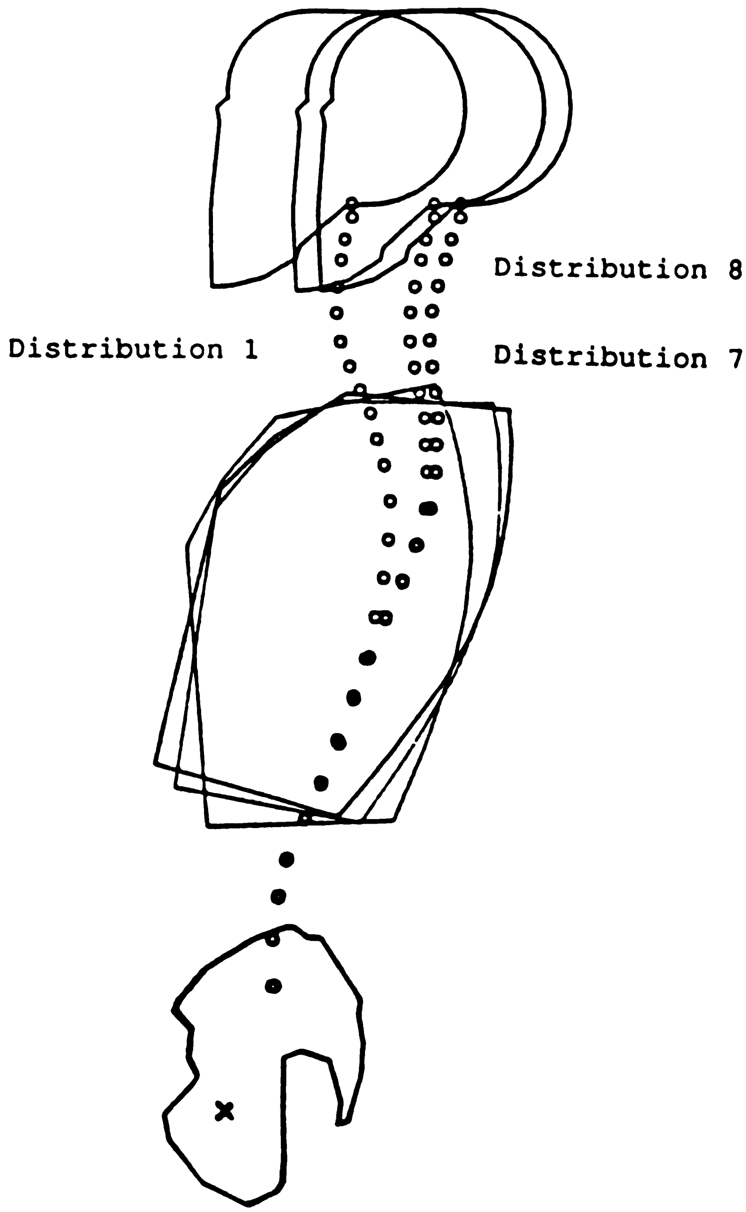


Figure 39 - Composite figure of Andersson +4 posture for the JOHN1 model for distributions one, seven, and eight

TABLE 12
Andersson et. al.[3] TLC and Pelvic Rotations for the JOHN1 Model

DISTRIBUTION NUMBER	TLC FOR POSTURES		PELVIC ROTATION FOR POSTURES IN DEGREES	
	+2	+4	+2	+4
1	24.2	44.5	37.77	44.52
2	23.1	42.4	37.77	44.52
3	25.3	46.4	37.77	44.52
4	22.7	41.7	37.77	44.52
5	25.4	46.6	37.77	44.52
6	25.7	47.1	37.77	44.52
7	31.9	58.5	37.77	44.52
8	34.7	63.7	37.77	44.52
9	23.3	42.8	37.77	44.52
10	22.1	40.6	37.77	44.52

At this point, the angular position of the pelvis relative to the lumbar spine and the thorax appears to be in good agreement with published literature. But the JOHN1 model is only one possible model for the skeleton. Another possible model of the skeleton is the JOHN2 model with a longer lumbar spine. The position of the pelvis relative to the lumbar spine does not change between the JOHN1 model and the JOHN2 model. But the position of the pelvis relative to the thorax does change between the two models.

3.5 Evaluation of the Rotation Distributions for the JOHN2 Model

The JOHN2 model was used to investigate if the different lumbar region would affect the results which had already been found. To accomplish this, the entire testing process as described in Section 2.9 was redone with the

JOHN2 model, instead of the JOHN1 model. The procedure to test for significant differences among the ten possible rotation distributions as outlined in Section 2.8.1 was redone with the JOHN2 model. Appendices 15-18 contain the differences between the coordinates for the multi-screen models of the JOHN2 model. The distances between joint centers are calculated as indicated in Figure 17.

Table 13 and Figure 40 contain the results for 10 degrees flexion. Since no value for the distances exceeded 12.7mm, the conclusion was that there was no significant differences between the various distributions for 10 degrees flexion.

Table 14 and Figure 41 contain the results of the testing for 10 degrees extension. As in the case for 10 degrees flexion, no value for the distances exceeded 12.7mm. Therefore, there was no significant differences between the various distributions for 10 degrees extension.

Table 15 and Figure 42 contain the results of the testing for 20 degrees extension. The only distributions which resulted in values in excess of 12.7mm were the two distributions seven and eight which involved thoracic motion. No other distributions were significantly different than the nominal distribution of even rotation.

Table 16 and Figure 43 contain the results of the testing for 30 degrees extension. Figures 44-52 are the comparisons at 30 degrees extension TLC between distribution one and each of distributions two through ten, respectively.

TABLE 13
Distances (mm) Between Interspaces
for the JOHN2 Model
10 Degrees Flexion

INTER-SPACES	DISTRIBUTION NUMBER 2	3	4	5	6	7	8	9	10
T5/T6	1.61	1.30	3.22	0.50	1.75	6.01	9.20	1.97	4.61
T6/T7	1.66	1.25	3.22	0.58	1.75	6.04	9.23	1.97	4.57
T7/T8	1.66	1.25	3.22	0.50	1.75	6.04	9.04	1.97	4.57
T8/T9	1.58	1.34	3.18	0.58	1.84	6.04	8.57	2.06	4.65
T9/T10	1.66	1.39	3.22	0.58	1.84	5.72	7.97	2.06	4.70
T10/T11	1.66	1.25	3.18	0.50	1.75	5.26	7.09	1.97	4.57
T11/T12	1.66	1.30	3.22	0.50	1.75	4.25	5.73	1.97	4.61
T12/L1	1.66	1.30	3.22	0.58	1.84	2.73	3.89	1.97	4.61
L1/L2	1.72	1.48	2.87	0.72	2.06	1.61	2.33	1.75	3.79
L2/L3	1.66	1.25	2.20	0.67	1.75	0.81	1.30	1.39	3.09
L3/L4	0.78	0.67	1.03	0.64	1.03	0.28	0.50	0.89	1.70
L4/L5	0.22	0.22	0.36	0.22	0.28	0.00	0.14	0.36	0.50
L5/S1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

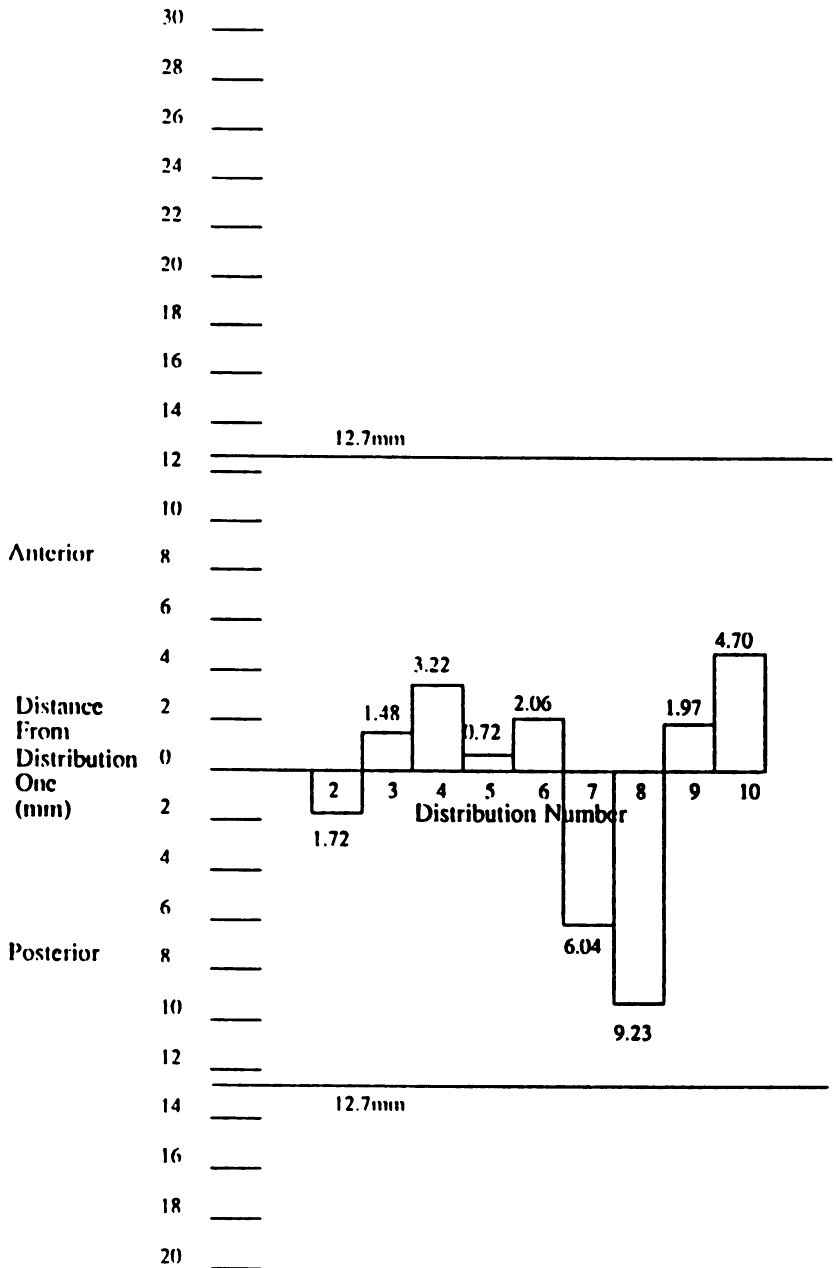


Figure 40 - 10 degrees flexion for the JOHN2 model

TABLE 14
Distances (mm) Between Interspaces
for the JOHN2 Model
10 Degrees Extension

INTER-SPACES	DISTRIBUTION NUMBER 2	3	4	5	6	7	8	9	10
T5/T6	1.91	1.12	3.00	0.40	1.61	6.36	9.51	1.75	4.42
T6/T7	1.70	1.28	3.26	0.50	1.84	6.10	6.28	1.92	4.61
T7/T8	1.64	1.28	3.19	0.50	1.78	6.05	9.13	1.98	4.61
T8/T9	1.77	1.22	3.14	0.54	1.72	6.16	8.71	1.94	4.55
T9/T10	1.64	1.28	3.26	0.58	1.78	5.82	7.99	2.06	4.69
T10/T11	1.64	1.42	3.26	0.58	1.84	5.30	7.10	2.06	4.61
T11/T12	1.64	1.28	3.26	0.58	1.78	4.34	5.70	2.06	4.61
T12/L1	1.64	1.28	3.19	0.50	1.70	2.84	3.91	1.98	4.53
L1/L2	1.99	1.51	2.85	0.73	2.07	1.62	2.33	1.79	4.13
L2/L3	1.64	1.35	2.20	0.78	1.84	0.72	1.14	1.42	3.12
L3/L4	0.86	0.64	1.00	0.50	1.00	0.28	0.45	0.78	1.64
L4/L5	0.32	0.22	0.28	0.28	0.28	0.10	0.10	0.28	0.50
L5/S1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

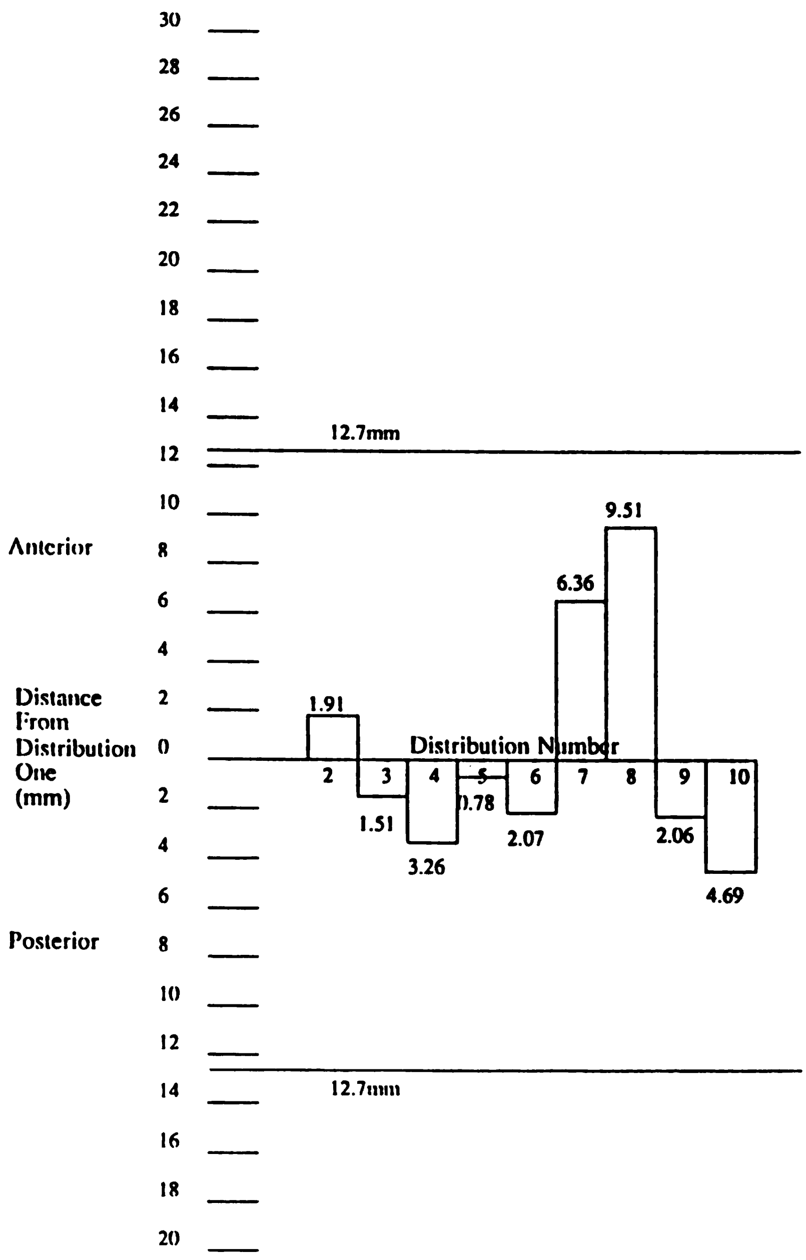


Figure 41 - 10 degrees extension for the JOHN2 model

TABLE 15
Distances (mm) Between Interspaces
for the JOHN2 Model
20 Degrees Extension

INTER- SPACES	DISTRIBUTION NUMBER 2	3	4	5	6	7	8	9	10
T5/T6	3.33	2.62	6.37	1.00	3.54	12.25	18.67	3.96	9.20
T6/T7	3.26	2.62	6.44	1.06	3.61	12.18	18.60	4.03	9.20
T7/T8	3.26	2.62	6.44	1.06	3.61	12.18	18.31	4.03	9.20
T8/T9	3.80	2.69	6.51	1.14	3.61	12.18	17.44	4.03	9.27
T9/T10	3.33	2.62	6.44	1.14	3.54	11.68	16.08	3.96	9.27
T10/T11	3.19	2.62	6.51	1.14	3.61	10.54	14.23	4.03	9.27
T11/T12	3.26	2.69	6.51	1.13	3.61	8.56	11.39	4.03	9.27
T12/L1	3.33	2.62	6.37	1.00	3.54	5.59	7.78	3.96	9.20
L1/L2	3.82	2.97	5.73	1.49	4.10	3.18	4.74	3.54	8.20
L2/L3	3.33	2.62	4.31	1.41	3.61	1.49	2.48	2.76	6.22
L3/L4	1.56	1.28	2.13	1.06	2.13	0.42	0.92	1.70	3.40
L4/L5	0.57	0.36	0.72	0.50	0.58	0.10	0.28	0.72	1.00
L5/S1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

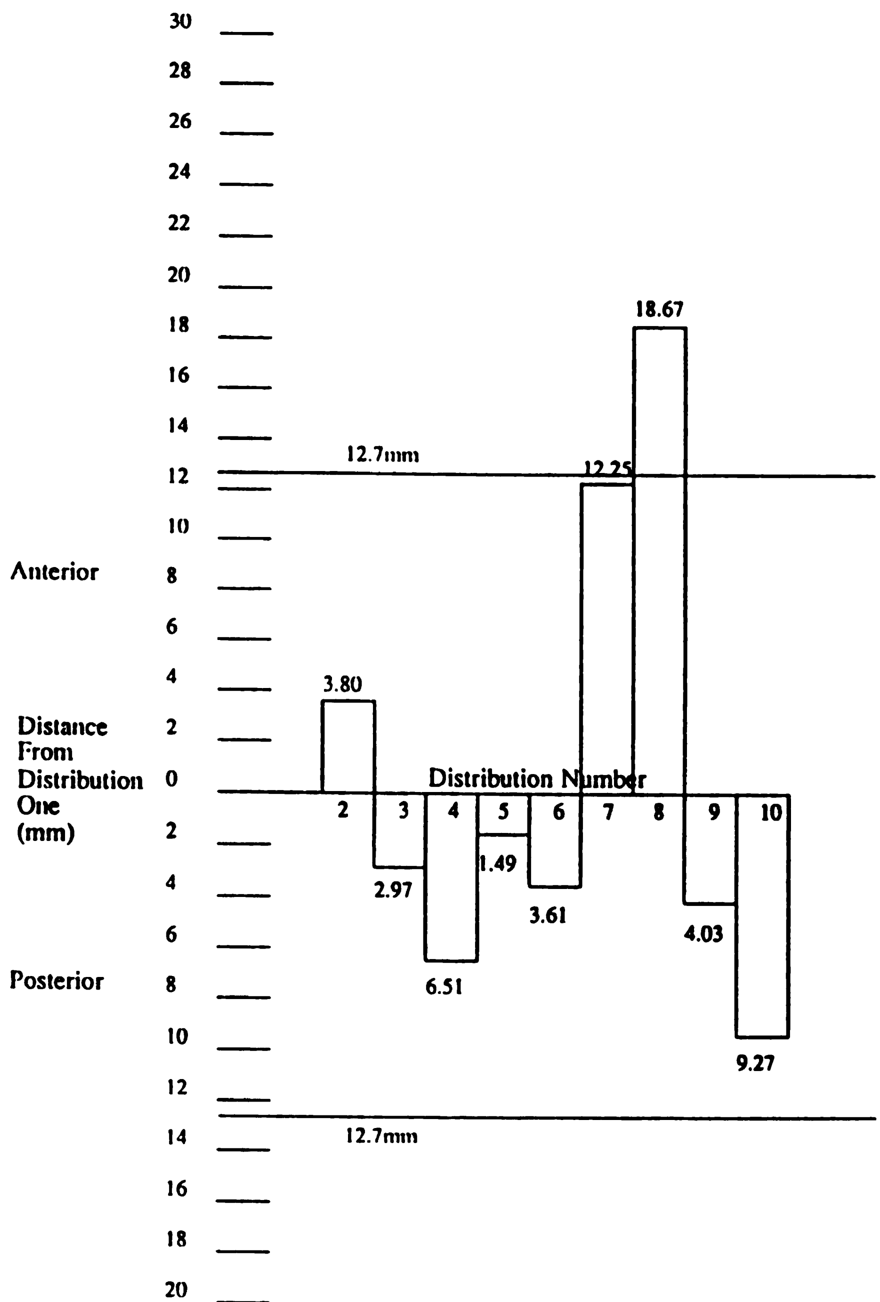


Figure 42 - 20 degrees extension for the JOHN2 model

TABLE 16
Distances (mm) Between Interspaces
for the JOHN2 Model
30 Degrees Extension

INTER- SPACES	DISTRIBUTION NUMBER 2	3	4	5	6	7	8	9	10
T5/T6	4.95	3.96	9.68	1.64	5.38	18.23	27.89	5.97	13.82
T6/T7	4.95	3.89	9.62	1.63	5.38	18.30	27.96	5.97	13.76
T7/T8	5.02	3.89	9.62	1.56	5.31	18.30	27.47	5.97	13.76
T8/T9	4.95	3.89	9.62	1.70	5.38	18.30	26.13	5.97	13.76
T9/T10	4.88	3.96	9.68	1.63	5.38	17.53	24.16	5.97	13.76
T10/T11	4.95	3.89	9.62	1.56	5.31	15.98	21.35	5.97	13.76
T11/T12	4.88	3.96	9.68	1.70	5.45	12.96	17.20	5.97	13.76
T12/L1	4.95	3.96	9.60	1.64	5.38	8.44	11.62	5.95	13.82
L1/L2	5.66	4.53	8.67	2.33	6.24	4.69	7.02	5.32	12.31
L2/L3	4.88	3.89	6.52	2.12	5.38	2.27	3.68	4.10	9.36
L3/L4	2.41	1.84	3.11	1.56	3.11	0.71	1.49	2.55	5.09
L4/L5	0.71	0.71	1.06	0.78	0.92	0.00	0.28	1.06	1.56
L5/S1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

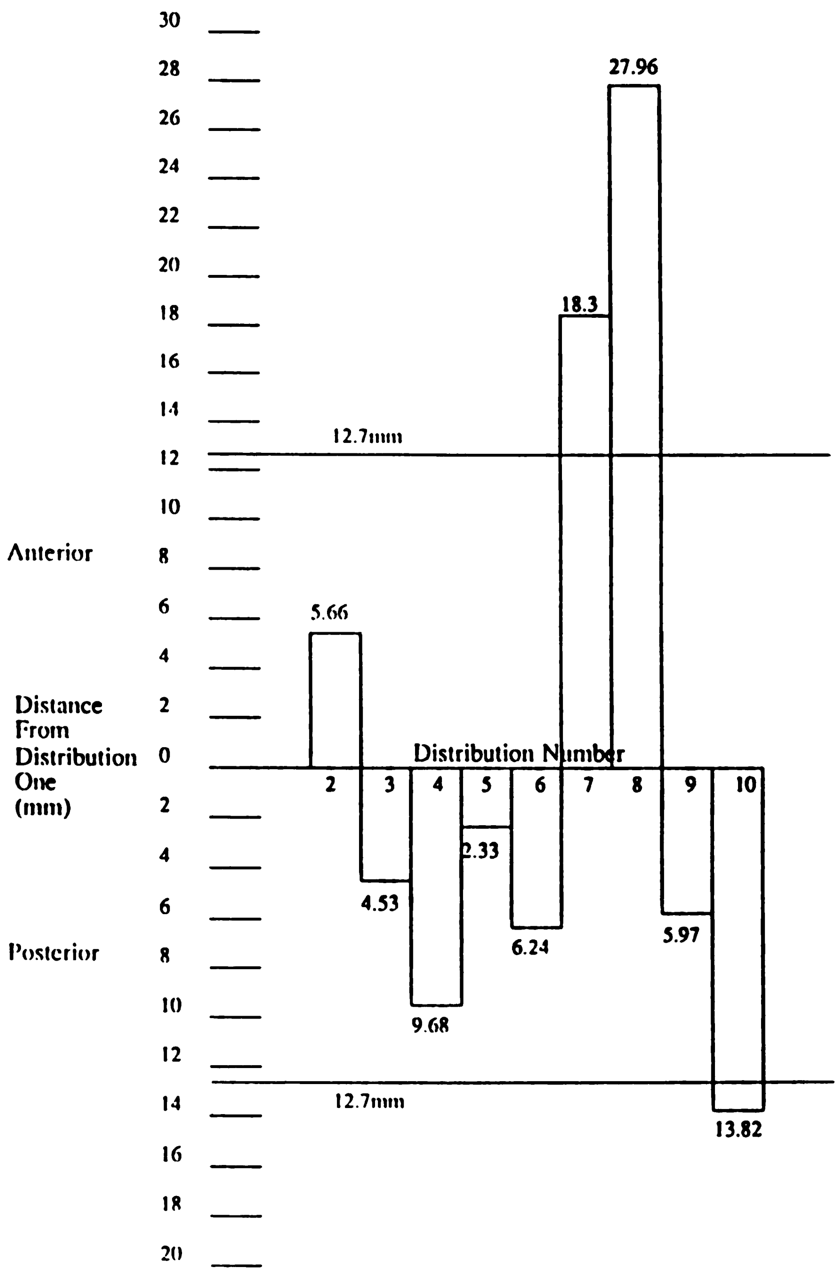


Figure 43 - 30 degrees extension for the JOHN2 model

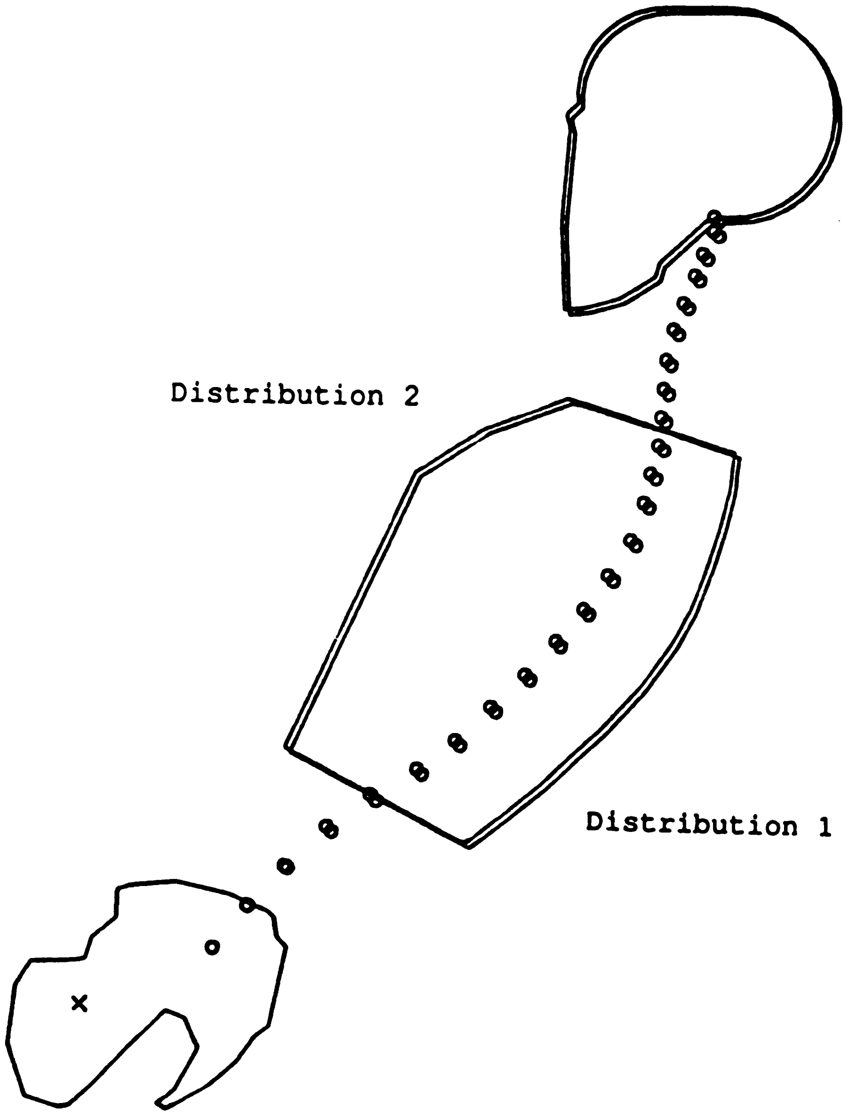


Figure 44 - Comparison of distribution one and distribution two at 30 degrees extension for the JOHN2 model

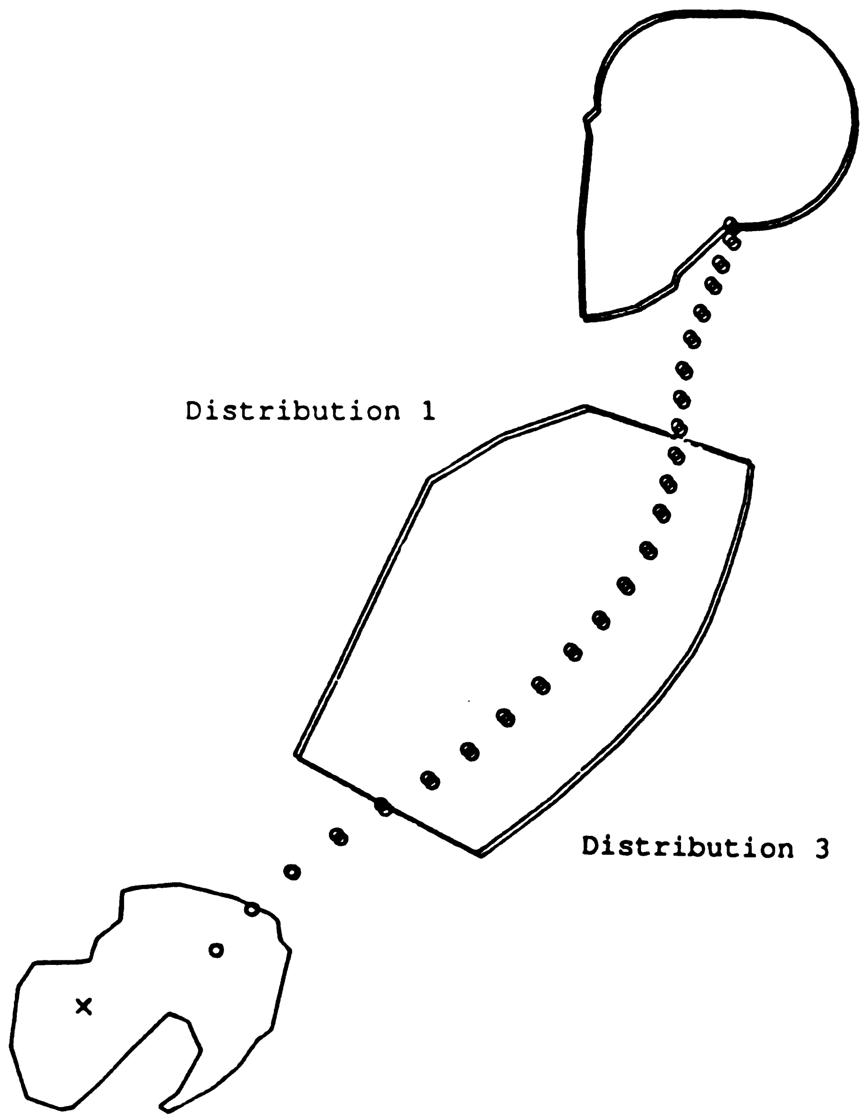


Figure 45 - Comparison of distribution one and distribution three at 30 degrees extension for the JOHN2 model

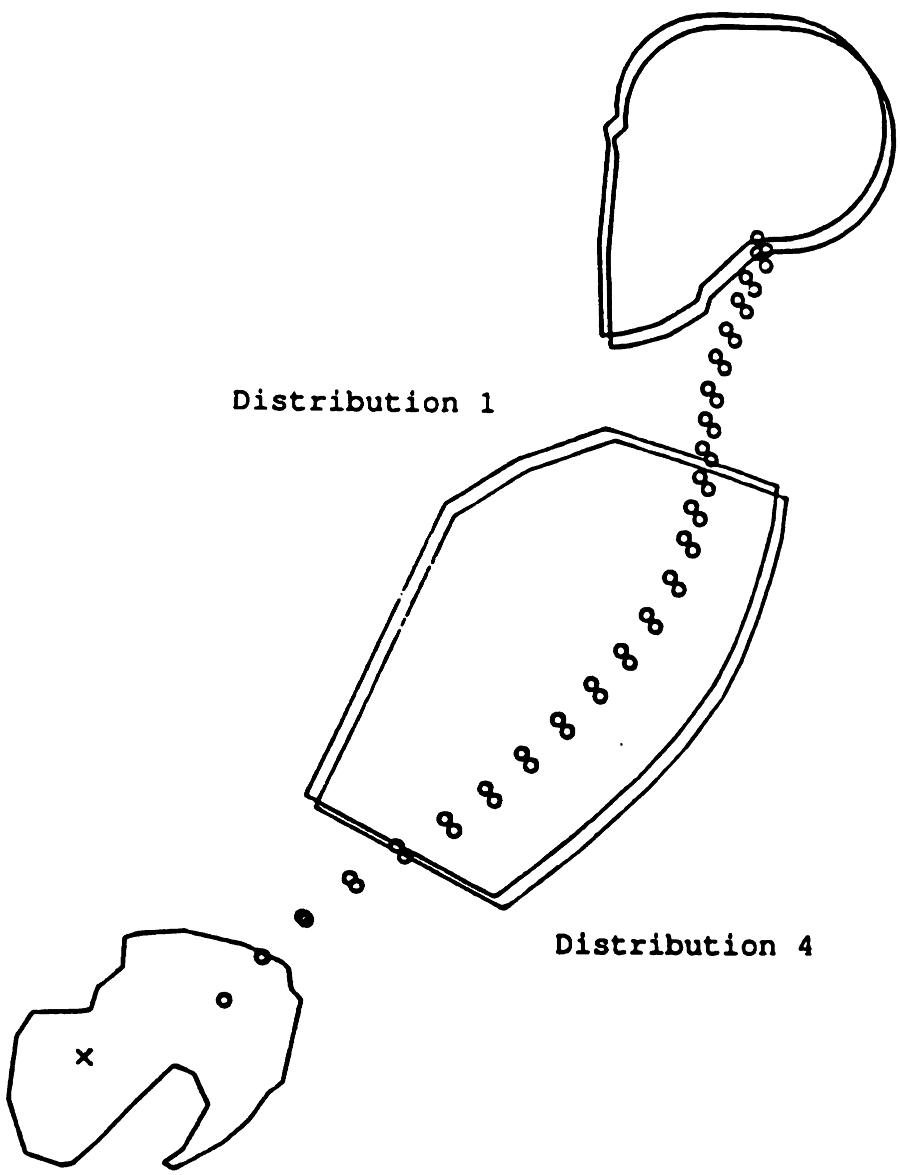


Figure 46 - Comparison of distribution one and distribution four at 30 degrees extension for the JOHN2 model

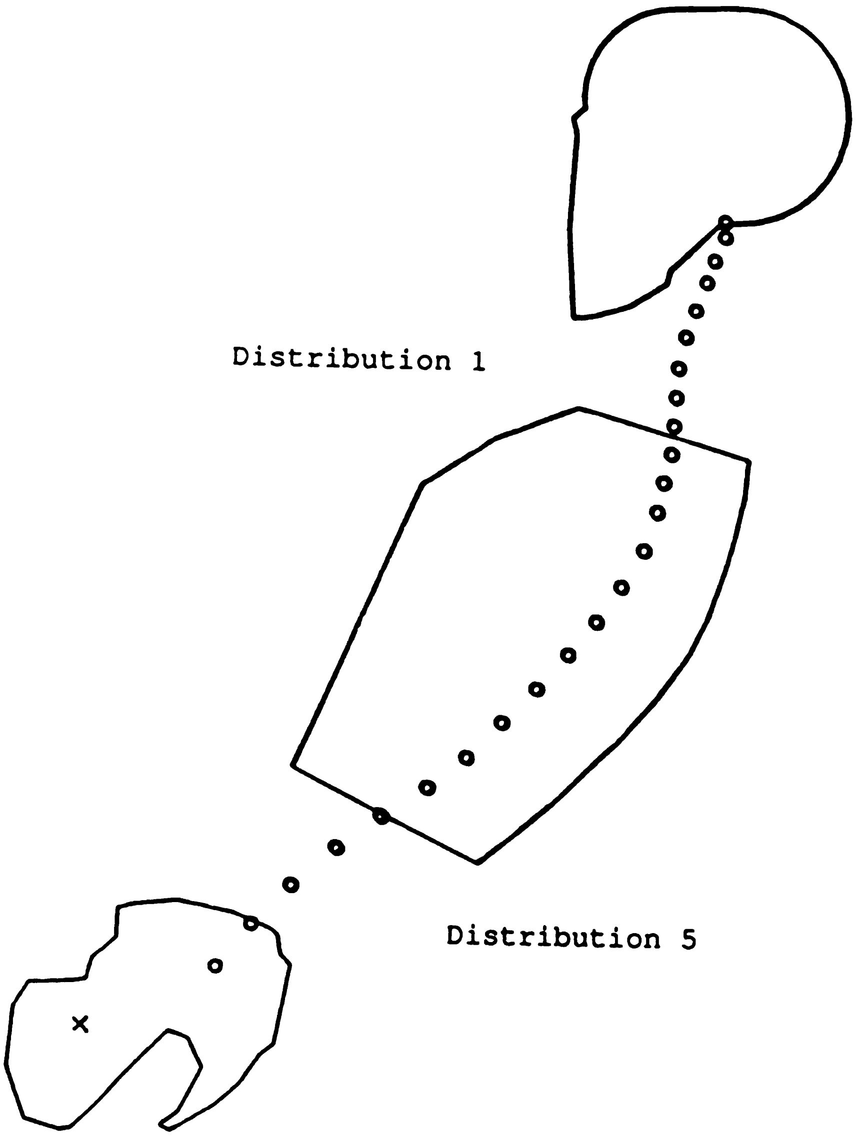


Figure 47 - Comparison of distribution one and distribution five at 30 degrees extension for the JOHN2 model

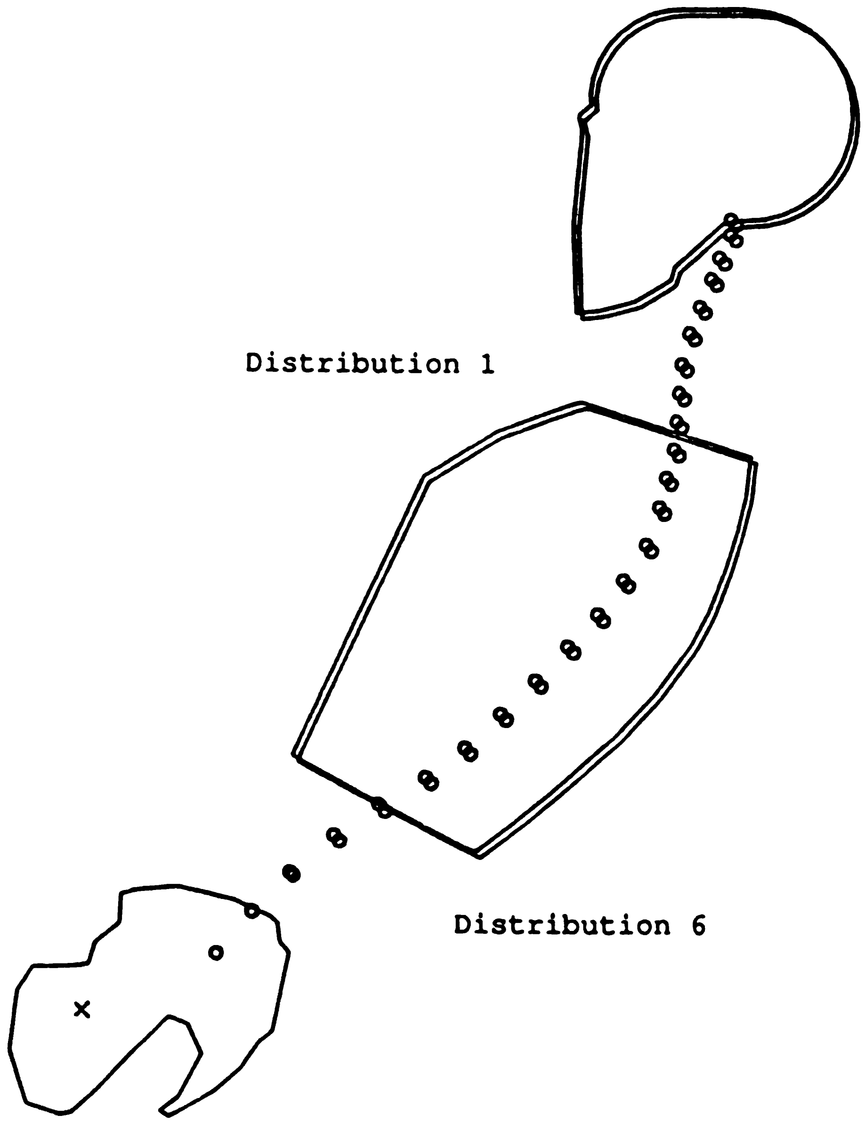


Figure 48 - Comparison of distribution one and distribution six at 30 degrees extension for the JOHN2 model

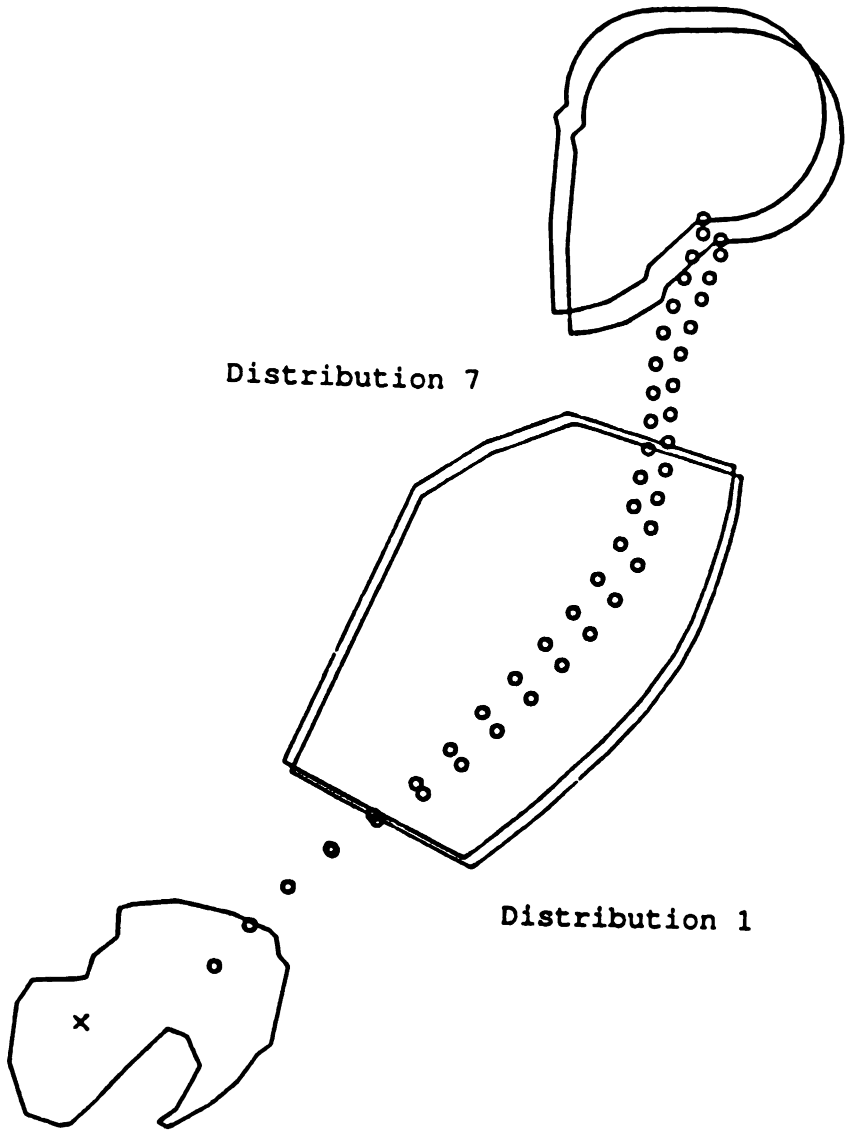


Figure 49 - Comparison of distribution one and distribution seven at 30 degrees extension for the JOHN2 model

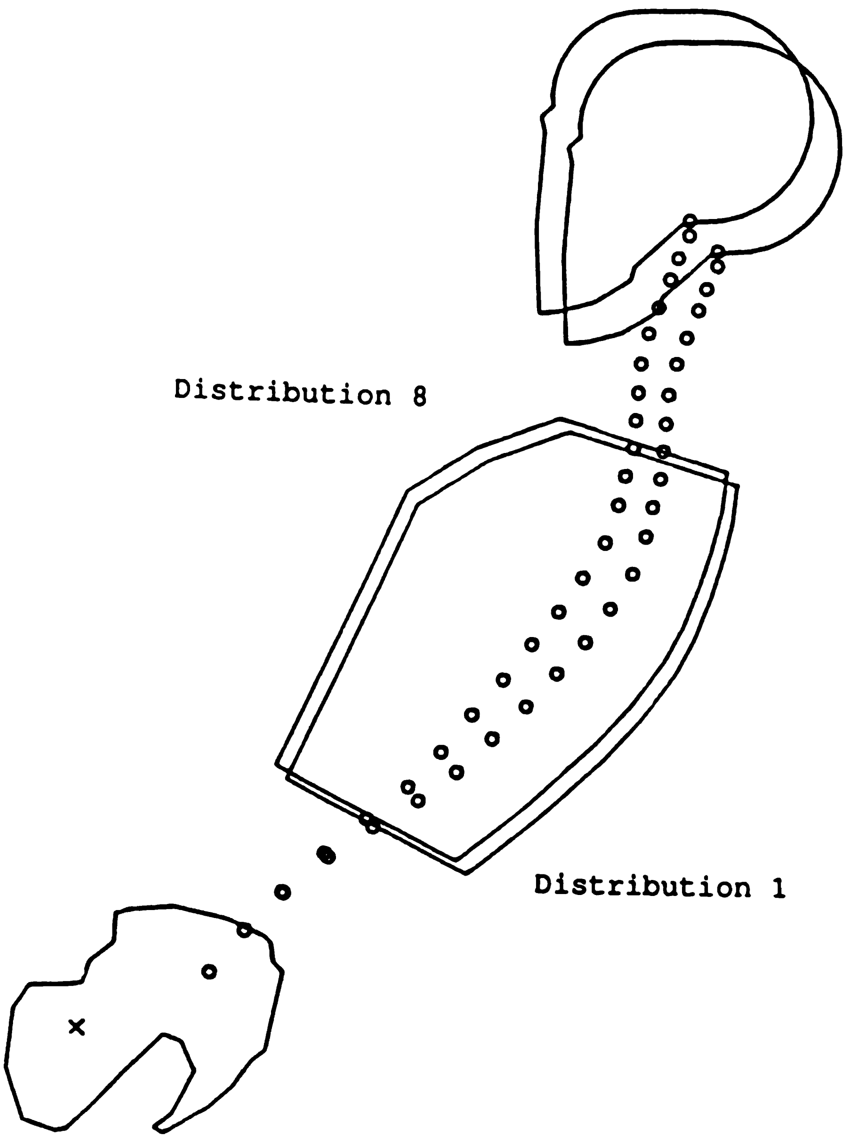


Figure 50 - Comparison of distribution one and distribution eight at 30 degrees extension for the JOHN2 model

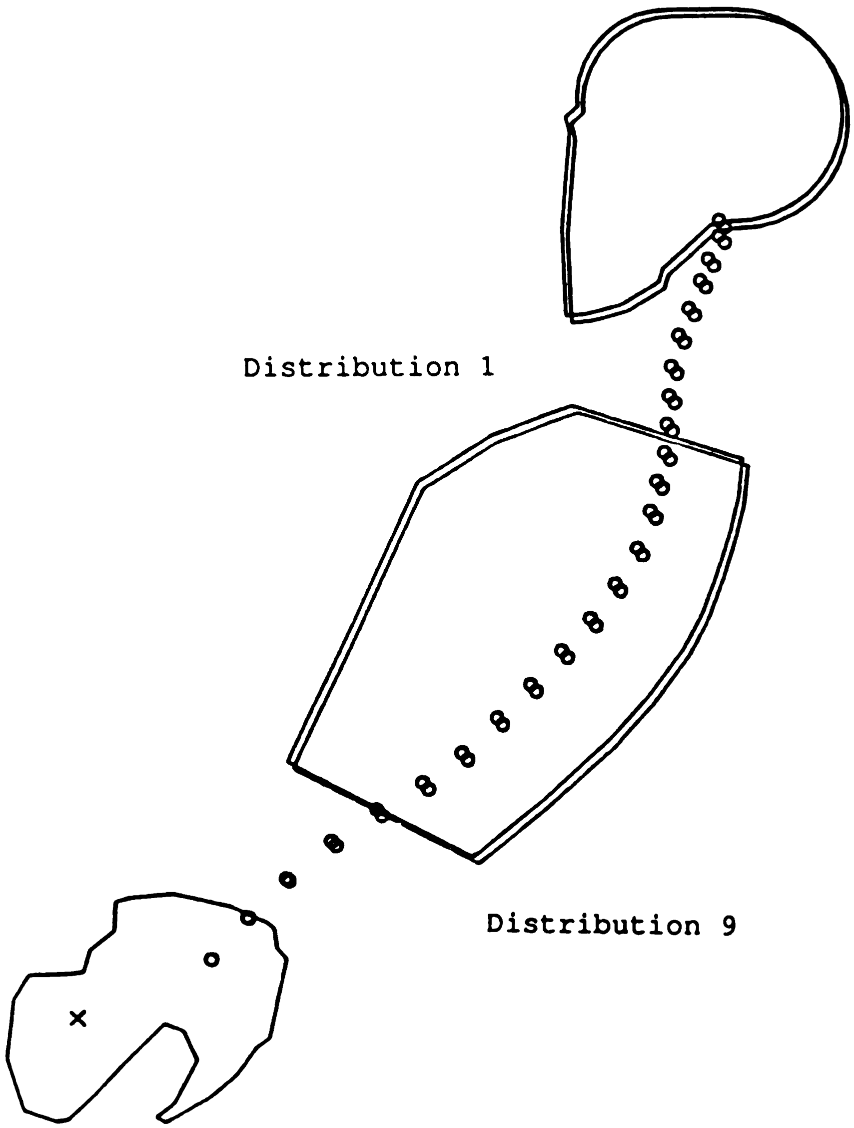


Figure 51 - Comparison of distribution one and distribution nine at 30 degrees extension for the JOHN2 model

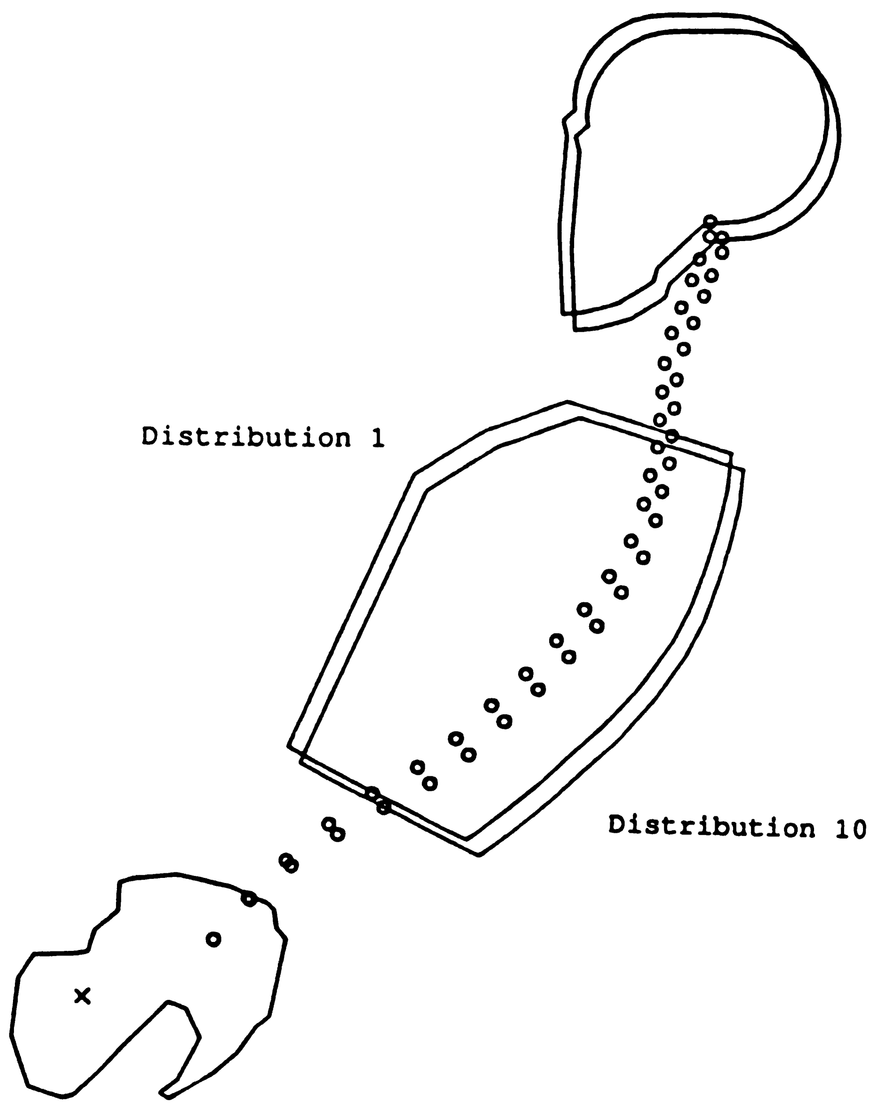


Figure 52 - Comparison of distribution one and distribution ten at 30 degrees extension for the JOHN2 model

For this case, there were three distributions which had values much greater than 12.7mm. As with the previous results in Section 3.1, the two distributions which involved thoracic mobility had values which exceeded 12.7mm. In addition distribution ten had differences which exceeded 12.7mm. This distribution had a rigid thorax. Therefore, for simulating the data in Robbins and Reynolds[4], Nyquist and Patrick[5], and Andersson[3], four distributions were used. Distributions one and ten represented the rigid thorax models and distributions seven and eight represented the models which incorporated a non-rigid thorax.

3.6 Simulation of Robbins and Reynolds[4] for the JOHN2 Model

The next procedure was to model the Robbins and Reynolds[4] study as outlined in Section 2.9.2. Once again the TLC, found in Table 17, was entered into the motion program and the model was rotated about the hip joint center to place the line between the T4/T5 and the T8/T9 vertebral interspaces of the computer model on the same angle from the vertical as the same line in the Robbins and Reynolds[4] study. Table 17 gives the rotations of the computer model for each of the four different distributions. Distribution one resulted in the rotation value closet to the desired value of 12 degrees. But as was the case with the JOHN1 model, in Section 3.2, all rotations were close to the desired value. Therefore, no conclusive decision was made at this point.

TABLE 17
Results of the Simulation of
Robbins and Reynolds[4]
for the JOHN2 Model

DISTRIBUTION NUMBER	TLC (DEGREES)	PELVIC ROTATION (DEGREES)
1	9.0	11.6
7	11.5	14.1
8	12.6	14.8
10	6.5	9.1

3.7 Simulation of Nyquist and Patrick[5] for the JOHN2 Model

Once again, the Nyquist and Patrick[5] study was modeled as described in Section 2.9.3 using only the first subject since the reliability of the pelvic angular position had been supported. The same method was used as before, estimating the TLC and matching the spine lines. Table 18 contains the results of the simulations for each of the four distributions. For this set of simulations, the distribution which gave the best fit to the desired value of 11 degrees was distribution one. The worst value was from distribution ten. Because all values were still close to each other, no conclusion could be made.

TABLE 18
Results of the Simulation of
Nyquist and Patrick[5]
for the JOHN2 Model

DISTRIBUTION NUMBER	TLC (DEGREES)	PELVIC ROTATIONS (DEGREES)
1	10.5	13.2
7	14.8	14.1
8	16.2	14.1
10	10.2	14.5

3.8 Simulation of Andersson et. al.[3] for the JOHN2 Model

The last set of tests involved modeling the Andersson et. al.[3] data as performed earlier in Section 3.4. Table 12 contains the values of pelvic rotation and TLC for each distribution. Figures 53-60 show the resulting postures. Figure 61 is a composite figure of the +2 postures. Figure 62 is a composite figure of the +4 postures. The two +4 postures for the non-rigid thorax cases (distributions 7 and 8) clearly are not representative postures for a man in a vertical seat back. The top of the torso of the model in each of these postures is rotated too far rearward to represent a person in a vertical seatback. All postures for distributions one and ten appear to be represent a person in a vertical seatback. Unlike for the JOHN1 model, no decisive conclusion could be drawn from the simulation of the Andersson et. al.[3] study. For both distribution 1 and distribution 10, the resultant postures appear to represent a person in a vertical seatback.

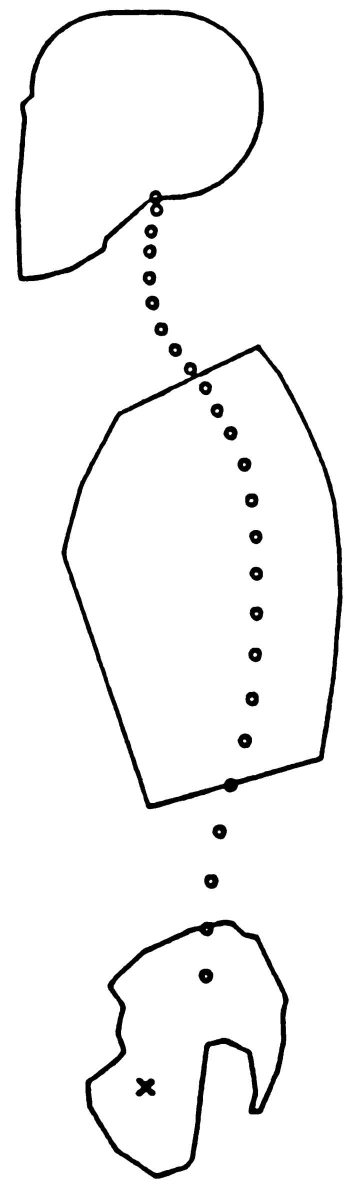


Figure 53 - Andersson +2 posture for the JOHN2 model with distribution one

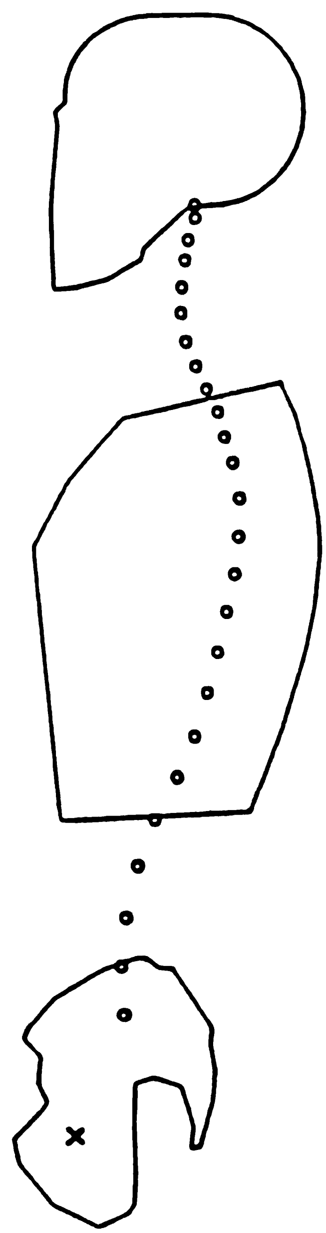


Figure 54 - Andersson +4 posture for the JOHN2 model
with distribution one

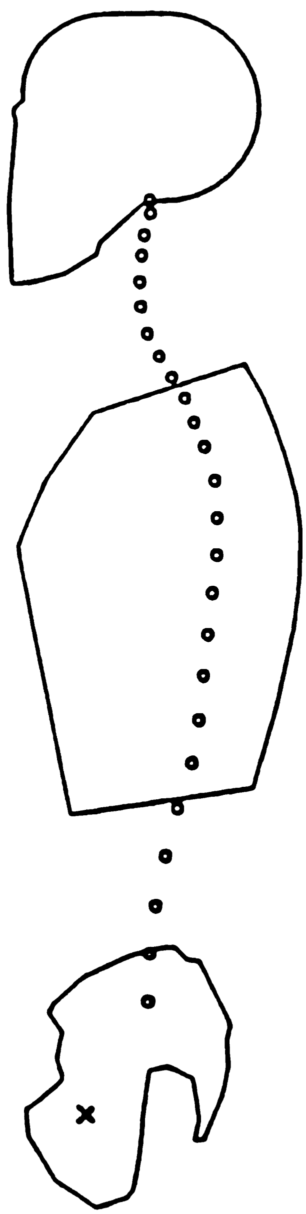


Figure 55 - Andersson +2 posture for the JOHN2 model with distribution seven

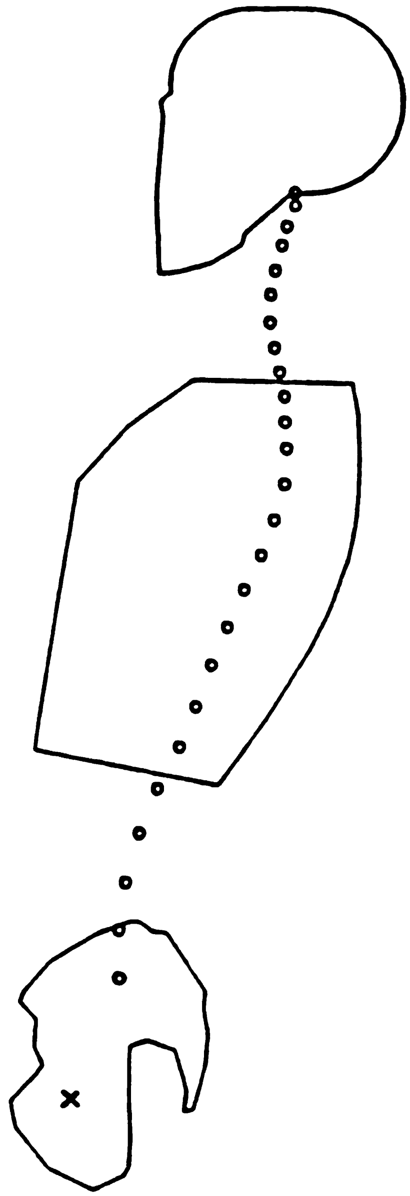


Figure 56 - Andersson +4 posture for the JOHN2 model with distribution seven

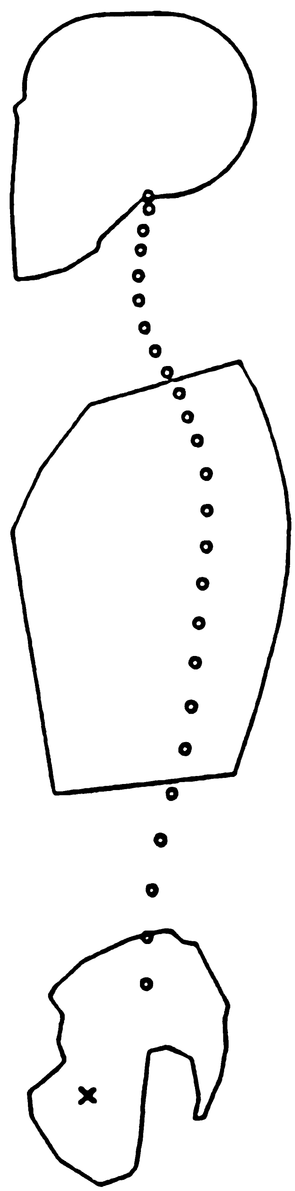


Figure 57 - Andersson +2 posture for the JOHN2 model with distribution eight

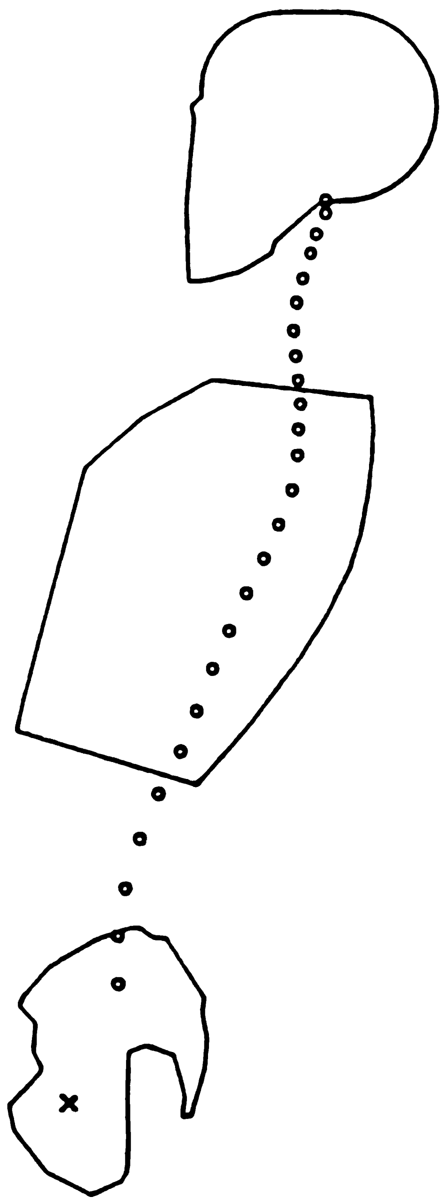


Figure 58 - Andersson +4 posture for the JOHN2 model
with distribution eight

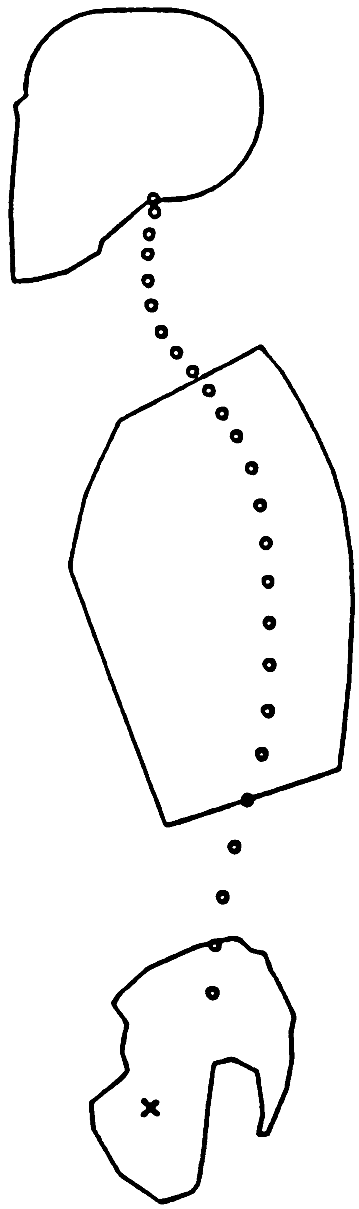


Figure 59 - Andersson +2 posture for the JOHN2 model with distribution ten

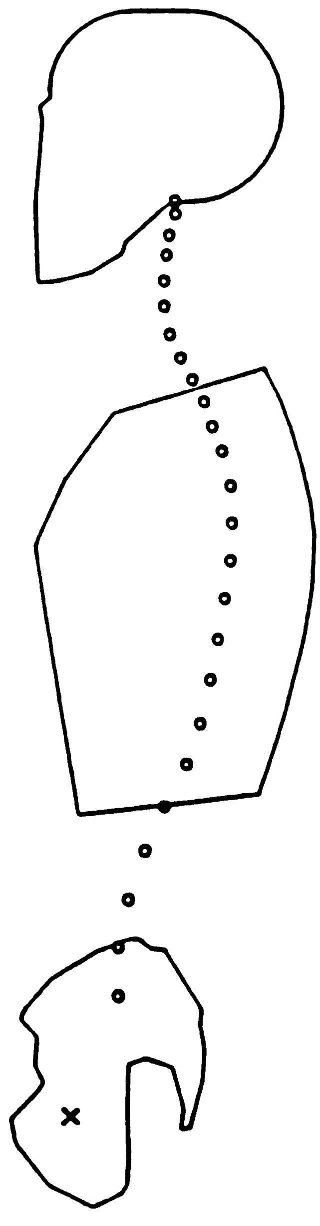


Figure 60 - Andersson +4 posture for the JOHN2 model with distribution ten

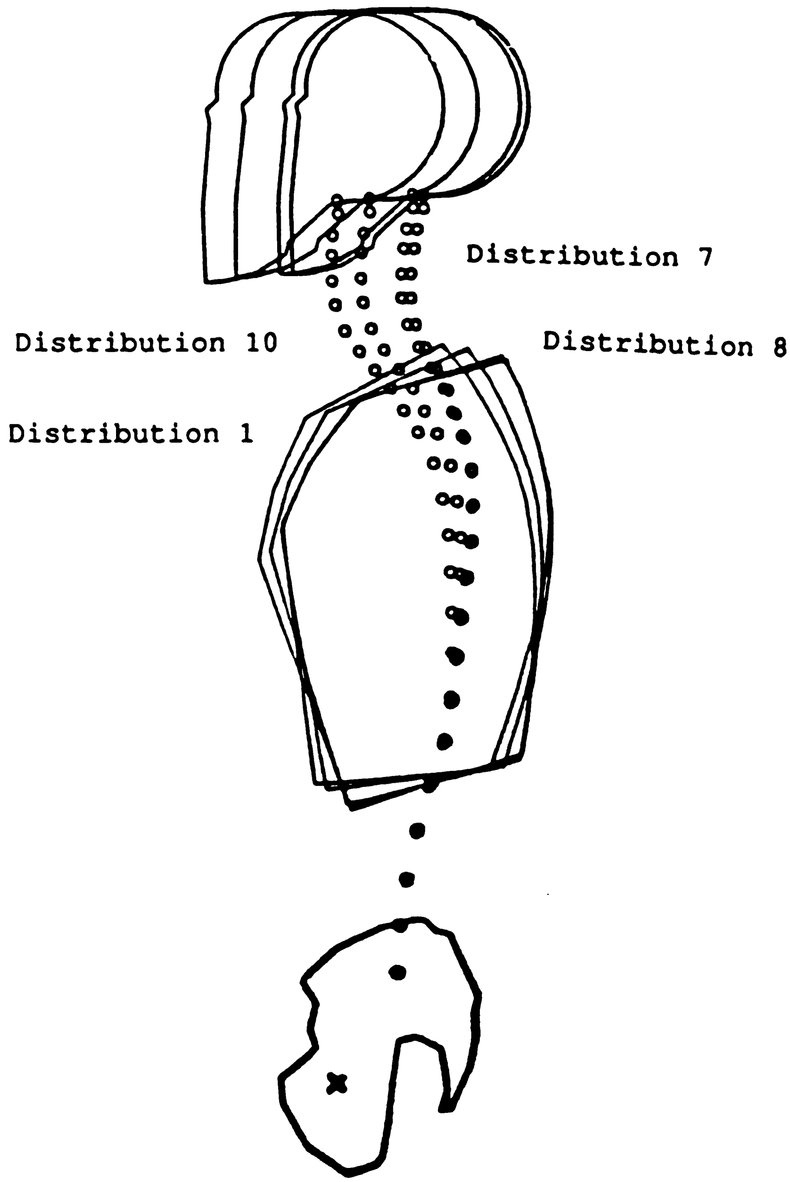


Figure 61 - Composite figure of Andersson +2 posture for the JOHN2 model for distributions one, seven, eight, and ten

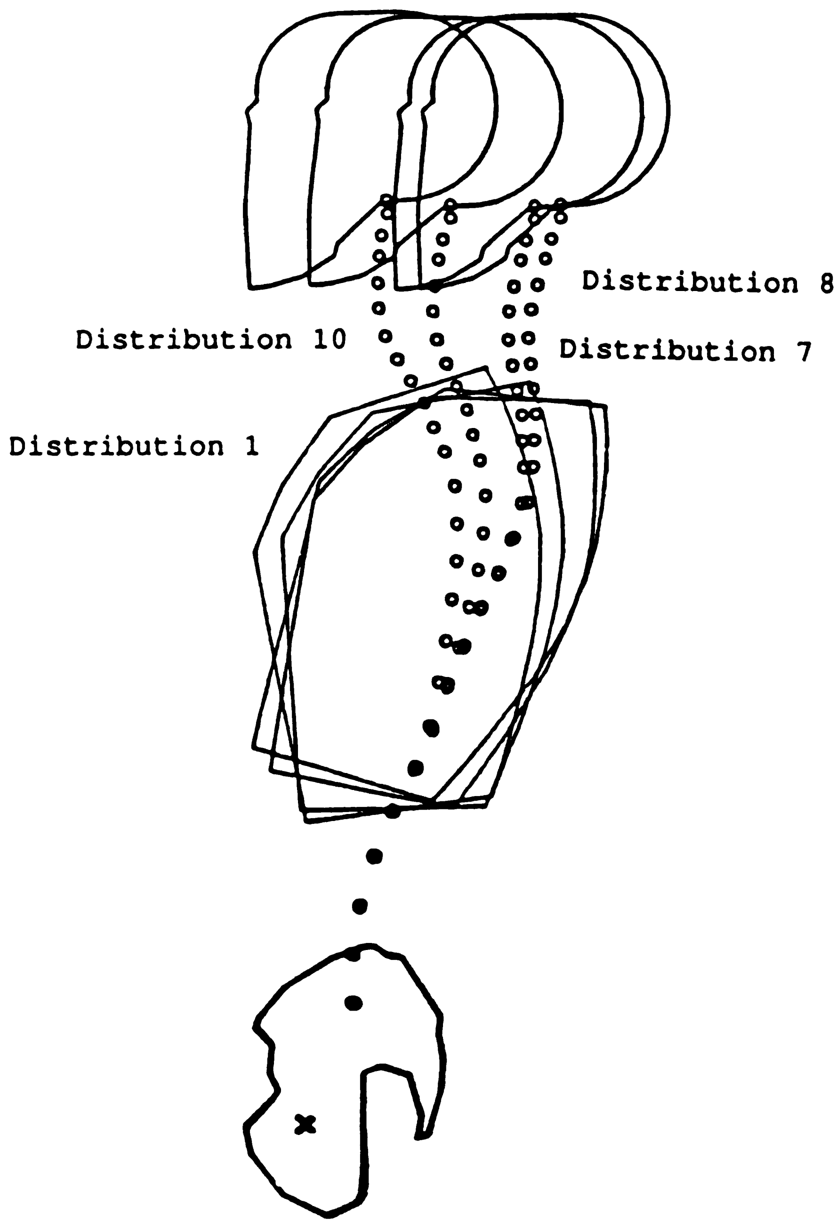


Figure 62 - Composite figure of Andersson +4 posture for the JOHN2 model for distributions one, seven, eight, and ten

By examining the results of the simulations of the literature, the conclusion was reached that distribution one would be the preferred distribution. The reasoning for this decision involved two factors. First, distribution one gave slightly better results for both the Robbins and Reynolds[4] study and the Nyquist and Patrick[5] study. Second, by choosing distribution one, both models would then use the same rotation distribution.

3.9 Choice of the JOHN1 Model or the JOHN2 Model

Judging on a basis of rotational position of pelvis and rib cage, the JOHN1 model and the JOHN2 model could be considered equivalent since both used the same rotation distribution. Also, the pelvic angular position was correct for both the JOHN1 model and the JOHN2 model. The choice still remained between using the JOHN1 model or the JOHN2 model.

To decide which skeletal model to use, the JOHN1 model or the JOHN2 model, a full scale drawing of the JOHN2 model was compared to the original UMTRI[1] drawing. There was not as large a distance between the surface of the buttocks and the bottom of the pelvis for the JOHN2 model (19mm) as there was for the JOHN1 model (46mm). Furthermore, there was more confidence in the exterior of the UMTRI[1] study than in the skeletal placement in that study. Since the motion distribution did not change between the models and the pelvis of the JOHN2 model was closer to the surface of the buttocks, the JOHN2 model was chosen as the skeletal model.

3.10 Movement into the Seatback

The last problem to solve in this research study was how the model should be moved into the seatback. Up to now the automobile industry has simply moved the 2-D drawing template and the three dimensional 3-D H-point machine into a designated seatback angle as measured on the template and the machine. This method is no longer valid for automobile seats which use lumbar support because the 2-D template and the 3-D H-point machine rotate forward on the lumbar support. But since the contour between the seatback and the human body is not known, the computer model cannot be simply rotated into the seatback angle. Therefore, a new method must be found which can move the model into the seatback.

To move the computer model in the simulations of published studies, several methods were used. For the Robbins and Reynolds[4] study, the TLC was known with the angle from the T4/T5 interspace to the T8/T9 interspace. For the Nyquist and Patrick[5] study, the TLC was known with the spine line angle, the angle from the vertical of the line between the L5/S1 interspace and the T12/L1 interspace. For the Andersson et. al.[3] study, the TLC was known with the pelvic-horizontal angle. In each different case, the

TLC and one body angle was known. The angle could be an angle defined within a rigid part of the body, such as the pelvic angle of the Andersson et. al.[3] study, or the thoracic angle for Robbins and Reynolds[4]. Alternatively, the angle could be an angle between two points in a non-rigid section of body, such as the spine line of Nyquist and Patrick[5]. Each of the three methods gave good results, as shown in sections 3.2, 3.3, 3.6, and 3.7. The method which gave results which were closest to the data in the literature was the method for simulating Robbins and Reynolds[4]. Therefore, to position the model in a seat design space, the seat designer should no longer use the seatback angle, but instead use the desired TLC and the angle between two defined points on the rigid thorax.

4. SUMMARY AND CONCLUSIONS

A computer modeling package was used to create a two-dimensional human postural model for automobile seating. The computer modeling package utilized in this research was the SDRC IDEAS 3.8 GEOMOD[10] Solid Modeling Package run on a SUN SYSTEM 3/60.

The data for the modeling of a skull were provided by Hubbard[9]. The data for the modeling of a skeletal pelvis were provided by Reynolds, et al.[8]. The data for a two-dimensional representation of the thorax were provided from drawings and data supplied by UMTRI[1]. To create the individual body segments, the Object Modeling option of the GEOMOD[10] package was used.

The two-dimensional representation of the thorax was modeled with data and drawings from UMTRI[1]. To form the two-dimensional models of the skull and the pelvis, three-dimensional models were first created. Two-dimensional models were then formed from these three-dimensional representations.

The individual skeletal segments were then assembled to form a representation of a human seated posture. Two postural models were created. The first model was a recreation of the posture supplied in the UMTRI[1] data. This study measured the external landmarks of the body and the position of the skeleton was positioned on the basis of these external landmarks. This model was called the JOHN1 model. A second model was formed because the bottom of the pelvis in the UMTRI[1] study was 46mm from the surface of the buttocks. In this second model, the original JOHN1 model was modified with a 29.6mm longer lumbar spine created using data supplied by the Link Study[2]. This model was called the JOHN2 model.

The initial orientation of the JOHN1 model in the seat design space was based on the data from UMTRI[1]. Since the JOHN2 model was a replica of the JOHN1 model except for the length of the lumbar spine, all points, from the T12/L1 interspace up for the two models were superimposed. The pelvis of the JOHN2 model was lower in the body than the pelvis of the JOHN1 model. This resulted in a distance of only 19mm between the surface of the buttocks and the bottom of the pelvis for the JOHN2 model.

The spine was modeled as a chain of rigid links for bending in the mid-sagittal plane. The effect of joint center movement could not be investigated since a rigid link model was used. Spinal bending was simulated through the use of a computer motion program. The necessary input for the computer motion program was the Total Lumbar Curvature (TLC) and one body angle. The TLC was defined as TLC= Pelvic Rotation-Thoracic Rotation.

From modeling several different distributions of spinal mobility, there was no significant difference found between the positions of the joint centers for models which had only lumbar motion and a rigid thorax based on a criteria of ±12.7mm. At the largest value of spinal curvature (TLC = 30 degrees), there were significant differences of greater than ±12.7mm between the positions of the joint centers when a model which had a non-rigid thorax was compared with a model which had a rigid thorax. To decide if a non-rigid thorax was needed for an automobile postural model, the results of studies by Robbins and Reynolds[4], Nyquist and Patrick5], and Andersson[3] were recreated. The closest agreements with published data for both the JOHN1 model and the JOHN2 model were obtained using an even distribution of lumbar rotation and a rigid thorax.

To move the postural model into a simulated seatback, the seat designers should use as input the desired TLC and the angle of one rigid part of the thorax. The motion program can be modified so that any rigid part of the thorax can be used by the designer. For seat design, the angle for one part of the rigid torso must be known. Up to this point in seat design the known angle has been on the torso of the 2-D template and the 3-D H-point machine. Now, the known angle must be on the thorax of the computer model. Once a force-deflection model has been created at some future time it will no longer be necessary to know one angle on the rigid thorax because the computer model can then simulate the settling into a car seat. Until a force-deflection model has been created, the seat designer must specify an angle on the rigid thorax. For this research the angle from the vertical between the T8/T9 and the T4/T5 interspaces was used.

5. LIMITATIONS AND FUTURE WORK

The positions of the pelvis, spine, thorax, and head are still not exactly known for the seated posture. The angle of the pelvis relative to the spine and the position of the thorax appear to be consistent with the available literature. However, not much literature was available. Further research should also be conducted on the positions of the pelvis, ribcage and head in the seated posture. Additional knowledge is needed to confirm or reject the preference of the JOHN2 model over the JOHN1 model.

Using the main conclusion from this study of a uniform distribution of lumbar rotation, a rigid thorax, and the placement of rib cage relative to the pelvis for zero lumbar curvature, the large male and small female could be simulated. This might best be done by using the geometric descriptions of these extreme sizes found in the UMTRI report [1].

The effects of joint center mobility and sacral motion were not explored in this project. Research should be done to investigate the effects of both sacral motion and joint center mobility. The cervical region also was not investigated in this study. A study similar to this lumbar research should be conducted for the cervical region. Furthermore, a force-deflection model is needed to adequately describe the position of a computer model in the seating environment.

It is hoped that this study will provide a new means to represent human postures for seating design.

APPENDICES

APPENDIX 1
COORDINATES FOR THE
LEFT HALF OF THE SKELETAL PELVIS

POINT NUMBER	COORDINATES
1	-77,100,74
3	-71,95,73
5	-71,87,-30
7	-85,66,-21
9	-103,63,7
11	-97,58,-14
13	-134,37,29
15	-131,35,11
17	-126,44,4
19	-123,45,-11
21	-111,52,-17
23	-89,60,-45
25	-90,54,-56
27	-84,81,-58
29	-91,72,-85
31	-99,48,-111
33	-96,60,-118
35	-73,94,-57
37	-61,73,-88
39	-41,25,-121
41	-45,29,-106
43	-29,34,-79
45	-13,41,-78
47	-56,62,-50
49	-12,9,-94
51	-24,68,-71
53	-21,64,-53
55	-25,87,-45
57	-34,98,-44
59	-16,95,-33
61	-60,95,-1
63	-15,104,-12
65	-40,108,1
67	-20,132,30
69	-46,133,42
71	-57,110,27
73	-70,89,5
75	-69,82,17
77	-49,96,10
79	-24,105,5
81	-3,112,9
127	-56,80,-5
129	-55,96,15

APPENDIX 1 (cont'd)

131	-51,109,37
133	-94,0,24
134	-104,0,32
135	-122,0,35
136	-134,0,18
137	-141,0,-2
138	-143,0,-25
139	-139,0,-60
140	-130,31,4
142	-99,26,40
144	-83,56,28
146	-87,44,48
148	-89,26,48
150	-85,17,44
152	-97,17,38
154	-81,17,31
156	-75,51,-5
158	-81,67,-114
160	-76,39,-132
162	-5,25,-76
164	0,113,0
166	-48,119,60
168	-29,5,-104
170	-9,4,-78
171	-79,0,33
172	-59,0,12
173	-69,26,29
175	-77,29,9
177	-74,0,9
178	-89,0,3
179	-113,0,-9
180	-123,0,-16
181	-126,0,-23
182	-132,0,-40
183	-132,0,-63
184	-135,9,-62
186	-132,29,-48
188	-118,44,-18
190	-69,26,29
192	-59,0,12
193	-18,123,34

APPENDIX 2
PELVIC COORDINATES
FOR THE JOHN1 AND JOHN2 MODELS

For the coordinates, pp() indicates a pelvic point. Each pelvic point is represented by three numbers. The first number is the X coordinate, the second number is the Y coordinate, and the third number is the Z coordinate.

ALL COORDINATES ARE IN MM
pp(1)=-25.27625
pp(2)=0
pp(3)=77.59583
pp(4)=-24.36138
pp(5)=0
pp(6)=58.40825
pp(7)=-7.943755
pp(8)=0
pp(9)=45.27579
pp(10)=-3.508106
pp(11)=0
pp(12)=30.94662
pp(13)=33.32959
pp(14)=0
pp(15)=28.95062
pp(16)=43.79724
pp(17)=0
pp(18)=12.72015
pp(19)=48.64297
pp(20)=0
pp(21)=-26.60566
pp(22)=37.01218
pp(23)=0
pp(24)=-61.40113
pp(25)=13.93997
pp(26)=0
pp(27)=-69.38067
pp(28)=6.511439
pp(29)=0
pp(30)=-67.70229
pp(31)=-11.97153
pp(32)=0
pp(33)=-50.60318
pp(34)=-32.74279
pp(35)=0
pp(36)=-28.14089
pp(37)=-58.14952
pp(38)=0
pp(39)=-3.554337

```
pp(40)=-70.85922
pp(41)=0
pp(42)=-9.163578
pp(43)=-79.94301
pp(44)=0
pp(45)=-28.51519
pp(46)=-63.86612
pp(47)=0
pp(48)=-57.45536
pp(49)=-51.72010
pp(50)=0
pp(51)=-66.25731
pp(52)=-58.25688
pp(53)=0
pp(54)=-70.16506
pp(55)=-88.94478
pp(56)=0
pp(57)=-52.86613
pp(58)=-106.3951
pp(59)=0
pp(60)=-37.75034
pp(61)=-118.4822
pp(62)=0
pp(63)=-20.34627
pp(64)=-127.3893
pp(65)=0
pp(66)=-13.89151
pp(67)=-138.6540
pp(68)=0
pp(69)=38.73079
pp(70)=-131.9763
pp(71)=0
pp(72)=46.24134
pp(73)=-130.3799
pp(74)=0
pp(75)=58.66920
pp(76)=-126.0494
pp(77)=0
pp(78)=62.94081
pp(79)=-102.0266
pp(80)=0
pp(81)=73.93635
pp(82)=-63.36956
pp(83)=0
pp(84)=82.97168
pp(85)=-34.32425
pp(86)=0
pp(87)=80.44778
```

APPENDIX 3
COORDINATES OF POINTS FOR THE 2-D THORAX

LANDMARK	COORDINATES (MM)
SUPRASTERNALE	-140,0,431
MESOSTERNALE	-101,0,385
SUBSTERNALE	-75,0,336
MID-POINT OF END OF 10TH RIBS	-93,0,133
T1 SPINOUS PROCESS	-256,0,457
T2 SPINOUS PROCESS	-266,0,435
T3 SPINOUS PROCESS	-273,0,411
T4 SPINOUS PROCESS	-279,0,385
T5 SPINOUS PROCESS	-284,0,355
T6 SPINOUS PROCESS	-285,0,329
T7 SPINOUS PROCESS	-281,0,291
T8 SPINOUS PROCESS	-273,0,254
T9 SPINOUS PROCESS	-265,0,230
T10 SPINOUS PROCESS	-255,0,199
T11 SPINOUS PROCESS	-244,0,171
T12 SPINOUS PROCESS	-231,0,139

APPENDIX 4
UMTRI[1] DATA

LANDMARK	COORDINATES (MM)
MID-POINT OF H-POINTS	0,0,0
SUPRASTERNALE	-140,0,431
MESOSTERNALE	-101,0,385
SUBSTERNALE	-75,0,336
MID-POINT OF 10TH RIBS	-93,0,133
GLABELLA	-87,0,651
MID-POINT OF INFRAORBITALES	-99,0,620
MID-POINT OF TRAGIONS	-185,0,614
L5/S1 INTERSPACE	-89,0,39
L2/L3 INTERSPACE	-142,0,115
T12/L1 INTERSPACE	-177,0,165
T8/T9 INTERSPACE	-215,0,287
T4/T5 INTERSPACE	-220,0,397
C7/T1 INTERSPACE	-193,0,469
SKULL/C1 INTERSPACE	-196,0,588

APPENDIX 5
LUMBAR COORDINATES
FOR THE JOHN1 MODEL

For the coordinates, lp() indicates a lumbar point. Each interspace is represented by three numbers. The first number is the X coordinate, the second number is the Y coordinate, and the third number is the Z coordinate.

ALL COORDINATES ARE IN MM
These are the coordinates for the T12/L1 interspace
lp(1)=-177
lp(2)=0
lp(3)=165
The coordinates for the L1/L2 interspace
lp(4)=-162
lp(5)=0
lp(6)=141
The coordinates for the L2/L3 interspace
#lp(7)=-142
lp(8)=0
lp(9)=115
The coordinates for the L3/L4 interspace
lp(10)=-127
lp(11)=0
lp(12)=92
The coordinates for the L4/L5 interspace
lp(13)=-109
lp(14)=0
lp(15)=67
The coordinates for the L5/S1 interspace
lp(16)=-89
lp(17)=0
lp(18)=39

APPENDIX 6
THORACIC COORDINATES
FOR THE JOHN1 MODEL

For the coordinates, tp() indicates a torso point. Each interspace is represented by three numbers. The first number is the X coordinate, the second number is the Y coordinate, and the third number is the Z coordinate.

```
ALL COORDINATES ARE IN MM
These are the coordinates for the C7/T1 interspace
tp(1)=-193
tp(2)=0
tp(3)=469
These are the coordinates for the T1/T2
tp(4)=-201
tp(5)=0
tp(6)=452
These are the coordinates for the T2/T3
tp(7)=-209
tp(8)=0
tp(9)=435
These are the coordinates for the T3/T4
tp(10)=-214
tp(11)=0
tp(12)=416
These are the coordinates for the T4/T5
tp(13)=-220
tp(14)=0
tp(15)=397
These are the coordinates for the T5/T6
tp(16)=-225
tp(17)=0
tp(18)=371
These are the coordinates for the T6/T7
tp(19)=-224
tp(20)=0
tp(21)=343
These are the coordinates for the T7/T8
tp(22)=-221
tp(23)=0
tp(24)=315
These are the coordinates for the T8/T9
tp(25)=-215
tp(26)=0
tp(27)=287
These are the coordinates for the T9/T10
tp(28)=-209
tp(29)=0
tp(30)=257
```

These are the coordinates for the T10/T11
tp(31)=-200
tp(32)=0
tp(33)=227
These are the coordinates for the T11/T12
tp(34)=-190
tp(35)=0
tp(36)=195
These are the coordinates for the T12/L1 interspace
tp(37)=-177
tp(38)=0
tp(39)=165

For the spinous process points, stp() represents a spinous process point. The first number is the X coordinate, the second number is the Y coordinate, and the third number is the Z coordinate.

ALL COORDINATES ARE IN MM
These are the coordinates of T1
stp(1)=-270
stp(2)=0
stp(3)=462
These are the coordinates for T2
stp(4)=-277
stp(5)=0
stp(6)=437
These are the coordinates for T3
stp(7)=-285
stp(8)=0
stp(9)=410
These are the coordinates for T4
stp(10)=-293
stp(11)=0
stp(12)=380
These are the coordinates for T5
stp(13)=-297
stp(14)=0
stp(15)=352
These are the coordinates for T6
stp(16)=-300
stp(17)=0
stp(18)=325
These are the coordinates for T7
stp(19)=-295
stp(20)=0
stp(21)=285

APPENDIX 6 (cont'd)

```
These are the coordinates for T8
stp(22)=-284
stp(23)=0
stp(24)=253
These are the coordinates for T9
stp(25)=-277
stp(26)=0
stp(27)=225
These are the coordinates for T10
stp(28)=-265
stp(29)=0
stp(30)=192
These are the coordinates for T11
stp(31)=-255
stp(32)=0
stp(33)=165
These are the coordinates for T12
stp(34)=-246
stp(35)=0
stp(36)=146
```

APPENDIX 7
CERVICAL COORDINATES
FOR THE JOHN1 MODEL

For the coordinates, cp() indicates a cervical point. Each interspace is represented by three numbers. The first number is the X coordinate, the second number is the Y coordinate, and the third number is the Z coordinate.

```
ALL COORDINATES ARE IN MM
These are the coordinates for the C1/SKULL interspace
(occipital condylar axis)
cp(1)=-196
cp(2)=0
cp(3)=588
These are the coordinates for the C1/C2 interspace
cp(4)=-196
cp(5)=0
cp(6)=578
These are the coordinates for the C2/C3 interspace
cp(7)=-190
cp(8)=0
cp(9)=562
These are the coordinates for the C3/C4 interspace
cp(10)=-187
cp(11)=0
cp(12)=547
These are the coordinates for the C4/C5 interspace
cp(13)=-184
cp(14)=0
cp(15)=527
These are the coordinates for the C5/C6 interspace
cp(16)=-183
cp(17)=0
cp(18)=508
These are the coordinates for the C6/C7 interspace
cp(19)=-186
cp(20)=0
cp(21)=487
These are the coordinates for the C7/T1 interspace
cp(22)=-193
cp(23)=0
cp(24)=469
```

APPENDIX 8
LUMBAR COORDINATES
FOR THE JOHN2 MODEL

For the coordinates, lp() indicates a lumbar point. Each interspace is represented by three numbers. The first number is the X coordinate, the second number is the Y coordinate, and the third number is the Z coordinate.

ALL COORDINATES ARE IN MM
These are the coordinates for the T12/L1 interspace
lp(1)=-194.1
lp(2)=0
lp(3)=189.2
The coordinates for the L1/L2 interspace
lp(4)=-173.7
lp(5)=0
lp(6)=160
The coordinates for the L2/L3 interspace
lp(7)=-152.9
lp(8)=0
lp(9)=130.3
The coordinates for the L3/L4 interspace
lp(10)=-130.8
lp(11)=0
lp(12)=98.7
The coordinates for the L4/L5 interspace
lp(13)=-110
lp(14)=0
lp(15)=69
The coordinates for the L5/S1 interspace
lp(16)=-89
lp(17)=0
lp(18)=39

APPENDIX 9
THORACIC COORDINATES
FOR THE JOHN2 MODEL

For the coordinates, tp() indicates a torso point. Each interspace is represented by three numbers. The first number is the X coordinate, the second number is the Y coordinate, and the third number is the Z coordinate.

```
ALL COORDINATES ARE IN MM
These are the coordinates for the C7/T1 interspace
tp(1)=-210
tp(2)=0
tp(3)=493
These are the coordinates for the T1/T2
tp(4)=-218
tp(5)=0
tp(6)=476
These are the coordinates for the T2/T3
tp(7)=-226
tp(8)=0
tp(9)=459
These are the coordinates for the T3/T4
tp(10)=-231
tp(11)=0
tp(12)=440
These are the coordinates for the T4/T5
tp(13)=-237
tp(14)=0
tp(15)=421
These are the coordinates for the T5/T6
tp(16)=-242
tp(17)=0
tp(18)=395
These are the coordinates for the T6/T7
tp(19)=-241
tp(20)=0
tp(21)=367
These are the coordinates for the T7/T8
tp(22)=-238
tp(23)=0
tp(24)=339
These are the coordinates for the T8/T9
tp(25)=-232
tp(26)=0
tp(27)=311
These are the coordinates for the T9/T10
tp(28)=-225
tp(29)=0
tp(30)=281
```

These are the coordinates for the T10/T11
tp(31)=-217
tp(32)=0
tp(33)=251
These are the coordinates for the T11/T12
tp(34)=-207
tp(35)=0
tp(36)=219
These are the coordinates for the T12/L1 interspace
tp(37)=-194.1
tp(38)=0
tp(39)=189.2

For the spinous process points, stp() represents a spinous process point. The first number is the X coordinate, the second number is the Y coordinate, and the third number is the Z coordinate.
ALL COORDINATES ARE IN MM
These are the coordinates for T1
stp(1)=-270
stp(2)=0
stp(3)=462
These are the coordinates for T2
stp(4)=-277
stp(5)=0
stp(6)=437
These are the coordinates for T3
stp(7)=-285
stp(8)=0
stp(9)=410
These are the coordinates for T4
stp(10)=-293
stp(11)=0
stp(12)=380
These are the coordinates for T5
stp(13)=-297
stp(14)=0
stp(15)=352
These are the coordinates for T6
stp(16)=-300
stp(17)=0
stp(18)=325
These are the coordinates for T7
stp(19)=-295
stp(20)=0
stp(21)=285

APPENDIX 9 (cont'd)

```
These are the coordinates for T8
stp(22)=-284
stp(23)=0
stp(24)=253
These are the coordinates for T9
stp(25)=-277
stp(26)=0
stp(27)=225
These are the coordinates for T10
stp(28)=-265
stp(29)=0
stp(30)=192
These are the coordinates for T11
stp(31)=-255
stp(32)=0
stp(33)=165
These are the coordinates for T12
stp(34)=-246
stp(35)=0
stp(36)=146
```

APPENDIX 10
CERVICAL COORDINATES
FOR THE JOHN2 MODEL

For the coordinates, cp() indicates a cervical point. Each interspace is represented by three numbers. The first number is the X coordinate, the second number is the Y coordinate, and the third number is the Z coordinate.

ALL COORDINATES ARE IN MM
These are the coordinates for the C1/SKULL interspace
(occipital condylar axis)
cp(1)=-213
cp(2)=0
cp(3)=612
These are the coordinates for the C1/C2 interspace
cp(4)=-213
cp(5)=0
cp(6)=602
These are the coordinates for the C2/C3 interspace
cp(7)=-207
cp(8)=0
cp(9)=586
These are the coordinates for the C3/C4 interspace
cp(10)=-204
cp(11)=0
cp(12)=571
These are the coordinates for the C4/C5 interspace
cp(13)=-201
cp(14)=0
cp(15)=551
These are the coordinates for the C5/C6 interspace
cp(16)=-200
cp(17)=0
cp(18)=532
These are the coordinates for the C6/C7 interspace
cp(19)=-203
cp(20)=0
cp(21)=511
These are the coordinates for the C7/T1 interspace
cp(22)=-210
cp(23)=0
cp(24)=493

APPENDIX 11
DIFFERENCES (MM) BETWEEN INTERSPACES FOR THE JOHN1 MODEL
10 DEGREES FLEXION

INTER-SPACE	DISTRIBUTION NUMBER 2	3	4	5	6	7	8	9	10	DIFF.
T5/T6	1.2	-0.9	-2.3	-0.3	-1.2	5.3	8.2	-1.4	-3.3	Delta X
	0.7	-0.5	-1.3	-0.2	-0.7	1.7	2.4	-0.8	-1.8	Delta Z
T6/T7	1.1	-0.9	-2.3	-0.4	-1.2	5.3	8.2	-1.4	-3.3	Delta X
	0.7	-0.6	-1.3	-0.3	-0.8	1.7	2.4	-0.9	-1.9	Delta Z
T7/T8	1.1	-0.9	-2.3	-0.4	-1.2	5.3	8.0	-1.4	-3.3	Delta X
	0.7	-0.6	-1.3	-0.3	-0.8	1.7	2.4	-0.9	-1.9	Delta Z
T8/T9	1.1	-0.9	-2.3	-0.4	-1.3	5.3	7.6	-1.5	-3.3	Delta X
	0.7	-0.6	-1.3	-0.3	-0.8	1.7	2.4	-0.8	-1.9	Delta Z
T9/T10	1.1	-0.9	-2.3	-0.4	-1.3	5.0	6.9	-1.5	-3.3	Delta X
	0.7	-0.6	-1.3	-0.3	-0.8	1.7	2.3	-0.9	-1.9	Delta Z
T10/T11	1.1	-0.9	-2.3	-0.4	-1.2	4.5	6.0	-1.4	-3.3	Delta X
	0.7	-0.6	-1.3	-0.3	-0.8	1.6	2.2	-0.9	-1.9	Delta Z
T11/T12	1.2	-0.9	-2.3	-0.3	-1.2	3.5	4.6	-1.4	-3.3	Delta X
	0.8	-0.5	-1.3	-0.2	-0.7	1.5	2.0	-0.8	-1.8	Delta Z
T12/L1	1.2	-0.9	-2.2	-0.3	-1.2	2.1	2.8	-1.4	-3.3	Delta X
	0.8	-0.5	-1.3	-0.2	-0.7	1.1	1.6	-0.8	-1.8	Delta Z
L1/L2	1.3	-1.1	-2.1	-0.6	-1.5	1.1	1.6	-1.3	-3.0	Delta X
	0.9	-0.6	-1.1	-0.3	-0.8	0.7	1.1	-0.7	-1.7	Delta Z
L2/L3	1.1	-0.9	-1.5	-0.5	-1.2	0.5	0.9	-0.9	-2.1	Delta X
	0.7	-0.5	-0.9	-0.3	-0.7	0.3	0.5	-0.6	-1.2	Delta Z
L3/L4	0.6	-0.5	-0.8	-0.4	-0.8	0.2	0.3	-0.6	-1.3	Delta X
	0.4	-0.3	-0.5	-0.2	-0.5	0.1	0.2	-0.4	-0.8	Delta Z
L4/L5	0.2	-0.2	-0.3	-0.2	-0.2	0.0	0.1	-0.3	-0.4	Delta X
	0.2	-0.2	-0.2	-0.1	-0.1	0.0	0.1	-0.2	-0.2	Delta Z
L5/S1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Delta X
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Delta Z

APPENDIX 12
DIFFERENCES (MM) BETWEEN INTERSPACES FOR THE JOHN1 MODEL 10 DEGREES EXTENSION

INTER-SPACE	DISTRIBUTION NUMBER 2	3	4	5	6	7	8	9	10	DIFF.
T5/T6	-1.0	0.8	2.0	0.4	1.2	-4.6	-7.3	1.3	2.9	Delta X
	-0.9	0.6	1.7	0.2	0.9	-3.1	-4.5	1.0	2.4	Delta Z
T6/T7	-1.1	0.8	2.0	0.3	1.1	-4.7	-7.3	1.3	2.9	Delta X
	-0.9	0.6	1.7	0.3	0.9	-3.1	-4.5	1.0	2.4	Delta Z
T7/T8	-1.1	0.8	2.0	0.3	1.1	-4.7	-7.2	1.2	2.8	Delta X
	-0.6	0.7	1.7	0.3	1.0	-3.1	-4.4	1.1	2.5	Delta Z
T8/T9	-1.1	0.8	2.0	0.4	1.1	-4.7	-6.8	1.3	2.9	Delta X
	-0.8	0.7	1.8	0.3	1.0	-3.0	-4.3	1.1	2.5	Delta Z
T9/T10	-1.9	0.8	2.0	0.3	1.1	-4.4	-6.2	1.3	2.9	Delta X
	-0.9	0.6	1.7	0.3	0.9	-3.0	-4.1	1.0	2.4	Delta Z
T10/T11	-1.0	0.8	2.0	0.4	1.1	-3.9	-5.3	1.3	2.9	Delta X
	-0.8	0.7	1.7	0.3	1.0	-2.7	-3.6	1.1	2.5	Delta Z
T11/T12	-1.0	0.8	2.0	0.4	1.1	-3.0	-4.0	1.3	2.9	Delta X
	-0.8	0.7	1.7	0.3	1.0	-2.3	-3.0	1.1	2.5	Delta Z
T12/L1	-1.1	0.8	2.0	0.3	1.1	-1.8	-2.5	1.3	2.9	Delta X
	-0.8	0.7	1.7	0.3	0.9	-1.5	-2.0	1.1	2.5	Delta Z
L1/L2	-1.2	0.9	1.8	0.5	1.3	-1.0	-1.5	1.1	2.5	Delta X
	-1.0	0.8	1.5	0.4	1.1	-0.9	-1.3	0.9	2.2	Delta Z
L2/L3	-1.0	0.8	1.3	0.5	1.1	-0.5	-0.8	0.9	1.9	Delta X
	-0.8	0.6	1.1	0.3	0.9	-0.4	-0.6	0.7	1.6	Delta Z
L3/L4	-0.5	0.5	0.8	0.4	0.7	-0.1	-0.3	0.6	1.2	Delta X
	-0.4	0.3	0.6	0.3	0.5	-0.1	-0.3	0.4	0.9	Delta Z
L4/L5	-0.2	0.2	0.3	0.2	1.2	0.0	-0.1	0.3	0.4	Delta X
	-0.2	0.1	0.2	0.1	0.2	0.4	-0.1	0.2	0.3	Delta Z
L5/S1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Delta X
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Delta Z

APPENDIX 13
DIFFERENCES (MM) BETWEEN INTERSPACES FOR THE JOHN1 MODEL
20 DEGREES EXTENSION

INTER-SPACE	DISTRIBUTION NUMBER 2	3	4	5	6	7	8	9	10	DIFF.
T5/T6	-2.0	1.6	3.7	0.7	2.1	-8.4	-13.3	2.4	5.2	Delta X
	-1.8	1.4	3.8	0.6	2.0	-7.4	-10.9	2.3	5.5	Delta Z
T6/T7	-2.0	1.5	3.7	0.7	2.1	-8.4	-13.3	2.4	5.2	Delta X
	-1.8	1.4	3.7	0.5	2.0	-7.4	-11.0	2.3	5.5	Delta Z
T7/T8	-2.0	1.5	3.7	0.7	2.1	-8.4	-13.0	2.4	5.2	Delta X
	-1.7	1.5	3.8	0.6	2.1	-7.4	-10.7	2.4	5.5	Delta Z
T8/T9	-2.0	1.5	3.6	0.7	2.1	-8.4	-12.3	2.3	5.2	Delta X
	-1.8	1.5	3.8	0.6	2.0	-7.4	-10.3	2.4	5.5	Delta Z
T9/T10	-2.0	1.5	3.6	0.7	2.1	-8.0	-11.1	2.3	5.2	Delta X
	-1.7	1.5	3.8	0.6	2.1	-7.1	-9.6	2.4	5.5	Delta Z
T10/T11	-2.0	1.5	3.6	0.7	2.1	-7.1	-9.6	2.3	5.2	Delta X
	-1.7	1.5	3.8	0.6	2.1	-6.4	-8.5	2.4	5.6	Delta Z
T11/T12	-2.0	1.6	3.7	0.7	2.2	-5.4	-7.3	2.4	4.7	Delta X
	-1.8	1.5	3.8	0.6	2.0	-5.3	-7.0	2.4	5.5	Delta Z
T12/L1	-2.0	1.5	3.6	0.7	2.1	-3.2	-4.5	2.3	5.2	Delta X
	-1.7	1.5	3.8	0.6	2.1	-3.3	-4.5	2.4	5.5	Delta Z
L1/L2	-2.3	1.8	3.3	1.0	2.4	-1.8	-2.7	2.1	4.7	Delta X
	-2.0	1.7	3.4	0.9	2.4	-1.9	-2.7	2.1	4.9	Delta Z
L2/L3	-1.9	1.6	2.6	1.0	2.2	-0.8	-1.4	1.7	3.6	Delta X
	-1.7	1.4	2.4	0.8	2.0	-0.7	-1.2	1.5	3.5	Delta Z
L3/L4	-1.1	0.8	1.4	0.7	1.3	-0.3	-0.6	1.1	2.2	Delta X
	-0.9	0.7	1.2	0.6	1.2	-0.3	-0.6	1.0	2.0	Delta Z
L4/L5	-0.4	0.3	0.5	0.3	0.4	0.0	-0.2	0.5	0.7	Delta X
	-0.3	0.3	0.4	0.3	0.4	0.0	-0.1	0.4	0.6	Delta Z
L5/S1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Delta X
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Delta Z

APPENDIX 14
DIFFERENCES (MM) BETWEEN INTERSPACES FOR THE JOHN1 MODEL
30 DEGREE EXTENSION

INTER-SPACE	DISTRIBUTION NUMBER 2	3	4	5	6	7	8	9	10	DIFF.
T5/T6	-2.9	2.3	4.9	1.0	3.9	-11.0	-17.7	3.2	6.9	Delta X
	-2.8	2.4	6.2	0.9	3.3	-12.7	-18.9	3.8	9.0	Delta Z
T6/T7	-2.8	2.2	4.9	1.1	3.0	-11.0	-17.7	3.2	7.0	Delta X
	-2.8	2.3	6.1	0.9	3.2	-12.7	-19.0	3.8	8.9	Delta Z
T7/T8	-2.8	2.2	4.9	1.1	3.0	-11.0	-17.2	3.2	7.0	Delta X
	-2.8	2.4	6.2	0.9	3.3	-12.7	-18.6	3.8	9.0	Delta Z
T8/T9	-2.8	2.2	4.9	1.1	3.0	-11.0	-16.3	3.2	7.0	Delta X
	-2.8	2.3	6.1	0.9	3.2	-12.7	-17.8	3.8	8.9	Delta Z
T9/T10	-2.8	2.2	4.9	1.1	3.0	-10.4	-14.7	3.2	7.0	Delta X
	-2.8	2.4	6.2	1.0	3.3	-12.2	-16.5	3.9	9.0	Delta Z
T10/T11	-2.8	2.2	4.9	1.1	3.0	-9.3	-12.7	3.2	7.0	Delta X
	-2.8	2.4	6.2	0.9	3.3	-11.0	-14.5	3.8	9.0	Delta Z
T11/T12	-2.9	2.1	4.9	1.0	2.9	-7.2	-9.7	3.2	6.9	Delta X
	-2.8	2.4	6.2	1.0	3.3	-8.9	-11.6	3.9	9.0	Delta Z
T12/L1	-2.8	2.1	4.9	1.0	3.0	-4.2	-5.9	3.2	7.0	Delta X
	-2.8	2.4	6.2	0.9	3.3	-5.5	-7.4	3.8	9.0	Delta Z
L1/L2	-3.2	2.4	4.4	1.3	3.3	-2.5	-3.8	2.9	6.3	Delta X
	-3.3	2.8	5.5	1.4	3.9	-3.1	-4.4	3.4	8.0	Delta Z
L2/L3	-2.8	2.1	3.5	1.3	2.9	-1.2	-2.0	2.3	4.9	Delta X
	-2.7	2.3	3.8	1.3	3.2	-1.2	-2.0	2.4	5.6	Delta Z
L3/L4	-1.5	1.2	2.0	1.0	1.9	-0.4	-0.9	1.6	3.1	Delta X
	-1.4	1.2	2.0	1.0	2.0	-0.4	-0.8	1.6	3.3	Delta Z
L4/L5	-0.6	0.4	0.7	0.5	0.6	-0.1	-0.3	0.7	1.0	Delta X
	-0.3	0.4	0.7	0.5	0.6	0.0	-0.2	0.7	1.0	Delta Z
L5/S1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Delta X
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Delta Z

APPENDIX 15
DIFFERENCES (MM) BETWEEN INTERSPACES FOR THE JOHN2 MODEL 10 DEGREES FLEXION

INTER-	DISTRIBUTION NUMBER									
SPACE	2	3	4	5	6	7	8	9	10	DIFF.
T5/T6	1.4	-1.1	-2.8	-0.4	-1.5	5.7	8.8	-1.7	-4.0	Delta X
	0.8	-0.7	-1.6	-0.3	-0.9	1.9	2.7	-1.0	-2.3	Delta Z
T6/T7	1.4	-1.1	-2.8	-0.5	-1.5	5.7	8.8	-1.7	-4.0	Delta X
	0.9	-0.6	-1.6	-0.3	-0.9	2.0	2.8	-1.0	-2.2	Delta Z
T7/T8	1.4	-1.1	-2.8	-0.4	-1.5	5.7	8.6	-1.7	-4.0	Delta X
	0.9	-0.6	-1.6	-0.3	-0.9	2.0	2.8	-1.0	-2.2	Delta Z
T8/T9	1.3	-1.2	-2.8	-0.5	-1.6	5.7	8.1	-1.8	-4.1	Delta X
	0.9	-0.6	-1.5	-0.3	-0.9	2.0	2.8	-1.0	-2.2	Delta Z
T9/T10	1.4	-1.2	-2.8	-0.5	-1.6	5.4	7.5	-1.8	-4.1	Delta X
	0.9	-0.7	-1.6	-0.3	-0.9	1.9	2.7	-1.0	-2.3	Delta Z
T10/T11	1.4	-1.1	-2.8	-0.4	-1.5	4.9	6.6	-1.7	-4.0	Delta X
	0.9	-0.6	-1.5	-0.3	-0.9	1.9	2.6	-1.0	-2.2	Delta Z
T11/T12	1.4	-1.1	-2.8	-0.4	-1.5	3.9	5.2	-1.7	-4.0	Delta X
	0.9	-0.7	-1.6	-0.3	-0.9	1.7	2.4	-1.0	-2.3	Delta Z
T12/L1	1.4	-1.1	-2.8	-0.5	-1.6	2.4	3.4	-1.7	-4.0	Delta X
	0.9	-0.7	-1.6	-0.3	-0.9	1.3	1.9	-1.0	-2.3	Delta Z
L1/L2	1.4	-1.3	-2.5	-0.6	-1.8	1.4	2.0	-1.5	-3.6	Delta X
	1.0	-0.7	-1.4	-0.4	-1.0	0.8	1.2	-0.9	-1.2	Delta Z
L2/L3	1.4	-1.1	-1.9	-0.6	-1.5	0.7	1.1	-1.2	-2.7	Delta X
	0.9	-0.6	-1.1	-0.3	-0.9	0.4	0.7	-0.7	-1.5	Delta Z
L3/L4	0.6	-0.6	-0.9	-0.5	-0.9	0.2	0.4	-0.8	-1.5	Delta X
	0.5	-0.3	-0.5	-0.4	-0.5	0.2	0.3	-0.4	-0.8	Delta Z
L4/L5	0.2	-0.2	-0.3	-0.2	-0.2	0.0	0.1	-0.3	-0.4	Delta X
	0.1	-0.1	-0.2	-0.1	-0.2	0.0	0.1	-0.2	-0.3	Delta Z
L5/S1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Delta X
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Delta Z

APPENDIX 16
DIFFERENCES (MM) BETWEEN INTERSPACES FOR THE JOHN2 MODEL 10 DEGREES EXTENSION

INTER-SPACE	2	3	4	5	6	7	8	9	10	DIFF.
	DISTRIBUTION NUMBER									
T5/T6	-1.3	1.0	2.4	0.4	1.4	-5.1	-7.9	1.5	3.5	Delta X
	-1.4	0.5	1.8	0.0	0.8	-3.8	-5.3	0.9	2.7	Delta Z
T6/T7	-1.3	1.0	2.5	0.4	1.4	-5.0	-3.8	1.5	3.5	Delta X
	-1.1	0.8	2.1	0.3	1.2	-3.5	-5.0	1.2	3.0	Delta Z
T7/T8	-1.3	1.0	2.4	0.4	1.4	-5.0	-7.7	1.5	3.5	Delta X
	-1.0	0.8	2.1	0.3	1.1	-3.4	-4.9	1.3	3.0	Delta Z
T8/T9	-1.3	1.0	2.5	0.5	1.4	-5.0	-7.2	1.6	3.5	Delta X
	-1.2	0.7	1.9	0.2	1.0	-3.6	-4.9	1.1	2.9	Delta Z
T9/T10	-1.3	1.0	2.5	0.5	1.4	-4.8	-6.6	1.6	3.6	Delta X
	-1.0	0.8	2.1	0.3	1.1	-3.3	-4.5	1.3	3.0	Delta Z
T10/T11	-1.3	1.1	2.5	0.5	1.4	-4.3	-5.8	1.6	3.5	Delta X
	-1.0	0.9	2.1	0.3	1.2	-3.1	-4.1	1.3	3.0	Delta Z
T11/T12	-1.3	1.0	2.5	0.5	1.4	-3.4	-4.5	1.6	3.5	Delta X
	-1.0	0.8	2.1	0.3	1.1	-2.7	-3.5	1.3	3.0	Delta Z
T12/L1	-1.3	1.0	2.4	0.4	1.3	-2.2	-3.0	1.5	3.4	Delta X
	-1.0	0.8	2.1	0.3	1.1	-1.8	-2.5	1.3	3.0	Delta Z
L1/L2	-1.6	1.2	2.2	0.6	1.6	-1.2	-1.8	1.4	3.2	Delta X
	-1.2	0.9	1.8	0.4	1.3	-1.1	-1.4	1.1	2.6	Delta Z
L2/L3	-1.3	1.0	1.7	0.6	1.4	-0.6	-0.9	1.1	2.4	Delta X
	-1.0	0.9	1.4	0.5	1.2	-0.4	-0.7	0.9	2.0	Delta Z
L3/L4	-0.7	0.5	0.8	0.4	0.8	-0.2	-0.4	0.6	1.3	Delta X
	-0.5	0.4	0.6	0.3	0.6	-0.2	-0.2	0.5	1.0	Delta Z
L4/L5	-0.3	0.1	0.2	0.2	0.2	-0.1	-0.1	0.2	0.4	Delta X
	-0.1	0.2	0.2	0.2	0.2	0.0	0.0	0.2	0.3	Delta Z
L5/S1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Delta X
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Delta Z

APPENDIX 17
DIFFERENCES (MM) BETWEEN INTERSPACES FOR THE JOHN2 MODEL 20 DEGREES EXTENSION

INTER-	DISTRIBUTION NUMBER									
SPACE	2	3	4	5	6	7	8	9	10	DIFF.
T5/T6	-2.5	1.9	4.4	0.8	2.6	-9.1	-14.3	2.8	6.3	Delta X
	-2.2	1.8	4.6	0.6	2.4	-8.2	-12.0	2.8	6.7	Delta Z
T6/T7	-2.5	1.9	4.4	0.8	2.6	-9.1	-14.3	2.8	6.3	Delta X
	-2.1	1.8	4.7	0.7	2.5	-8.1	-11.9	2.9	6.7	Delta Z
T7/T8	-2.5	1.9	4.4	0.8	2.6	-9.1	-14.0	2.8	6.3	Delta X
	-2.1	1.8	4.7	0.7	2.5	-8.1	-11.8	2.9	6.7	Delta Z
T8/T9	-3.1	2.0	4.5	0.9	2.7	-9.0	-13.2	2.9	6.4	Delta X
	-2.2	1.8	4.7	0.7	2.4	-8.2	-11.4	2.8	6.7	Delta Z
T9/T10	-2.5	1.9	4.5	0.9	2.6	-8.6	-12.0	2.8	6.4	Delta X
	-2.2	1.8	4.6	0.7	2.4	-7.9	-10.7	2.8	6.7	Delta Z
T10/T11	-2.4	1.9	4.5	0.9	2.6	-7.7	-10.5	2.8	6.4	Delta X
	-2.1	1.8	4.7	0.7	2.5	-7.2	-9.6	2.9	6.7	Delta Z
T11/T12	-2.5	1.9	4.5	0.8	2.6	-6.1	-8.2	2.8	6.3	Delta X
	-2.1	1.9	4.7	0.8	2.5	-6.0	-7.9	2.9	6.8	Delta Z
T12/L1	-2.5	1.9	4.4	0.8	2.6	-3.8	-5.4	2.8	6.3	Delta X
	-2.2	1.8	4.6	0.6	2.4	-4.1	-5.6	2.8	6.7	Delta Z
L1/L2	-2.8	2.1	4.0	1.1	2.9	-2.3	-3.4	2.5	5.7	Delta X
	-2.6	2.1	4.1	1.0	2.9	-2.2	-3.3	2.5	5.9	Delta Z
L2/L3	-2.5	1.9	3.1	1.0	2.6	-1.1	-1.8	2.0	4.4	Delta X
	-2.2	1.8	3.0	1.0	2.5	-1.0	-1.7	1.9	4.4	Delta Z
L3/L4	-1.2	1.0	1.6	0.8	1.6	-0.3	-0.7	1.3	2.5	Delta X
	-1.0	0.8	1.4	0.7	1.4	-0.3	-0.6	1.1	2.3	Delta Z
L4/L5	-0.4	0.3	0.6	0.4	0.5	0.0	-0.2	0.6	0.8	Delta X
	-0.4	0.2	0.4	0.3	0.3	-0.1	-0.2	0.4	0.6	Delta Z
L5/S1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Delta X
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Delta Z

APPENDIX 18
DIFFERENCES (MM) BETWEEN INTERSPACES FOR THE JOHN2 MODEL 30 DEGREES EXTENSION

INTER-SPACE	DISTRIBUTION NUMBER 2	3	4	5	6	7	8	9	10	DIFF.
T5/T6	-3.5	2.7	6.0	1.3	3.7	-11.8	-18.8	3.8	8.5	Delta X
	-3.5	2.9	7.6	1.0	3.9	-13.9	-20.6	4.6	10.9	Delta Z
T6/T7	-3.6	2.6	5.9	1.2	3.6	-11.9	-18.9	3.8	8.4	Delta X
	-3.4	2.9	7.6	1.1	4.0	-13.9	-20.6	4.6	10.9	Delta Z
T7/T8	-3.6	2.6	5.9	1.2	3.6	-11.9	-18.5	3.8	8.4	Delta X
	-3.5	2.9	7.6	1.0	3.9	-13.9	-20.3	4.6	10.9	Delta Z
T8/T9	-3.6	2.6	5.9	1.3	3.6	-11.9	-17.5	3.8	8.4	Delta X
	-3.4	2.9	7.6	1.1	4.0	-13.9	-19.4	4.6	10.9	Delta Z
T9/T10	-3.5	2.7	6.0	1.2	3.6	-11.3	-16.0	3.8	8.4	Delta X
	-3.4	2.9	7.6	1.1	4.0	-13.4	-18.1	4.6	10.9	Delta Z
T10/T11	-3.6	2.6	5.9	1.2	3.6	-10.2	-13.9	3.8	8.4	Delta X
	-3.4	2.9	7.6	1.0	3.9	-12.3	-16.2	4.6	10.9	Delta Z
T11/T12	-3.5	2.7	6.0	1.3	3.7	-8.0	-10.9	3.8	8.4	Delta X
	-3.4	2.9	7.6	1.1	4.0	-10.2	-13.3	4.6	10.9	Delta Z
T12/L1	-3.5	2.7	6.0	1.3	3.7	-5.0	-7.1	3.9	8.5	Delta X
	-3.5	2.9	7.5	1.0	3.9	-6.8	-9.2	4.5	10.9	Delta Z
L1/L2	-3.9	3.0	5.5	1.6	4.1	-3.0	-4.6	3.5	7.7	Delta X
	-4.1	3.4	6.7	1.7	4.7	-3.6	-5.3	4.0	9.6	Delta Z
L2/L3	-3.4	2.6	4.3	1.5	3.6	-1.5	-2.5	2.8	6.1	Delta X
	-3.5	2.9	4.9	1.5	4.0	-1.7	-2.7	3.0	7.1	Delta Z
L3/L4	-1.8	1.3	2.2	1.1	2.2	-0.5	-1.1	1.8	3.5	Delta X
	-1.6	1.3	2.2	1.1	2.2	-0.5	-1.0	1.8	3.7	Delta Z
L4/L5	-0.5	0.5	0.8	0.6	0.7	0.0	-0.2	0.8	1.2	Delta X
	-0.5	0.5	0.7	0.5	0.6	0.0	-0.2	0.7	1.0	Delta Z
L5/S1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Delta X
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Delta Z

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