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TWO-DIMENSIONAL DRAFTING TEMPLATE AND THREE-DIMENSIONAL COMPUTER MODEL REPRESENTING THE AVERAGE ADULT MALE IN AUTOMOTIVE SEATED POSTURES

presented by

Neil James Bush

has been accepted towards fulfillment of the requirements for

Masters degree in Mechanics

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TWO-DIMENSIONAL DRAFTING TEMPLATE AND THREE-DIMENSIONAL COMPUTER MODEL REPRESENTING THE AVERAGE ADULT MALE IN AUTOMOTIVE SEATED POSTURES

By

Neil James Bush

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for the degree of

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ABSTRACT

TWO-DIMENSIONAL DRAFTING TEMPLATE AND THREE-DIMENSIONAL COMPUTER MODEL REPRESENTING THE AVERAGE ADULT MALE IN AUTOMOTIVE SEATED POSTURES

By

Neil James Bush

A growing interest for automobile customers is the comfort of the seats in their cars. The automotive seats should fit the body shapes of people and move the way people move in seated postures.

This thesis describes the development of a template (JOHN 2-D) that represents the skeletal framework of the human body for the average adult male in seated postures. JOHN 2-D represents the body with a skull, thorax, pelvis and a gear system to represent the cervical and lumbar segments of the spine. JOHN 2-D moves the thorax relative to the pelvis with lumbar articulation and moves the skull relative to the thorax with cervical spine articulation.

The torso of the average adult male was investigated to develop a representative outer body surface of the back of an occupant in an automobile seat. This outer body surface was created on a three-dimensional computer model (JOHN 3-D) of the human skeleton. The vertebral column and back muscles were added to the skeleton and then a skin layer was created over the back surface of the model. A motion program was developed to locate JOHN 3-D in different body postures. Then a skin was created for the model in these postures.

It was concluded that the work presented in this thesis can be used to compare existing automotive seat designs with human body postures and develop new seat designs to better fit the average adult male body.

DEDICATION

To my parents for their guidance and support in everything that I have ever set out to do. To my fiancee who gave me the inspiration to obtain this goal because without her it would not have been a goal at all.

Thank you Tamara

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1. BACKGROUND AND OBJECTIVES

Automotive seat design is an important concern for both the automotive companies and the automotive consumers. A key factor involved in seat design is comfort, and the automotive seats should be developed with that in mind. For a comfortable seat, it is essential that the seat contour fits people and allows them to change to a position compatible with the geometry of their bodies and their movements. Human accommodation is important in the design process, therefore, it is essential that the human body be well represented as an anatomical structure.

Common practice in the automotive industry has been to design seats using the tools developed by the Society of Automotive Engineers (SAE) [1]. SAE developed a two-dimensional (2-D) drafting template and a three-dimensional (3-D) seat testing device (H-point machine) to represent the average adult male torso. The 2-D template and 3-D testing device are shown in Figure 1 and Figure 2, respectively. These tools were originally intended only to ensure consistent positioning of the occupant in the vehicle. They were not originally intended to be an anatomical guide.

The 2-D SAE template is used as the starting point for automotive seating design lay-out. The template locates the torso in the seat with two descriptive parameters:

1. H-point (intended by SAE to represent the location of the center of rotation of the hip joint)
2. Seat Back Angle (SBA) measured from vertical to a line on the torso.

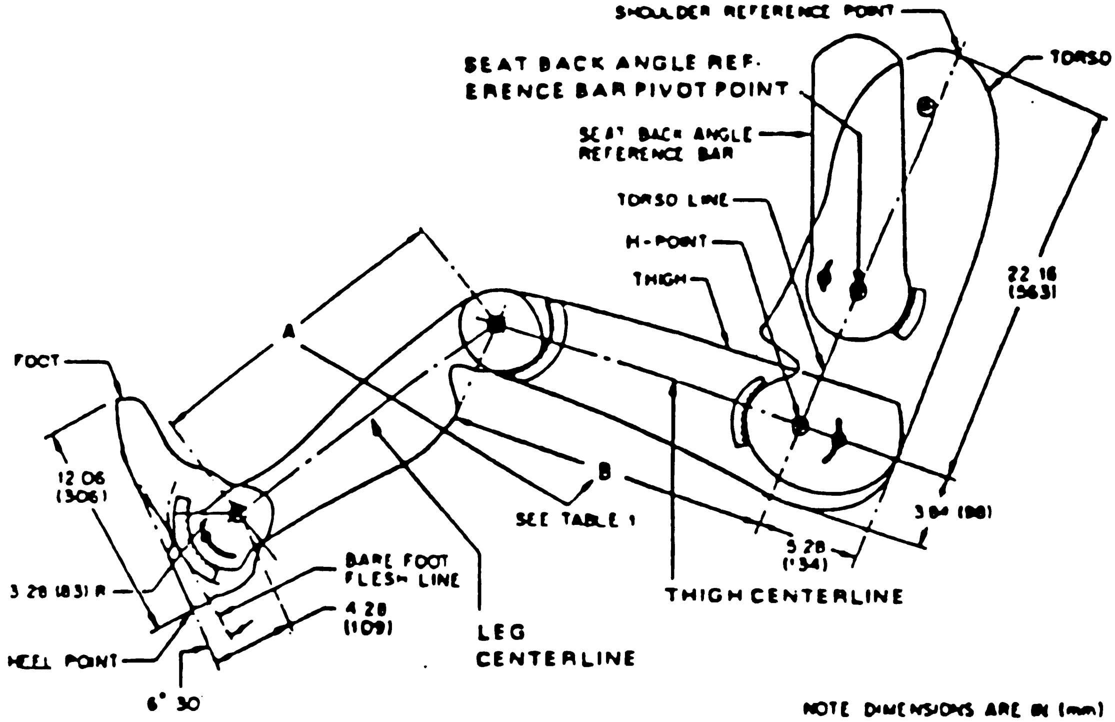


FIGURE 1: THE SAE 2-D DRAFTING TEMPLATE

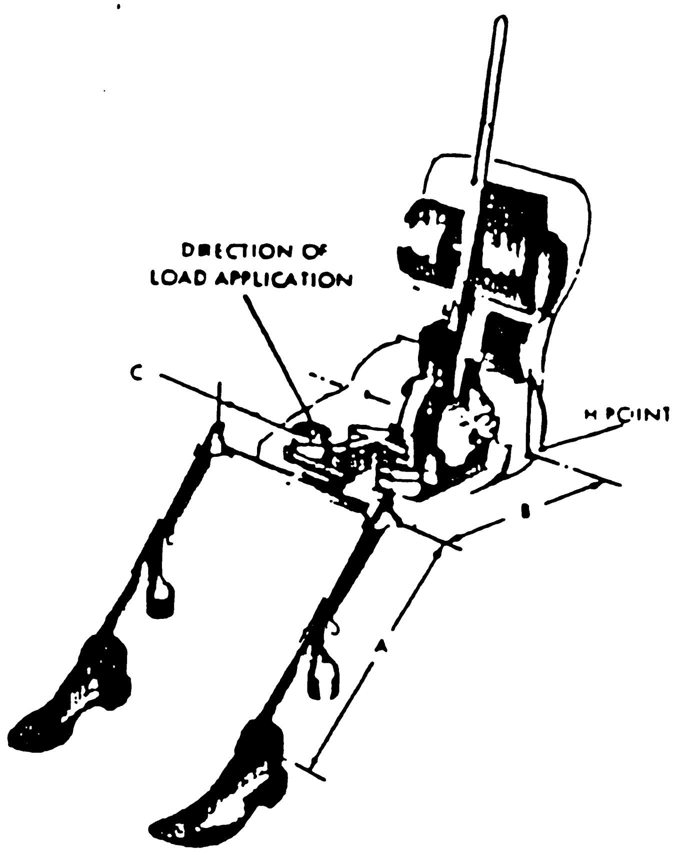


FIGURE 2: THE SAE 3-D H-POINT MACHINE

The specifications of H-point and SBA are set by the interior package design; these parameters are typically used for locating the occupant in the vehicle. Next the seat designer positions the 2-D template in the design position and then designs the seat around the template. Quite often the actual deflected seat contour is taken directly from the 2-D template.

This design procedure relies on the template for the comfort and positioning of the occupant. The SAE 2-D template is constructed to pivot the torso about one point, the H-point; this configuration does not account for motions of the pelvis and lumbar curvature. The SAE 2-D template locates the occupant with a flat back in a slumped posture. The slumped posture occurs when the lumbar spine is straight or bent into a kyphotic, convex curve as opposed to an erect posture where the lumbar spine is in a lordotic, concave curve. The lumbar spine curve is lordotic when the body is in a standing posture. Chaffin and Anderson [2] say that a posture with the lumbar spine curved in a lordotic manner can reduce lumbar spinal disc pressure. This disc pressure can cause discomfort.

The 3-D SAE H-point machine is similar in configuration to the 2-D template in that the torso pivots solely about the H-point and the lumbar region is flat. This H-point machine is used in automotive seats to measure the location of the H-point and SBA for comparison with the designed location. Seats have been designed with side and lumbar supports to attempt to accommodate the occupant in a comfortable position. When the H-point machine is used to test a highly contoured seat with side and lumbar support it often locates the H-point and reads the SBA at different values than were designed. This conflict in measurements occurs because the one piece torso design of the SAE 2-D template and the 3-D H-point machine do not articulate like the human pelvis, rib cage and spinal column. There are two reasons for this:

1. With the H-point held in the correct position, the thorax rotates forward at the top. This results in a smaller Seat Back Angle than was predicted by the SAE 2-D template.
2. With the SBA set at the design value, the H-point is pushed further forward in the seat by the lumbar support than was predicted by the SAE 2-D template.

This testing could result in a incorrect design because there currently is no way to represent and accommodate people in the design process.

By developing models that accurately represent the geometry of the body and allow for posture change, improvements can be made in the design of automotive seats. The design standards that guide seat design could be reevaluated, then seats could be designed to support the body more comfortably.

An extensive study on human anthropometry in automotive seats has been completed by the University of Michigan Transportation Institute (UM-TRI) [3]. This study developed a 3-D set of data points taken from human test subjects in a relaxed seated position. Each data point represents an anatomical landmark or a digitized position taken from a casting made on the seat surface. The points were averaged, then used with a study by Snyder et al. (Link Study)[4] to locate the position of the bones which could not be palpated. This resulted in a representation of the skeletal positions of the seated occupant. With this information, UM-TRI [3] assembled full scale drawings, and molded body forms which represent the 50th and 95th percentile adult male and the 5th percentile adult female. The 50th percentile male is shown in Figure 3.

A 2-D computer model which incorporated the UM-TRI [3] data for the 50th percentile adult male was developed by Haas [5]. This model represented the human body with three rigid segments, the skull, thorax and pelvis connected by two flexible links, the neck and lumbar regions. The work done by Haas

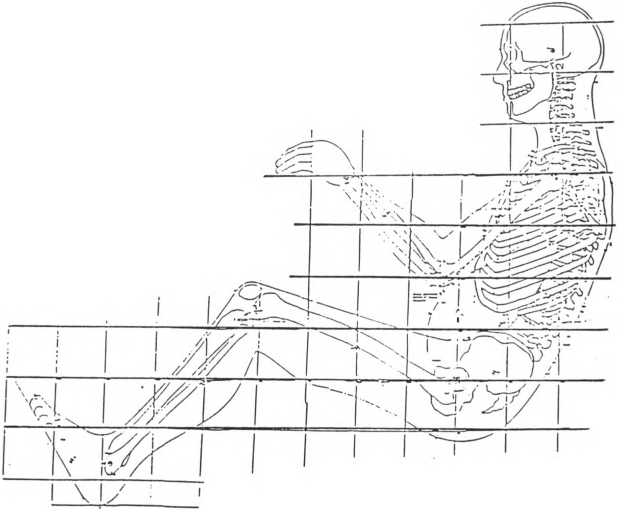


FIGURE 3: UM-TRI DRAWING 50TH PERCENTILE ADULT MALE

determined that the pelvis represented in the UM-TRI study was not in the correct location. The result of the Haas investigation [5] was to lower the pelvis and lengthen the lumbar spine leaving the thorax and skull in the original positions. Figure 4 shows the 2-D computer model. This model was used with a computer program which moves the thorax relative to the pelvis with lumbar articulation. The program rotates the thorax about each of the six lumbar joint centers. Haas examined different spine rotation distributions to compare with a uniform rotation about each of the lumbar joint centers. The distributions by White and Panjabi [6] and Allbrook [7] measured spinal motions with vertebral pairs. Haas also studied idealized distributions with twice as much joint motion in the upper part or in the lower part of the lumbar spine and some alternatives with motions in the thoracic spine. Haas determined that uniform rotation about each of the lumbar joint centers and no rotation in the thoracic region could be used to locate the thorax relative to the pelvis. Figure 5 illustrates the 2-D model and its motion as presented by Haas.

Further work has been done by Boughner [8] to develop a 3-D computer model of the 50th percentile human skeleton. This research used the information from UM-TRI [3] and other literature [8,9,10] to construct solid models of the human bone structure. The 3-D model is shown in Figure 6. In addition to modeling the 3-D skeleton, Boughner analyzed different methods of modeling muscle shapes and hamstring muscle length.

The objectives of this thesis are to continue to work with the 2-D and 3-D models and progress toward usable tools for representing the human body. More specifically the objectives of this thesis are to:

(1) Develop an articulated 2-D template that can be used as a physical representation of the 2-D computer model.

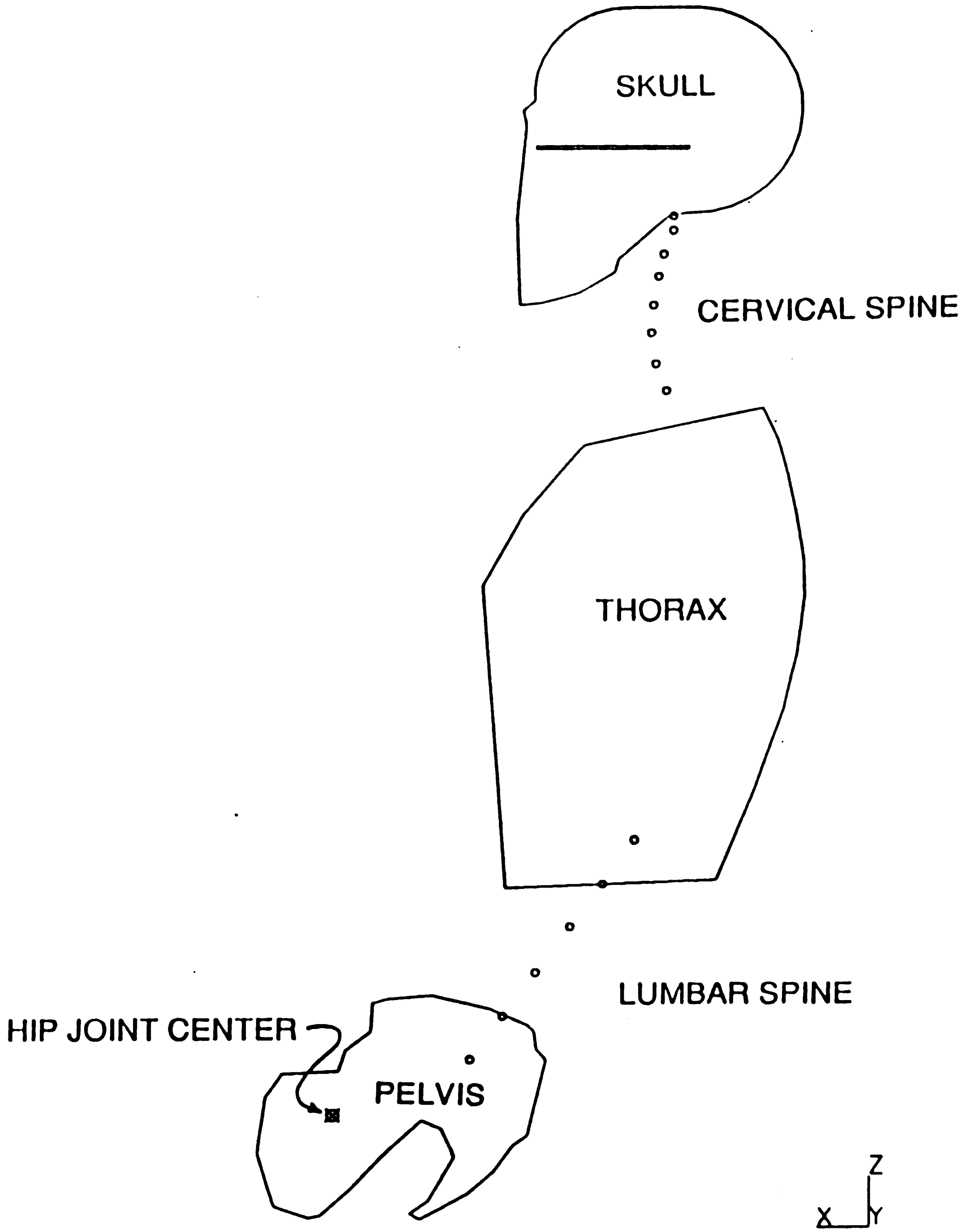


FIGURE 4: 2-D COMPUTER MODEL

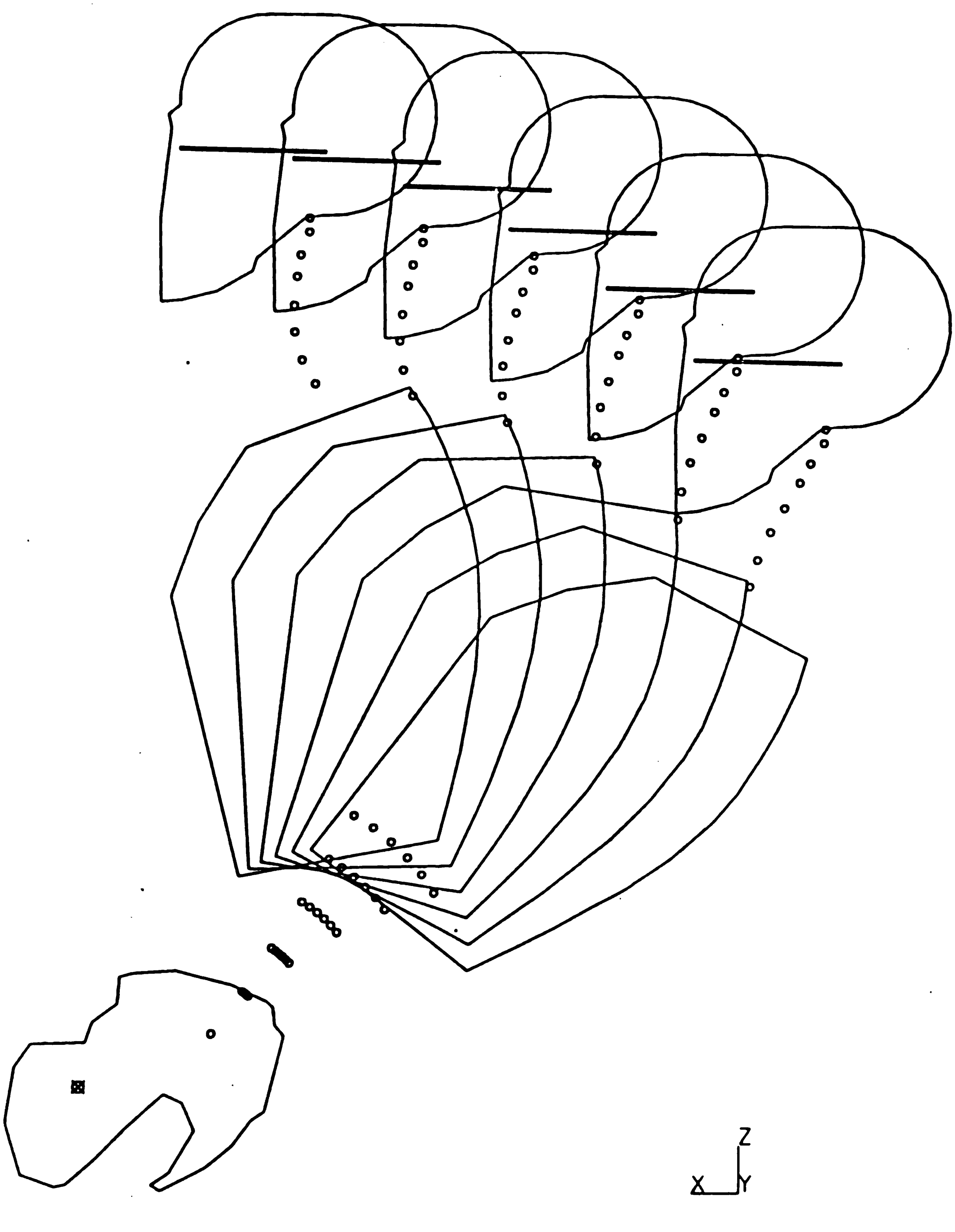


FIGURE 5: 2-D COMPUTER MODEL WITH LUMBAR MOTION

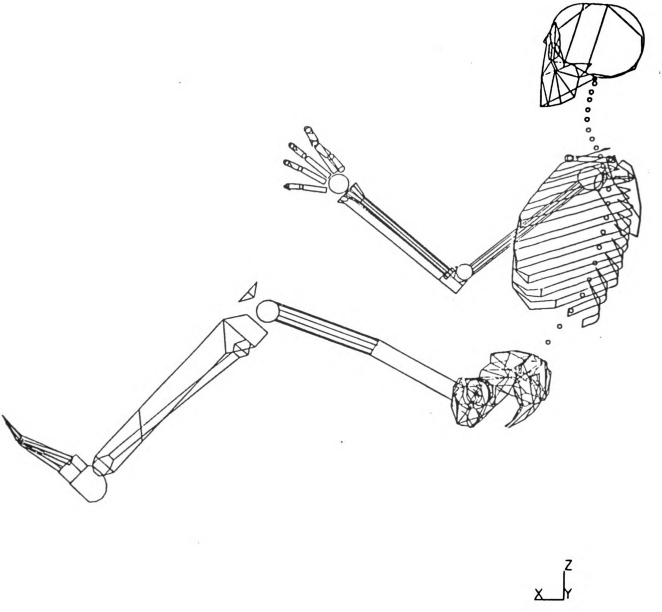


FIGURE 6: 3-D SKELETAL COMPUTER MODEL

(2) Further develop the 3-D model by adding components to better represent the thoracic region (vertebrae, muscles and skin) and project outer body contours.

(3) Develop motion programs for the 3-D model including the back contours at different postural positions.

This thesis is structured into two sections: one devoted to the 2-D template and its development and usage and the second devoted to the 3-D model improvement and usage.

2. ARTICULATED 2-D TEMPLATE

2.1 Introduction

Automotive seats should be designed to comfortably accommodate the occupant in the vehicle. The seat must be designed to fit a range of human sizes and a range of positions representative of the human skeletal motion. Studies have been completed on the geometry of the body in seated positions, but unfortunately this data has not been implemented into automotive seat development. Computer aided design is commonly used to design automotive seats, yet many automotive seat designs today are developed on drafting tables. The designers need accurate up-to-date tools. It is the intention of this study to develop a drafting template that represents the pelvis, thorax and head for the 50th percentile adult male and articulates according to the movement of the human skeleton.

The two-dimensional template was created using the computer model (JOHN 2-D) developed by Haas [5]. JOHN 2-D is a two-dimensional representation of the position and articulation of the pelvis, thorax, skull and spinal column for a 50th percentile adult male. The reference posture for the JOHN 2-D model has a straight lumbar spine. This initial posture was adopted from the UM-TRI study [3] and then compared to additional studies that were available [12,13,14]. The position of the pelvis was determined by the angle from vertical to the line going from the Pubic Sympysis to the midpoint between the right and left Anterior Superior Iliac Spine (ASIS) when viewed from the side; for the initial position this angle is equal to 54°. The thorax location is determined by the angle between the line going through the Suprasternale and the Substernale and the vertical plane; this angle was equal to 38° for the initial posture. Haas [5] determined that the initial posture with the UM-TRI pelvic and thoracic angles should be used for JOHN 2-D. There are four important variables involved in positioning the JOHN 2-D model:

1. Hip Joint Center (HJC) - location of the centers of the right and left hip joints in the pelvis.
2. Total Lumbar Curvature (TLC) - measurement of lumbar spine curvature defined as pelvic rotation minus thoracic rotation. Pelvic and thoracic rotations are about an axis parallel to the positive going, left lateral Y-axis and are positive according to the right hand rule. TLC=0° corresponds to a straight lumbar spine.
3. Torso Recline Angle (TRA) - angle measured from vertical of the line going through the top and bottom lumbar joint centers.
4. Head Rotation Angle (HRA) - angle measured between the eye-line and the horizontal plane. The eye-line is a line, developed by Hubbard and McLeod [15], going from the pupil of the eye rearward parallel to the frankfort plane which is level when looking forward.

Figure 7 shows JOHN 2-D and each of these variables along with the coordinate system set up by Haas [5].

2.2 Methods

The 2-D, side view geometry and spine articulation for JOHN 2-D was developed by Haas [5]. It was this information that led to the development of a template that could be used to represent the same information with hands-on capabilities.

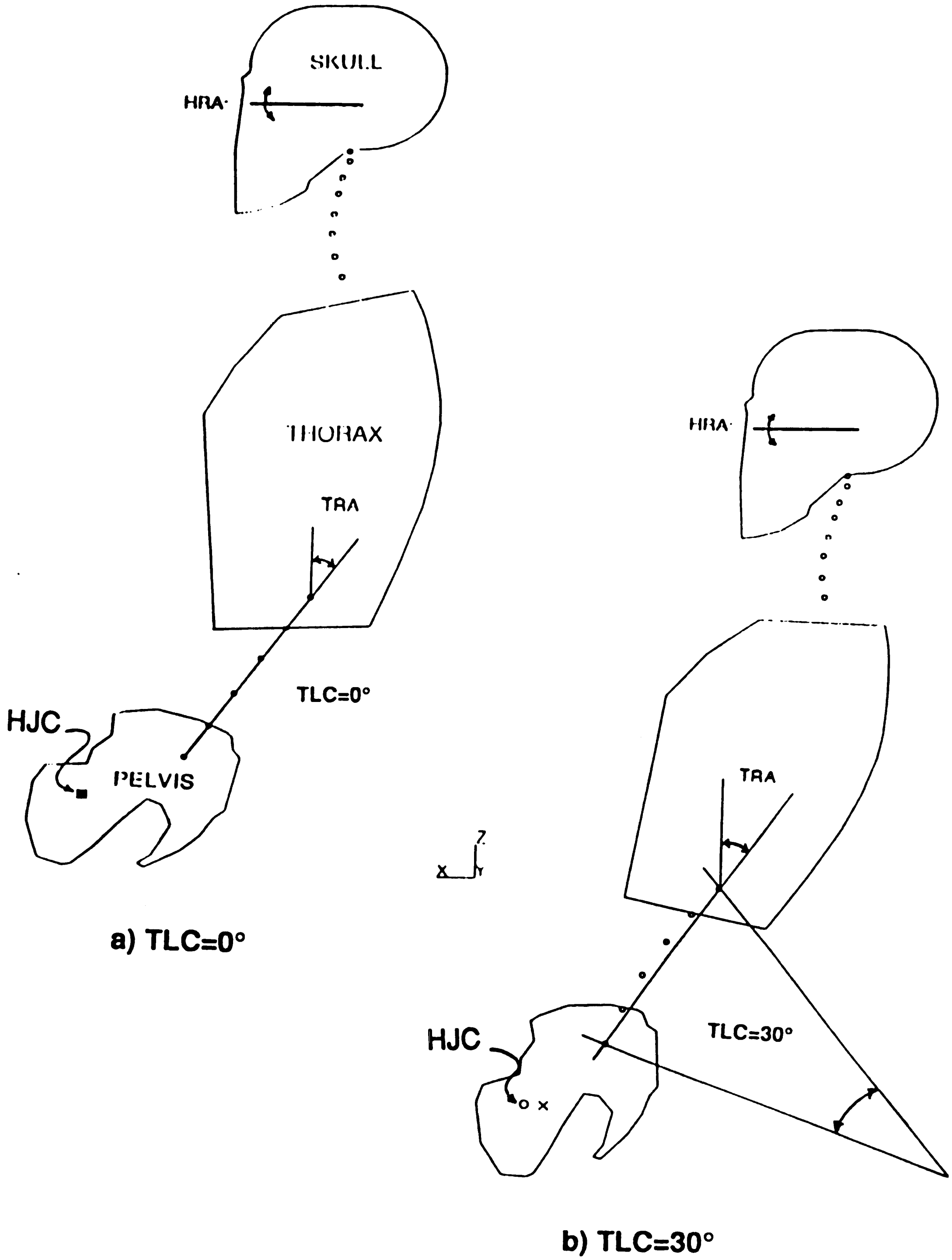


FIGURE 7: JOHN 2-D COMPUTER MODEL

a) TLC=0° b) TLC=30°

2.2.1 Lumbar Linkage

With the pelvis held stationary, the computer model was examined for a range of lumbar motion. It was then determined that the path of the top lumbar joint center (T12/L1) followed a 183 mm radius about the bottom lumbar joint center (L5/S1). This measurement was taken at -10 and 40 degrees of lumbar curvature with a deviation of 1 mm found for the full range of motion. Figure 8 shows JOHN 2-D for the range of lumbar motion and the radius measurements. Because of this common distance, one bar could be used to connect the thorax to the pelvis. This bar was designed to attach the thorax at the top lumbar vertebral joint (T12/L1) to the pelvis at the bottom lumbar vertebral joint (L5/S1) with a shoulder bolt at each position to permit smooth rotation about these points.

2.2.2 Body Components

The template was designed with three body components: the skull, rib cage and pelvis. Each component was designed with the same shape and dimensions as 2-D computer model Haas [5] developed. The skull, rib cage and pelvis were cut out of 1/4 inch Plexiglass.

2.2.3 Sprocket Articulation

The lumbar curvature for JOHN 2-D was developed using uniform rotation about each of the lumbar joint centers. This rotates both the thorax and pelvis an amount equal to one half TLC. Because of the assumption that each of the lumbar vertebrae are the same size, the joint centers were equally spaced along the vertebral column. With these two conditions, a two sprocket system was developed with a chain connecting the two together. The sprockets were the same size due to the uniform motion and spacing of the joint centers.

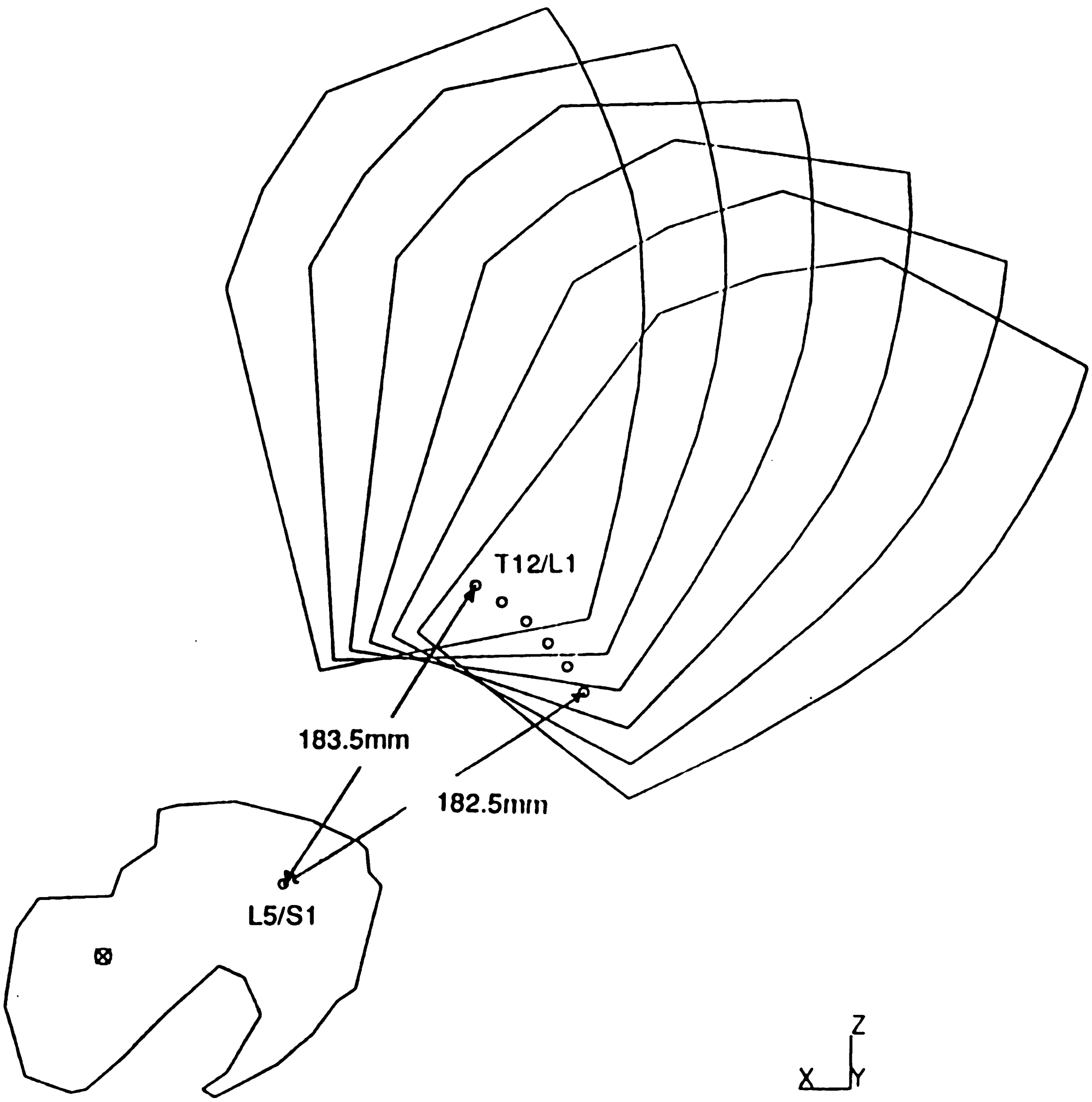


FIGURE 8: JOHN 2-D FOR A RANGE OF LUMBAR MOTION

The sprockets were made of anodized aluminum and had a pitch diameter of 1.6 inches. One sprocket was positioned at the top lumbar joint center and was attached rigidly to the thorax; the other was positioned at the bottom lumbar joint center and was attached rigidly to the pelvis. A flexible chain was used to connect the two sprockets, and the chain was twisted to create an equal rotation in opposite directions. Figure 9 shows the sprocket and chain system used for JOHN 2-D. The chain has a configuration similar to a ladder with evenly distributed rungs connecting the sides. The chain was made of polyurethane with cable reinforcement for strength; this type was selected because of its flexibility and its minimal backlash characteristics. The chain was cut to the correct length, determined by the distance between the sprockets and the diameter of the sprockets, and then spliced together to form a continuous chain. Figure 10 illustrates the sprocket and chain used for the JOHN 2-D template. The bar was connected to the gears and bodies with shoulder bolts which allowed smooth rotation. Wing nuts then tighten to lock the template in at the desired positions.

2.2.4 Cervical Linkage

The linkage between the skull and thorax was also represented with a one bar linkage. The vertebrae of the cervical spine as represented by UM-TRI [3] were not of uniform size; the upper vertebrae are shorter. A motion pattern was developed by Haas [5] for uniform rotation at each cervical joint. However, this cervical motion pattern has not been validated against measured neck motions. It was determined that because of the size difference between each vertebrae the cervical spine orientation could be represented with a 1 to 1.12 ratio of rotation, thus, the template was constructed with a small sprocket (1.6 inch pitch diameter) fixed to the skull at the top cervical vertebral joint and a large sprocket

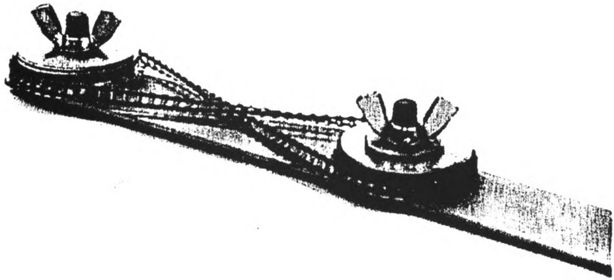
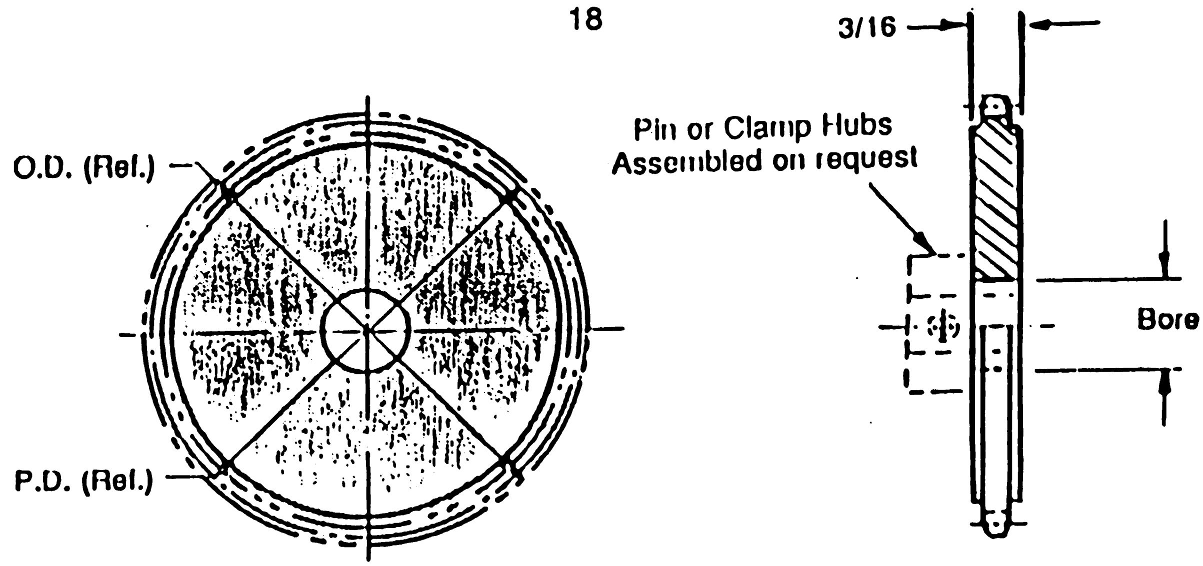
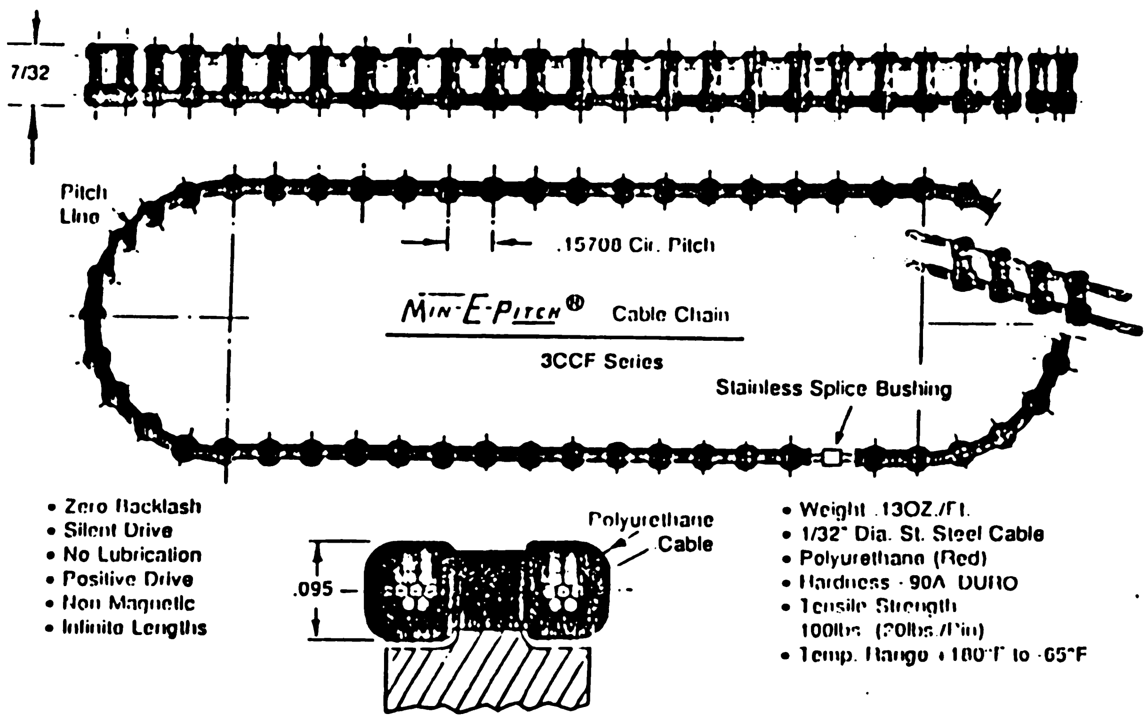


FIGURE 9: SPROCKET AND CHAIN SYSTEM



a) SPROCKET



b) CHAIN

FIGURE 10: a) ANODIZED ALUMINUM SPROCKET b) FLEXIBLE CHAIN

(1.8 inch pitch diameter) fixed to the thorax at bottom cervical vertebral joint. The chain used for the cervical linkage was the same as that described above for the lumbar linkage. Again, the chain was twisted to couple the sprockets in opposite directions and with a 1 to 1.12 ratio of rotation.

2.2.5 Spinal Curvature Scale

A guide was developed to indicate the Total Lumbar Curvature (TLC). The bar that connects the thorax to the pelvis was extended up past the top lumbar joint center. Markings were then made on the bar and on the thorax to indicate different values of TLC. The cervical linkage has the same type bar, although at this time there are no markings to locate the amount of cervical curvature. The head was simply positioned with the eye line horizontal for this part of the study. Figure 11 is a picture of the JOHN 2-D template.

2.2.6 Three Link System

The one link system described in section 2.2.3 does not curve during rotation like the actual lumbar spine. Consequently a second linkage system was studied, one that would locate the thorax relative to the pelvis as well as move with a curvature more like the human lumbar spine. A system of three equal length links was built with six sprockets. The three link template is shown in Figure 12. Two sprockets positioned at the same places on the pelvis and thorax, as that for the one link template. Two pairs of additional sprockets were placed between the first two, both attached rigidly to a link between them. Two more sprockets were then positioned on top of the two center gears. The second sprocket down from the T12/L1 joint center was attached rigidly to a link which pivots about the T12/L1 joint. The third sprocket down from the T12/L1 joint center was attached rigidly to a link which pivots about the L5/S1 joint. The

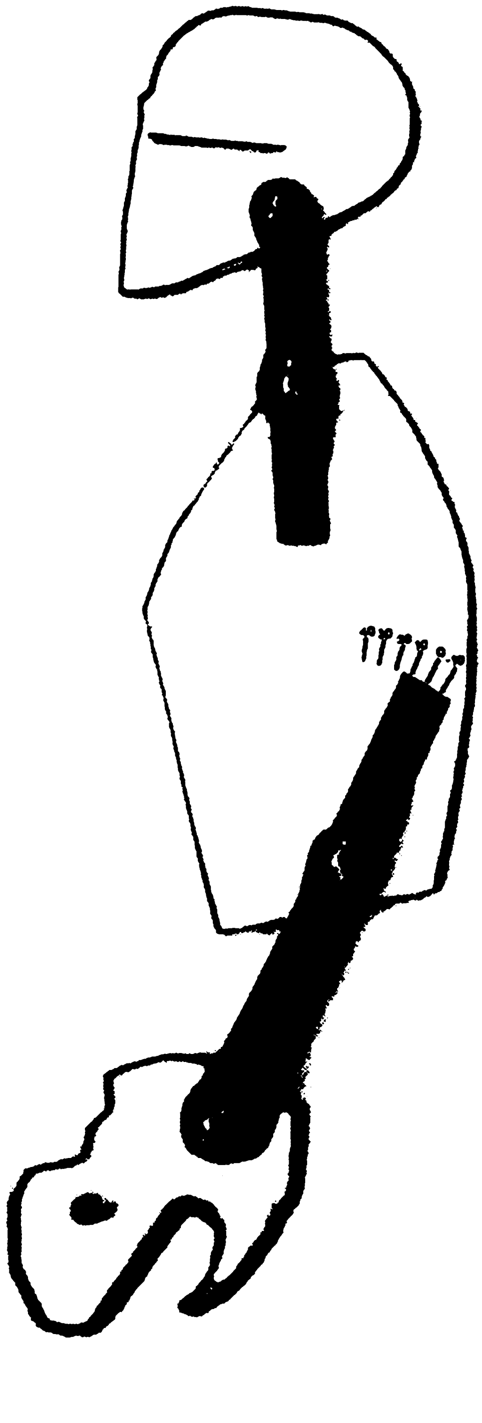


FIGURE 11: THE JOHN 2-D TEMPLATE

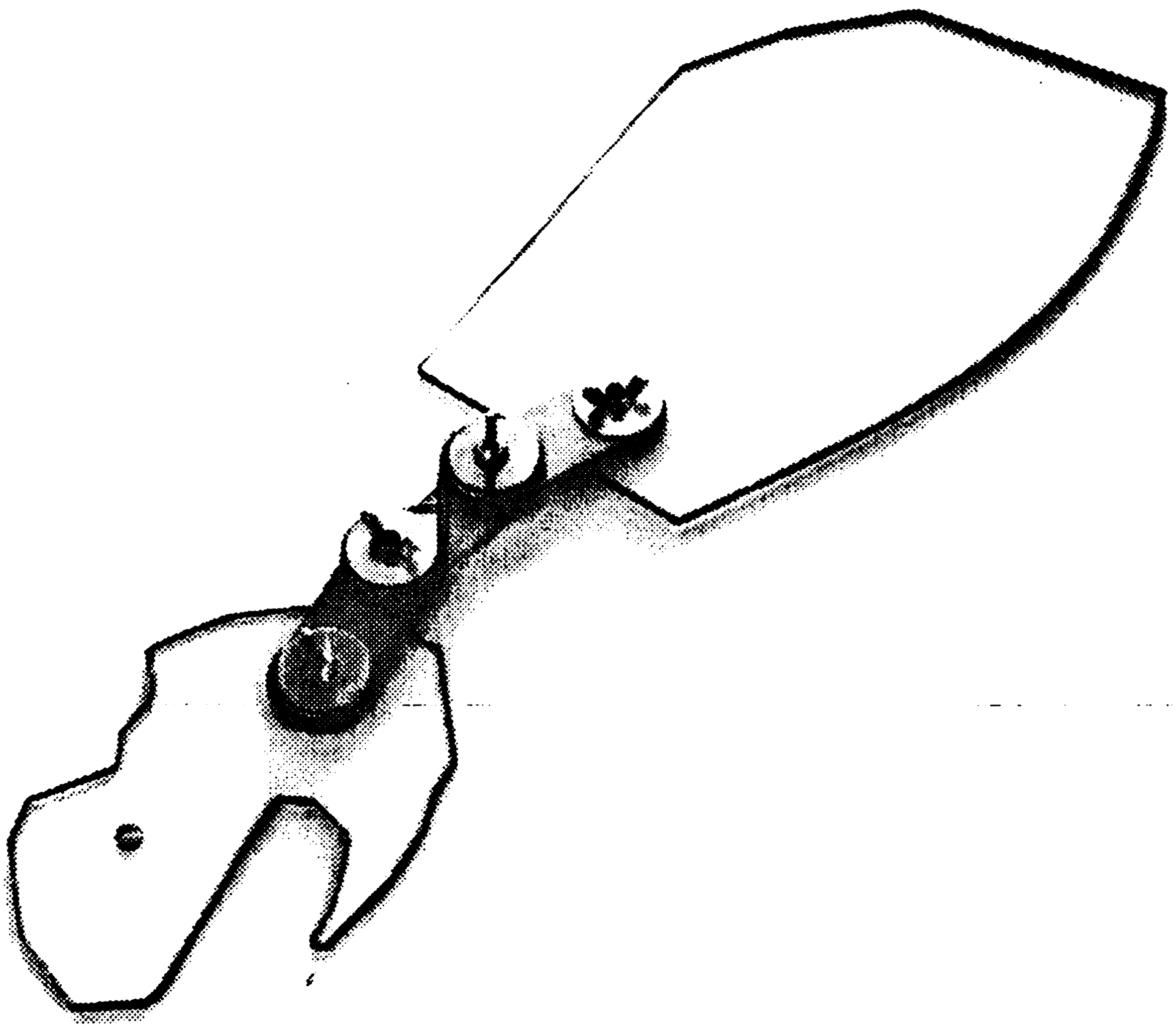


FIGURE 12: THE THREE LINK TEMPLATE

sprocket at T12/L1 was coupled with the bottom sproket at the joint second from the top. The sprocket at L5/S1 was coupled with the bottom sprocket at the joint third from the top. The two top sprockets were coupled together. Sprockets with a pitch diameter of 1.6 inches were used for the three linkage template just as for the lumbar region of the one linkage template. The sprockets were coupled with the same type of chain as that used for the one bar linkage. A twist was made in the chain between each sprocket; this created equal and opposite rotations of each adjacent bar.

2.3 Results and Discussion

2.3.1 Comparing the One Link Template to the Computer Model

The one linkage template moves like the computer model to within 1mm for a range of lumbar curvatures from -10° to 40°. This was determined comparing the template to the drawings made by the computer model at different TLC values and corresponding positions of the rib cage relative to the pelvis. The one linkage template is a simple structure which represents a complex motion of the human bone structure in the seated posture.

2.3.2 Comparing the Three Link Template to the Computer Model

The three link template moved with the curved articulation as was hoped, but it did not have a consistent and accurate movement. With the addition of two additional links and four sprockets, the system was too sloppy and uncontrolled. For a complex system like this to work, a more precise mechanism would be required. Refinement of the three link system was not continued because the one link template functioned very well.

2.3.3 Using JOHN 2-D to Represent Different Body Postures

The JOHN 2-D model can be used to study a range of positions and the relationships between each position. These relationships are representative of human motion in seated postures, and this information can lead to innovative designs when integrated into the design process. The JOHN 2-D template has three degrees of freedom: Total Lumbar Curvature, Torso Recline Angle and Head Rotation Angle. A series of scenarios were examined by changing one of the variables while holding the other two constant. The first scenario was to change the TLC from -10° to 40° of rotation, in increments of 10°, and the TRA and HRA were held constant. Figure 13 illustrates the relationship of the TLC with the TRA fixed at 35°, the HRA fixed at 0° and the pelvis rotated about a line through the right and left ischial tuberosities at the bottom of the pelvis. The model predicts that there is a point that the thorax apparently pivots about in this range of motion.

The next scenario was to change the TRA from 20° to 45°, in increments of 5°, and keep the TLC and HRA constant. Figures 14 and 15 show this relationship with TLC held at either 0° or 30°, respectively, while HRA was held at 0°. In this example, it was assumed that the pelvis rotates about the ischial tuberosities. This situation can be correlated with keeping the occupant in one posture and changing the back angle of the seat.

Finally, the HRA was changed, and both the TLC and TRA were held constant. The HRA was ranged from -10° to 15°, in increments of 5°. The TLC was held at 0° and the TRA at 25°. Figure 16 shows this scenario. The head rotation is an approximate range of motion for the occupant looking at the dashboard to looking at the visor. These different situations can be very useful for the design of automotive seats.

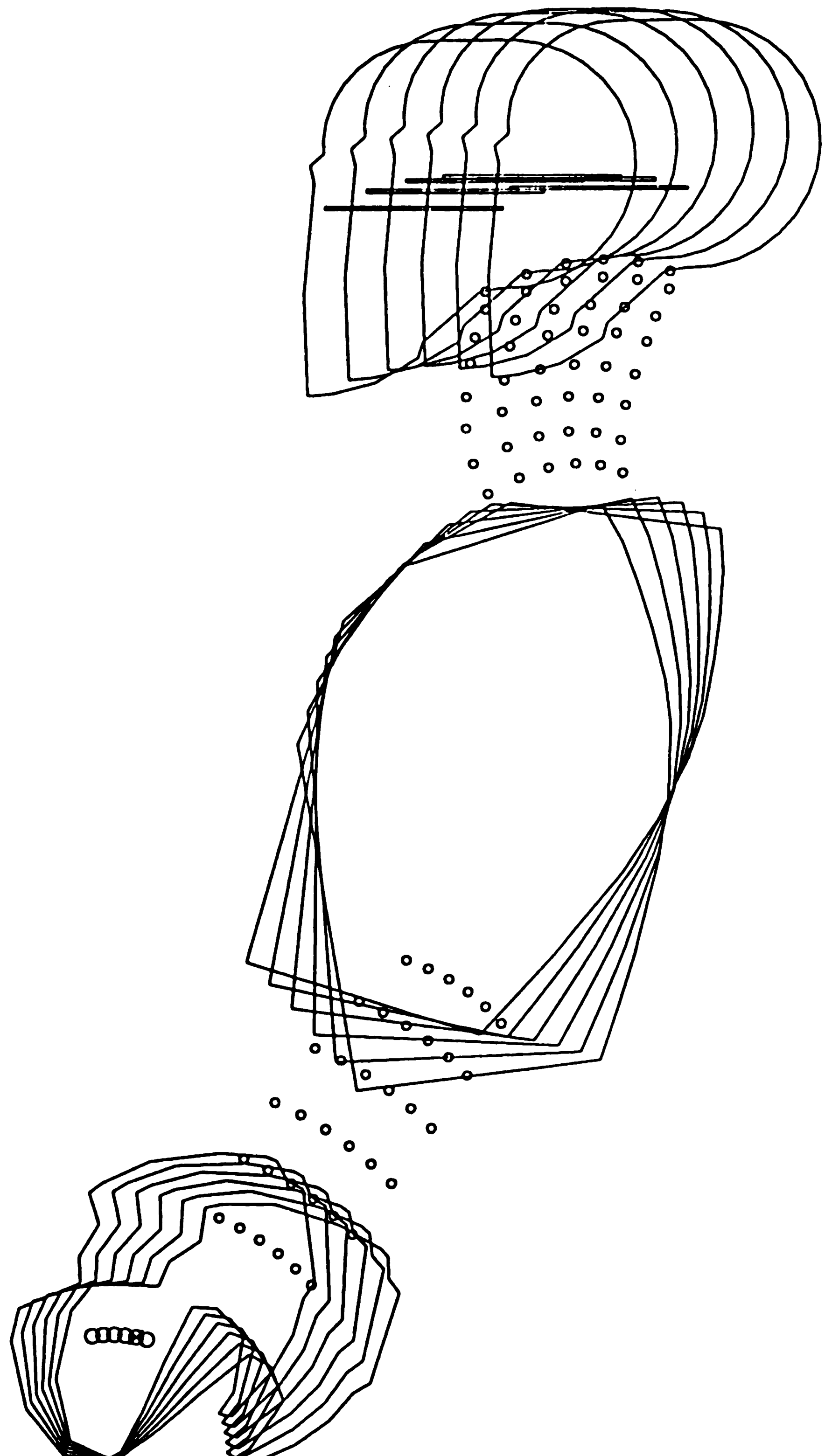


FIGURE 13: JOHN 2-D WITH TLC=-10° to 40°,TRA=35° and HRA=0°

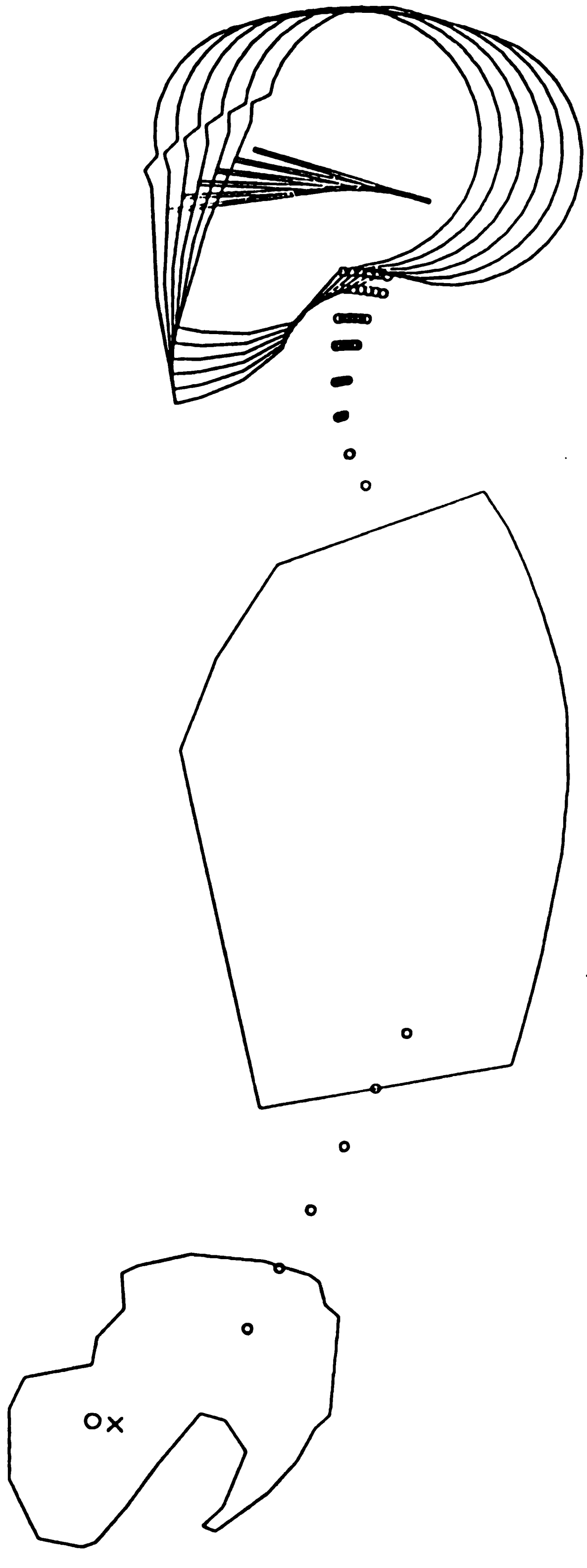


FIGURE 16: JOHN 2-D WITH HRA=-10° to 15°, TLC=0° and TRA=25°

If the seat designer can develop the seat to accommodate each of the positions, then comfort can be achieved, assuming that accommodation of the occupants preference of position is the key to their comfort.

2.3.4 Comparing JOHN 2-D to the SAE Template

The 2-D template will be referred to as JOHN 2-D, like the computer model, for comparison with the SAE template. The SAE tools [1] represent the pelvis as part of the upper leg segment and the torso as a single piece with no lumbar articulation. JOHN 2-D represents the upper leg, pelvis, lumbar and rib cage segments as separate components and JOHN 2-D articulates each component about anatomical joint center locations. For comparison to the SAE 2-D template with SBA=25° JOHN 2-D was subjectively positioned with TLC equal to 10° and TRA equal to 25°. Then JOHN 2-D was given a different posture with TLC equal to 30° and TRA remaining equal to 25°. Figure 17 shows these comparisons. By increasing lumbar curvature, the pelvis rotated forward and upward at the top, and the rib cage rotated forward at the bottom and rearward at the top. Because of the SAE torso representation the SAE template could not represent this change in posture due to lumbar articulation. Comparing the two models: JOHN 2-D has the HJC to compare with the SAE H-point and JOHN 2-D has the TRA to compare with the SAE SBA. JOHN 2-D then has the ability to change the TLC which the SAE template cannot accomplish. With the JOHN 2-D template set in an erect posture, with a lordotic lumbar curvature, it conflicted with the seats designed with the SAE template. This conflict would force the occupant to sit in a slumped posture, with a kyphotic lumbar curvature. To support JOHN 2-D with an erect posture, the automotive seat should move forward at the pelvis, lumbar spine and lower rib cage areas and allow rearward movement of the upper rib cage and shoulders. It is important to note that

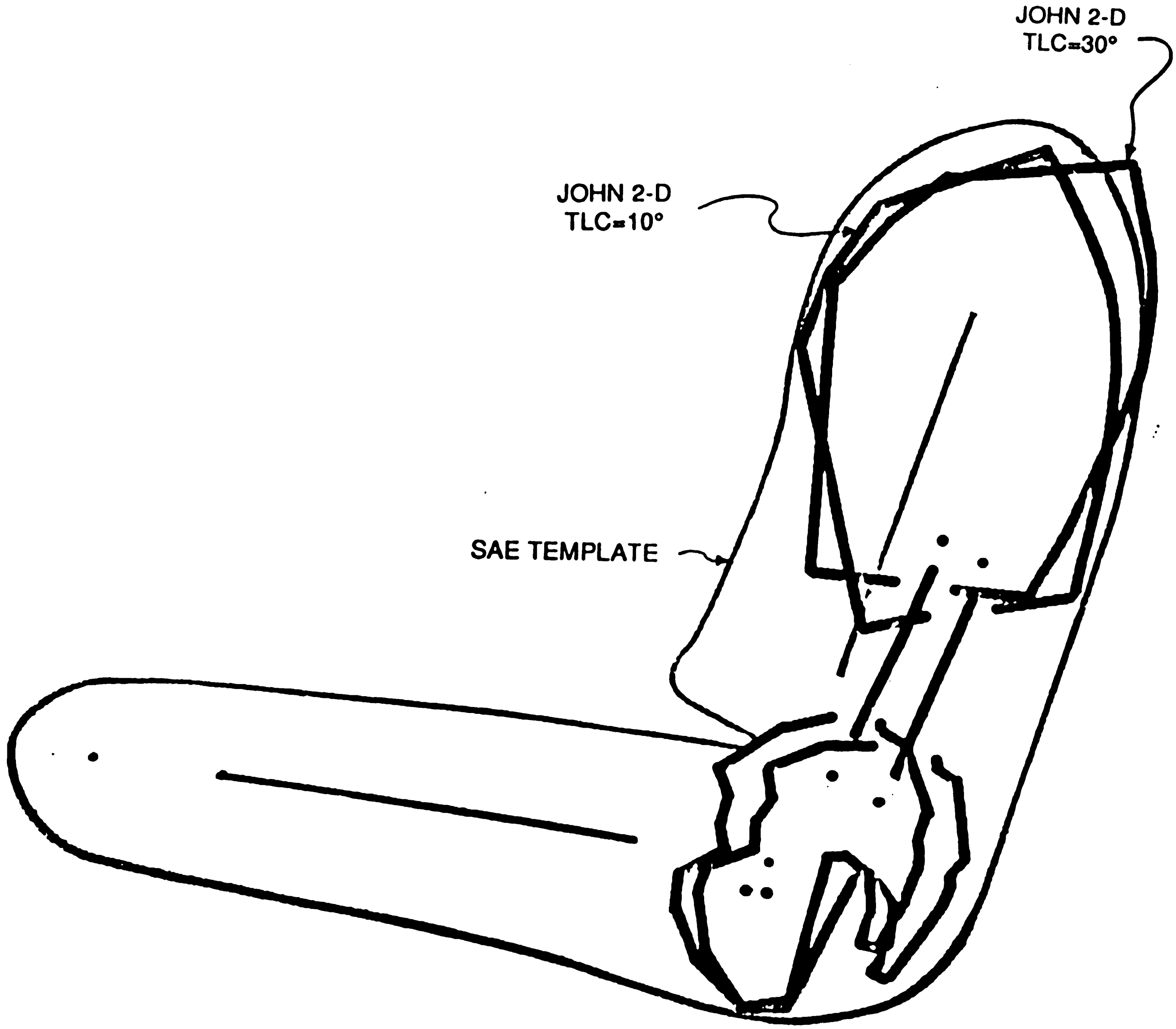


FIGURE 17: COMPARING JOHN 2-D TO THE SAE TEMPLATE

JOHN 2-D can be positioned in the same posture as the SAE template, therefore, it can be used with existing designs. The advantage of the JOHN 2-D template is the lumbar mobility and what it can add to future automotive seat design.

3. 3-D HUMAN OUTER BODY CONTOURS

3.1 Introduction

Automotive seat comfort is dependent directly on the interaction between the seat surface and the outer surface of the person's body who is in that seat. The better the seat and body surfaces fit together the more comfortable the seat will feel to the occupant. When these surfaces do not align correctly, muscle fatigue and body soreness is often the result. A 3-D skeleton has been developed by Boughner [8] to represent the fiftieth percentile adult male. However, the spinal column was only represented as small spheres at the vertebral joint centers as shown in Figure 6. This portion of the thesis is devoted to the continued work on the 3-D skeleton, adding detail in the thoracic and lumbar spines and the development of back surface contours. After developing a detailed skeletal model with muscle groups, a representative skin contour can be generated to fit over the model.

3.2 Methods

3.2.1 Computer System and Software

Each of the components developed to represent the fiftieth percentile adult male was generated using a Hewlett Packard computer system and the SDRC IDEAS software [16]. IDEAS includes a solid modeling package that allows the user to create three-dimensional solid objects, assemble them, and integrate the motions. Each component of the model was developed as a separate object.

These objects were then linked together to anatomically resemble a human fiftieth percentile adult male skeleton (JOHN 3-D).

3.2.2 The Vertebral Column

The lumbar vertebrae were developed by using simple shapes to resemble each vertebrae. Figure 18 illustrates one lumbar vertebrae and its dimensions. The individual vertebrae were made with four pieces, each constructed as objects and then merged together. The vertebral body was first generated as a cylinder with an elliptical cross section. Second, the spinous process was created as a simple six sided object and added to the vertebral body. Finally, the transverse and accessory processes were created as five sided objects and added to the vertebrae. The dimensions used to create the lumbar vertebrae were taken from anatomical sections published by Koritke and Sick [17]. For this thesis, it was assumed that each of the lumbar vertebrae could be represented as one size and each was equally spaced between the lumbar joint centers.

The thoracic vertebral column was assumed to move rigidly with the rib cage. Because of this assumption, the thoracic vertebrae were represented by their spinous processes only. The dimensions for the spinous processes were taken from the UM-TRI study [3]. It was important to correctly represent the most posterior point on each spinous process, but the shape and dimensions had less importance for this model in the thoracic region. Figure 19 shows the thoracic vertebral column. Figure 20 shows JOHN 3-D with the vertebral column.

3.2.3 Muscle Modeling

The back is made up of many muscles which all have a function in maintaining posture when seated. It was important to determine which muscles

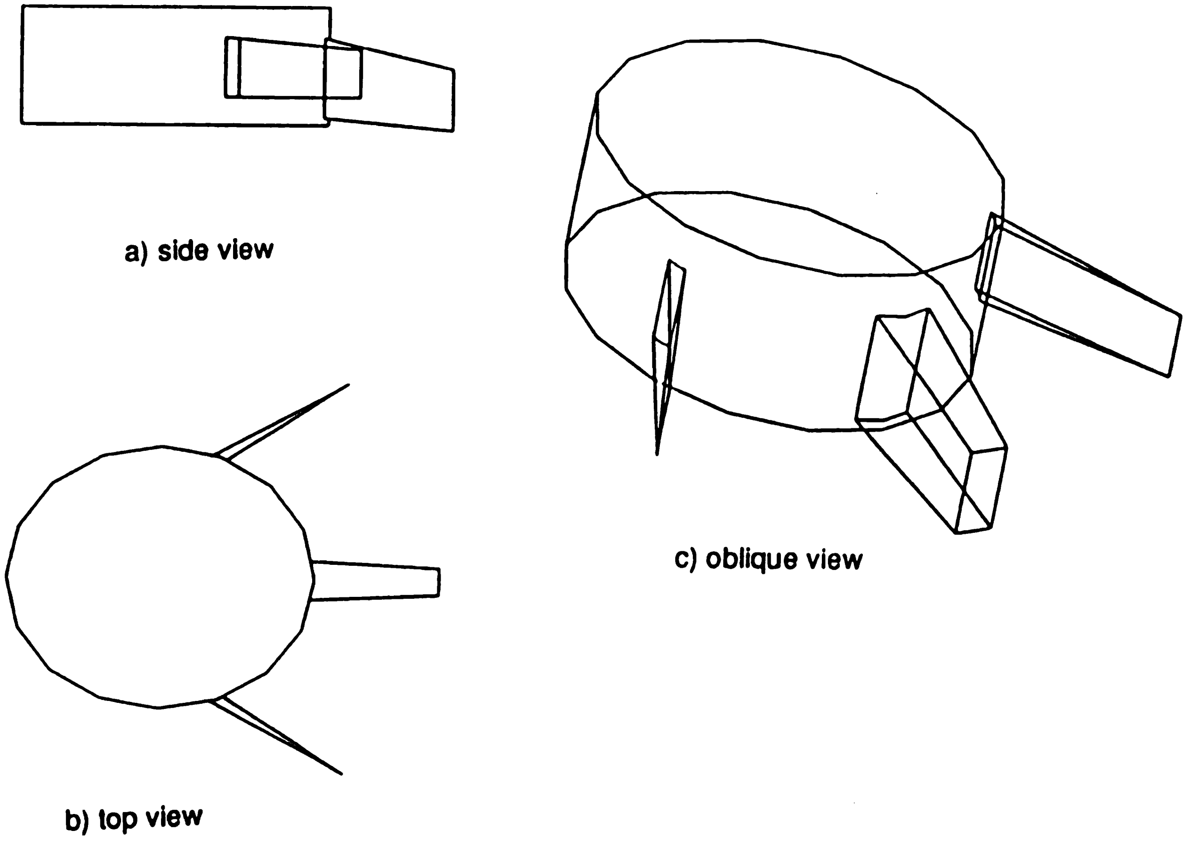


FIGURE 18: LUMBAR VERTEBRAE a) side view b) top view c) oblique view

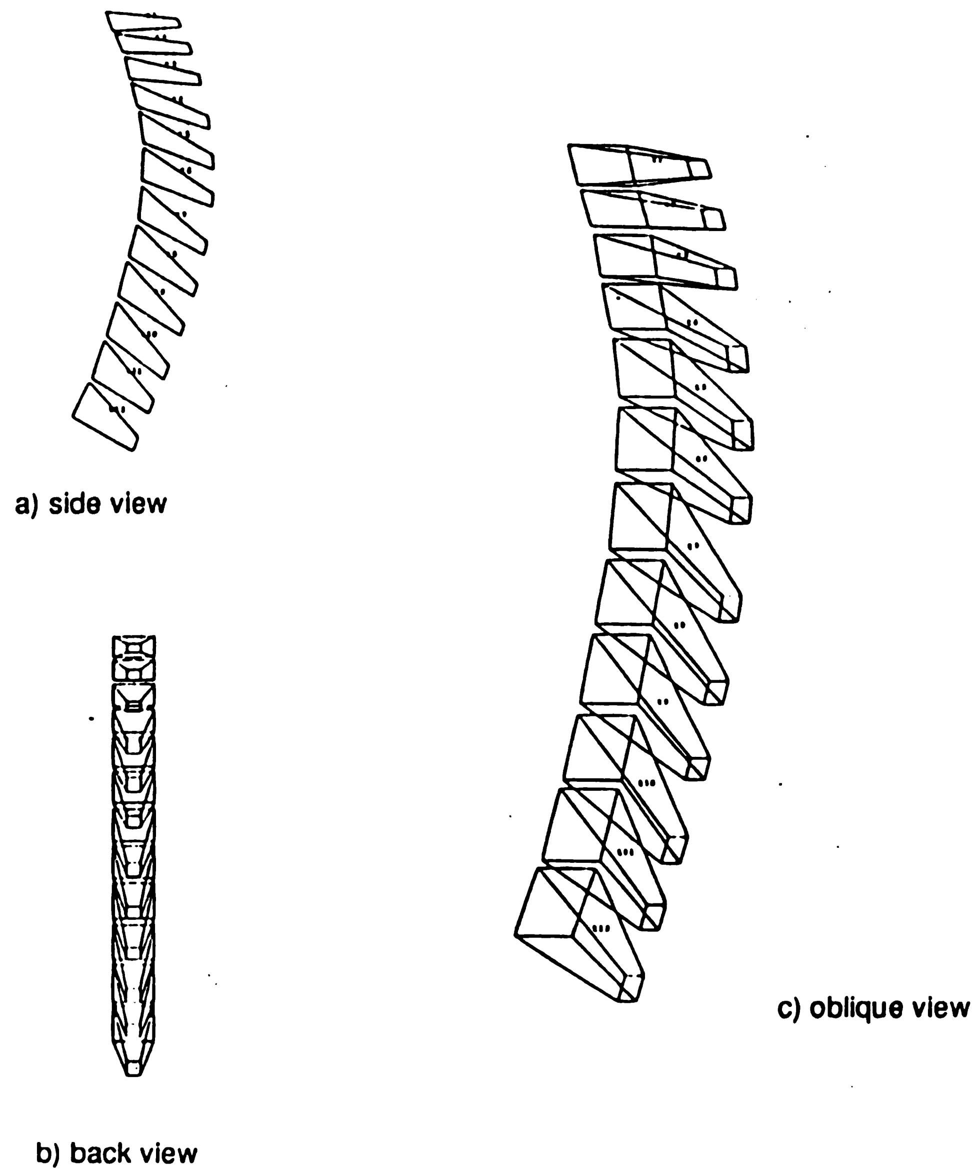


FIGURE 19: THORACIC VERTEBRAL COLUMN

a) side view b) back view c) oblique view

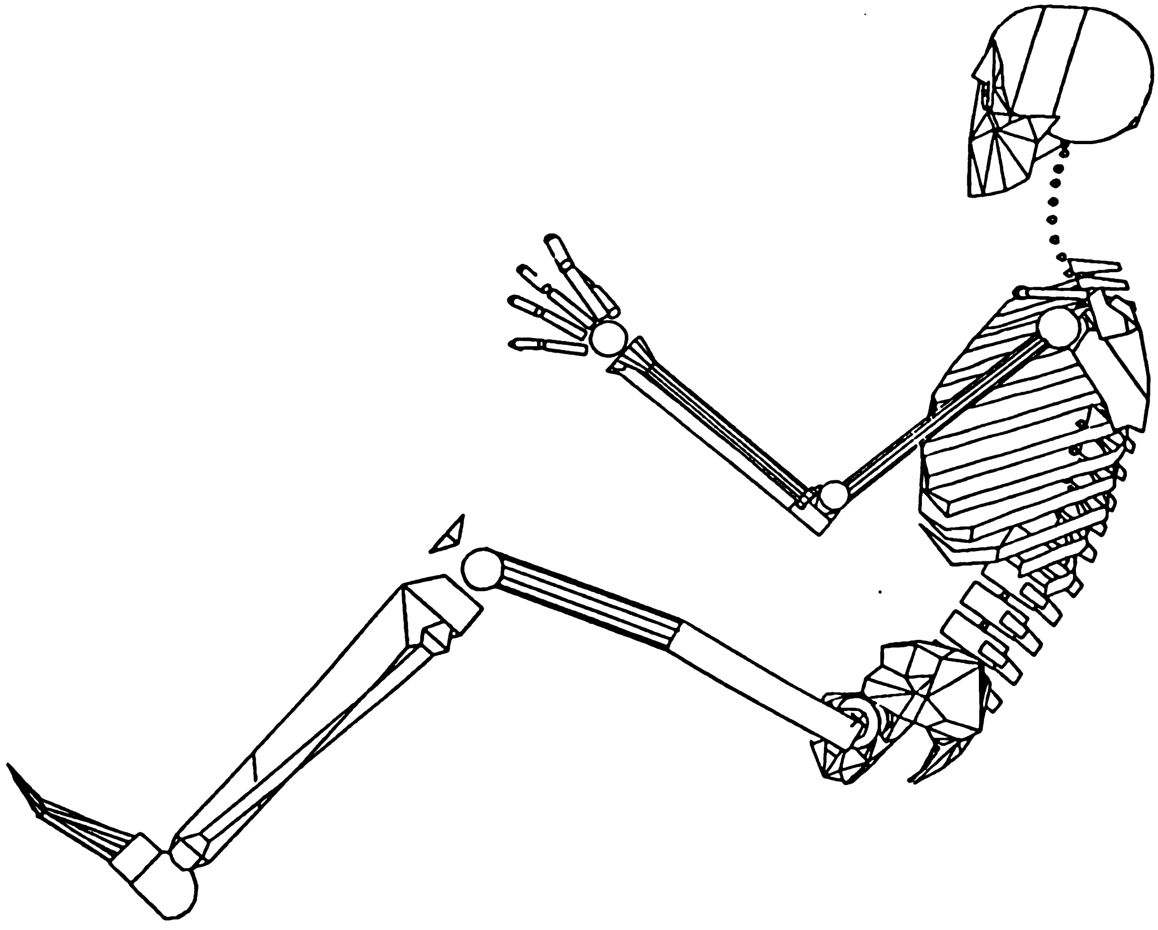


FIGURE 20: JOHN 3-D WITH THORACIC AND LUMBAR VERTEBRAE

had direct effect on the outer surface contours. It was apparent by cadaver studies that the *erector spinae* muscle group contributed the most to the surface contours along both sides of the vertebral column. Figure 21 is a detailed representation of the *erector spinae* muscles by Netter [18]. The *erector spinae* muscle group is made up of three separate muscles, the *longissimus*, *spinalis* and *iliocostalus*. These muscles stretch along the spine from the skull to the pelvis. On the sides of the torso the *externus* and *internus obliquus abdominis* muscles dominated the surface shapes; the *obliquus abdominis* muscles connect the pelvis to the rib cage.

By reviewing Boughner's work [8], it was determined that the *erector spinae* would be most accurately modeled on the computer by constructing profiles that resemble the shape of the muscle bellies and then by creating a surface over each of these profiles. The profile method was chosen over the method of using ellipsoids to represent muscle groups. Ellipsoids would make the model very complex and hard to manage. The *erector spinae* originates at many positions along the vertebral column and rib cage as shown in Figure 22 taken from Stone and Stone [19]. The *erector spinae* was represented in two sections, one for the thoracic region and one for the lumbar region. The thoracic part of the *erector spinae* was rigidly connected along the rib cage and follows the rib cage motion. For the lumbar region the *iliocostalus* muscles of the *erector spinae* group bridge from the rib cage to the pelvis as shown in Figure 22. Therefore, the lumbar part lengthens and shortens when the posture is slumped and erect, respectively.

The first step in creating the *erector spinae* muscles was to make horizontal cross section plots of the 3-D computer model (JOHN 3-D) along the torso. Figure 23 indicates the location of each cross section. Each of these plots was compared with sections from Koritke and Sick [17] to determine

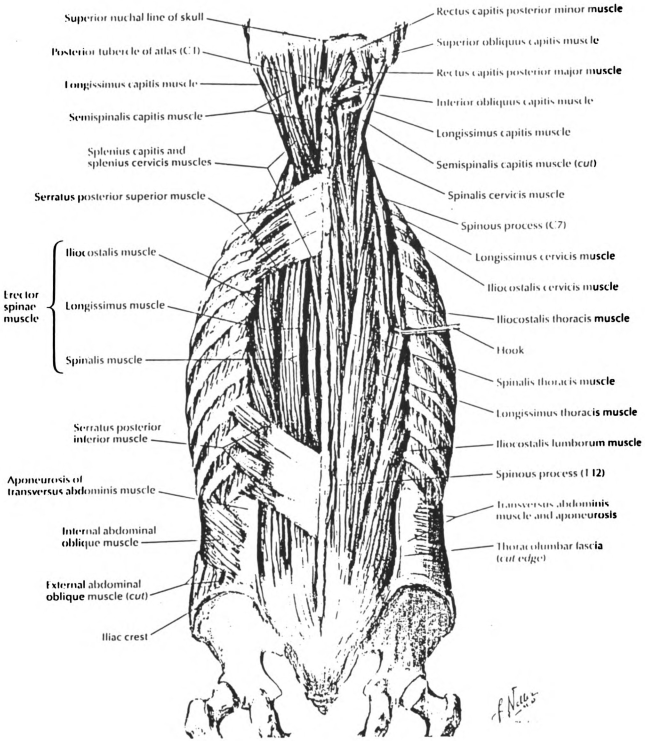
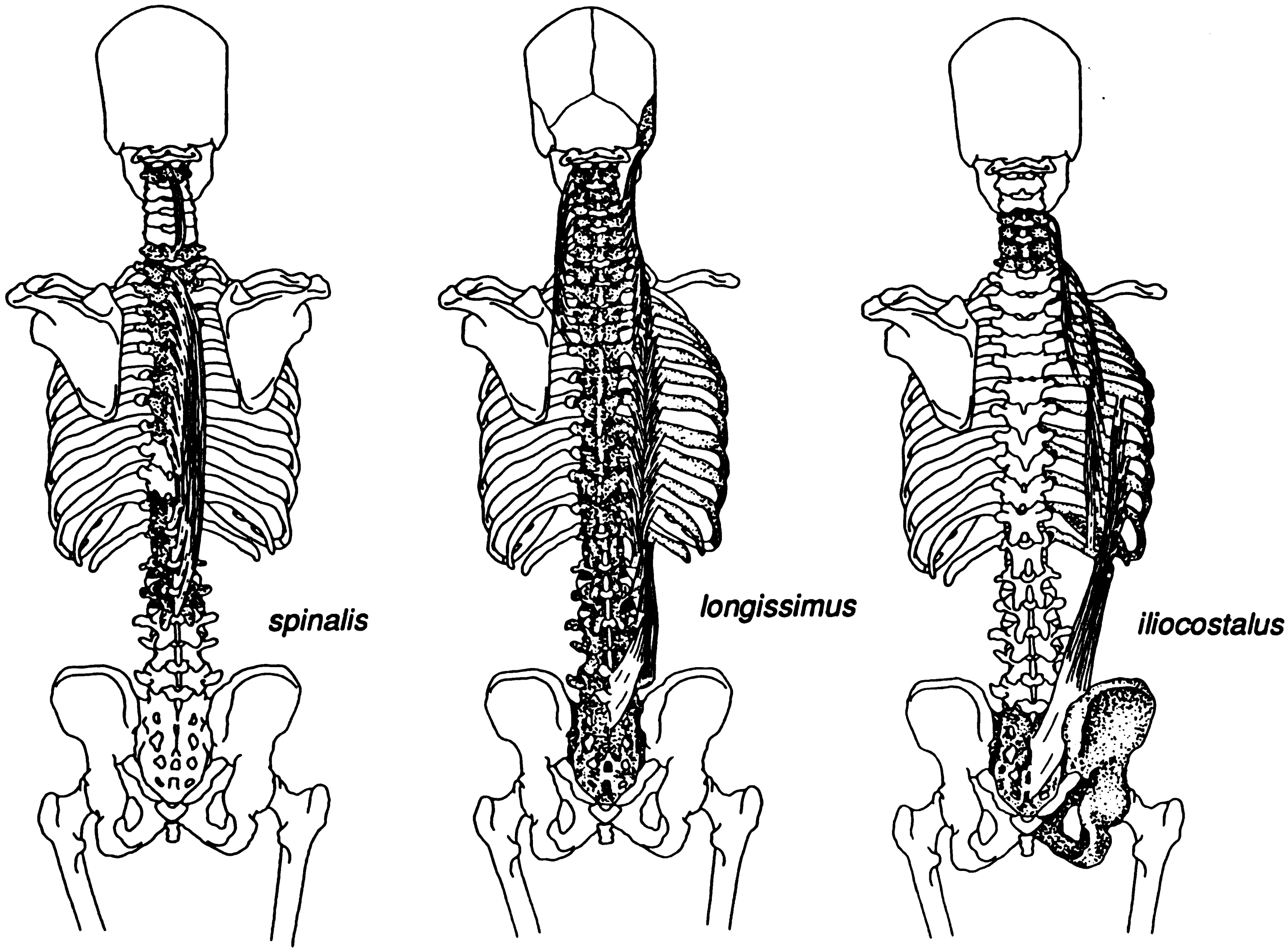


FIGURE 21: DETAILED DRAWING OF THE BACK MUSCLES



Trunk—dorsal view **Trunk—dorsal view** **Trunk—dorsal view**

FIGURE 22: THE *ERECTOR SPINAE* MUSCLES

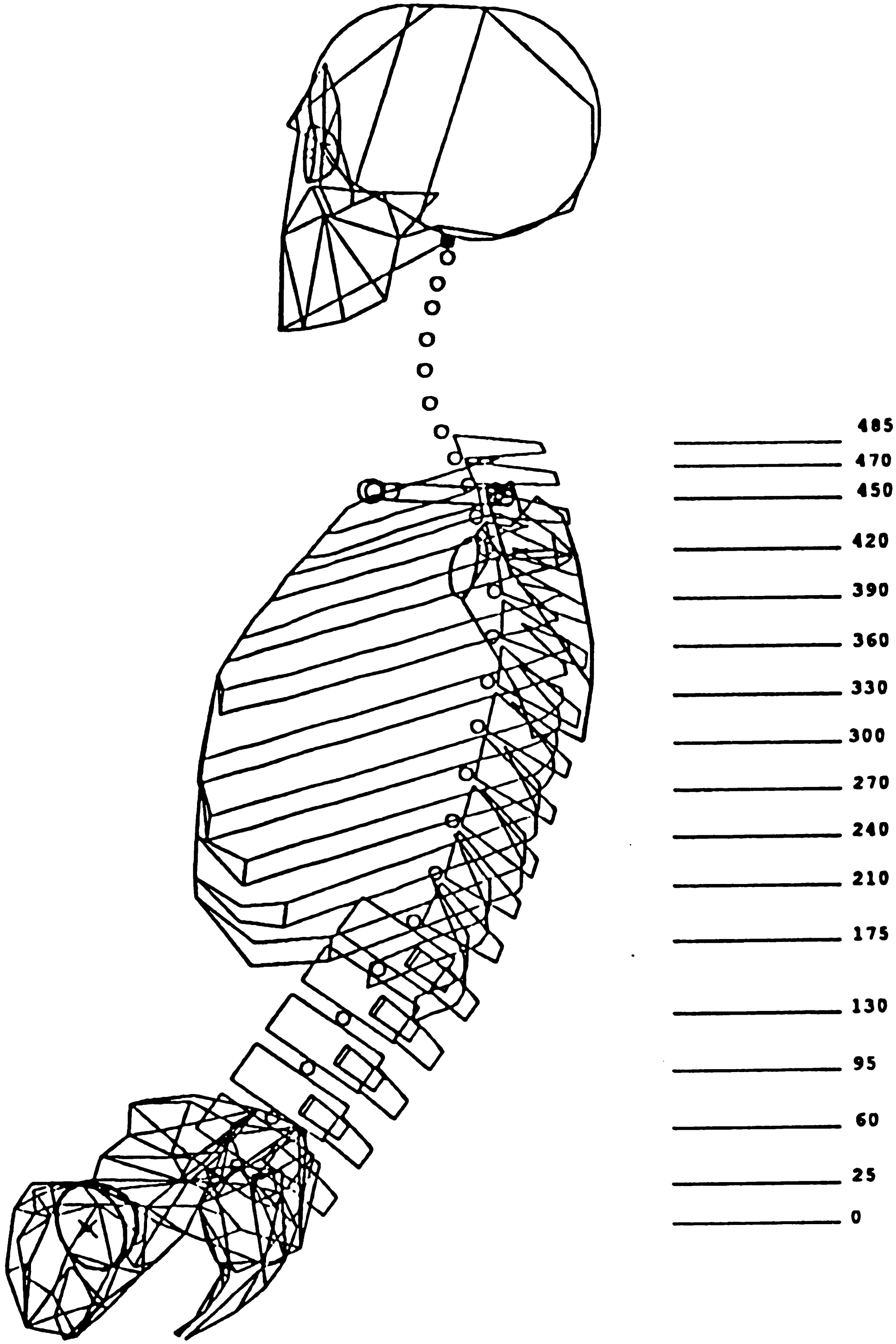


FIGURE 23: LOCATION OF CROSS SECTIONS ON JOHN 3-D

representative muscle cross section shapes to fit JOHN 3-D. The shapes were then scaled directly from the plots and used to make profiles. These profiles were then generated with the Construction Geometry section of the IDEAS [13] software. Again, each of the profiles was created separately, using the X and Y axis coordinates, then positioned along the Z axis at the location they were generated from the plots. Once the profiles were in position, a surface was generated over each profile to make a solid object. Figure 24 illustrates the thoracic *erector spinae* muscle group and the lumbar *erector spinae* muscle group.

A different method was used to model the *obliquus abdominis* muscles on the sides of the torso between the rib cage and pelvis; this method might be called "String Art" and has been used by Dostal et al. [20] to connect the origin and insertion points of hip musculature with string. This approach was taken because the *obliquus abdominis* muscles have a very small cross section and would be hard to develop as section profiles. The *obliquus abdominis* muscles connect the pelvis to the rib cage which move relative to each other. The muscles lengthen and shorten with this movement. The location of the origin and insertion points for the *obliquus abdominis* muscles was based on Stone and Stone [19], who give a detailed description of these locations. Figure 25 is an illustration of the *obliquus abdominis* taken from Stone and Stone [19]. To represent the *obliquus abdominis* muscle origin and insertion points on JOHN 3-D, the points were created by using the Auxiliary Geometry attributes of the IDEAS [16] software, and each point was represented as a node. Next, straight lines were generated between each of the nodes; these lines represent the muscles in the "String Art" approach. Each node was created as part of the object on which it lies, then, as the object moves, the node moves with it. Figure 26 shows the computer model (JOHN 3-D) with muscles.

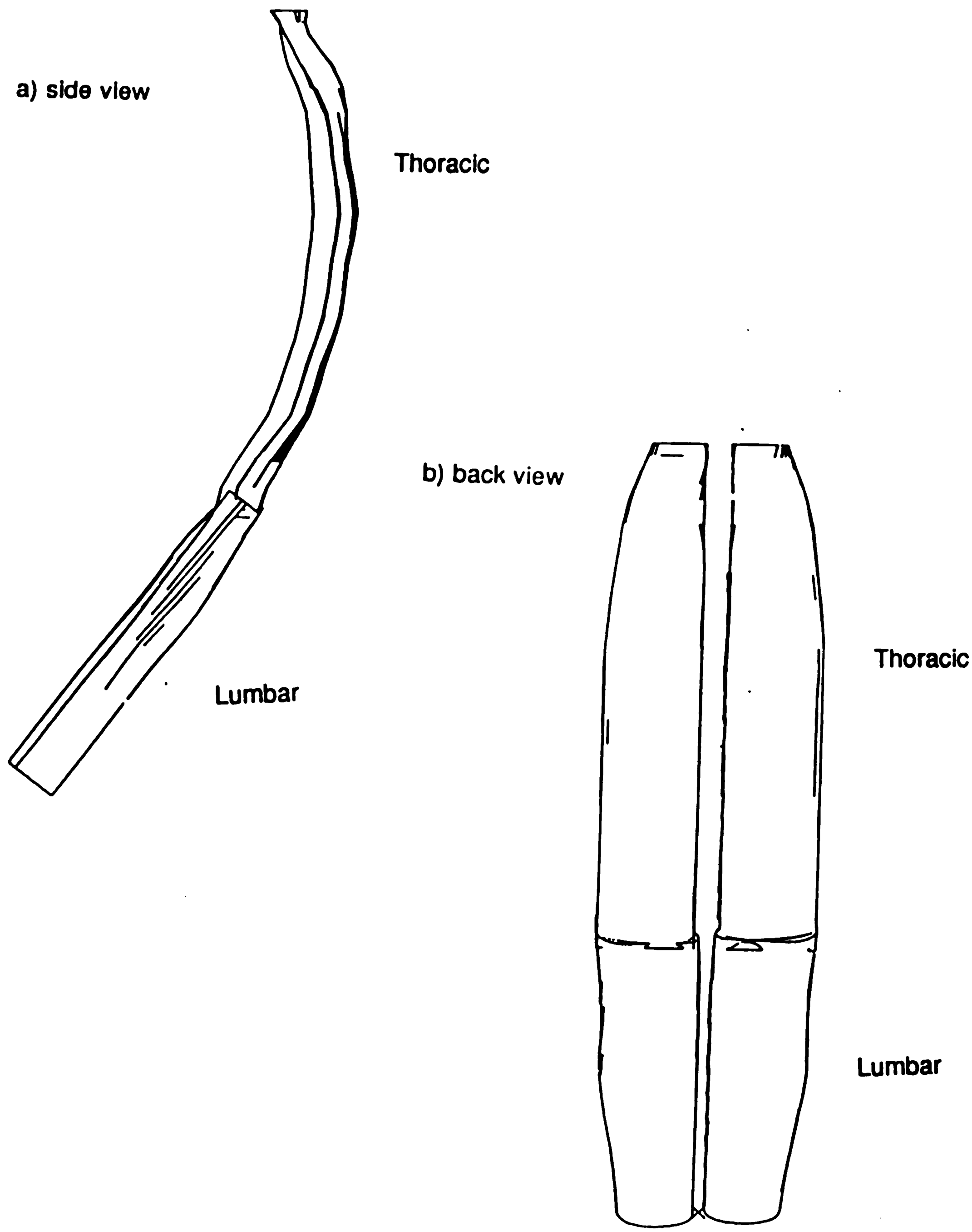
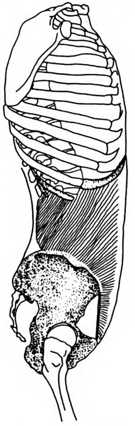


FIGURE 24: THE *ERECTOR SPINAE* MUSCLES a) side view b) back view

OBLIQUUS EXTERNUS ABDOMINIS

Trunk—lateral view

OBLIQUUS INTERNUS ABDOMINIS



Trunk—lateral view

FIGURE 25: THE *OBLIQUUS ABDOMINIS* MUSCLES

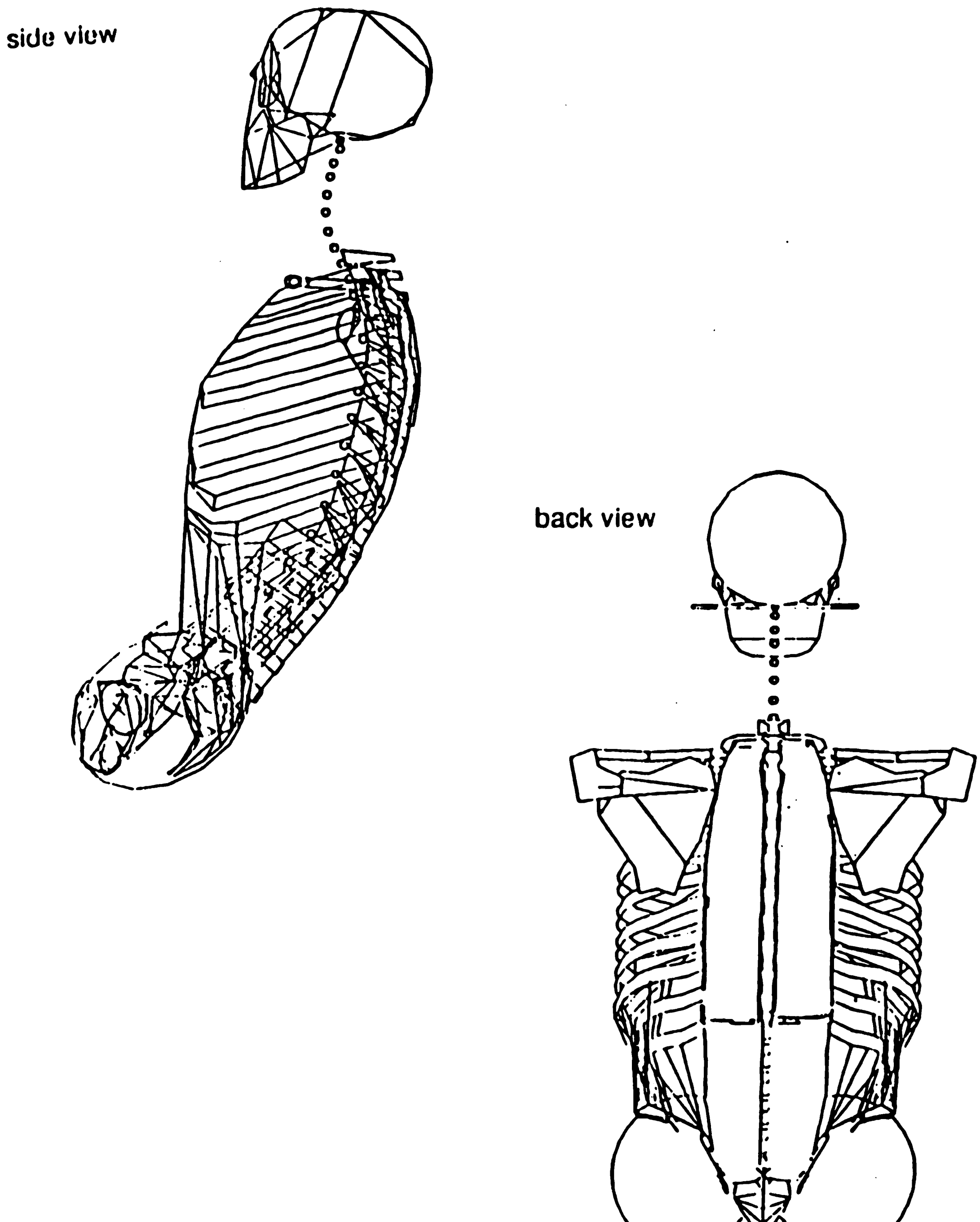


FIGURE 26: JOHN 3-D WITH MUSCLES REPRESENTED

3.2.4 Motion Program

Haas [5] developed the vertebral articulation and constructed a program that represents this motion for the JOHN 2-D model. A similar program located in Appendix A was generated for the JOHN 3-D model. This program uses the approach from Haas and then adds some further body movement. One addition was the pivoting of the torso about the ischial tuberosities to locate the Torso Recline Angle (TRA). Another task of the program was to move the muscles. The program starts by asking the user to input their desired Total Lumbar Curvature (TLC), Torso Recline Angle (TRA) and Head Rotation Angle (HRA). Starting with a straight lumbar spine (ie. TLC equal to 0°), the first step for the program was to locate the head. The head was rotated equally about each of the cervical joint centers starting at the top and moving down. The head is rotated with respect to the eye-line; for an HRA of 0°, the eye-line is horizontal. The program calculates the amount of rotation needed to hold the eye-line level, given the values of TLC and TRA, and then rotates the amount input for HRA. The program rotates about the cervical joint centers which are positioned above and below each vertebrae. There are eight joint centers in the cervical spine, therefore, the amount rotation for each vertebrae was equal to 1/8 the value input for TLC, starting at TLC equal to 0°, minus the amount of rotation that was needed to locate the body into the TRA position, starting with TRA equal to 35°, the HRA was then added. The lumbar articulation was performed by rotating about each of the six lumbar joint centers, an amount equal to 1/6 the value input for TLC. When the program rotates about a joint center it rotates each component located above that joint. The locations of each of the vertebral joint centers in three-dimensional space for the initial position of TLC equal to 0° have been added in Appendix B. These positions are used in the program. Once the cervical and lumbar spines were articulated, then the model was rotated about the ischial tuberosities to position the torso in the position as defined by the TRA. The last process of the program was made to relocate the muscles according to the articulated skeletal position. The arms and legs have not been examined for this study, therefore, the program simply locates them in their original orientation. Figure 27 represents the three-dimensional motion of the model.

3.2.5 Generating Skin

The back surface of JOHN 3-D was created by adding a skin layer over the skeleton and muscles. This process began by generating horizontal cross section plots of the torso from the JOHN 3-D computer model. Figure 28 shows the torso of JOHN 3-D and the location of the cross sections. The plots were examined and compared to Koritke and Sick [17] to determine a representative skin thickness. On each of the plots, a surface was hand drawn which was directly contoured to the bones and muscles; this surface represented the skin. Once the surface was hand drawn, points were measured at consistent positions along the Y axis on the plot. These points were then input to the computer using the Construction Geometry task of the IDEAS [16] software and cubic splines were generated through each point to make a mesh of curves. This mesh of curves is represented in Figure 29. Then, by going into the Object Modeling task, a skin was created from the mesh of curves. The same process was then used to generate skin on the model at positions for TLC ranging from -10° to 40°, in increments of 10°. Tables 1-6 in Appendix C indicate the points used to skin the model. Figures 30 through 35 illustrate the model skinned for the different TLC postures with TRA and HRA equal to 0° in each figure. Cross sectional plots were made along the torso perpendicular to the TRA and are represented in Appendix D.

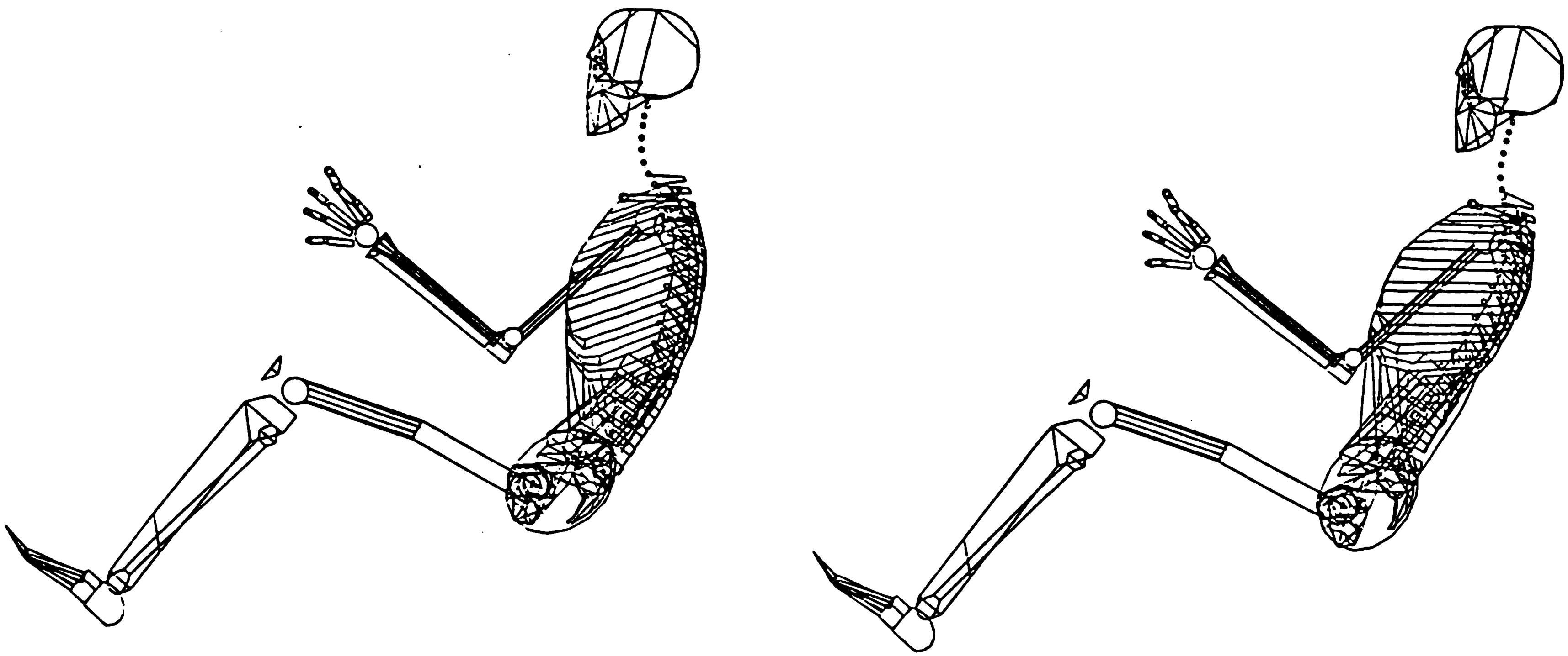


FIGURE 27: JOHN 3-D WITH LUMBAR MOTION

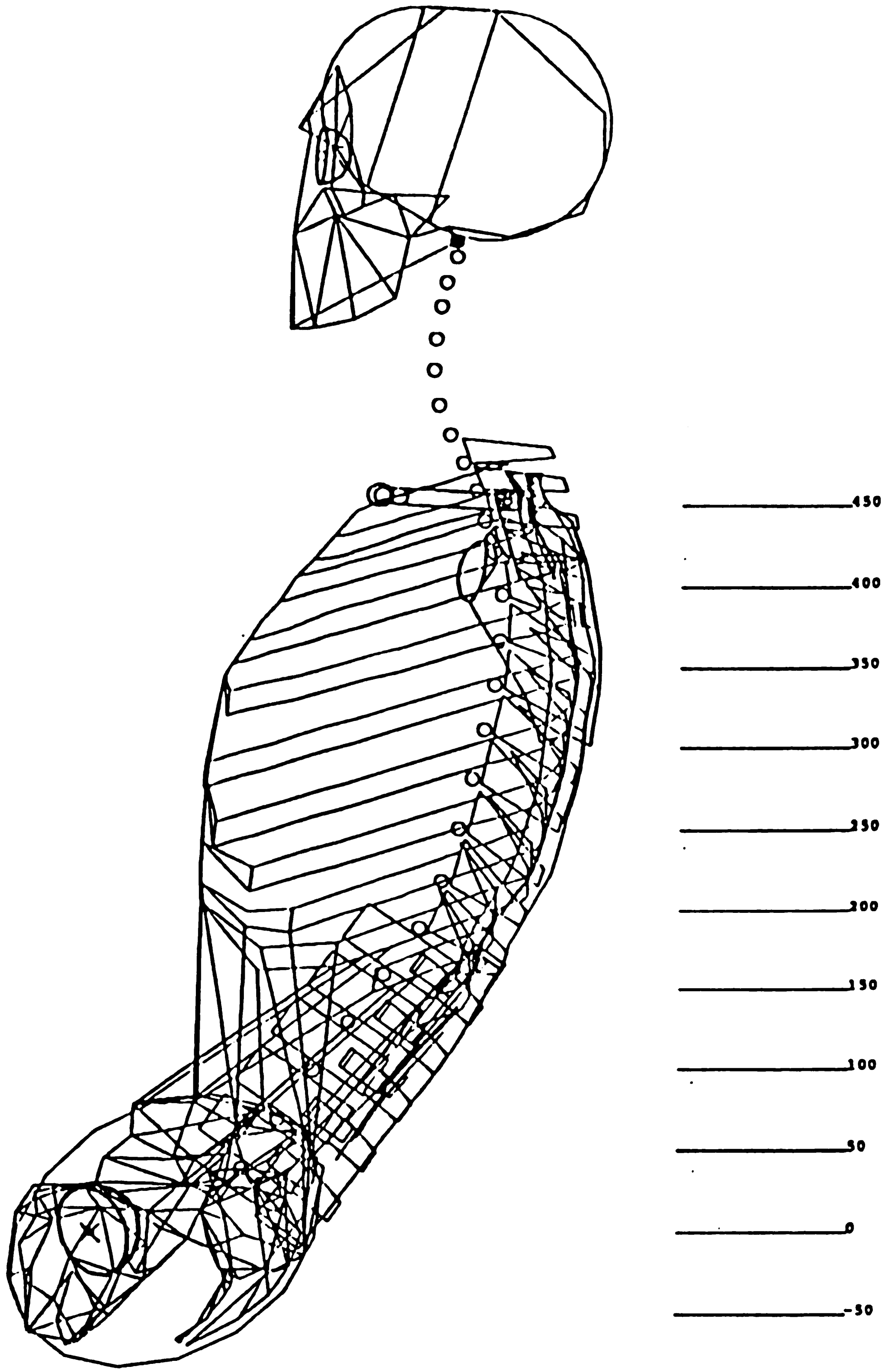
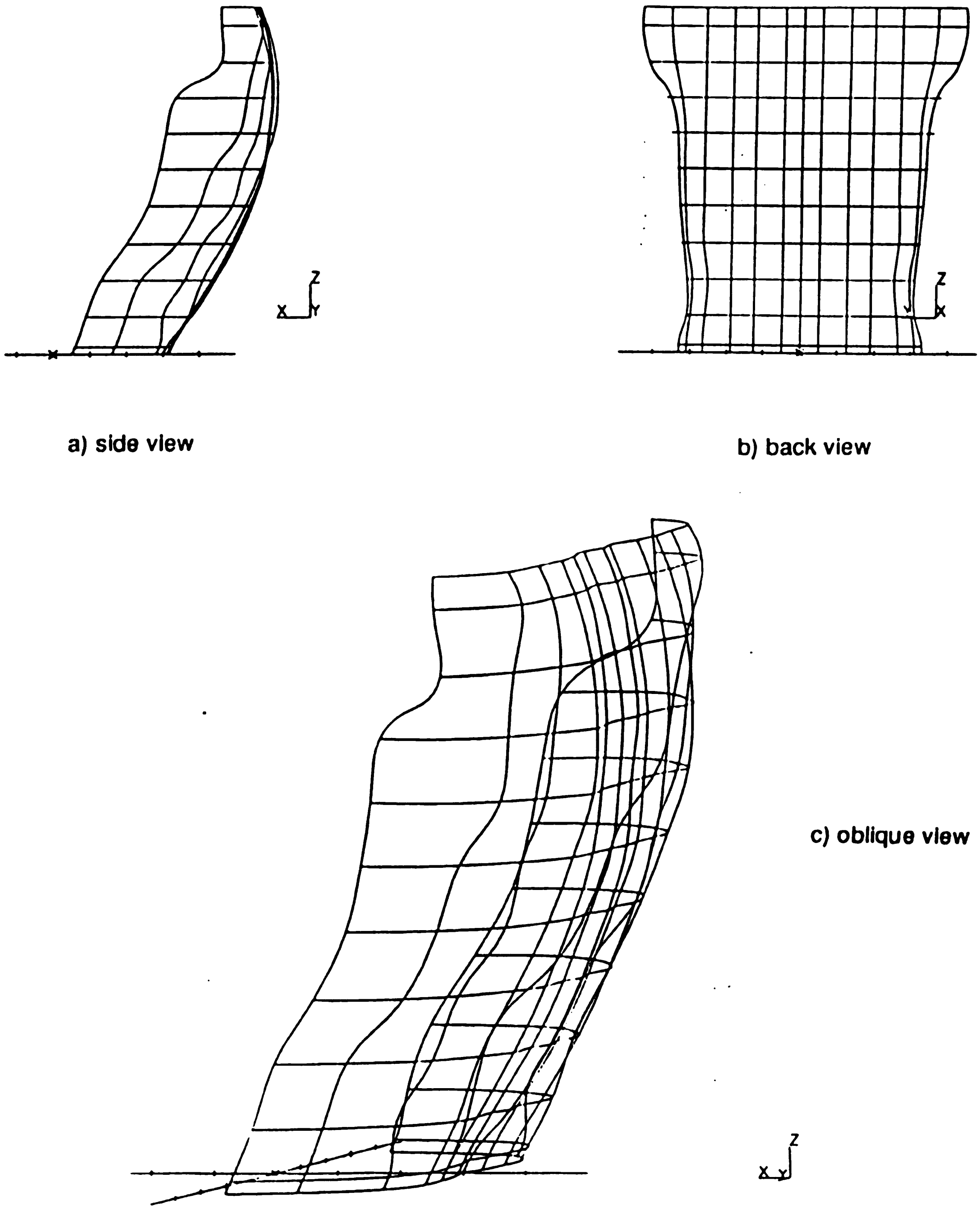


FIGURE 28: JOHN 3-D TORSO WITH CROSS SECTION LOCATIONS



a) side view

b) back view

c) oblique view

FIGURE 29: MESH OF CURVES FOR BACK SKIN

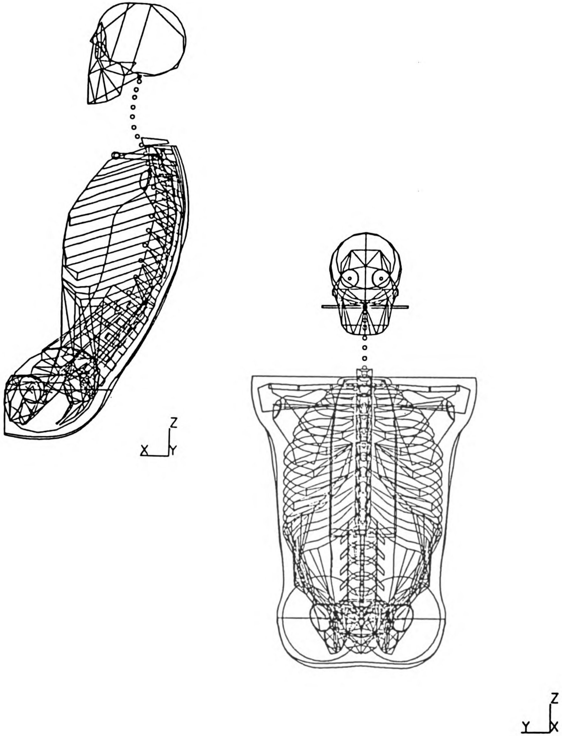


FIGURE 30: JOHN 3-D SKINNED AT TLC=0°

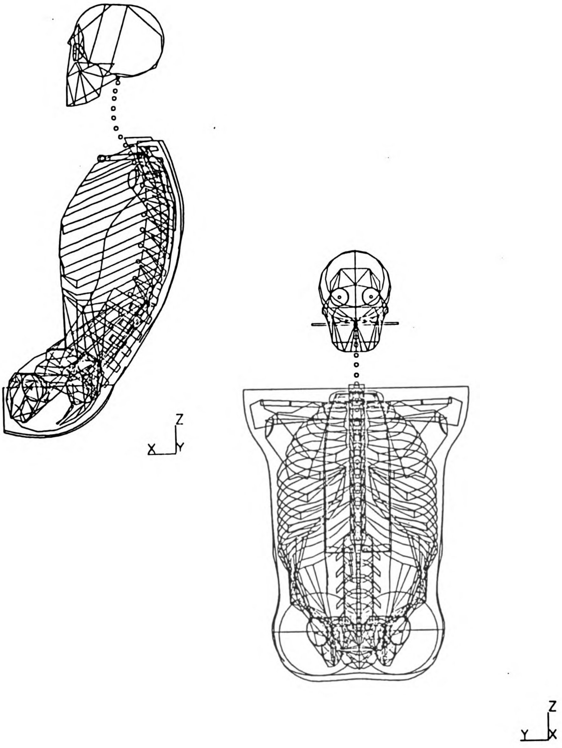
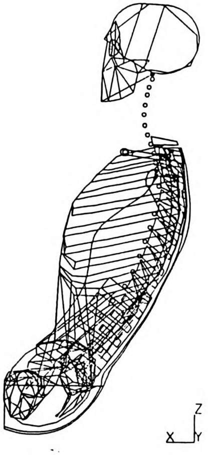


FIGURE 31: JOHN 3-D SKINNED AT TLC=-10°



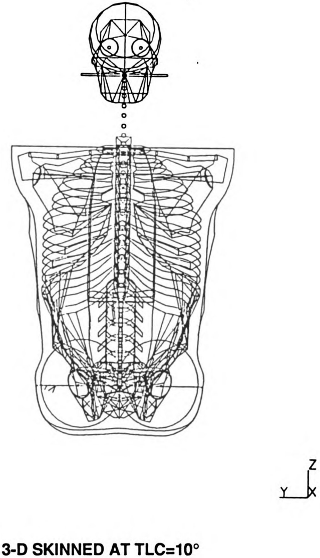


FIGURE 32: JOHN 3-D SKINNED AT TLC=10°

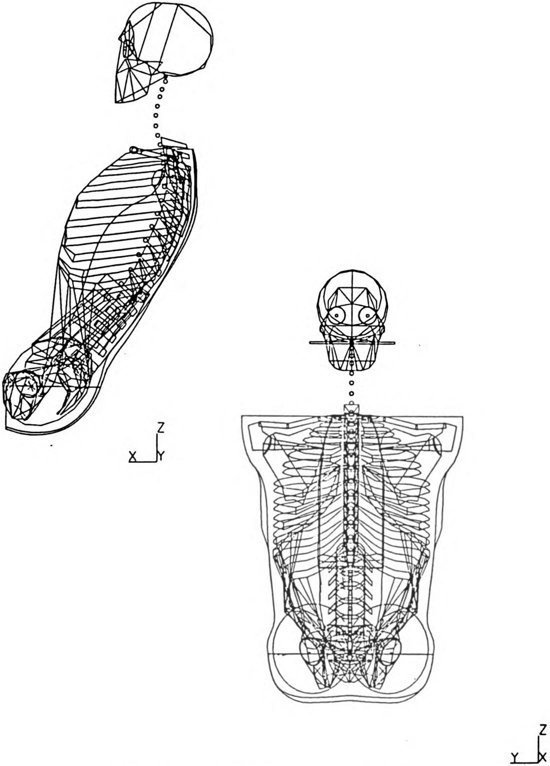


FIGURE 33: JOHN 3-D SKINNED AT TLC=20°

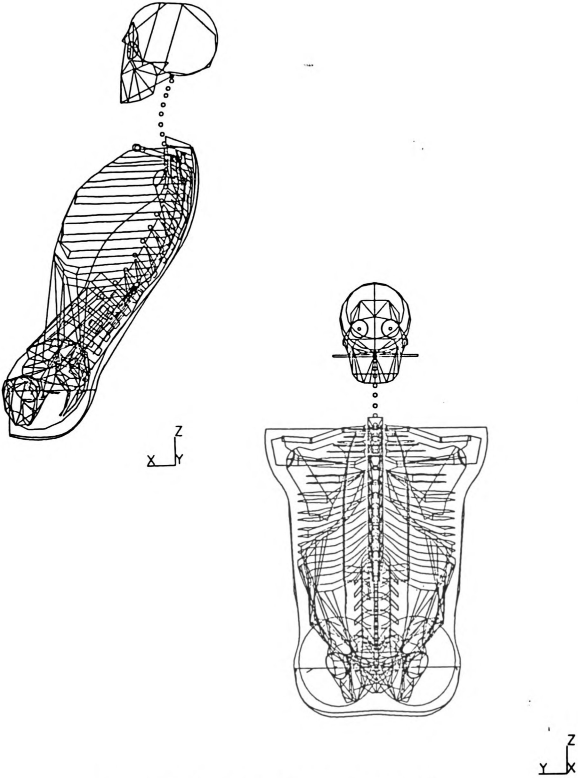


FIGURE 34: JOHN 3-D SKINNED AT TLC=30°

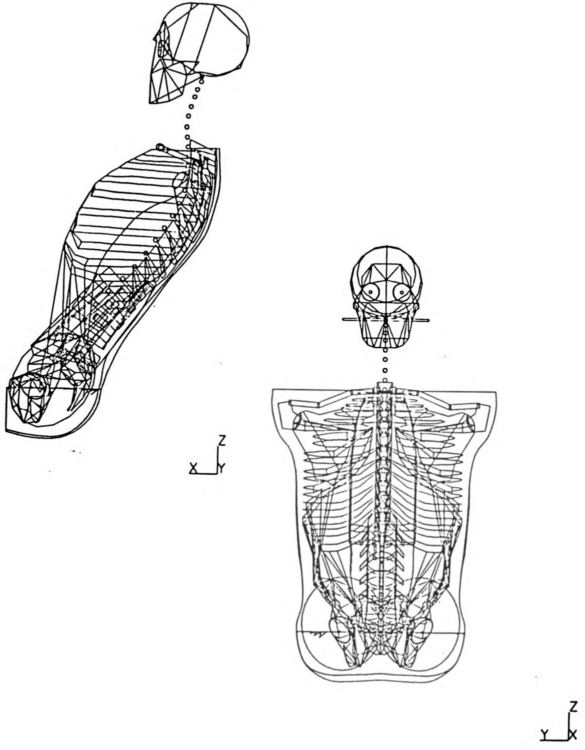


FIGURE 35: JOHN 3-D SKINNED AT TLC=40°

3.3 Results and Discussion

3.3.1 Comparing JOHN 3-D with the UM-TRI Study

UM-TRI [3] developed a three-dimensional body form that represents the fiftieth percentile adult male in a single posture which has been adopted for JOHN 2-D and JOHN 3-D with TLC=0°. The UM-TRI body form was created by the collection of data taken in 3-D space on human subjects. These subjects were selected to match the fiftieth percentile human stature. They were tested in a laboratory while sitting in automotive seats. JOHN 3-D skeleton was developed with the use of the UM-TRI [3] study but the skin on JOHN 3-D was created independent of the UM-TRI study. A comparison was made by examining the horizontal cross sections of each model. The UM-TRI body form was digitized by the Advanced Design Staff at General Motors, then a 3-D computer model was made of the body surface. Figure 36 represents a side view of the UM-TRI model and the JOHN 3-D model. Horizontal sections, on the UM-TRI model, were made at vertical levels of 0, 100, 200, 300 and 400 mm from an origin at the Hip Joint Center as described by UM-TRI. JOHN 3-D has a different Hip Joint Center location than UM-TRI which is 25mm below the UM-TRI HJC location in the vertical direction with a posture at TLC equal to 0°. This difference in position was due to Haas [5] who concluded that the lumbar spine length was longer than represented by UM-TRI [3]. The coordinate system for JOHN 3-D originates at the Hip Joint Center, therefore, for accurate comparison the horizontal sections made on JOHN 3-D were taken at 25, 125, 225, 325 and 425mm above the HJC. Cross section plots (Figures 37 through 41) were made for each model and then overlaid for this comparison.

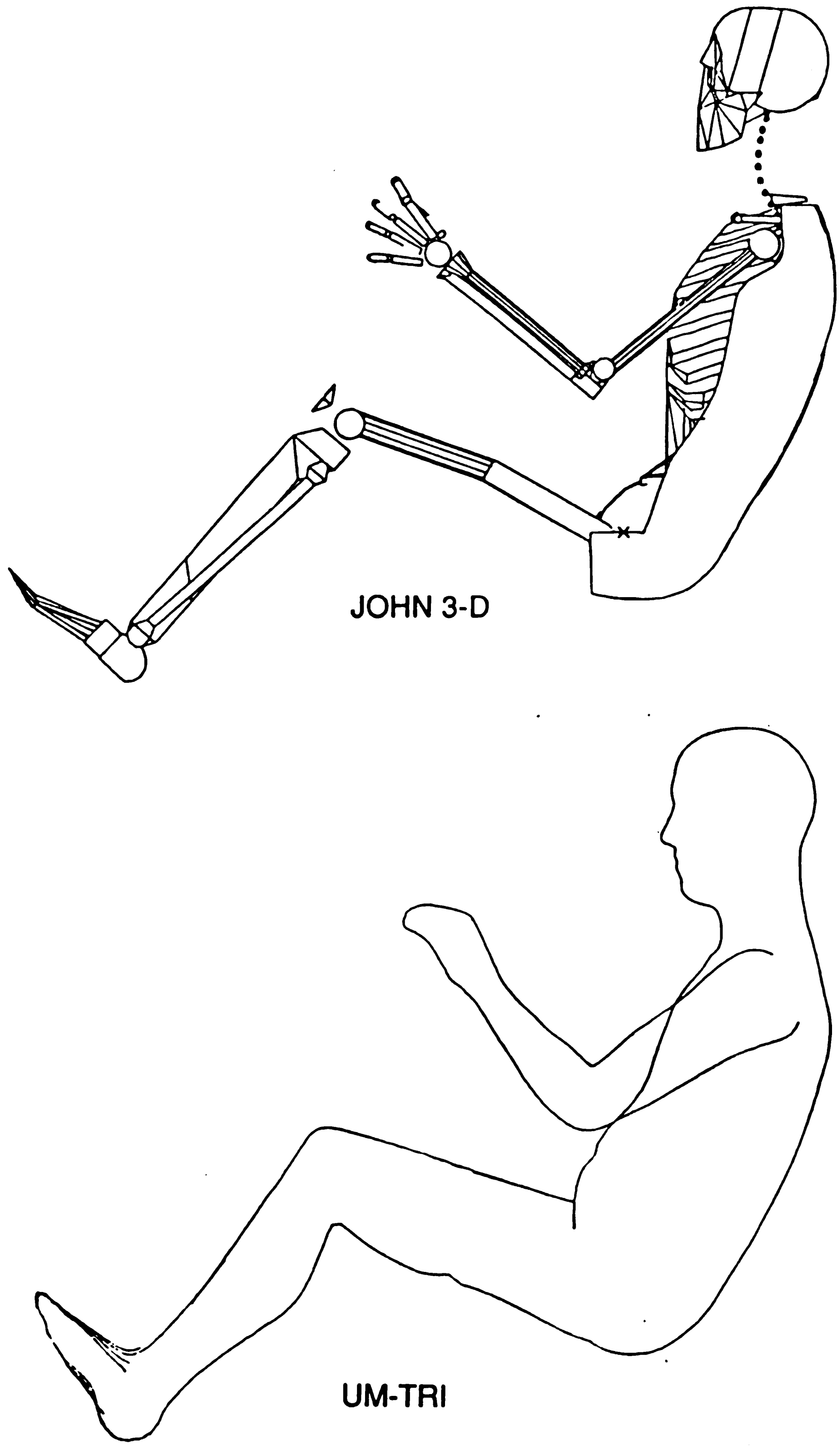


FIGURE 36: SIDE VIEW JOHN 3-D vs UM-TRI BODY FORM

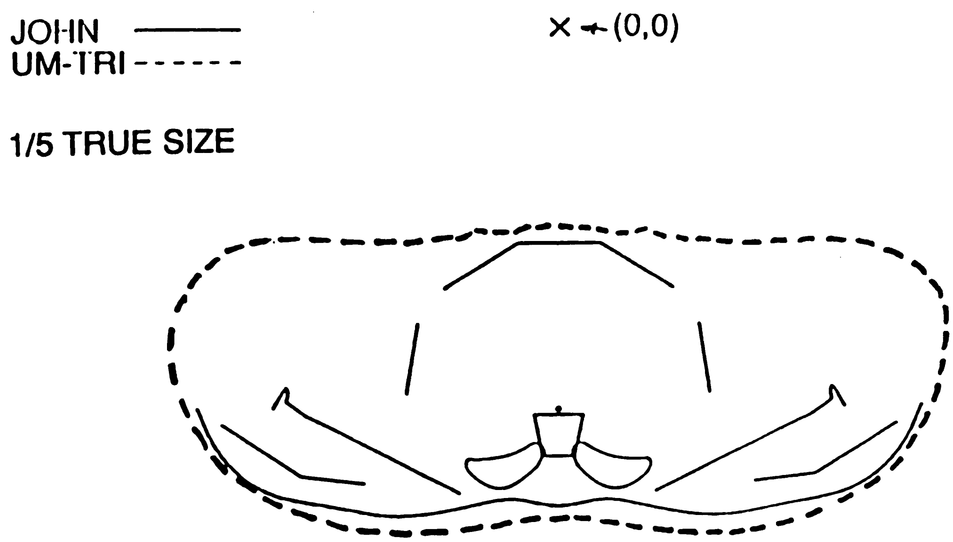


FIGURE 37: CROSS SECTIONS AT 400mm

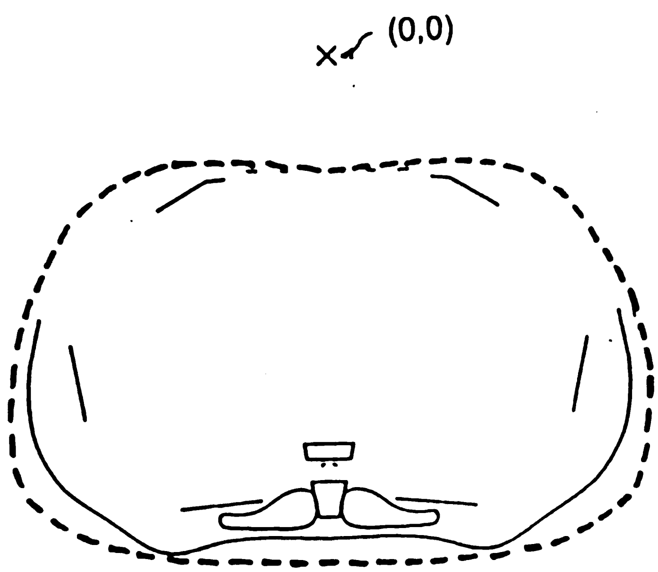


FIGURE 38: CROSS SECTIONS AT 300mm

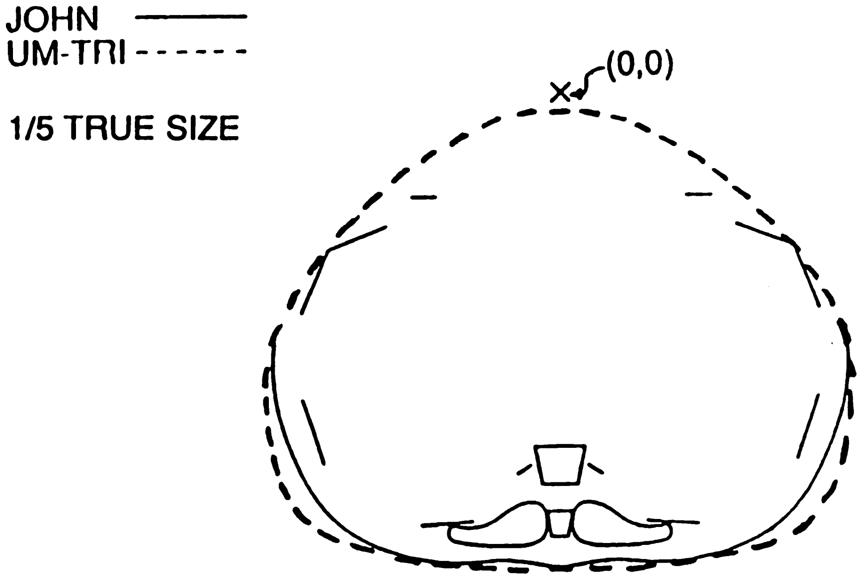


FIGURE 39: CROSS SECTIONS AT 200mm

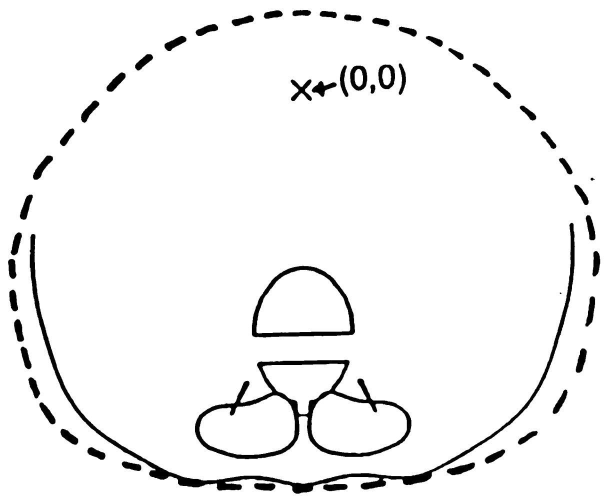


FIGURE 40: CROSS SECTIONS AT 100mm

JOHN ———
UM-TRI - - - - - -

1/5 TRUE SIZE

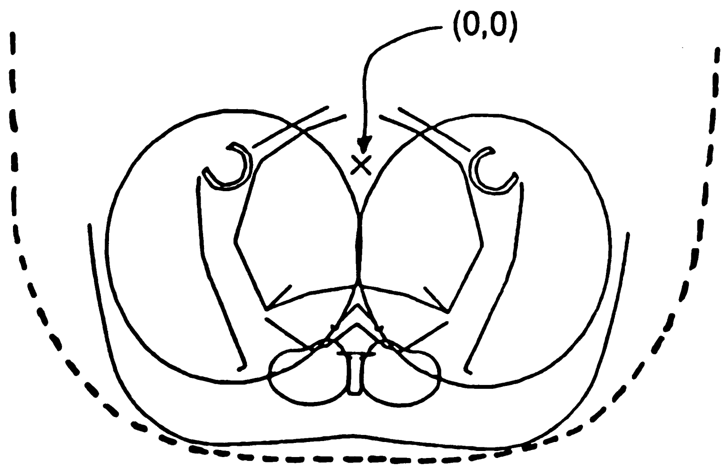


FIGURE 41: CROSS SECTIONS AT 0mm

The comparison of JOHN 3-D and the UM-TRI [3] body form indicated similarities in the body surface location at each section. The models resemble the same body size and overall surface shape. The major difference was the back surface contours; JOHN 3-D has a more contoured back, and the UM-TRI body form has a less contoured back. One significant reason for the difference in contour is that the UM-TRI body form is the result of the interaction between the human body and the automotive seat. The seats used for the test were not contoured, and the body conformed to the seat. JOHN 3-D was created without the interaction of the seat, therefore, the JOHN 3-D contour has been predicted only by the body structure and not the seat. Another possible reason for the contrast was the body casting technique used for the UM-TRI body form. Scotch Cast tape was placed on the seat, then the tape hardened after the subject sat in the seat. The tape most likely bridged across the deep contours. Also, the data taken from each subject in the UM-TRI [3] study was averaged to develop one set of points. The process of averaging the data could have caused some of the high contour points cancel, between each subject causing the curves to smooth out. A fourth scenario was that human body fat has not been represented on JOHN 3-D which could flatten out some of the contours. Body fat is located differently for each person, and to try and develop a universal location was beyond the scope of this thesis.

4. CONCLUSION

Each of the objectives investigated for this thesis have been accomplished.

The JOHN 2-D template was developed to represent the two-dimensional computer model created by Haas [5]. This template accurately locates the thorax relative to the pelvis within 1mm, for seated postures as defined by Haas [5]. JOHN 2-D can be used to compare existing automotive seat designs with human postures as well as develop new seat designs by studying the mobility of the human body in the seated position.

The vertebral column and back muscles have been added to the three-dimensional computer model (JOHN 3-D) to define the contours of the thoracic region. A skin was also generated on the back side of the JOHN 3-D torso. The JOHN 3-D skin represents the back surface of an average male in a seated posture without soft tissue deflection due to seat/body contact. This thesis compares the JOHN 3-D skin to the UM-TRI body form [3] which represents an average male in a seated posture with the effect of the seat on the body. JOHN 3-D compared well to the UM-TRI body form in size and overall shape, the major difference was the back contour of each skin. JOHN 3-D has a more contoured back than the UM-TRI body form.

A motion program was created to articulate the JOHN 3-D computer model. This program has the user input values for Total Lumbar Curvature (TLC), Torso Recline Angle (TRA) and Head Rotation Angle (HRA). Then the program moves JOHN 3-D to fit these input specifications. Skin was generated for JOHN 3-D at six different postural positions. The positions were determined by the value of TLC equal to -10 through 40 degrees in increments of 10 degrees.

The JOHN 2-D template, which represents the skeletal structures of the pelvis, thorax and skull should be further developed by representing the outer body surface as developed for the JOHN 3-D computer model in this thesis. Further work should also be concentrated on the development of these models for different size people.

Each of the tasks completed in this thesis, i.e., development of the JOHN 2-D template, and the JOHN 3-D computer model with skin and body movement, are important new biomechanical models of humans for automotive seat design. These models represent the geometry of people in automotive seated postures. When there is a conflict between the body and seat, high pressure points develop on the body resulting in discomfort by restricting blood flow and compressing nerves. If seats can be designed to geometrically accommodate the contours of people as they sit in different positions, then their seats will be more comfortable.

APPENDICES

APPENDIX A

Motion Program

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C :
C :
C :          MOTION PROGRAM FOR THE 3-D JOHN MODEL
C :
C :
C : ***** TLC-TOTAL LUMBAR CURVATURE *****
C : ******* TRA-TORSO RECLINE ANGLE ******
C : ******* HRA-HEAD ROTATION ANGLE ******
K : /
K : !DO
K : BL
K : B
K : *
K : #ECHO NONE
K : #DECLARE TLC(1)
K : #DECLARE TRA(1)
K : #DECLARE TRAN(1)
K : #DECLARE TILT(1)
K : #DECLARE CERV(1)
K : #DECLARE LUMB(1)
K : #DECLARE HRA(1)
? : #INPUT"WHAT IS THE DESIRED TLC?" TLC
? : #INPUT"WHAT IS THE DESIRED TRA?" TRA
? : #INPUT"WHAT IS THE DESIRED HRA?" HRA
K : #LUMB=((TLC)/6)
K : #MUS=(TLC/2)
K : #TRAN=((TLC/2)+35)
K : #TILT=TRAN-TRA
K : #CERV=((HRA+(TLC-TILT)/8))
K : /
K : !O
C :
C : ----------LEG ROTATION------------
C :
K : R
K : I
K : H
K : 2
K : 3
K : 46
K : 54
K : 55
K : 56
K : D
K : K
K : 0 0 0
K : 0 -TILT 0
C :
C : ----------ARM ROTATION------------
C :
K : R
K : I
K : H
K : 6
K : 7
K : 42
K : 43
K : 45
K : 49
K : 50
K : 51
K : D
K : K
K : -235 177 413
K : 0 TILT 0
C :
```

```
C : ----------HEAD ROTATION-----------
C :
C : ROTATE ABOUT SKULL/C1
C :
K : R
K : I
K : H
K : 52
K : 38
K : 37
K : 36
K : 35
K : 34
K : 33
K : D
K : K
K : -213 0 612
K : 0 cerv 0
C :
C : ROTATE ABOUT C1/C2
C :
K : R
K : I
K : H
K : 52
K : 38
K : 37
K : 36
K : 35
K : 34
K : 33
K : 21
K : D
K : K
K : -213 0 602
K : 0 CERV 0
C :
C : ROTATE ABOUT C2/C3
C :
K : R
K : I
K : H
K : 52
K : 38
K : 37
K : 36
K : 35
K : 34
K : 33
K : 21
K : 20
K : D
K : K
K : -207 0 586
K : 0 CERV 0
C :
C : ROTATE ABOUT C3/C4
C :
K : R
K : I
K : H
K : 52
K : 38
K : 37
K : 36
K : 35
```

```
K : 34
K : 33
K : 21
K : 20
K : 19
K : D
K : K
K : -204 0 571
K : 0 CERV 0
C :
C : ROTATE ABOUT C4/C5
C :
K : R
K : I
K : H
K : 52
K : 38
K : 37
K : 36
K : 35
K : 34
K : 33
K : 21
K : 20
K : 19
K : 18
K : D
K : K
K : -201 0 551
K : 0 CERV 0
C :
C : ROTATE ABOUT C5/C6
C :
K : R
K : I
K : H
K : 52
K : 38
K : 37
K : 36
K : 35
K : 34
K : 33
K : 21
K : 20
K : 19
K : 18
K : 17
K : D
K : K
K : -200 0 532
K : 0 CERV 0
C :
C : ROTATE ABOUT C6/C7
C :
K : R
K : I
K : H
K : 52
K : 38
K : 37
K : 36
K : 35
K : 34
K : 33
K : 21
```

```
K : 20
K : 19
K : 18
K : 17
K : 16
K : D
K : K
K : -203 0 511
K : 0 CERV 0
C :
C : ROTATE ABOUT C7/C8
C :
K : R
K : I
K : H
K : 52
K : 38
K : 37
K : 36
K : 35
K : 34
K : 33
K : 21
K : 20
K : 19
K : 18
K : 17
K : 16
K : 15
K : D
K : K
K : -210 0 493
K : 0 CERV 0
C :
C : ------------THORAX ROTATION------------
C :
C : ROTATE ABOUT T12/L1
C :
K : R
K : I
K : H
K : 52
K : 38
K : 37
K : 36
K : 35
K : 34
K : 33
K : 21
K : 20
K : 19
K : 18
K : 17
K : 16
K : 15
K : 14
K : 51
K : 50
K : 49
K : 48
K : 47
K : D
K : K
K : -194.1 0 189.2
K : 0 -LUMB 0
K : R
```

```
K : I
K : H
K : 45
K : 44
K : 43
K : 42
K : 41
K : 32
K : 31
K : 30
K : 29
K : 28
K : 27
K : 26
K : D
K : K
K : -194.1 0 189.2
K : 0 -LUMB 0
K : R
K : I
K : H
K : 25
K : 24
K : 23
K : 22
K : 7
K : 6
K : 5
K : 4
K : 75
K : 98
K : D
K : K
K : -194.1 0 189.2
K : 0 -LUMB 0
C :
C : ROTATE ABOUT L1/L2
C :
K : R
K : I
K : H
K : 52
K : 38
K : 37
K : 36
K : 35
K : 34
K : 33
K : 21
K : 20
K : 19
K : 18
K : 17
K : 16
K : 15
K : 14
K : 51
K : 50
K : 49
K : 48
K : 47
K : D
K : K
K : -173.08 0 159.16
K : 0 -LUMB 0
K : R
```

```
K : I
K : H
K : 45
K : 44
K : 43
K : 42
K : 41
K : 32
K : 31
K : 30
K : 29
K : 28
K : 27
K : 26
K : 25
K : 24
K : 23
K : 22
K : 7
K : 6
K : 5
K : 4
K : D
K : K
K : -173.08 0 159.16
K : 0 -LUMB 0
K : R
K : I
K : H
K : 75
K : 88
K : 13
K : 98
K : D
K : K
K : -173.08 0 159.16
K : 0 -LUMB 0
C :
C : ROTATE ABOUT L2/L3
C :
K : R
K : I
K : H
K : 52
K : 38
K : 37
K : 36
K : 35
K : 34
K : 33
K : 21
K : 20
K : 19
K : 18
K : 17
K : 16
K : 15
K : 14
K : 51
K : 50
K : 49
K : 48
K : 47
K : D
K : K
K : -152.06 0 129.12
```

```
K : 0 -LUMB 0
K : R
K : I
K : H
K : 45
K : 44
K : 43
K : 42
K : 41
K : 32
K : 31
K : 30
K : 29
K : 28
K : 27
K : 26
K : 25
K : 24
K : 23
K : 22
K : 7
K : 6
K : 5
K : 4
K : D
K : K
K : -152.06 0 129.12
K : 0 -LUMB 0
K : R
K : I
K : H
K : 75
K : 88
K : 13
K : 89
K : 12
K : 98
K : D
K : K
K : -152.06 0 129.16
K : 0 -LUMB 0
C :
C : ROTATE ABOUT L3/L4
C :
K : R
K : I
K : H
K : 52
K : 38
K : 37
K : 36
K : 35
K : 34
K : 33
K : 21
K : 20
K : 19
K : 18
K : 17
K : 16
K : 15
K : 14
K : 51
K : 50
K : 49
K : 48
```

```
K : 47
K : D
K : K
K : -131.04 0 99.08
K : 0 -LUMB 0
K : R
K : I
K : H
K : 45
K : 44
K : 43
K : 42
K : 41
K : 32
K : 31
K : 30
K : 29
K : 28
K : 27
K : 26
K : 25
K : 24
K : 23
K : 22
K : 7
K : 6
K : 5
K : 4
K : D
K : K
K : -131.04 0 99.08
K : 0 -LUMB 0
K : R
K : I
K : H
K : 75
K : 88
K : 13
K : 89
K : 12
K : 90
K : 11
K : 98
K : D
K : K
K : -131.04 0 99.08
K : 0 -LUMB 0
C :
C :
C : ROTATE ABOUT L4/L5
C :
K : R
K : I
K : H
K : 52
K : 38
K : 37
K : 36
K : 35
K : 34
K : 33
K : 21
K : 20
K : 19
K : 18
K : 17
```

```
K : 16
K : 15
K : 14
K : 51
K : 50
K : 49
K : 48
K : 47
K : D
K : K
K : -110 0 69
K : 0 -LUMB 0
K : R
K : I
K : H
K : 45
K : 44
K : 43
K : 42
K : 41
K : 32
K : 31
K : 30
K : 29
K : 28
K : 27
K : 26
K : 25
K : 24
K : 23
K : 22
K : 7
K : 6
K : 5
K : 4
K : D
K : K
K : -110 0 69
K : 0 -LUMB 0
K : R
K : I
K : H
K : 75
K : 88
K : 13
K : 89
K : 12
K : 90
K : 11
K : 91
K : 10
K : 98
K : D
K : K
K : -110 0 69
K : 0 -LUMB 0
C :
C : ROTATE ABOUT L5/S1
C :
K : R
K : I
K : H
K : 52
K : 38
K : 37
K : 36
```

```
K : 35
K : 34
K : 33
K : 21
K : 20
K : 19
K : 18
K : 17
K : 16
K : 15
K : 14
K : 51
K : 50
K : 49
K : 48
K : 47
K : D
K : K
K : -89 0 39
K : 0 -LUMB 0
K : R
K : I
K : H
K : 45
K : 44
K : 43
K : 42
K : 41
K : 32
K : 31
K : 30
K : 29
K : 28
K : 27
K : 26
K : 25
K : 24
K : 23
K : 22
K : 7
K : 6
K : 5
K : 4
K : D
K : K
K : -89 0 39
K : 0 -LUMB 0
K : R
K : I
K : H
K : 75
K : 92
K : 13
K : 91
K : 12
K : 90
K : 11
K : 89
K : 10
K : 88
K : 9
K : 98
K : D
K : K
K : -89 0 39
K : 0 -LUMB 0
```

```
C :
K : R
K : I
K : H
K : 101
K : D
K : K
K : -100 0 10
K : 0 -mus 0
C :
C : ---TILT JOHN2 INTO TRA---
C :
K : R
K : I
K : *
K : K
K : 13.69 0 -69
K : 0 TILT 0
C :
C : -----CONNECT MUSCLES-----
C :
C :
K : /
K : !AUX
K : L
K : DE
K : *
K : Y
C :
K : /
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 41
K : 1
K : ND
K : H
K : 53
K : 1
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 41
K : 2
K : ND
K : H
K : 53
K : 2
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 41
K : 3
K : ND
K : H
```

```
K : 53
K : 4
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 41
K : 4
K : ND
K : H
K : 53
K : 3
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 41
K : 5
K : ND
K : H
K : 53
K : 5
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 41
K : 6
K : ND
K : H
K : 53
K : 6
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 41
K : 7
K : ND
K : H
K : 53
K : 8
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 41
K : 8
K : ND
K : H
K : 53
```

```
K : 7
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 41
K : 9
K : ND
K : H
K : 53
K : 9
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 41
K : 10
K : ND
K : H
K : 53
K : 9
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 41
K : 11
K : ND
K : H
K : 53
K : 10
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 41
K : 12
K : ND
K : H
K : 53
K : 11
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 41
K : 13
K : ND
K : H
K : 53
K : 13
```

K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 41
K : 14
K : ND
K : H
K : 53
K : 12
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 41
K : 15
K : ND
K : H
K : 53
K : 14
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 41
K : 16
K : ND
K : H
K : 53
K : 15
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 41
K : 17
K : ND
K : H
K : 53
K : 17
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 41
K : 18
K : ND
K : H
K : 53
K : 16
K : D

```
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 41
K : 19
K : ND
K : H
K : 53
K : 18
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 41
K : 20
K : ND
K : H
K : 53
K : 18
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 53
K : 3
K : ND
K : H
K : 5
K : 1
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 53
K : 4
K : ND
K : H
K : 5
K : 2
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 53
K : 5
K : ND
K : H
K : 5
K : 3
K : D
K : !AUX
```

```
K : L
K : P
K : L
K : ND
K : H
K : 53
K : 5
K : ND
K : H
K : 5
K : 8
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 53
K : 6
K : ND
K : H
K : 5
K : 4
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 53
K : 7
K : ND
K : H
K : 5
K : 6
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 53
K : 8
K : ND
K : H
K : 5
K : 5
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 53
K : 9
K : ND
K : H
K : 5
K : 7
K : D
K : !AUX
K : L
```

K : P
K : L
K : ND
K : H
K : 53
K : 12
K : ND
K : H
K : 5
K : 9
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 53
K : 13
K : ND
K : H
K : 5
K : 10
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 53
K : 14
K : ND
K : H
K : 5
K : 11
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 53
K : 14
K : ND
K : H
K : 5
K : 16
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 53
K : 15
K : ND
K : H
K : 5
K : 12
K : D
K : !AUX
K : L
K : P

```
K : L
K : ND
K : H
K : 53
K : 16
K : ND
K : H
K : 5
K : 14
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 53
K : 17
K : ND
K : H
K : 5
K : 13
K : D
K : !AUX
K : L
K : P
K : L
K : ND
K : H
K : 53
K : 18
K : ND
K : H
K : 5
K : 15
K : D
K : A
K : C
K : *
K : 11
K : Y
C :
K : !ECHO ALL
K : /
K : !DO
K : BL
K : U
K : *
K : /
E :
```

APPENDIX B

Spine Joint Center Coordinates

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

ALL COORDINATES ARE IN MM

Coordinates for the C1/SKULL interspace
cp(1)= -213
cp(2)= 0
cp(3)= 612
Coordinates for the C1/C2 interspace
cp(4)= -213
cp(5)= 0
cp(6)= 602
Coordinates for the C2/C3 interspace
cp(7)= -207
cp(8)= 0
cp(9)= 586
Coordinates for the C3/C4 interspace
cp(10)= -204
cp(11)= 0
cp(12)= 571
Coordinates for the C4/C5 interspace
cp(13)= -201
cp(14)= 0
cp(15)= 551
Coordinates for the C5/C6 interspace
cp(16)= -200
cp(17)= 0
cp(18)= 532
Coordinates for the C6/C7 interspace
cp(19)= -203
cp(20)= 0
cp(21)= 511
Coordinates for the C7/C8 interspace
cp(22)= -210
cp(23)= 0
cp(24)= 493

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

Coordinates for the C7/T1 interspace
tp(1)= -210
tp(2)= 0
tp(3)= 493
Coordinates for the T1/T2 interspace
tp(4)= -218
tp(5)= 0
tp(6)= 476
Coordinates for the T2/T3 interspace
tp(7)= -226
tp(8)= 0
tp(9)= 459
Coordinates for the T3/T4 interspace
tp(10)= -231
tp(11)= 0
tp(12)= 440
Coordinates for the T4/T5 interspace
tp(13)= -237
tp(14)= 0
tp(15)= 421
Coordinates for the T5/T6 interspace
tp(16)= -242
tp(17)= 0
tp(18)= 395
Coordinates for the T6/T7 interspace
tp(19)= -241
tp(20)= 0
tp(21)= 367
Coordinates for the T7/T8 interspace
tp(22)= -238
tp(23)= 0
tp(24)= 339
Coordinates for the T8/T9 interspace
tp(25)= -232
tp(26)= 0
tp(27)= 311
Coordinates for the T9/T10 interspace
tp(28)= -225
tp(29)= 0
tp(30)= 281
Coordinates for the T10/T11 interspace
tp(31)= -217
tp(32)= 0
tp(33)= 251
Coordinates for the T11/T12 interspace
tp(34)= -207
tp(35)= 0
tp(36)= 251

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

Coordinates for the T12/L1 interspace
lp(1)= -194.1
lp(2)= 0
lp(3)= 189.2
Coordinates for the L1/L2 interspace
lp(4)= -173.7
lp(5)= 0
lp(6)= 159.16
Coordinates for the L2/L3 interspace
lp(7)= -152.06
lp(8)= 0
lp(9)= 129.12
Coordinates for the L3/L4 interspace
lp(10)= -131.04
lp(11)= 0
lp(12)= 99.08
Coordinates for the L4/L5 interspace
lp(13)= -110.02
lp(14)= 0
lp(15)= 69.04
Coordinates for the L5/S1 interspace
lp(16)= -89
lp(17)= 0
lp(18)= 39

APPENDIX C

Table of Skin Points

Table 1 Skin Points for TLC=0°

	1	2	3	4	5	6	7	8	9	10	11	12	13
X	-230	-275	-280	-283	-280	-273	-278	-273	-280	-283	-280	-275	-230
Y	218	180	133	95	63	25	0	-25	-63	-95	-133	-180	-218
Z	475	475	475	475	475	475	475	475	475	475	475	475	475
X	-230	-285	-290	-293	-290	-283	-288	-283	-290	-293	-290	-285	-230
Y	220	180	133	95	63	25	0	-25	-63	-95	-133	-180	-220
Z	450	450	450	450	450	450	450	450	450	450	450	450	450
X	-230	-275	-295	-305	-300	-295	-298	-295	-300	-305	-295	-275	-230
Y	210	175	133	95	63	25	0	-25	-63	-95	-133	-175	-210
Z	400	400	400	400	400	400	400	400	400	400	400	400	400
X	-168	-265	-288	-308	-302	-300	-302	-300	-302	-308	-288	-265	-168
Y	180	165	133	95	63	25	0	-25	-63	-95	-133	-165	-180
Z	350	350	350	350	350	350	350	350	350	350	350	350	350
X	-155	-255	-280	-303	-297	-295	-295	-295	-297	-303	-280	-255	-155
Y	170	160	133	95	63	25	0	-25	-63	-95	-133	-160	-170
Z	300	300	300	300	300	300	300	300	300	300	300	300	300
X	-145	-220	-260	-285	-288	-288	-290	-288	-288	-285	-260	-220	-145
Y	168	160	133	95	63	25	0	-25	-63	-95	-133	-160	-168
Z	250	250	250	250	250	250	250	250	250	250	250	250	250
X	-130	-200	-245	-263	-270	-268	-273	-268	-270	-263	-245	-200	-130
Y	165	158	133	95	63	25	0	-25	-63	-95	-133	-158	-165
Z	200	200	200	200	200	200	200	200	200	200	200	200	200
X	-100	-170	-205	-235	-246	-245	-250	-245	-246	-235	-205	-170	-100
Y	160	155	133	95	63	25	0	-25	-63	-95	-133	-155	-160
Z	150	150	150	150	150	150	150	150	150	150	150	150	150
X	-65	-120	-180	-205	-220	-218	-223	-218	-220	-205	-180	-120	-65
Y	155	148	133	95	63	25	0	-25	-63	-95	-133	-148	-155
Z	100	100	100	100	100	100	100	100	100	100	100	100	100
X	-45	-100	-150	-185	-188	-185	-190	-185	-188	-185	-150	-100	-45
Y	155	150	133	95	63	25	0	-25	-63	-95	-133	-150	-155
Z	50	50	50	50	50	50	50	50	50	50	50	50	50
X	-25	-80	-140	-158	-158	-155	-150	-155	-158	-158	-140	-80	-25
Y	165	155	133	95	63	25	0	-25	-63	-95	-133	-155	-165
Z	0	0	0	0	0	0	0	0	0	0	0	0	0
X	-15	-55	-80	-122	-124	-123	-122	-123	-124	-122	-80	-55	-15
Y	165	160	145	95	63	25	0	-25	-63	-95	-145	-160	-165
Z	0	-20	-33	-52	-54	-53	-52	-53	-54	-52	-33	-20	0
X	-3	-25	-50	-83	-85	-83	-82	-83	-85	-83	-50	-25	-3
Y	165	160	145	95	63	25	0	-25	-63	-95	-145	-160	-165
Z	0	-25	-50	-83	-85	-83	-82	-83	-85	-83	-50	-25	0
X	0	0	0	0	0	0	0	0	0	0	0	0	0
Y	165	160	145	95	63	25	0	-25	-63	-95	-145	-160	-165
Z	0	-30	-65	-96	-96	-94	-92	-94	-96	-96	-65	-30	0
X	50	50	50	50	50	50	50	50	50	50	50	50	50
Y	165	160	145	95	63	25	0	-25	-63	-95	-145	-160	-165
Z	0	-30	-65	-88	-88	-86	-85	-86	-88	-88	-65	-30	0

Table 2 Skin Points for TLC= -10°

	1	2	3	4	5	6	7	8	9	10	11	12	13
X	-225	-260	-265	-270	-274	-270	-265	-270	-274	-270	-265	-260	-225
Y	220	180	133	95	63	25	0	-25	-63	-95	-133	-180	-220
Z	475	475	475	475	475	475	475	475	475	475	475	475	475
X	-225	-260	-275	-280	-285	-280	-277	-280	-285	-280	-275	-260	-225
Y	220	180	133	95	63	25	0	-25	-63	-95	-133	-180	-220
Z	450	450	450	450	450	450	450	450	450	450	450	450	450
X	-238	-270	-287	-294	-300	-293	-295	-293	-300	-294	-287	-270	-238
Y	210	175	133	95	63	25	0	-25	-63	-95	-133	-175	-210
Z	400	400	400	400	400	400	400	400	400	400	400	400	400
X	-200	-250	-283	-305	-311	-307	-305	-307	-311	-305	-283	-250	-200
Y	180	165	133	95	63	25	0	-25	-63	-95	-133	-165	-180
Z	350	350	350	350	350	350	350	350	350	350	350	350	350
X	-160	-228	-290	-309	-308	-306	-305	-306	-308	-309	-290	-228	-160
Y	170	160	133	95	63	25	0	-25	-63	-95	-133	-160	-170
Z	300	300	300	300	300	300	300	300	300	300	300	300	300
X	-150	-215	-269	-288	-298	-298	-300	-298	-298	-288	-269	-215	-150
Y	168	160	133	95	63	25	0	-25	-63	-95	-133	-160	-168
Z	250	250	250	250	250	250	250	250	250	250	250	250	250
X	-138	-210	-258	-275	-284	-283	-285	-283	-284	-275	-258	-210	-138
Y	165	158	133	95	63	25	0	-25	-63	-95	-133	-158	-165
Z	200	200	200	200	200	200	200	200	200	200	200	200	200
X	-110	-180	-205	-245	-263	-263	-264	-263	-263	-245	-205	-180	-110
Y	160	155	133	95	63	25	0	-25	-63	-95	-133	-155	-160
Z	150	150	150	150	150	150	150	150	150	150	150	150	150
X	-75	-143	-180	-217	-229	-230	-235	-230	-229	-217	-180	-143	-75
Y	155	148	133	95	63	25	0	-25	-63	-95	-133	-148	-155
Z	100	100	100	100	100	100	100	100	100	100	100	100	100
X	-40	-125	-158	-183	-194	-202	-203	-202	-194	-183	-158	-125	-40
Y	155	150	133	95	63	25	0	-25	-63	-95	-133	-150	-155
Z	50	50	50	50	50	50	50	50	50	50	50	50	50
X	-30	-120	-148	-163	-167	-167	-165	-167	-167	-163	-148	-120	-30
Y	165	155	133	95	63	25	0	-25	-63	-95	-133	-155	-165
Z	0	0	0	0	0	0	0	0	0	0	0	0	0
X	-15	-89	-118	-133	-135	-134	-132	-134	-135	-133	-118	-89	-15
Y	165	160	145	95	63	25	0	-25	-63	-95	-145	-160	-165
Z	0	-30	-45	-51	-53	-52	-50	-52	-53	-51	-45	-30	0
X	-3	-28	-47	-58	-60	-58	-57	-58	-60	-58	-47	-28	-3
Y	165	160	145	95	63	25	0	-25	-63	-95	-145	-160	-165
Z	0	-30	-59	-93	-95	-93	-92	-93	-95	-93	-59	-30	0
X	0	0	0	0	0	0	0	0	0	0	0	0	0
Y	165	160	145	95	63	25	0	-25	-63	-95	-145	-160	-165
Z	0	-30	-65	-96	-96	-94	-92	-94	-96	-96	-65	-30	0
X	50	50	50	50	50	50	50	50	50	50	50	50	50
Y	165	160	145	95	63	25	0	-25	-63	-95	-145	-160	-165
Z	0	-30	-65	-86	-85	-84	-82	-84	-85	-86	-65	-30	0

Table 3 Skin Points for TLC=10°

	1	2	3	4	5	6	7	8	9	10	11	12	13
X	-250	-287	-290	-293	-290	-289	-288	-289	-290	-293	-290	-287	-250
Y	220	180	133	95	63	25	0	-25	-63	-95	-133	-180	-220
Z	475	475	475	475	475	475	475	475	475	475	475	475	475
X	-250	-296	-299	-301	-299	-295	-297	-295	-299	-301	-299	-296	-250
Y	220	180	133	95	63	25	0	-25	-63	-95	-133	-180	-220
Z	450	450	450	450	450	450	450	450	450	450	450	450	450
X	-235	-280	-300	-308	-305	-300	-303	-300	-305	-308	-300	-280	-235
Y	210	175	133	95	63	25	0	-25	-63	-95	-133	-175	-210
Z	400	400	400	400	400	400	400	400	400	400	400	400	400
X	-175	-275	-300	-312	-310	-304	-306	-304	-310	-312	-300	-275	-175
Y	180	165	133	95	63	25	0	-25	-63	-95	-133	-165	-180
Z	350	350	350	350	350	350	350	350	350	350	350	350	350
X	-125	-260	-285	-305	-304	-298	-298	-298	-304	-305	-285	-260	-125
Y	170	160	133	95	63	25	0	-25	-63	-95	-133	-160	-170
Z	300	300	300	300	300	300	300	300	300	300	300	300	300
X	-115	-220	-260	-283	-285	-285	-283	-285	-285	-283	-260	-220	-115
Y	168	160	133	95	63	25	0	-25	-63	-95	-133	-160	-168
Z	250	250	250	250	250	250	250	250	250	250	250	250	250
X	-105	-180	-225	-250	-260	-259	-258	-259	-260	-250	-225	-180	-105
Y	165	158	133	95	63	25	0	-25	-63	-95	-133	-158	-165
Z	200	200	200	200	200	200	200	200	200	200	200	200	200
X	-75	-165	-200	-230	-235	-236	-233	-236	-235	-230	-200	-165	-75
Y	160	155	133	95	63	25	0	-25	-63	-95	-133	-155	-160
Z	150	150	150	150	150	150	150	150	150	150	150	150	150
X	-40	-120	-180	-200	-203	-203	-200	-203	-203	-200	-180	-120	-40
Y	155	148	133	95	63	25	0	-25	-63	-95	-133	-148	-155
Z	100	100	100	100	100	100	100	100	100	100	100	100	100
X	-25	-90	-140	-165	-168	-170	-165	-170	-168	-165	-140	-90	-25
Y	155	150	133	95	63	25	0	-25	-63	-95	-133	-150	-155
Z	50	50	50	50	50	50	50	50	50	50	50	50	50
X	-15	-65	-125	-143	-145	-143	-140	-143	-145	-143	-125	-65	-15
Y	165	155	133	95	63	25	0	-25	-63	-95	-133	-155	-165
Z	0	0	0	0	0	0	0	0	0	0	0	0	0
X	-10	-45	-73	-113	-115	-114	-113	-114	-115	-113	-73	-45	-10
Y	165	160	145	95	63	25	0	-25	-63	-95	-145	-160	-165
Z	0	-30	-45	-51	-53	-52	-50	-52	-53	-51	-45	-30	0
X	-3	-24	-45	-65	-66	-65	-64	-65	-66	-65	-45	-24	-3
Y	165	160	145	95	63	25	0	-25	-63	-95	-145	-160	-165
Z	0	-30	-59	-93	-95	-93	-92	-93	-95	-93	-59	-30	0
X	0	0	0	0	0	0	0	0	0	0	0	0	0
Y	165	160	145	95	63	25	0	-25	-63	-95	-145	-160	-165
Z	0	-30	-65	-96	-96	-94	-92	-94	-96	-96	-65	-30	0
X	50	50	50	50	50	50	50	50	50	50	50	50	50
Y	165	160	145	95	63	25	0	-25	-63	-95	-145	-160	-165
Z	0	-30	-65	-86	-85	-84	-82	-84	-85	-86	-65	-30	0

Table 4 Skin Points for TLC=20°

	1	2	3	4	5	6	7	8	9	10	11	12	13
X	-260	-305	-310	-314	-311	-310	-310	-310	-311	-314	-310	-305	-260
Y	220	180	133	95	63	25	0	-25	-63	-95	-133	-180	-220
Z	475	475	475	475	475	475	475	475	475	475	475	475	475
X	-260	-314	-316	-318	-317	-313	-315	-313	-317	-318	-316	-314	-260
Y	220	180	133	95	63	25	0	-25	-63	-95	-133	-180	-220
Z	450	450	450	450	450	450	450	450	450	450	450	450	450
X	-245	-296	-316	-320	-319	-316	-318	-316	-319	-320	-316	-296	-245
Y	210	175	133	95	63	25	0	-25	-63	-95	-133	-175	-210
Z	400	400	400	400	400	400	400	400	400	400	400	400	400
X	-175	-280	-310	-320	-318	-313	-315	-313	-318	-320	-310	-280	-175
Y	180	165	133	95	63	25	0	-25	-63	-95	-133	-165	-180
Z	350	350	350	350	350	350	350	350	350	350	350	350	350
X	-135	-260	-284	-304	-305	-300	-300	-300	-305	-304	-284	-260	-135
Y	170	160	133	95	63	25	0	-25	-63	-95	-133	-160	-170
Z	300	300	300	300	300	300	300	300	300	300	300	300	300
X	-115	-230	-254	-277	-280	-279	-276	-279	-280	-277	-254	-230	-115
Y	168	160	133	95	63	25	0	-25	-63	-95	-133	-160	-168
Z	250	250	250	250	250	250	250	250	250	250	250	250	250
X	-100	-150	-200	-239	-249	-248	-248	-248	-249	-239	-200	-150	-100
Y	165	158	133	95	63	25	0	-25	-63	-95	-133	-158	-165
Z	200	200	200	200	200	200	200	200	200	200	200	200	200
X	-85	-140	-180	-212	-219	-220	-215	-220	-219	-212	-180	-140	-85
Y	160	155	133	95	63	25	0	-25	-63	-95	-133	-155	-160
Z	150	150	150	150	150	150	150	150	150	150	150	150	150
X	-60	-90	-150	-178	-188	-188	-178	-188	-188	-178	-150	-90	-60
Y	155	148	133	95	63	25	0	-25	-63	-95	-133	-148	-155
Z	100	100	100	100	100	100	100	100	100	100	100	100	100
X	-30	-70	-120	-145	-153	-155	-145	-155	-153	-145	-120	-70	-30
Y	155	150	133	95	63	25	0	-25	-63	-95	-133	-150	-155
Z	50	50	50	50	50	50	50	50	50	50	50	50	50
X	-20	-60	-115	-134	-136	-135	-130	-135	-136	-134	-115	-60	-20
Y	165	155	133	95	63	25	0	-25	-63	-95	-133	-155	-165
Z	0	0	0	0	0	0	0	0	0	0	0	0	0
X	-8	-42	-68	-113	-115	-114	-111	-114	-115	-113	-68	-42	-8
Y	165	160	145	95	63	25	0	-25	-63	-95	-145	-160	-165
Z	0	-8	-24	-40	-42	-41	-40	-41	-42	-40	-24	-8	0
X	-3	-24	-45	-65	-66	-65	-64	-65	-66	-65	-45	-24	-3
Y	165	160	145	95	63	25	0	-25	-63	-95	-145	-160	-165
Z	0	-23	-50	-83	-85	-84	-82	-84	-85	-83	-50	-23	0
X	0	0	0	0	0	0	0	0	0	0	0	0	0
Y	165	160	145	95	63	25	0	-25	-63	-95	-145	-160	-165
Z	0	-30	-65	-96	-96	-94	-92	-94	-96	-96	-65	-30	0
X	50	50	50	50	50	50	50	50	50	50	50	50	50
Y	165	160	145	95	63	25	0	-25	-63	-95	-145	-160	-165
Z	0	-30	-65	-86	-86	-84	-82	-84	-86	-86	-65	-30	0

Table 5 Skin Points for TLC=30°

	1	2	3	4	5	6	7	8	9	10	11	12	13
X	-260	-305	-312	-315	-312	-311	-312	-311	-312	-315	-312	-305	-260
Y	218	180	133	95	63	25	0	-25	-63	-95	-133	-180	-218
Z	475	475	475	475	475	475	475	475	475	475	475	475	475
X	-260	-318	-320	-323	-320	-315	-320	-315	-320	-323	-320	-318	-260
Y	220	180	133	95	63	25	0	-25	-63	-95	-133	-180	-220
Z	450	450	450	450	450	450	450	450	450	450	450	450	450
X	-260	-305	-318	-326	-323	-318	-320	-318	-323	-326	-318	-305	-260
Y	210	175	133	95	63	25	0	-25	-63	-95	-133	-175	-210
Z	400	400	400	400	400	400	400	400	400	400	400	400	400
X	-205	-250	-292	-318	-317	-313	-312	-313	-317	-318	-292	-250	-205
Y	180	165	133	95	63	25	0	-25	-63	-95	-133	-165	-180
Z	350	350	350	350	350	350	350	350	350	350	350	350	350
X	-150	-240	-275	-302	-299	-296	-295	-296	-299	-302	-275	-240	-150
Y	170	160	133	95	63	25	0	-25	-63	-95	-133	-160	-170
Z	300	300	300	300	300	300	300	300	300	300	300	300	300
X	-120	-200	-246	-268	-271	-270	-271	-270	-271	-268	-246	-200	-120
Y	168	160	133	95	63	25	0	-25	-63	-95	-133	-160	-168
Z	250	250	250	250	250	250	250	250	250	250	250	250	250
X	-100	-163	-200	-225	-235	-236	-235	-236	-235	-225	-200	-163	-100
Y	165	158	133	95	63	25	0	-25	-63	-95	-133	-158	-165
Z	200	200	200	200	200	200	200	200	200	200	200	200	200
X	-50	-130	-165	-195	-200	-202	-195	-202	-200	-195	-165	-130	-50
Y	160	155	133	95	63	25	0	-25	-63	-95	-133	-155	-160
Z	150	150	150	150	150	150	150	150	150	150	150	150	150
X	-10	-80	-140	-160	-165	-170	-155	-170	-165	-160	-140	-80	-10
Y	155	148	133	95	63	25	0	-25	-63	-95	-133	-148	-155
Z	100	100	100	100	100	100	100	100	100	100	100	100	100
X	0	-60	-110	-135	-138	-140	-130	-140	-138	-135	-110	-60	0
Y	155	150	133	95	63	25	0	-25	-63	-95	-133	-150	-155
Z	50	50	50	50	50	50	50	50	50	50	50	50	50
X	10	-42	-102	-120	-122	-117	-112	-117	-122	-120	-102	-42	10
Y	165	155	133	95	63	25	0	-25	-63	-95	-133	-155	-165
Z	0	0	0	0	0	0	0	0	0	0	0	0	0
X	-15	-38	-65	-103	-105	-104	-102	-104	-105	-103	-65	-38	-15
Y	165	160	145	95	63	25	0	-25	-63	-95	-145	-160	-165
Z	0	-8	-23	-39	-40	-39	-38	-39	-40	-39	-23	-8	0
X	-3	-24	-45	-65	-66	-65	-64	-65	-66	-65	-45	-24	-3
Y	165	160	145	95	63	25	0	-25	-63	-95	-145	-160	-165
Z	0	-23	-50	-83	-85	-83	-82	-83	-85	-83	-50	-23	0
X	0	0	0	0	0	0	0	0	0	0	0	0	0
Y	165	160	145	95	63	25	0	-25	-63	-95	-145	-160	-165
Z	0	-30	-65	-96	-96	-94	-92	-94	-96	-96	-65	-30	0
X	50	50	50	50	50	50	50	50	50	50	50	50	50
Y	165	160	145	95	63	25	0	-25	-63	-95	-145	-160	-165
Z	0	-30	-65	-86	-86	-84	-82	-84	-86	-86	-65	-30	0

Table 6 Skin Points for TLC=40°

	1	2	3	4	5	6	7	8	9	10	11	12	13
X	-300	-320	-350	-354	-350	-347	-348	-347	-350	-354	-350	-320	-300
Y	218	180	133	95	63	25	0	-25	-63	-95	-133	-180	-218
Z	475	475	475	475	475	475	475	475	475	475	475	475	475
X	-300	-325	-350	-355	-350	-347	-350	-347	-350	-355	-350	-325	-300
Y	220	180	133	95	63	25	0	-25	-63	-95	-133	-180	-220
Z	450	450	450	450	450	450	450	450	450	450	450	450	450
X	-290	-315	-348	-356	-352	-346	-348	-346	-352	-356	-348	-315	-290
Y	210	175	133	95	63	25	0	-25	-63	-95	-133	-175	-210
Z	400	400	400	400	400	400	400	400	400	400	400	400	400
X	-210	-260	-330	-345	-343	-340	-338	-340	-343	-345	-330	-260	-210
Y	180	165	133	95	63	25	0	-25	-63	-95	-133	-165	-180
Z	350	350	350	350	350	350	350	350	350	350	350	350	350
X	-165	-250	-300	-328	-325	-322	-320	-322	-325	-328	-300	-250	-165
Y	170	160	133	95	63	25	0	-25	-63	-95	-133	-160	-170
Z	300	300	300	300	300	300	300	300	300	300	300	300	300
X	-130	-215	-260	-285	-292	-286	-285	-286	-292	-285	-260	-215	-130
Y	168	160	133	95	63	25	0	-25	-63	-95	-133	-160	-168
Z	250	250	250	250	250	250	250	250	250	250	250	250	250
X	-110	-175	-210	-239	-249	-250	-246	-250	-249	-239	-210	-175	-110
Y	165	158	133	95	63	25	0	-25	-63	-95	-133	-158	-165
Z	200	200	200	200	200	200	200	200	200	200	200	200	200
X	-75	-140	-175	-205	-213	-215	-205	-215	-213	-205	-175	-140	-75
Y	160	155	133	95	63	25	0	-25	-63	-95	-133	-155	-160
Z	150	150	150	150	150	150	150	150	150	150	150	150	150
X	-35	-100	-150	-165	-175	-178	-168	-178	-175	-165	-150	-100	-35
Y	155	148	133	95	63	25	0	-25	-63	-95	-133	-148	-155
Z	100	100	100	100	100	100	100	100	100	100	100	100	100
X	-20	-70	-120	-145	-150	-152	-140	-152	-150	-145	-120	-70	-20
Y	155	150	133	95	63	25	0	-25	-63	-95	-133	-150	-155
Z	50	50	50	50	50	50	50	50	50	50	50	50	50
X	-15	-60	-120	-134	-135	-133	-130	-133	-135	-134	-120	-60	-15
Y	165	155	133	95	63	25	0	-25	-63	-95	-133	-155	-165
Z	0	0	0	0	0	0	0	0	0	0	0	0	0
X	-10	-38	-65	-107	-112	-109	-106	-109	-112	-107	-65	-38	-10
Y	165	160	145	95	63	25	0	-25	-63	-95	-145	-160	-165
Z	0	-8	-23	-45	-40	-39	-38	-39	-40	-45	-23	-8	0
X	-3	-24	-45	-65	-66	-65	-64	-65	-66	-65	-45	-24	-3
Y	165	160	145	95	63	25	0	-25	-63	-95	-145	-160	-165
Z	0	-23	-50	-83	-85	-83	-82	-83	-85	-83	-50	-23	0
X	0	0	0	0	0	0	0	0	0	0	0	0	0
Y	165	160	145	95	63	25	0	-25	-63	-95	-145	-160	-165
Z	0	-30	-65	-96	-96	-94	-92	-94	-96	-96	-65	-30	0
X	50	50	50	50	50	50	50	50	50	50	50	50	50
Y	165	160	145	95	63	25	0	-25	-63	-95	-145	-160	-165
Z	0	-30	-65	-86	-86	-84	-82	-84	-86	-86	-65	-30	0

APPENDIX D

JOHN 3-D CROSS SECTIONS

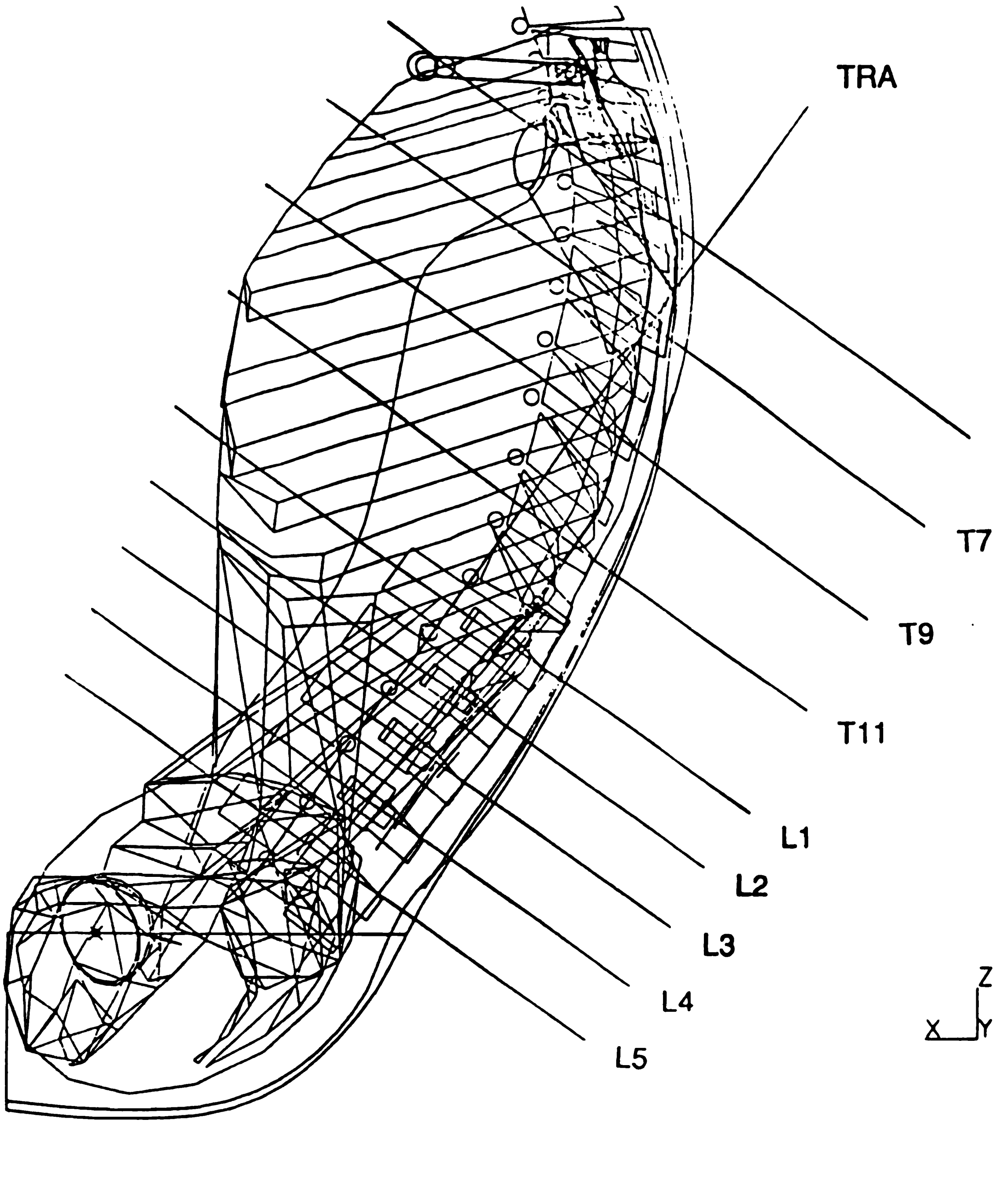

FIGURE 42: JOHN 3-D TORSO SIDE VIEW WITH SECTIONS

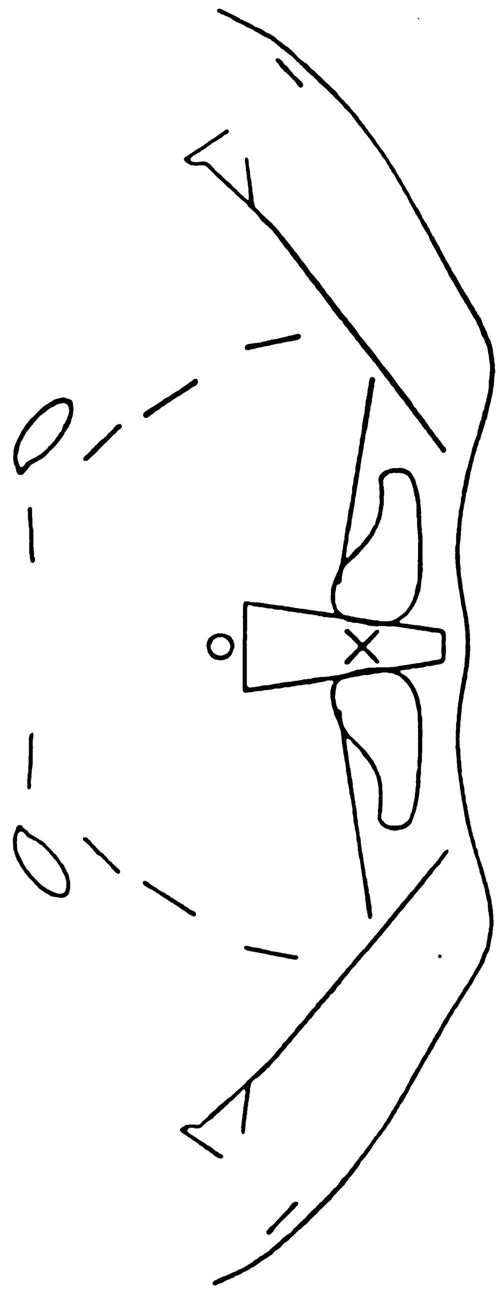

FIGURE 43: SECTION AT T5

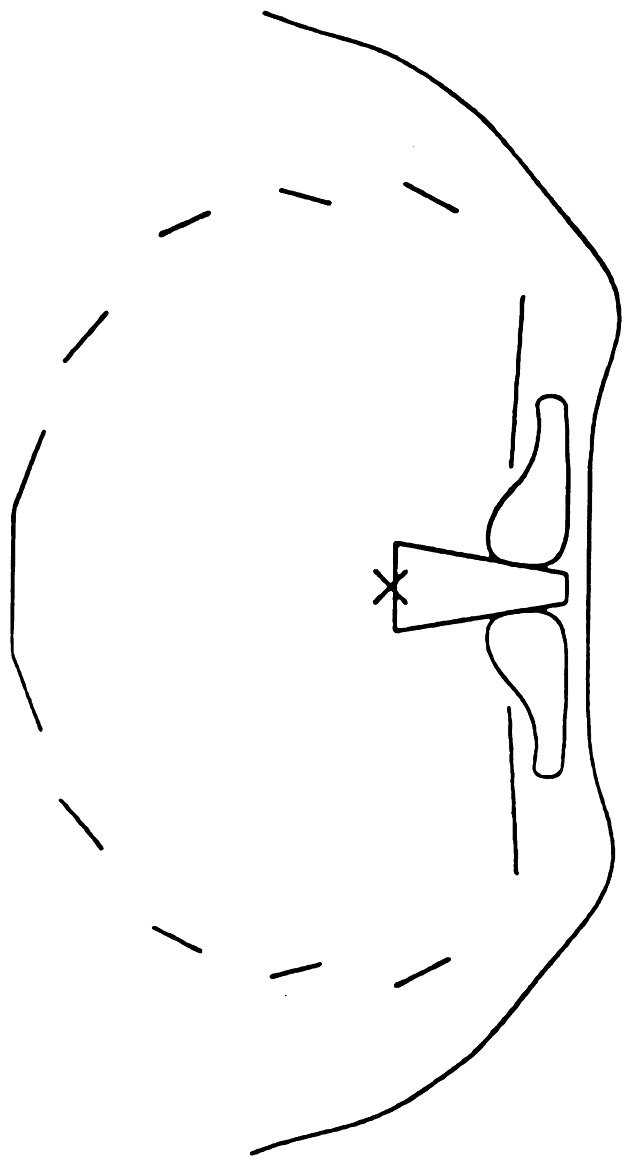

FIGURE 44: SECTION AT T7

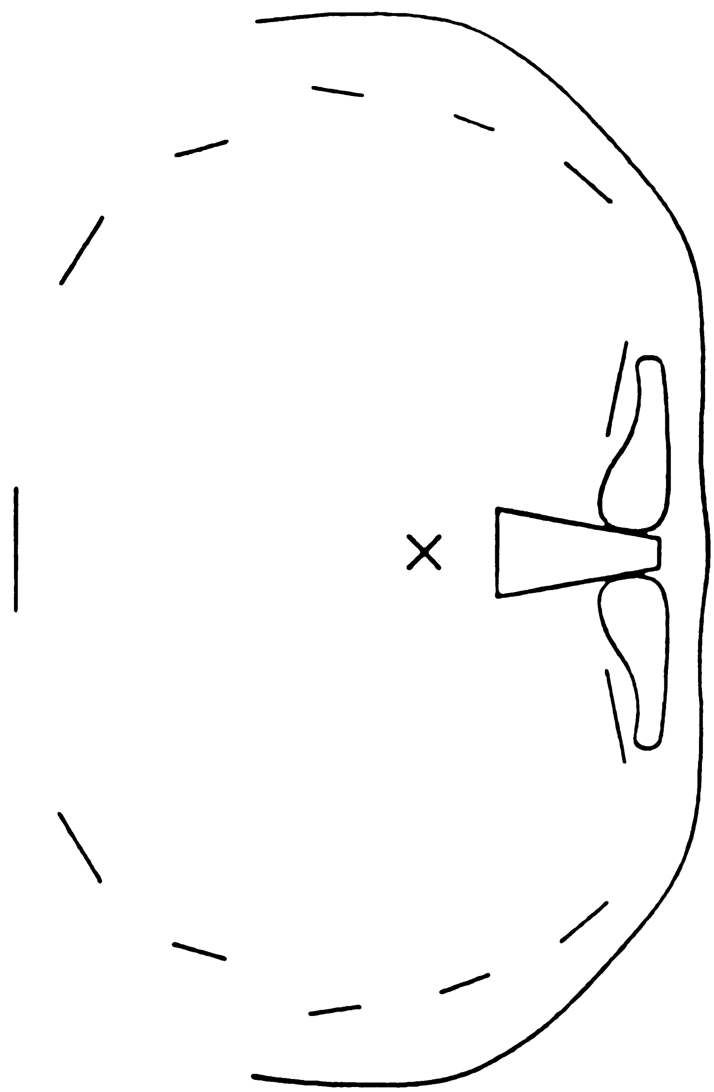

FIGURE 45: SECTION AT T9

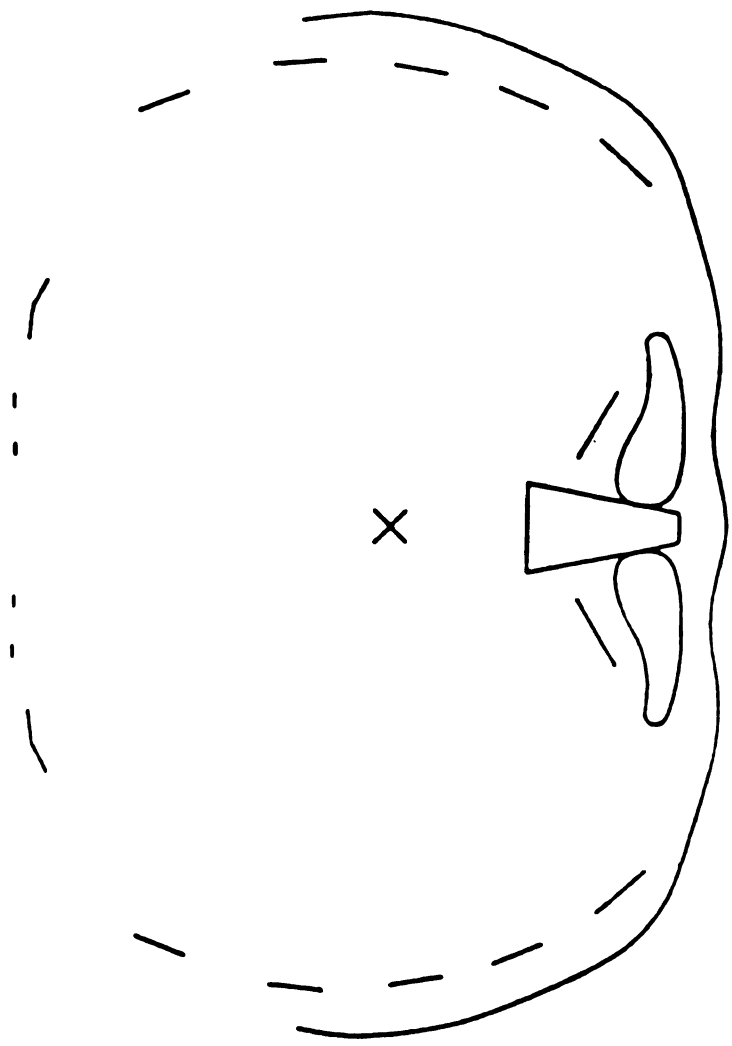

FIGURE 46: SECTION AT T11

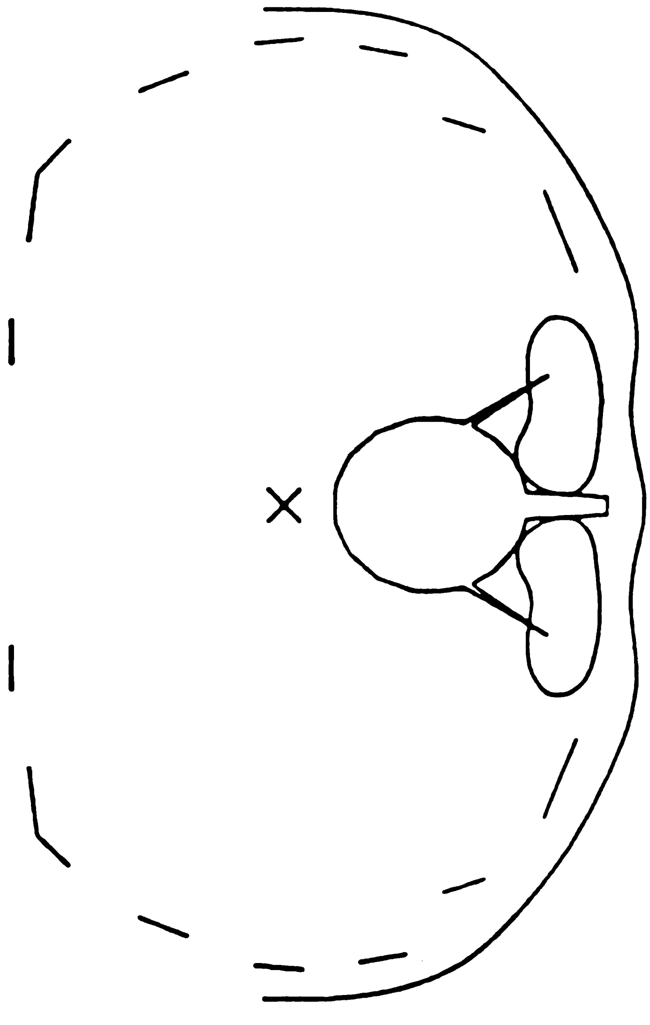

FIGURE 47: SECTION AT L1

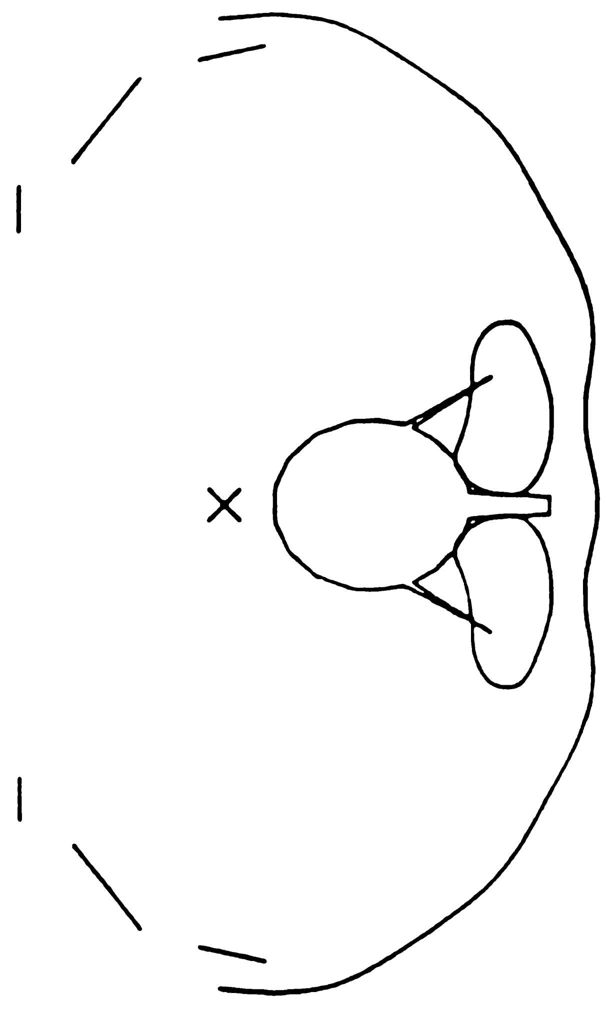

FIGURE 48: SECTION AT L2

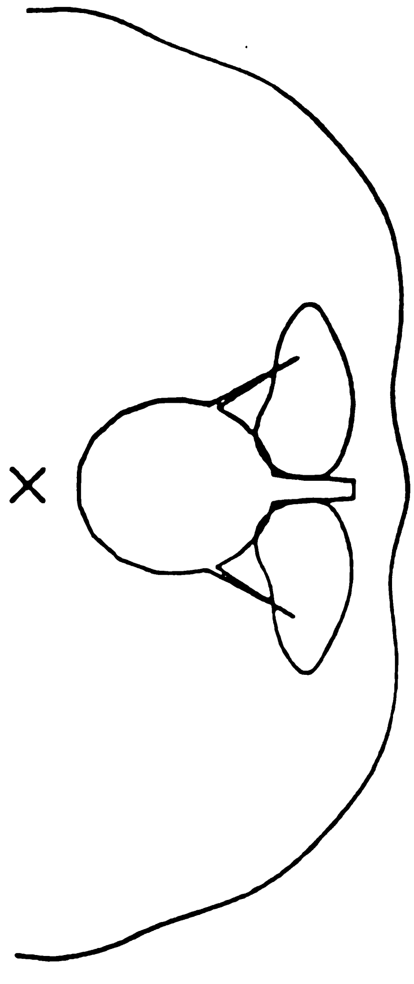

FIGURE 49: SECTION AT L3

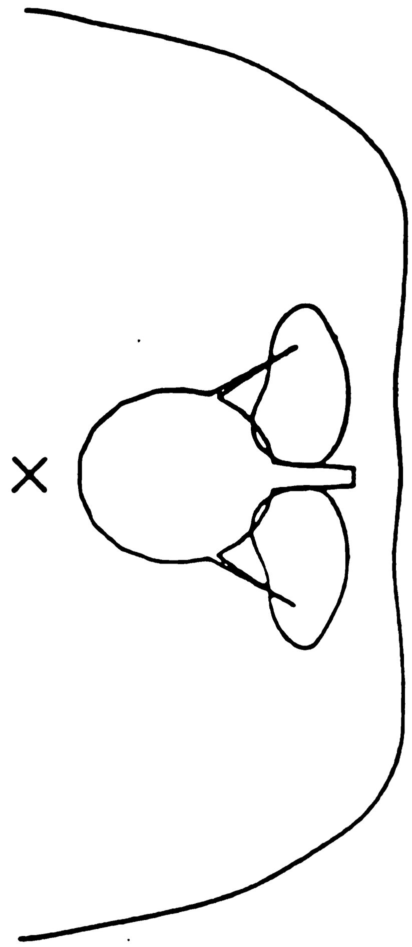

FIGURE 50: SECTION AT L4

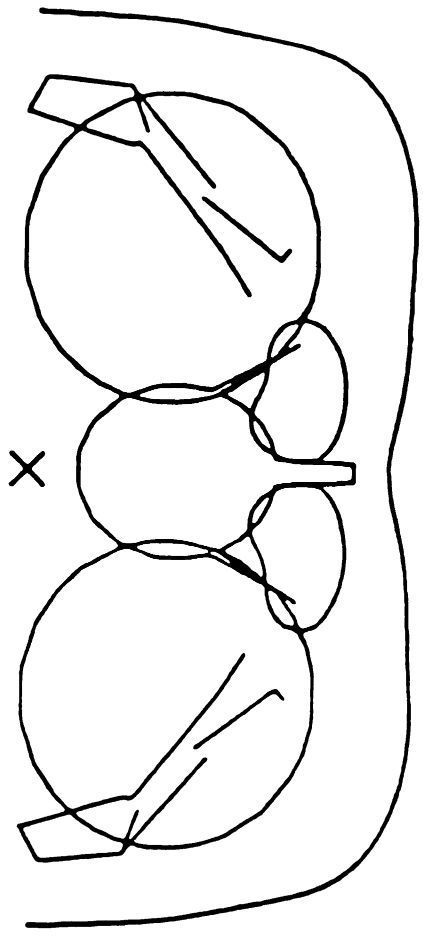

FIGURE 51: SECTION AT L5

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