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INFLUENCE OF MOTOR VEHICLE SEAT GEOMETRY
ON PELVIC INCLINATION

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Master's degree in Biomechanics

Herbert M. Reynolds
Major professor

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INFLUENCE OF MOTOR VEHICLE SEAT GEOMETRY
ON PELVIC INCLINATION

By

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ABSTRACT

INFLUENCE OF MOTOR VEHICLE SEAT GEOMETRY ON PELVIC INCLINATION

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The purpose of the study was to investigate the influence of seat geometry and physical characteristics on pelvic inclination. Twenty-four males were studied in hard seat geometries representative of motor vehicle seating postures. A sonic digitizer was used to measure the inclination of the pelvis. The pelvis rotated 6° for every 11° increase in seat back angle from 108° to 130°, and 1° for every 8 cm decrease in seat height from 31 cm to 15 cm. Minimal correlation was found between physical characteristics and pelvic inclination. The center of rotation (CR) of the pelvis was 12 cm in front of the seat reference point and 3 cm below the seat pan. A 2.5 cm rearward translation of CR was calculated by increasing seat back angle to 130°. Subjects were measured in their preferred seat geometry. A method for estimating the location of pelvic landmarks was presented.

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INTRODUCTION

The goals of automotive seat design are to optimize function, safety and comfort of the driver. The initial position of the occupant in the automobile seat is dependent upon the contour and geometry of the seat, personal preference and the tasks of driving (Reynolds and Hubbard, 1986). Knowledge of the initial position of the driver would assist seat designers in achieving their goals.

In automotive seat design, the driver should be positioned so as to optimize function. Driving requires continuous observation of the environment while maintaining a fixed position in a seat over a long period of time. As a result, joint angles are constrained within a narrow range to minimize stress without compromising the ease of access to the vehicle controls.

In the driver's seat, the buttock and thighs of the occupant rest on the seat pan while the torso rests on the seat back. The seat pan is inclined rearwards to prevent the driver from sliding forwards (Åkerblom, 1948) and help restrain the driver in the seat during an emergency stop (Jacobs et al, 1980). The seat back is inclined rearwards to reduce axial loading on the spine and reduce spinal stress from road shock and vibration (Troup, 1978). Upon

sitting, the pelvis rotates rearward and the lumbar spine moves toward kyphosis (Åkerblom, 1948). How variations in seat design and physical differences between individuals influence the posture of the pelvis and lumbar spine is largely unknown.

The location and orientation of the pelvis within the vehicle seat determines how effectively a seat belt system restrains the occupant in the event of a crash. Sato (1987) found that many occupants who were seriously injured or killed in car crashes appeared to have improper placement of their seat belts. He postulated that the seat belt rode up over the anterior superior iliac spines (ASIS) and restrained the occupant through the abdomen thus causing intra-abdominal injuries. Knowledge of the location and orientation of the pelvis will provide effective guidelines for placement and orientation of the seat belt system to insure effective restraint of the pelvis in a crash.

Inclination of the pelvis in the initial position may also influence the comfort of the driver by increasing stress on the posterior soft tissue structures of the low back. The pelvis rotates rearward 28° to 40° when moving from standing to sitting without a seat back (Åkerblom, 1948; Schoberth, 1962; Carlsöö, 1972; Andersson et al, 1979). Radiographic studies of various sitting postures have demonstrated a relationship between pelvic inclination and lumbar spine curvature (Keegan, 1953; Andersson et al, 1979). Andersson et al (1974a) states that, "the posture of

the lumbar spine is directly related to the inclination of the pelvis, i.e. the lumbar spine moves toward lordosis when the pelvis rotates forwards, and towards kyphosis when it rotates backwards." Therefore, knowledge of the mechanical events of the pelvis in seating, can be used to infer changes in lumbar spine curvature and possibly comfort and health of the seated operator.

The purposes of this study were therefore to:

1. Establish baseline data on pelvic angle in hard seat geometries representative of motor vehicle seating.

2. Develop a methodology to estimate the location and orientation of the pelvis.

3. Investigate the reproducibility of preferred seat geometries in a hard seat.

LITERATURE REVIEW

<u>Pelvic Inclination/Lumbar Curvature in Seating</u>: In seating, inclination of the pelvis can be influenced by the geometry of the seat as well as posture of the lower extremities. Åkerblom (1948) measured lumbar curvature and pelvic inclination using lateral radiographs of 36 subjects. The radiographs were taken with the subjects sitting relaxed at seat heights of 37 cm and 50 cm without back support. No significant difference in pelvic inclination or lumbar curvature was reported between the two seat heights.

Keegan (1953) examined the change in lumbar curvature of two subjects in various sitting postures by superimposing the lateral radiographs of sacrums. The male subject sat in a chair with lumbar support while the female subject sat in a straight chair. The lumbar spines of both subjects moved toward kyphosis when the knees were fully extended from 90°. The male subject was asked to flex his knees beneath the chair which resulted in the lumbar spine moving toward lordosis. Keegan attributed the change in lumbar curvature to the change in tension of the posterior thigh muscles. The lumbar spine of the female subject moved toward lordosis when lumbar support was used in sitting.

Using a pelvic plate to track the pelvis, Demster(1955) took side-view photographs of 41 seated subjects to measure change in pelvic inclination as a function of seat height. Subjects of four different body types sat without a seat back and maintained their knees in full extension. Photographs were taken incrementally from a seat height of 0 cm through 76 cm. From seat heights of 0 through 38 cm, the pelvis rotated 13° forward. Minimal change was noted at seat heights of 38 cm through 61 cm, but from 61 cm through 76 cm seat heights, the pelvis rotated forward another 7°. No difference was found between subjects of different body types.

Geoffrey (1961) radiographed twelve male subjects of 80th percentile stature and weight in two sitting postures. In the first posture, subjects were seated erect while in the second posture subjects sat slumped in a bench style automobile seat with a 113° seat back angle. The average pelvic rotation from the erect sitting to the automobile sitting posture was 29.8° ±9.9° From the radiographic data, the hip to shoulder joint geometry and back contour from above the lumbar spine to the buttocks were measured. From these measurements and the appendicular linkage system measurements of Demster (1955), a side view drafting template has been constructed known as "Oscar." This template has been used by the automobile industry as a tool for designing space and seating requirements.

Burandt (1969) studied pelvic inclination as a function of seat pan angle. Radiographs were taken of 21 female switchboard operators with the seat pan angulated 6° forward and 6° rearward from the horizontal. The pelves of these subjects were found to be more upright when the seat pan was sloped rearward. This finding was interpreted as a reaction of the erector spinae muscles to the forces acting on the lumbar spine and the tendency of the pelvis to roll down the slope of the seat pan.

Nyquist and Patrick (1976) investigated the geometry of the lumbar spine and pelvis using radiographs of two vehicle seated operators. Initial attempts with an actual vehicle seat failed due to interference of the seat cushion. Therefore, plaster molds of each occupant/seat interface were used to construct a wooden seat for each subject. The inclination of the pelvis was determined by the included angle of a line drawn in the sagittal plane from the ASIS to the pubic symphysis and a vertical axis. The measured angles of the pelves of the two volunteers were 54.5° and 44.0°, respectively.

Andersson et al (1979) radiographed ten subjects in an experimental chair to determine the affect of various support parameters on pelvic inclination and lumbar curvature. Pelvic inclination was defined by the pelvic-horizontal angle which was formed by the intersection of a line from the superior corner of the sacrum to the uppermost point on the acetabulum with a horizontal line passing

through the superior-posterior corner of the sacrum. The seat back inclination was varied from 80° to 110° in 10° increments. The corresponding pelvic-horizontal angles were 53.2°, 37.6°, 24.7° and 21.6°, respectively. Total lumbar angle was used as a measure of lumbar curvature. It was defined as the angle formed by the intersection of a line along the superior surface of the first lumbar vertebral body and a line along the sacral endplate. Corresponding total lumbar angles for each increment of seat back angle were 33.4°, 28.1°, 25.0° and 29.1°, respectively. With the seat back maintained at 90°, the effect of a lumbar support was measured in another ten subjects. The mean pelvic-horizontal and total lumbar angles of the sample were both found to increase as lumbar support increased in 2 cm increments from -2 cm to +4 cm. The lumbar support was placed at vertebral levels L1, L3 and L5 without significant influence on pelvic inclination or total lumbar angle.

Stokes and Abery (1980) tested the hypothesis that short hamstring muscles cause excessive rearward rotation of the pelvis and thus move the lumbar spine further toward kyphosis in some seated postures. In 38 healthy adult subjects, a toe touch test was used to measure range of hip flexion with the knees fully extended. Sagittal tracings of lumbar curvature were recorded by moving a hand-held stylus connected to a potentiometer over the spinous processes of the lumbar spine. Measurements were taken with the subjects standing and sitting with the knees flexed at 90° and 135°.

When moving from a standing posture to an upright seated posture with the knees flexed at 90°, a significant reduction in the lumbar lordosis was noted. A further reduction of the curvature was noted when the knees were extended 45°. Subjects with tighter hamstrings, as measured by the toe touch test, tended to lose more of their lordosis when extending their knees from 90° to 135°. The only exceptions were subjects with less than 40° hip flexion of the toe-touch test. These subjects lost most of their lordosis when moving from the standing to sitting posture.

In 1983, University of Michigan Transportation Research Institute (UMTRI) studied the position of the pelvis in soft and hard seats. The soft seats were taken from four different vehicles while the hard seats were designed from plaster castings of the subjects seated in the vehicle seats in an attempt to reproduce the seat/subject interface. Markers were placed over skeletal landmarks of the twenty-four subjects and photographed to estimate the seated geometry of each subject. To estimate the location of the pelvis, subjects placed the tips of long probes over their anterior superior iliac spines and the pubic symphysis. A close match was found in the location of the pelvis in the soft and hard seats. The location of the pelvis was sightly more forward in the vehicle seat.

The influence of seat pan angle on the orientation of the pelvis and lumbar curvature was examined by Bendix and Biering-Sorensen (1983). Lumbar curvature was measured

using a statometric method. The measurements were taken periodically over 60 minutes in ten subjects reading at a desk supporting themselves with their elbows. The seat pan was tilted forwards in 5° increments from the horizontal to 15°. The lumbar spine was found to move toward lordosis as the slope of the seat pan increased. Only a slight move toward kyphosis occurred over the time duration. Subjects reported that they were most comfortable with the seat pan on the horizontal and tilted 5° forward.

Brunswic (1984) measured the configuration of the lumbar spine of 22 seated subjects using a hydrogoniometer. The seat pan angle was altered in 5° increments from -25° from the horizontal to +25° with the subjects sitting upright. Lumbar curvature was measured as a percentage of total lumbar flexion. A linear relationship was found between seat pan angle and percentage of total lumbar curvature. As the seat pan tilted backward, the percentage of total lumbar flexion increased. Lumbar curvature was also measured as a function of knee angle. As the knee was flexed from 170° to 110°, the lumbar spine moved toward lordosis.

Preferred Seating: Lay and Fisher (1940) reported a study conducted at the University of Michigan where the preferred seat geometries of 250 adults were studied. Subjects sat in a test seat while the dimensions of the seat were adjusted to their preference for driving. The mean seat pan/back angle of the sample was 105.3°, while the mean

seat pan angle was 6.4°. The mean vertical and horizontal distances from the subjects' heel to the seat pan/back junction were 34.5 cm and 78.0 cm, respectively. The mean angle of the foot to the horizontal was 38°.

In 1975, Rebiffé' constructed a geometrical model of the body in an automobile seat to predict comfortable joint angles for driving. The predicted range of trunk-thigh angles was 95° - 120° and the range of knee angles was 95° - 135°. A seat back angle of 25° ±5 was predicted. Seat height was determined by the stature of the driver.

Schneider et al (1980) investigated the preferred horizontal seat position of 108 subjects in six different vehicles under driving and nondriving conditions. Subjects were found to move the seat 0.5" forward while driving. Although the difference in seat position was statistically significant, it was not considered practically significant. Seat position was found to relate to stature; however, considerable variability existed among individuals of the same height.

Verriest and Alonzo (1986) studied postural variability in 60 adults. Subjects sat in an experimental seat using a steering wheel and footrest to simulate driving. Seat geometry was set by the subjects, as well as lumbar and thoracic support, from a random initial geometry. The selected seat settings enabled the subjects to operate the steering wheel while playing video games. Once the seat settings were selected, the subjects were photographed so

that their posture could be measured. This procedure was repeated four times at ten minute intervals. The mean posture of the sample consisted of a trunk-thigh angle of 101° ±8.3 and a knee angle of 116° ±8.7. For a given subject, the mean range of trunk-thigh angles was 10° and the mean range of knee angles was 14°. The range of joint angles of the sample was three times higher than the range of a given individual. The investigators concluded that sitting postures were reproducible.

Previous investigations have shown that the posture of the pelvis and lumbar spine can be influenced by seat geometry, however, normative data of pelvic inclination and lumbar curvature in automobile seating is lacking. Hard office chairs were used in many of the previous studies making comparisons to cushioned automobile seats difficult. The lumbar spines of the elderly have been found to be less lordotic (Milne and Lauder, 1974), therefore postural variations between age groups are likely. In recent years lumbar supports have been installed in many automobile seats, yet research regarding their influence on posture and comfort is minimal. Future study should expand our understanding of automobile seating postures and ultimately lead to a safer and more comfortable seat design.

MATERIALS AND METHODS

Sample: Twenty-four healthy males volunteered to participate in the study. Ages ranged from 21 to 34 years with a mean of 25.8 years. Subjects, mostly students, were recruited locally. All subjects reported driving a motor vehicle, usually a compact car, for less than 10 hours per week. The majority of the participants were physically active exercising two or more days per week.

Subjects were accepted into the study on the condition that they were not experiencing any joint pain on the day of testing. Six of the twenty-four participants reported that they had sought medical attention for past complaints of back pain. However, all six were free of back pain for the six week period prior to their participation in the study. No subjects were suffering any medical problems which affected their sitting posture.

A screening examination was performed on each subject to rule out gross mobility deficits of the spine and lower extremities (Appendix 4). Subject's were required to bend forward with the knees fully extended and reach their fingertips past the mid-portion of their tibia without pain to remain in the study.

Sonic Digitizing System: Subjects were fitted with the pelvic plate to measure positional changes of the pelvis in different seating postures. Location of the pelvic plate in the laboratory was determined through use of a GP-8-3D Sonic Digitizer, Science Accessories Corporation (Grambo, 1989). Sound impulses were emitted sequentially from spark gaps, three located on the pelvic plate and three rigidly attached to the seat assembly. The sound impulses were received by four microphones located on a square frame approximately 1.2 m above the pelvic plate.

The microphones were rigidly attached to a frame constructed from Unistrut steel channels (Figure 1). Placement of the four microphones formed the corners of a square with sides of 151.4 cm in length. The frame was rotated 23.5° to horizontal to improve reception of sound emissions. Therefore, with the pelvic plate applied to the seated subject, the plane of the microphones approached a plane parallel to the plane of the pelvic plate spark gaps.

Pelvic Plate: Sound emitters were rigidly attached to a 1.30 cm thick aluminum plate and identified as P1, P2 and P3. The three sound emitters formed an isosceles triangle 2.00 cm above and parallel to the pelvic plate plane. The sides of the triangle (17.55 cm) corresponded to the ASIS to pubic symphysis axes and the base (27.90 cm) corresponded to bispinous breadth (Figure 2a).

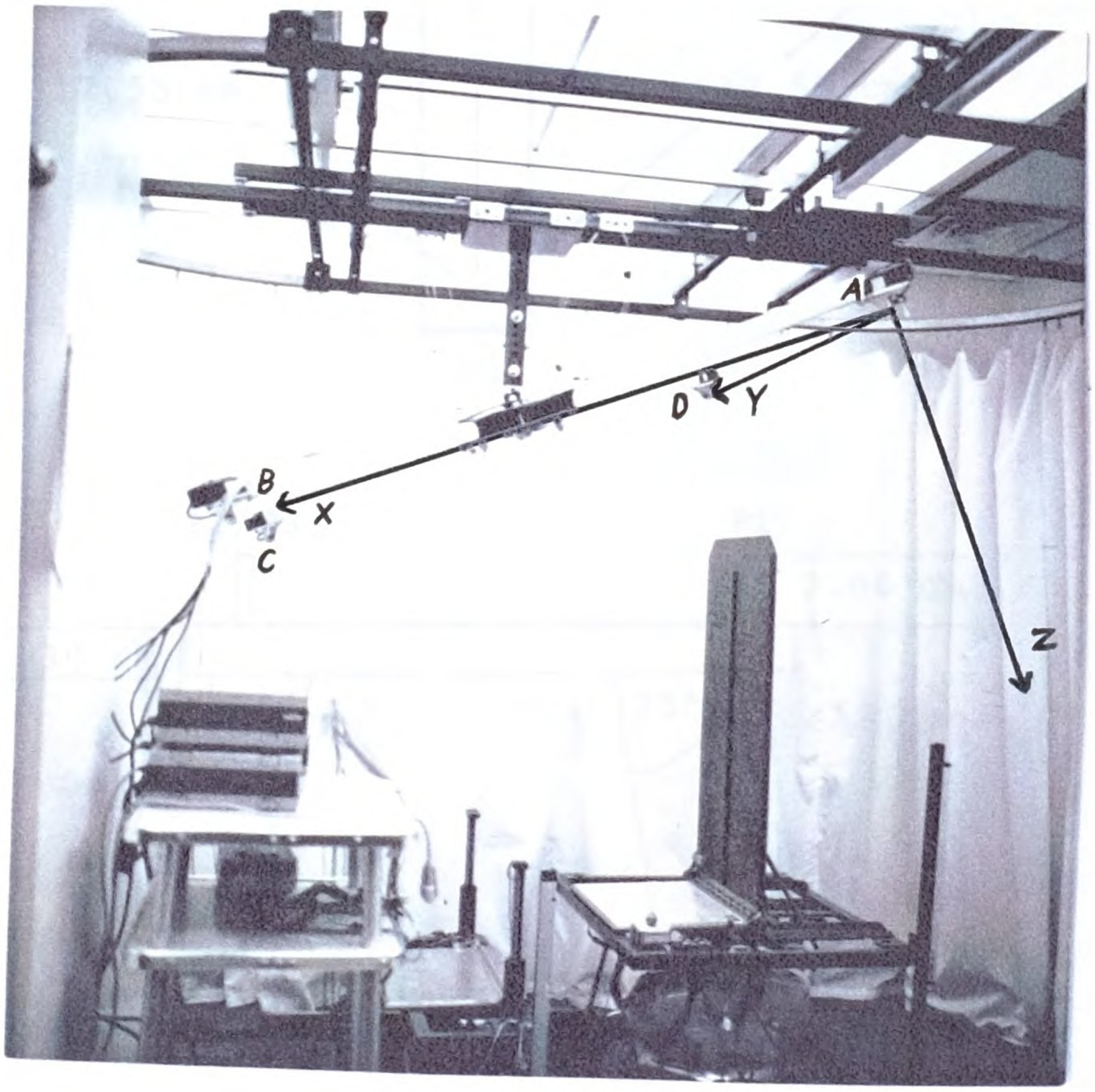
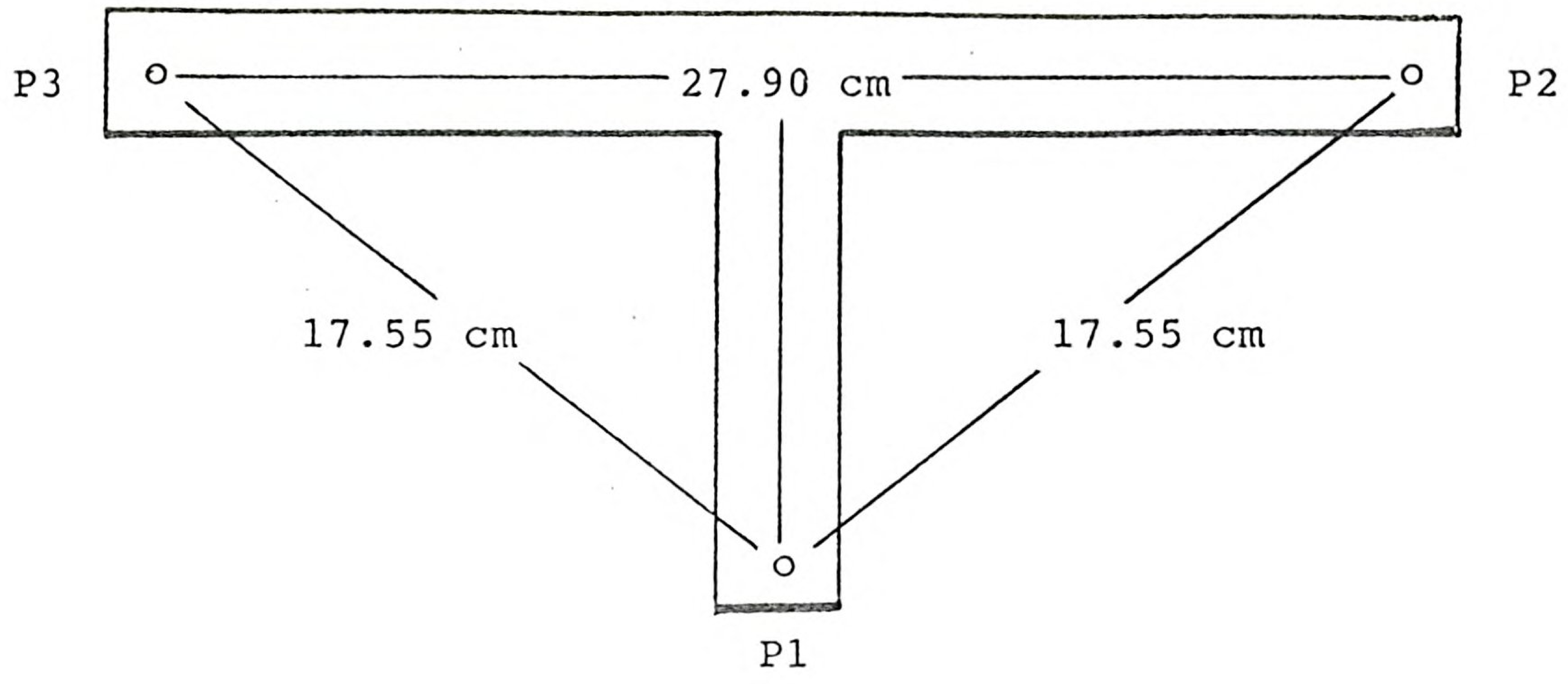


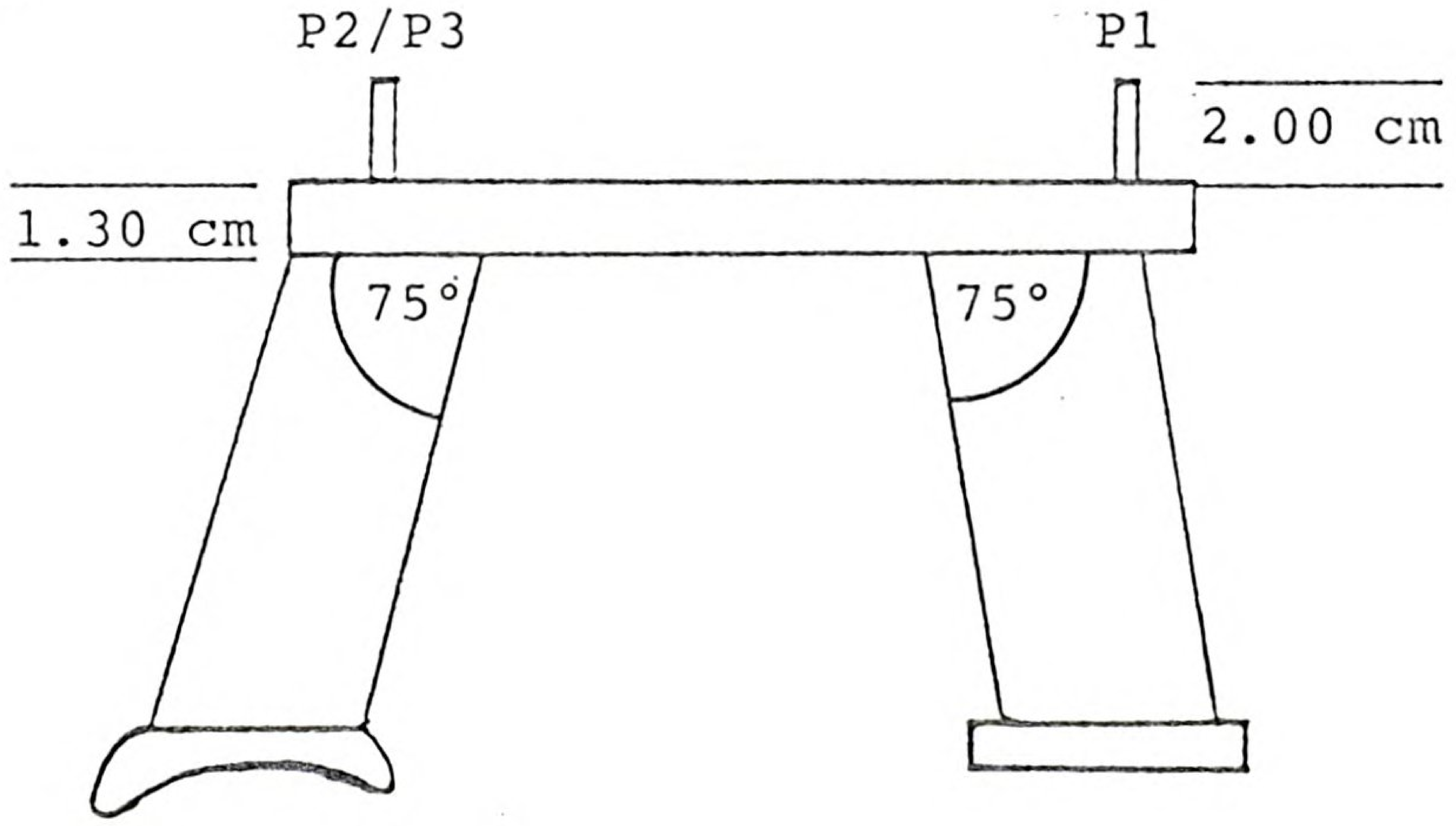
Figure 1. Microphones mounted to steel frame and laboratory axis system shown with origin at microphone A.

Figure 2. Pelvic plate dimensions in three planes.

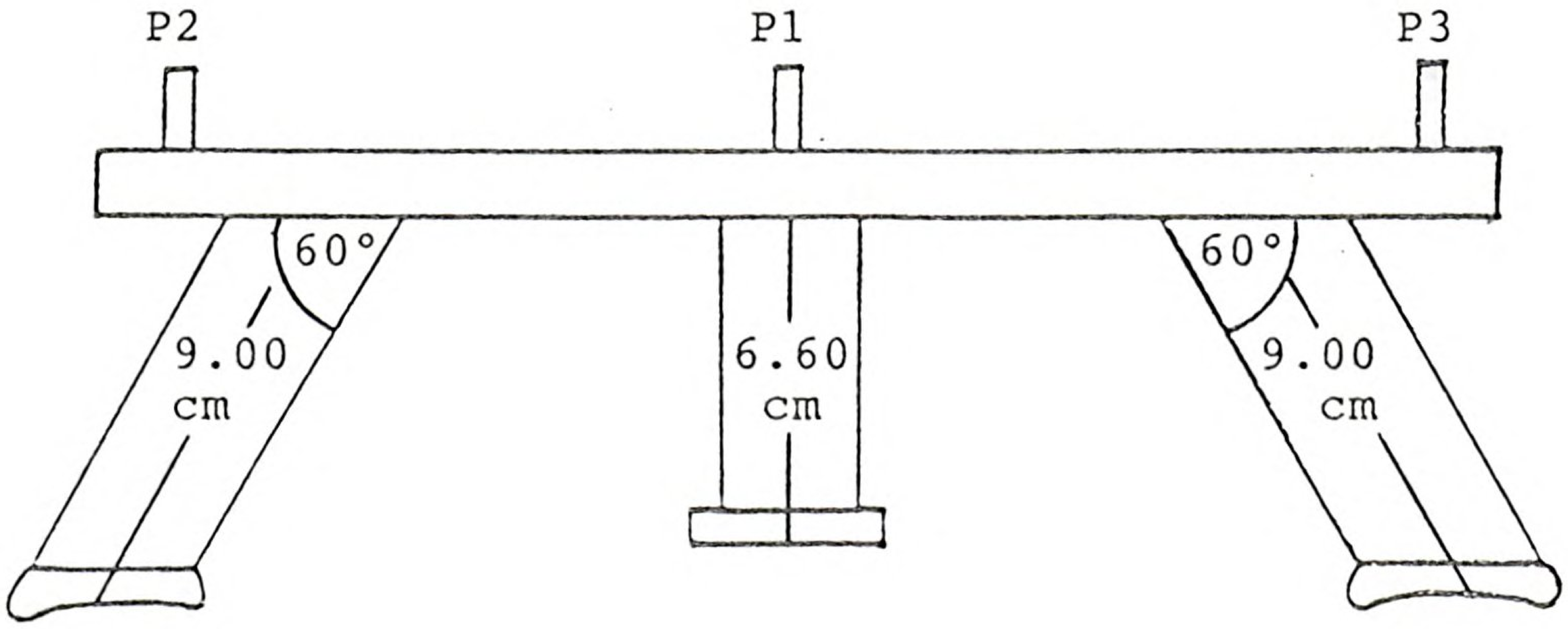
a. Top view



b. Side view



c. Front view



The posts were named in reference to the corresponding sound emitter. The aluminum posts extending from the plate terminated with Orthoplast moldings to contact the body. The Orthoplast moldings of posts 2 and 3 were shaped to cup each ASIS, while the molding of post 1 contacted the anterior-superior aspect of symphysion. Post 1 was 6.60 cm and posts 2 and 3 were 9.00 cm in length. In side view (Figure 2b), posts 1, 2, and 3 formed a 75° angle with the plate. As shown in Figure 2c, post 1 was perpendicular to the plate and posts 2 and 3 formed a 60° angle with the plate.

Posts 2 and 3 were adjustable to allow for differences in bispinous breadth between individuals. Post 1 was adjustable to allow for differences in the perpendicular distance between the pubic symphysis and the bispinous axis. Nylon straps were used to pull the plate securely against the subject's pelvis. Thus, the pelvic plate, when strapped on and adjusted to fit each individual, applied compressive and shear forces at the contact points over the pelvis which rigidly coupled the movements of the plate to the subject's pelvis.

Seat Assembly: The seat and footrest were mounted on a wooden platform (Figure 3). The seat consisted of a hydraulic lift, steel frame, seat pan and back. The seat pan and back were attached to the steel frame which was moved vertically by an electro-hydraulic lift. The seat

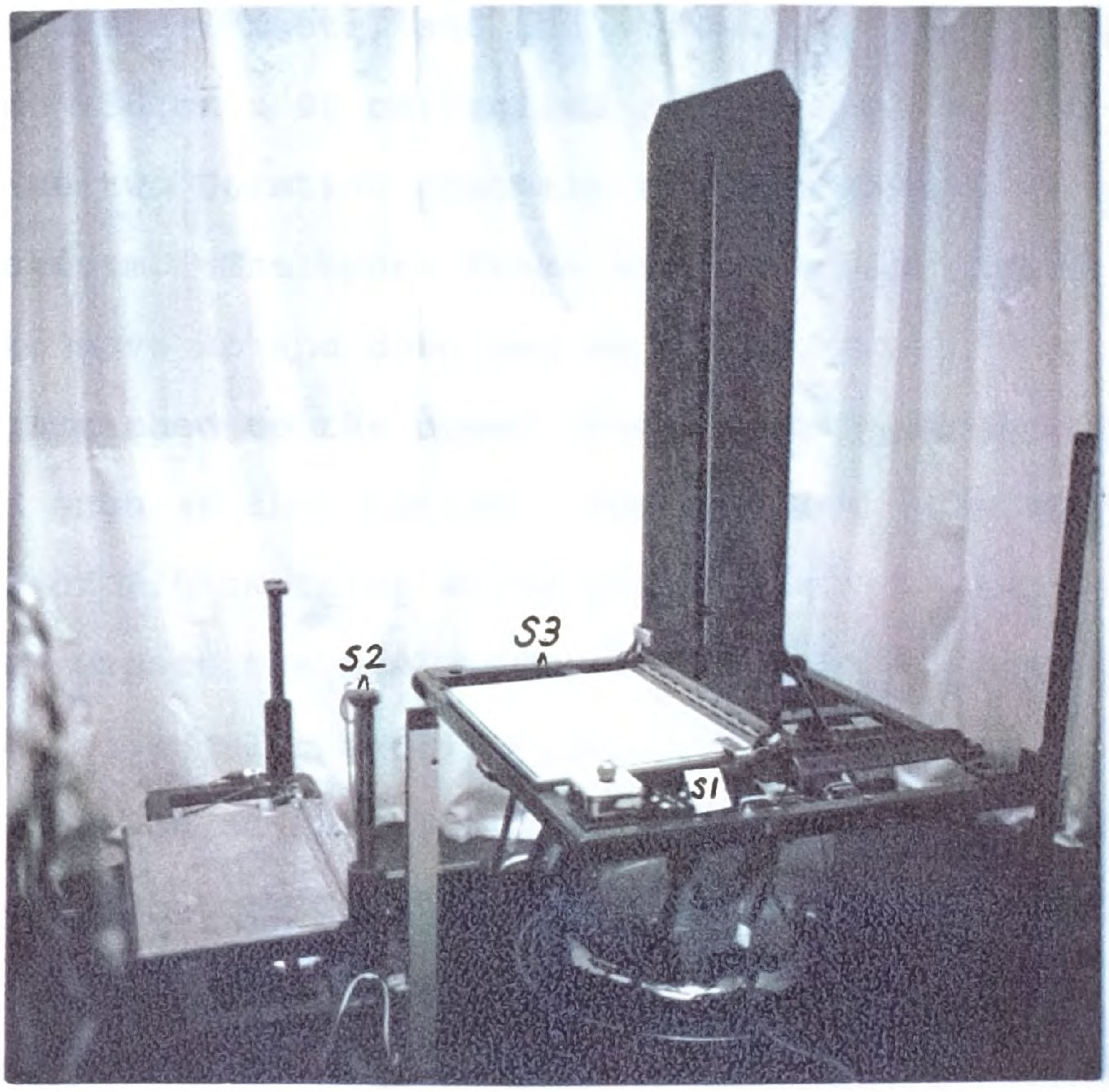


Figure 3. Seat assembly and sound emitters S1 and S2 located on steel frame and S3 located on footrest.

pan and back were each constructed of 2.0 cm thick plywood. Dimensions of the seat pan were 38.0 cm x 51.0 cm and the seat back, 102.0 cm x 51.0 cm.

The footrest apparatus consisted of two steel frames, two vertical steel posts, and the wooden footrest. The lower frame (30 cm x 91 cm) rolled on four wheels, two per side, inside two Unistrut channels rigidly mounted to the wooden platform. The upper frame used Thompson linear bearings to move up and down two vertical posts. The footrest, attached to the upper frame, was adjustable for height and angular inclination. The footrest consisted of two pieces of 2.0 cm thick white pine plywood: one rigidly mounted to support the heels during testing and the other, adjustable for angular inclination.

The location of the seat in the microphone axis system was determined by the location of three spark gaps rigidly mounted on the seat assembly. The seat assembly spark gaps were identified as S1, S2, and S3. S1 and S2 were mounted to the steel frame on either side of the seat, while S3 was mounted on the left post of the footrest (Figure 3).

The seat pan, seat back and footrest apparatus were powered by electric screw mechanisms. Vertical translation of the seat and footrest as well as horizontal translation of the footrest were electronically measured by linear encoders and digital displays (Anilan Electronics Corporation). Angular changes of the seat back and footrest

were measured by rotary encoders and a digital display (C-TEK).

Seat geometry was measured relative to the seat axis system (Figure 4). The seat axis system was a right-handed orthogonal system where the X and Y axes lie in the horizontal plane and the Z-axis was defined normal to the X-Y plane. The seat pan and seat back rotated about the Y-axis and the corresponding angles of inclination were measured from the X-axis in the X-Z plane (Figure 4). Seat height was defined as the vertical distance from seat reference point (SRP) to the heel point. SRP is located at the midpoint of the intersect between the seat back and seat pan planes, while the heel point is located at the midpoint of the intersect between the two supporting surfaces of the footrest apparatus. Foot-X is the horizontal distance from SRP to heel point. Foot angle is the included angle between the footrest and the horizontal axis.

Testing Parameters: A range of driver selected seat back and pan angles (Maertans, 1990) and seat heights (Tighe, 1988) commonly found in motor vehicles were used to establish test cells of the set seat geometries. The nine cells are reported in Table 1 as a 3 x 3 matrix defined by seat height and back angle.

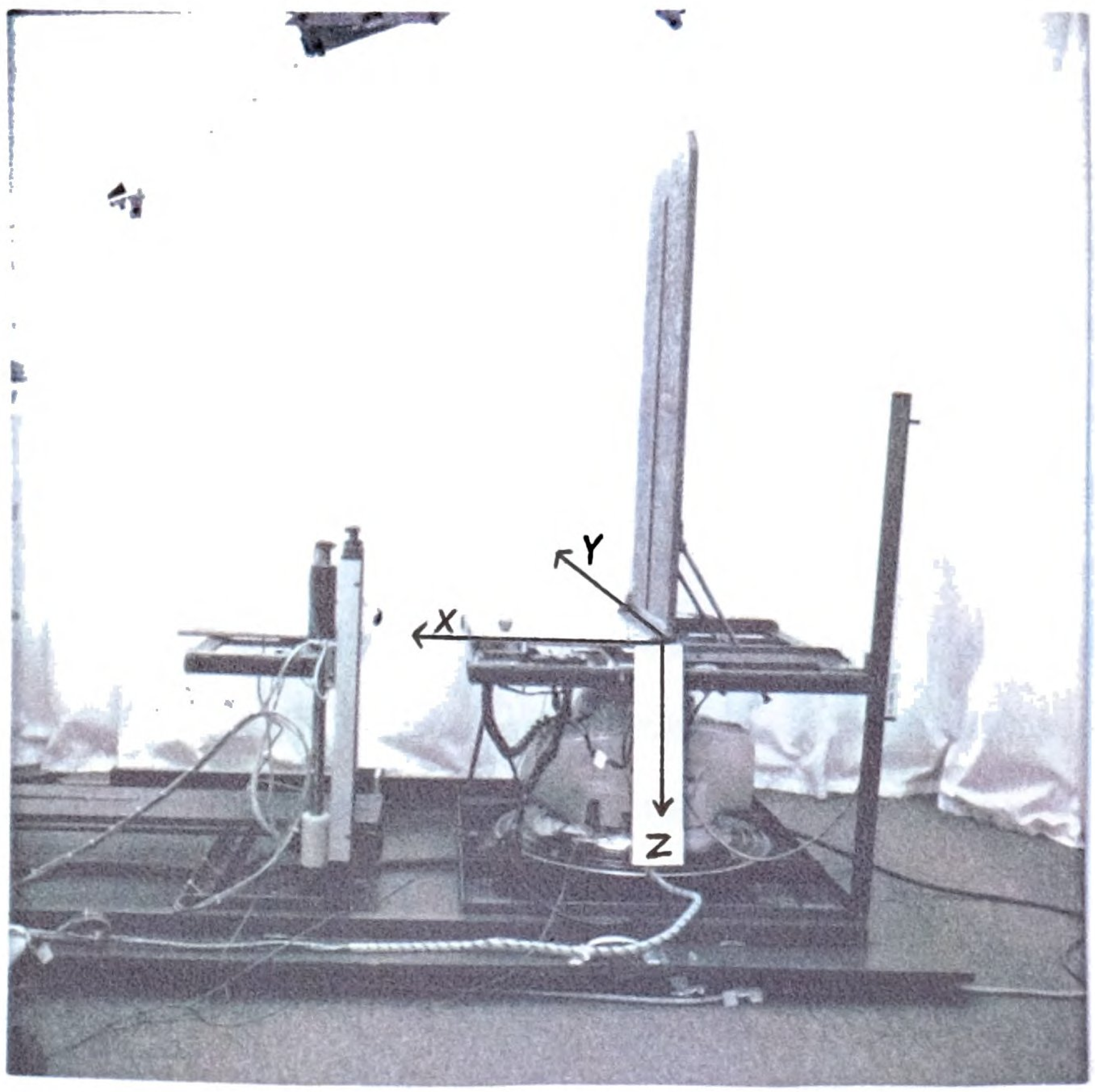


Figure 4. Seat reference position and axis system.

Table 1. Numbering system to represent experimental seat geometries

Seat Height	Seat Back Angle 108°	119°	130°
Low (15 cm)	1	2	3
Medium (23 cm)	4	5	6
High (31 cm)	7	8	9

Determination of Pelvic Plate Coordinates: Nine sets of microphone axis system coordinates for the pelvic plate spark gaps were collected for each test. Because of the possibility of blockage of sound transmissions or reflection of sound off equipment surfaces, the coordinate data were edited. Coordinates outside the range of possible distance measurements were discarded which left an average of seven sets of spark gap coordinates per test. The mean values of the coordinates were calculated for each test. Position vectors $\overrightarrow{P1}_M$, $\overrightarrow{P2}_M$, and $\overrightarrow{P3}_M$ represent the mean coordinates of the pelvic plate spark gaps within the microphone axis system. To analyze the sagittal orientation of the pelvic plate, the midpoint ($\overrightarrow{MP}_M$) of P2 and P3 was calculated by the following formula:

$$\overrightarrow{MP}_M = (\overrightarrow{P2}_M + \overrightarrow{P3}_M)/2 \qquad (1)$$

Mean values of the microphone axis system coordinates of P1 and MP were entered into Microsoft's Multiplan, a spread sheet program, where they were transformed into coordinates of the seat axis system.

Coordinate Transformation from Microphone to Seat Axis System. The microphone frame (Figure 1) defined a right-handed, orthogonal axis system with an origin at microphone A, +X from microphone A to B, +Y from microphone A to D, and +Z directed downward, normal to the XY plane. The transformation from microphone to seat axis system kept the general orientation of the axis system with the X and Y axes forming a horizontal plane and their cross product defining a right-handed system with the Z axis pointing in a downward direction.

The locations of spark gaps within the seat axis system were calculated from two sets of transformations. First, the seat was postioned in the reference position (Figure 4). That is, the seat was positioned at its minimum height, the seat back was vertical, and the seat pan was horizontal. The footrest was at its rearward limit and at the same height as the seat. Spark gaps, S1, S2, and S3 (see Figure 3) were measured in the microphone axis system, and a spark gap axis system was established from their geometry.

The spark gap axis system in the reference position was defined with the X and Y axes defining a plane 30° from the horizontal and the Z axis defined by the right-hand rule normal to the XY plane. A new vector in the XY plane was established by

$$\overrightarrow{Y_G} = \overrightarrow{S2}_M - \overrightarrow{S1}_M \qquad (2)$$

where $\vec{Y}_G$ is a vector in the Y direction of the spark gap axis system; $\vec{S2}_M$ and $\vec{S1}_M$ are vectors of spark gaps S2 and S1 measured in the microphone axis system.

Since $\vec{S3}_M$ is not perpendicular to the $\vec{Y}_G$ vector at S1, a new vector, $\vec{A}_G$ must be formed as follows:

$$\vec{A}_G = \vec{S3}_M - \vec{S1}_M \quad (3)$$

with terms defined as in equation (2). Now, the cross product between $\vec{A}_G$ and $\vec{Y}_G$ defines an axis normal to the XY plane containing S1, S2, and S3. The remaining two axes can now be defined relative to S1 by

$$\vec{Z}_G = \vec{A}_G \times \vec{Y}_G \quad (4)$$

and,

$$\vec{X}_G = \vec{Y}_G \times \vec{Z}_G \quad (5)$$

The resulting vectors have components in the microphone axis system defined in the following manner:

$$X_G = x_x i + y_x j + z_x k \quad (6)$$

$$Y_G = x_y i + y_y j + z_y k \quad (7)$$

$$Z_G = x_z i + y_z j + z_z k \quad (8)$$

The x, y, z elements are direction cosines which define the direction of the spark gap axis system relative to the microphone axis system. When equations (6-8) are written in matrix form, the 3x3 matrix [G] composed of the direction cosines can be used to rotate the coordinates of all sound

emitters in the microphone axis system into the orientation of the reference position of the spark gap axis system.

The seat axis system was defined to calculate the position and orientation of the pelvis relative to the seat pan in the measured fixed seat geometries. That is, the X and Y axes are coincident with the seat pan and the Z axis is defined by the right-hand rule perpendicular to the seat pan (see Figure 4). The origin of the seat axis system is located at the edge of the intersection between seat back and seat pan. The location of the origin, 0, was measured relative to S1 with a caliper and transformed into the position vector, $\overrightarrow{O_M}$, in the microphone axis system. Spark gaps, S1, S2, and S3 (see Figure 3) were measured with a caliper in the seat axis system. Using the position vectors in the seat axis system for S1, S2, and S3, a spark gap axis system was once again established from their geometry as in equations (2-8) above to define a 3 x 3 rotation matrix [S]. Rotation matrix [S] can be used to rotate the coordinates of all sound emitters in the seat axis system into the orientation of the spark gap axis system.

Now a linear equation in matrix form can be written to transform the spark gaps in the microphone axis system to the seat axis system. The transformation is made by

$$\begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix} = [S]^T [G] \left[\begin{bmatrix} X_M \\ Y_M \\ Z_M \end{bmatrix} - [O_M] \right] \qquad (9)$$

where X_S, for example, is the X coordinate of a sound emitter in the seat axis system; [S] & [G] are rotation matrices defined above; X_M, for example, is the X coordinate of a sound emitter in the laboratory axis system; and $[O_M]$ is the translation of the origin from laboratory to seat axis sytem.

Experimental Procedure: All participants were informed of the purpose, procedure and instrumentation used in the study before testing and then signed an informed consent statement (Appendix 2). Subjects completed parts A and D of a questionnaire which inquired about driving background and general activity level (Appendix 3). Parts B and C of the questionnaire were completed by interview with a licensed Physical Therapist. Subjects dressed in surgical shorts and walking shoes prior to testing. Anthropometric measurements were taken of each subject (Table 2). Anthropometric

Table 2. Anthropometry with body mass in kg, knee extension angle in degrees and all other measures in cm.

	Mean	St. Dev.	Min.	Max.
Standing Hgt	181.70	7.44	165.10	191.70
Sitting Hgt	93.02	3.32	85.10	98.20
Body Mass	78.73	10.70	62.50	99.30
ASIS Hgt	103.71	5.67	93.10	112.20
Troch Hgt	97.03	5.40	87.50	106.70
Tibiale Hgt	50.85	3.03	46.80	58.70
Spherion Hgt	10.13	0.90	7.80	11.70
ASIS to ASIS	22.69	1.68	19.30	27.00
ASIS to PSIS	15.09	1.22	13.00	16.80
ASIS to Pub Sym	13.98	0.95	12.30	16.10
Wst Circum	102.13	19.98	86.70	192.70
Thigh Circum	53.58	3.78	47.80	63.20
Calf Circum	36.34	2.23	32.00	42.10
Left Knee Ang	135.46	8.80	118.00	154.00

dimensions of the individual subjects are found in Appendix 1. The subjects were also screened to rule out gross mobility limitations of the low back and lower extremities.

Hamstring length was measured by a modified version of the method described by Gajdosik and Lusin (1983). The pelvic plate was then fitted with the subject supine. Excursion of the three posts was estimated prior to placement on the pelvis. Nylon straps were wrapped around the waist, through the crotch to the lower aspect of the pelvic plate, and around the inferior aspect of the buttocks. The straps were then tightened so that contact surfaces of the aluminum plate were pressed firmly against the boney landmarks of the pelvis (right and left ASIS, and pubic symphysis).

The subject was then assisted to the seat where the fitted plate was rechecked and retightened for firm contact with the boney landmarks. To check the fit of the pelvic plate, manual pressure was applied over each of the pelvic plate posts. Contact was considered firm if movement of the plate relative to the pelvis was minimal. The subject was instructed to sit with his buttocks against the seat back in the middle of the seat. The spinous processes were palpated through a slot in the seat back to ensure that the subject was centered in the seat. The subject was asked to place his heels on the footrest with the lateral border of his shoes aligned with the lateral border of the footrest. Hands were placed on the lateral edges of the seat pan with

instruction not to bear body weight through the hands. The subject was asked to repeat this positioning procedure prior to each trial if contact of his buttock with the seat back was lost when changing seat geometries.

The seat was then adjusted to the first test position. For each test position, the seat height was set first followed by the seat back angle. The seat pan angle was fixed at 15°, and the knee angle was kept at 115° (Rebiffe, 1966) using a plexiglass template for each of the nine seat geometries. Subjects adjusted the footrest angle to their preference. The seat X and Z coordinates, foot angle, foot X coordinate and temperature were recorded. Curtains were closed to minimize reflection of sound transmissions. The subject was asked to relax and look straight ahead as if driving while the spark gap locations were digitized. This procedure was repeated for all nine of the fixed seat geometries. The sequence of seat geometries was randomly chosen prior to the test.

Only two subjects complained of discomfort during the testing, that being pressure of post 1 over the pubic symphysis when a seat back angle of 130° was used. Both subjects noted relief of the pressure by rotating their pelvis forward, therefore both were permitted this posture between sonic measurements. During the actual sonic digitizing, both subjects reported that they could relax in the test posture for the test duration without difficulty.

After measuring the nine fixed seat geometries, the subject was asked to step out of the seat so that the chair could be moved to the reference position. The subject then returned to the seat and was given thorough instruction on operation of the seat and footrest controls. The subject then adjusted the seat to his preferred geometry for driving. Pelvic plate fit was once again checked, the chosen seat geometry was recorded as well as goniometric measurement of the left knee angle. Subjects were asked to maintain placement of the hands and feet as previously described. The position of the pelvic plate was digitized and this procedure was repeated for two more trials. At the conclusion of testing, the plate was removed. The positions of the post-plate junction on the plate surface were measured and recorded for each post.

Preferred seat geometry of five subjects from the sample was measured without wearing the plate for an additional three trials. These subjects were selected because their testing had proceeded swiftly and they agreed to participate in the additional trials. This group was representative of the sample with a mean age was 25 years. All were students and all but one drove a compact car. The mean anthropometric measurements of this subsample were within one standard deviation of the sample mean.

<u>Calculation of Pelvic Angle</u>: The pelvic angle is the obtuse angle in the sagittal plane created by the intersection of the vector extending from P1 to MP with the

horizontal. Therefore, the pelvic angle was calculated from the seat axis system coordinates using the following formula:

$$PA = \arctan ((P1z - MPz) / (P1x - MPx)) \quad (10)$$

Calculation of the Center of Rotation: The center of rotation (CR) of the pelvic plate resulting from change in seat back angle was calculated using an algorithm described by Panjabi (1979). The X and Z coordinates for points P1 and MP within the seat axis system were entered into Panjabi's formulae for determining the center of rotation of the pelvis. Since Panjabi found that rotations of less than five degrees have large errors in CR calculations, all data with a change in pelvic angle less than five degrees were excluded from the analysis. Also, any displacements of points P1 or MP in the +X or +Z directions, resulted in exclusion of the set of points involved in the displacement.

Estimated Location of Pelvic Landmarks from Pelvic Plate Measurements. Data from subject #14 were chosen to calculate the position of pelvic landmarks from the pelvic plate coordinates. This subject best represented the sample by age, occupation, driving experience, body size, and preferred seat geometry.

Coordinates of P1, P2, and P3 in the seat axis system were transformed into a pelvic plate (subscript "P") axis

system with origin at MP in the same manner used for transforming coordinates from microphone to seat axis system. A slight modification of equation (10) resulted since only one rotation is required to re-orient the data. Thus,

$$\begin{bmatrix} X_P \\ Y_P \\ Z_P \end{bmatrix} = [W] \begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix} - [MP_S] \qquad (11)$$

where X_P, for example, is the X coordinate in the pelvic axis system; [W] is the 3 x 3 rotation matrix; X_S, for example, is the X coordinate in the seat axis system; and $[MP_S]$ is the translation vector of the seat axis system to the pelvic plate axis system.

Location of the left and right ASISs within the pelvic plate axis system were estimated by the contact points of posts 2 and 3. To estimate the location of Symphysion, 1.0 cm and 2.0 cm were added in two different calculations to the length of post 1 to correct for soft tissue thickness. Again, the same algorigthm as described to develop equation (10) was used to transform the spark gap locations in the pelvic plate to an anatomical axis system (subscript "A") in the pelvis. The anatomical axis system was defined with an origin at midpoint between the right and left ASISs, MA, and +Y passing through the left ASIS, -Z passing through Symphysion, and +X defined by the right-hand rule from the cross product of the +Y and +Z axes. To make the

transformation, the following linear equation was established:

$$\begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} = [N] \begin{bmatrix} X_P \\ Y_P \\ Z_P \end{bmatrix} - [MA_P] \qquad (12)$$

where X_A, for example, is the X coordinate in the anatomical axis system; [N] is the 3 x 3 rotation matrix between the two axes systems; X_P, for example, is the X coordinate in the pelvic plate axis system; and $[MA_P]$ is the translation vector between the origins in the pelvic plate axis system.

Three-dimensional data on pelvic geometry (Reynolds, 1981) were scaled to match the ASIS breadth of the subject by a factor of 1.0052. The anatomical coordinates were then transformed into the seat axis system by

$$\begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix} = [MP_S] + [W]^T[MA_P] + [N] \begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} \qquad (13)$$

where X_S, for example, is the X coordinate of the anatomical pointmark in the seat axis system; [W] is the 3 x 3 rotation matrix from seat to pelvic plate axes systems; $[MA_P]$ is the location of the anatomical axis system in the pelvic plate axis system; [N] is the 3 x 3 rotation matrix from pelvic plate to anatomical axes systems; and X_A, for example, is the X coordinate of the anatomical pointmark in the anatomical axis system.

Two angles were calculated from the pelvic landmark coordinates for each estimate of soft tissue thickness over Symphysion. The pelvic horizontal angle was defined similar

to Andersson et al (1979). These angles were calculated as follows:

AIIS-ASIS/Horizontal Angle

$$= \text{Arctan} \quad (ASIS_Z - AIIS_Z)/(ASIS_X - AIIS_X) \qquad (14)$$

where ASIS was the anterior superior iliac spine and AIIS is the anterior inferior iliac spine; and,

Pelvic Horizontal Angle

$$= \text{Arctan} \quad (\text{P of } S1_Z - SA_Z)/(\text{P of } S1_X - SA_X) \qquad (15)$$

where P of S1 is the posterior point on the first sacral vertebral body and SA is the superior acetabulion pointmark in the pelvis.

RESULTS

<u>Accuracy of Distance Measurements</u>: The accuracy of digitized distances was analyzed using the coordinate data from six randomly chosen subjects. From the microphone axis system coordinates of P1, P2 and P3, distance measurements between each of the spark gaps were calculated. These values were averaged for comparison with distances measured with a caliper shown in Figure 2a. The average digitized distances from P1 to P2, P1 to P3 and P2 to P3 were 17.64 ±0.11 cm, 17.44 ±0.07 cm, and 27.88 ±0.09 cm, respectively. Thus, the mean digitized distances were within 0.6% of the caliper measurements.

<u>Fixed Seat Geometries</u>: Systat, a statistical software package (Wilkinson, 1986), was used to analyze the data. The level of significance needed to reject a null hypothesis was 0.05. For each seat geometry, the average pelvic angle and standard deviation were calculated (Table 3).

Analysis of variance (ANOVA) was used to determine if the pelvic angle significantly differed either as a function of seat back angle or seat height. Pelvic angle was found to vary significantly as a function of seat back angle ($P < 0.001$). Significant differences in pelvic angle were also noted as a function of seat height at a 108° and 119° seat

back angles ($P < 0.01$) and even more significant at 130° seat back angle ($P < 0.001$).

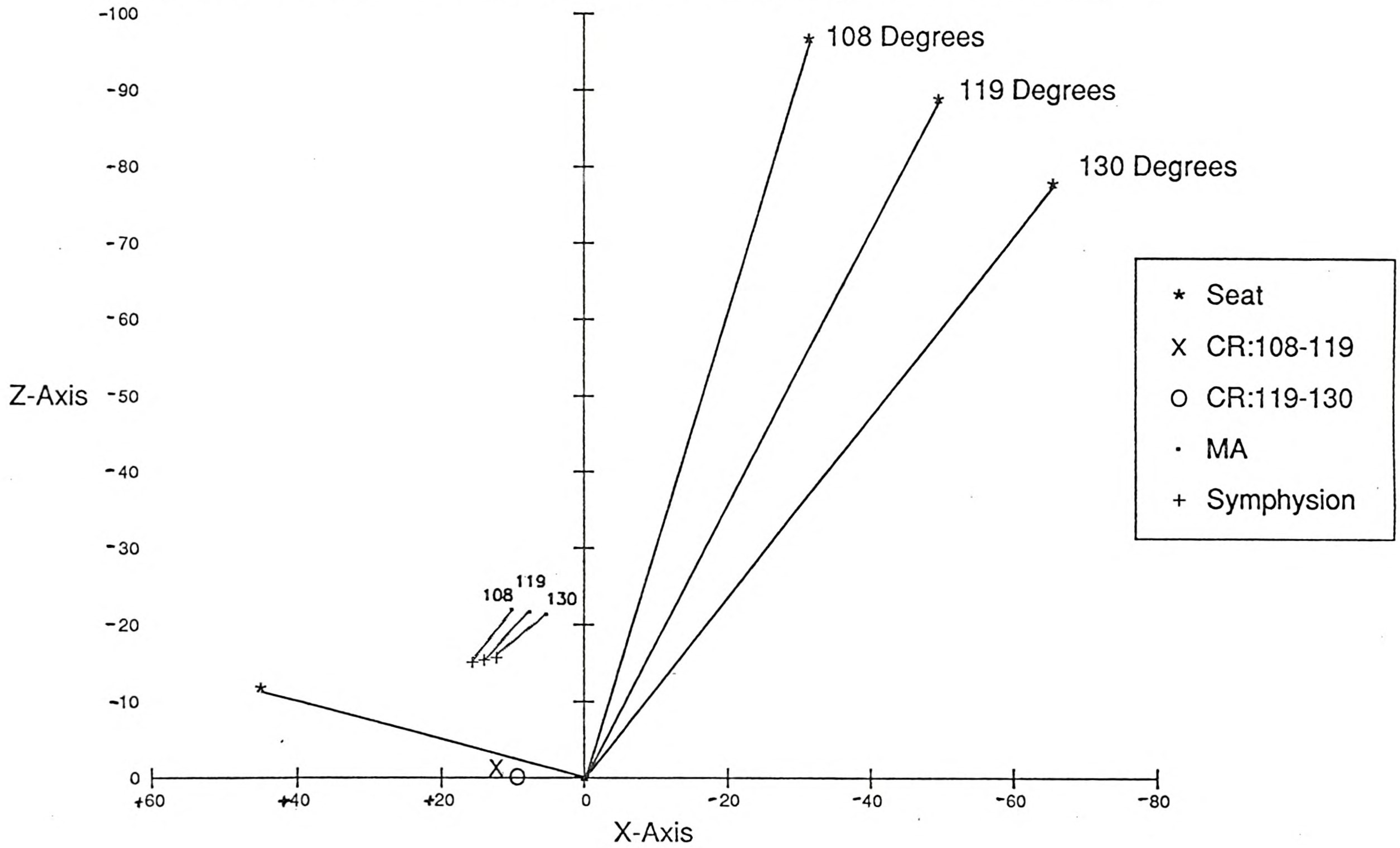
Table 3. The average pelvic angle in degrees at each of nine fixed seat geometries defined by seat height and seat back angle.

Seat Height	Seat Back Angle 108°	119°	130°
Low	129.1 ±5.3	136.0 ±5.5	142.5 ±5.7
Medium	128.3 ±5.4	134.9 ±5.9	140.6 ±6.1
High	127.7 ±5.2	134.5 ±6.2	139.3 ±6.5

Pearson correlation coefficients were calculated for anthropometric dimensions, hamstring length, pelvic angle, foot angle and foot-X of the 24 subjects. In a sample of 24, a linear correlation is statistically different from 0 if the correlation coefficient is at least ±0.404 (Johnson, 1984). A positive linear correlation was found between foot-X and trochanterion height in all nine of the seat geometries (range, $r = 0.90$ to 0.94). No evidence of a linear relationship was present between any other of the variables.

Center of Rotation of the Pelvic Plate: The mean X and Z coordinates of the pelvic plate center of rotation between seat back angles are reported in Table 4. Figure 5 shows the locations of the centers of rotation for each increment of seat back angle and the locations and orientation of MA (average right and left ASIS X- and Z-coordinates) and

Figure 5. Locations of centers of rotation, MA, and Symphysion in seat axis system.



Symphysion. Since seat height did not significantly affect the locations of the centers of rotation, data from the three seat heights were combined and averaged in Figure 5.

Table 4. The average coordinates of the pelvic center of rotation in centimeters at each of six rotations as defined by change in seat back angle and seat height.

Seat Height	Seat Back Angle 108° - 119° X	Z	119° - 130° X	Z
Low	12.4 ±2.2	-2.2 ±4.6	9.3 ±1.5	-0.9 ±5.1
	N = 19		N = 20	
Medium	12.5 ±2.3	-0.0 ±4.9	8.7 ±2.6	-0.1 ±4.4
	N = 20		N = 20	
High	12.0 ±1.8	-2.2 ±4.8	10.0 ±2.9	0.6 ±6.1
	N = 20		N = 14	
AVE	12.3 ±2.1	-1.4 ±4.8	9.3 ±2.3	-0.2 ±5.1

An ANOVA was used to investigate differences in the X and Z values of the center of rotation. The X coordinates for all six rotations of the pelvis were significantly different ($P < 0.001$), while no significant differences were found between the Z coordinates. Mean X coordinates were not found to differ between seat heights at either the 108° to 119° rotation or the 119° to 130° rotation. Since the mean X coordinates did not differ between seat heights, the X values of each seat height were combined to compare mean X coordinates of the 108° to 119° rotation with the 119° to 130° rotation. Using a Student's T-test, a significant difference was found in the mean X coordinates ($P < 0.001$).

Marker angles were calculated from the P1 and MP coordinates of three randomly chosen subjects for each of

the nine set seat geometries. The calculations were performed using the sample mean center of rotation associated with the given seat geometry. For a total of 27 angles, the mean marker angle was 23.3° ±1.7°.

Displacement of the Pelvis: The approximate seat axis system coordinates for the midpoint of the ASIS's (MA) and symphysion (S) were calculated for each seat geometry of each subject. A 1.0 cm soft tissue thickness was used to estimate the location of symphysion. For each increment of seat back angle, the displacements of points MA and S along the X and Z axes were calculated. Combining the displacements from all three seat heights, the mean displacements and standard deviations of points MA and S are reported in Table 5 and shown in Figure 5.

Table 5: The average displacements (cm) of MA and S with change in seat back angle.

	Change in Seat Back Angle			
	108° - 119°		119° - 130°	
	X	Z	X	Z
MA	-2.53 ±0.36	0.44 ±0.27	-2.27 ±0.54	0.34 ±0.36
S	-1.75 ±0.42	-0.29 ±0.34	-1.69 ±0.51	-0.34 ±0.29

Estimation of Pelvic Landmark Locations: The locations of the left anterior superior iliac spine (ASIS), symphysion, H-point, left ischiale, anterior inferior iliac spine (AIIS), posterior point on the first sacral vertebral body, posterior superior iliospinale (PSIS) and superior acetabulion within the seat were estimated from the data set

of a single subject are shown in Figure 6. Anthropometric and pelvic plate measurements of pelvic dimensions are reported in Table 6. The pubic symphysis soft tissue thickness was not estimated for anthropometric measurements. The effect of error in the estimation of soft tissue depth is reported in Table 7.

Table 6. A comparison between measurements with an anthropometer and the pelvic plate.

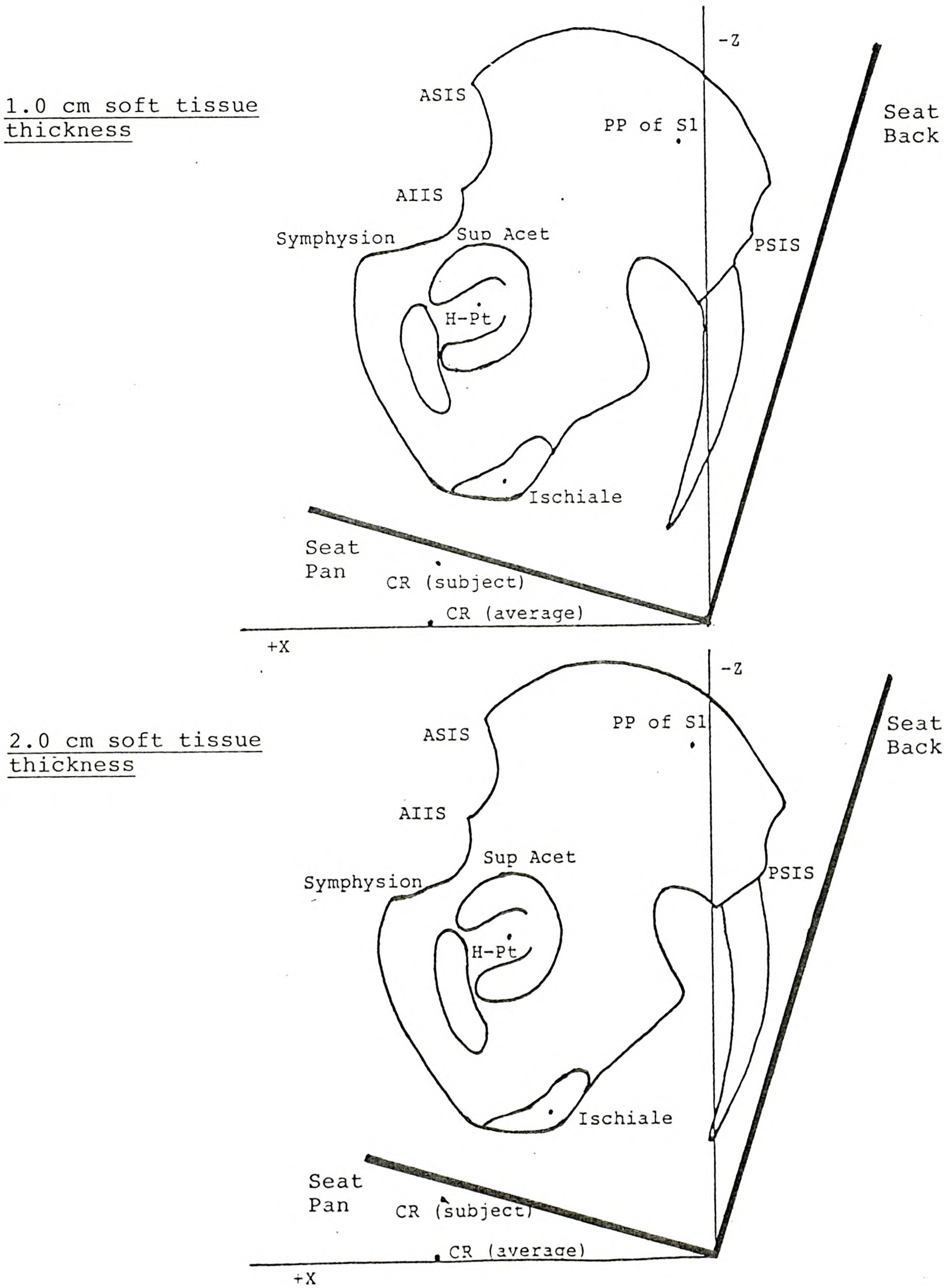
	Anthropometer	Pelvic Plate
ASIS Breadth	23.3	23.1
Symphysion to Left ASIS	13.7	14.4
Symphysion to Right ASIS	13.5	14.4

Table 7. Comparison of pelvic inclination estimations for 1.0 and 2.0 cm pubic symphysis soft tissue thicknesses.

Angle	Thickness (cm) 1.0	2.0	Difference
AIIS-ASIS	82.1°	88.3°	6.2°
Pelvic-Horizontal	27.1°	33.6°	6.5°

<u>Preferred Seating</u>: Pelvic angles were calculated for all three comfort trials for 23 of 24 subjects. On the second trial of one subject, all sonic data sets were flagged by the filter. This occurrence may be explained by blockage or reflection of sound emissions preventing clear transmission to two or more microphones during the test. Pearson correlation coefficients were calculated for anthropometric dimensions, hamstring length, seat geometry, pelvic angle, knee angle, foot angle and foot-X of the 24

Figure 6. Pelvic Landmark Estimations.



subjects. A positive linear correlation was found between trochanterion height and seat height (r = 0.500 and 0.610) in the second and third trials, as well as trochanterion height and foot-X in all three trials (r = 0.667, 0.603 and 0.601). In the second and third trials, a positive linear relationship was found between left hamstring length and pelvic angle (r = 0.515 and 0.467). No evidence of a linear relationship was present between any other of the variables.

An ANOVA was used to test if any significant difference existed between the mean values of the three trials in regards to pelvic angle, seat height, seat back angle, seat pan angle, foot-X, knee angle and foot angle. No statistically significant difference was found between mean values of pelvic angle, seat height, seat back angle, seat pan angle and foot-rest angle. The data for each of the three trials were therefore combined and averaged. Means, standard deviations and ranges are listed in Table 8. The

Table 8. The mean, standard deviation and range of preferred seating geometry.

Seating Geometry	Mean	SD	Total Range	Ave Range
Pelvic Angle	142.1	8.1	29.6	3.8
Seat Height	24.9	6.3	32.0	5.4
Seat Back Angle	110.7	4.7	18.3	3.7
Seat Pan Angle	8.4	4.9	21.0	3.2
Foot Angle	34.6	7.6	33.8	5.8

total range was the difference between the lowest and highest values of the sample. The average range was the average difference between the lowest and highest values of each subject.

Mean values for knee angle ($P < 0.01$) and foot-X ($P < 0.001$) for the three trials were found to be significantly different. Viewing the seated subject in the context of a linkage system, as the knee angle increases, the position of the foot is expected to be further from the trunk. Positive correlations were found between knee angle and foot-X for all three trials ($r = 0.62$ to 0.81). Average knee angle increased with each successive trial (Table 9). In 16 of 24 subjects, knee angle was greatest on the third trial.

Table 9. The mean, standard deviation, and range of preferred knee angles for each trial.

Trial	Mean	SD	Range
1	119.6	±9.2	40
2	120.9	±9.8	38
3	122.6	±9.0	35

(Average range per subject = 4.88°)

Preferred seat geometries were measured in five subjects with the pelvic plate removed. No significant differences were found between trials with or without wearing the pelvic plate in each of the seat parameters except knee angle while wearing the plate. The mean values were therefore calculated for each of the parameters except knee angle and a t-test applied to determine if significant

variability exists between the values measured while wearing the plate and not wearing the plate (Table 10).

Table 10: The mean, standard deviation and percent differences of preferred seating variables with and without wearing the pelvic plate.

Variable	With plate	Without plate	% Difference
Seat Height	32.3 ±6.4	31.5 ±7.2	2.5
Seat Back Angle	113.1 ±3.3	113.1 ±5.3	0.0
Seat Pan Angle	7.5 ±3.6	6.5 ±3.3	13.0
Foot Angle	31.3 ±2.1	29.8 ±7.9	4.8

An ANOVA was applied to trial 3 knee angles and the knee angles measured without wearing the pelvic plate. No significant difference was found between the trials.

DISCUSSION

<u>Pelvic Inclination:</u> Pelvic inclination has been found to be influenced by the geometry of the seat as well as the posture of the lower extremities. The safety and comfort of the driver are influenced by the inclination of the pelvis. That is, if the pelvis is inclined too far rearward, the occupant will submarine under the belt restraining the torso in the soft abdomen. Likewise for comfort, as the pelvis rotates rearward, the lumbar spine moves toward kyphosis causing increased stress on the posterior soft tissue structures of the lumbar spine. Thus, seats that produce a large rearward rotation of the pelvis may be both unsafe and uncomfortable.

In supported sitting, weight is transferred from the trunk to the seat back so that inclining the seat back causes rearward rotation of the trunk and pelvis. When Andersson et al (1979) moved the seat back from 80° to 110° in 10° increments, the pelvis rotated rearward 15.6°, 12.9° and 3.1°, respectively. In the present study, the pelvis rotated rearward approximately 6° for each 11° increment in seat back angle when the seat back was moved from 108° to 130°.

Andersson et al (1979) found the total lumbar angle to vary in the different seating postures as a result of positional changes of the fourth and fifth lumbar vertebrae. He concluded that the change in lumbar curvature associated with seat back angle, was due to the inclination of the pelvis. In the present study, as the seat back was reclined, the trunk maintained contact with the seat back and thus rotated the full 11°. Since the pelvis rotated only 6°, the lumbar spine may have compensated for the remaining five degrees of rotation by moving toward lordosis.

The height of the seat was of little importance to the change in pelvic angle associated with altering the seat back angle. Thus, the response of the pelvis to seat back angle appears similar regardless of the type of vehicle.

Several differences in methodology were noted between the present study and that of Andersson et al (1979). Andersson et al used steeper seat back angles, ranging from 80° to 110°, as opposed to 108° to 130° used in the present study. At steeper seat back angles, a greater proportion of torso weight is transferred through the pelvis to the seat pan. Thus, a greater tendency for the pelvis to rotate rearward may exist at more upright seat back angles. This may explain the large rotational displacements of the pelvis when the seat back was moved from 80° to 100°.

Andersson et al's subjects sat on a horizontal seat pan as opposed to a seat pan reclined 15° rearward. The

tendency of the pelvis to rotate rearward would seem to be greater when it is placed on a seat pan inclined rearward. Thus, the relatively small change in pelvic inclination from 100° to 110° seat back angle may be partially attributable to the horizontal seat pan.

Finally, a knee angle more representative of office and automotive sitting was used in Andersson et al's study while in this study the knees were maintained at 115° to simulate driving. Several investigators have demonstrated the effect of knee angle on pelvic inclination/lumbar curvature (Keegan, 1953; Stokes and Abery, 1980; Brunswic, 1984). Thus, maintaining the knee angle at 115° would seem to provide a greater tendency for the pelvis to rotate rearward.

A second parameter found to consistently influence pelvic inclination was seat height. In the present study, the pelvis rotated 1° forward for every 8.0 cm increase in seat height, regardless of seat back angle. Akerblom (1948) found no change in pelvic inclination when seat height was increased from 37 cm to 50 cm. These heights, however, were much higher than the seat heights used in this study. The results of this study were similar to that of Demster (1955) in that lower seats caused rearward rotation of the pelvis. Demster found the pelvis to rotate 7° forward when the seat height was incrementally increased from 15 cm to 31 cm. Seat height is postively correlated with pelvic inclination. That is, with the trunk and knee angle held constant, an

increase in seat height will result in a increase in the trunk-thigh angle. Keegan examined lumbar curvature radiographically and found that as the trunk-thigh angle increased, the lumbar spine moves toward lordosis. He attributed the increased lordosis to decreased tension of the hamstring muscles which occurred when the hip was extended while maintaining a constant knee angle.

Previous investigations have demonstrated an influence of the posterior thigh muscles on pelvic inclination/lumbar curvature in sitting (Stokes and Abery, 1980; Brunswic, 1984; Keegan, 1953). In the present study, no correlation was found between hamstring length and pelvic angle in the fixed seat geometries. In the previous studies, lumbar curvature was varied by changing the subjects' knee angle. Stokes and Abery (1980) also found that the extent of hamstring tightness influenced lumbar curvature in unsupported sitting. In this study, the knee angle was held constant in the fixed seat geometries and a seat back was used which may have limited rearward rotation of the pelvis. Minimal evidence of hamstring muscle influence was noted in the preferred seat geometry trials, thus there is little indication that asymptomatic individuals orient their pelves in an automobile seat according to hamstring length.

Pelvic angle was found to differ by as much as 27° between subjects for a given seat geometry. Virtually no correlations were found between anthropometric measurements and pelvic angle of the fixed seat geometries.

If sitting posture produces a torso center of gravity rearward of the ischial tuberosities, the pelvis rotates rearward. If the seat back restricts rotation of the pelvis, the placement of the ischial tuberosities relative to the seat back will likely determine pelvic angle. That is, placement of the ischial tuberosities further from the seat back will allow more rearward rotation than placement near the seat back. The rotation of the pelvis may also be limited by the hip flexor musculature through the attachments to the innominate bone. Their effect would seem to be most evident at low seat heights and large seat back angles. Finally, the soft tissue structures of the lumbar spine may have the potential to limit rearward pelvic rotation through their attachments to the sacrum and innominate bones.

The CR in this study describes motion of the pelvic plate in response to changes in seat back angle. CR is therefore assumed to correspond to the CR of the torso. Upon rearward rotation of the seat back, the pelvis was expected to rotate an amount equivalent to that of the seat back. This was not the case. The pelvis rotated only 6° for each 11° increment in seat back angle. Thus, it was hypothesized that in addition to the rearward rotation of the pelvis, the pelvis also translated rearward when the seat back rotated rearward. To test this hypothesis, the center of rotation of the pelvic plate was calculated. There is no previous quantitative data found in the

literature which describes the center of rotation of the seated torso.

Branton (1969) modeled the sitting torso and described the movement of the unsupported pelvis as "rocking over the ischial tuberosities." Andersson et al (1979) postulated the rotational axis of the body in furniture seating to be at the ischial tuberosities. In interpreting the center of rotation findings, one should consider that the calculations were not applied to actual motion data, but rather positional data subject to postural changes associated with the testing protocol. The present data shows the center of rotation to lie slightly below the seat pan in the vicinity of the ischial tuberosities. It was displaced rearward by rotating the seat back rearward. These findings appear similar to that which was previously hypothesized by Branton and Andersson et al.

Panjabi (1979) studied the error magnification associated with the method used to determine the center of rotation. He found the magnitude of the marker angle influenced the magnitude of error in the center of rotation calculations. A marker angle of 23° was calculated. Panjabi reported that errors could be minimized by using marker angles approaching 90°. Therefore, the experimental design could have been improved by widening the distance between spark gaps P2 and P3 and spark gap P1 so that the marker angle approached 90°. The standard deviation of the Z component for the center of rotation was notably larger

than that of the X component. This is consistent with the dimensions of the error zone reported by Panjabi.

Panjabi reported that marker angles approaching 90° minimized output error. The marker angle (M) is the included angle between lines extending from the center of rotation to points P1 and MP. Panjabi found that when a 20° marker angle was used, a 0.1 mm error in the input value resulted in a mean error in the center of rotation of 2.85 mm with a range of 10.71 mm.

The location of the torso center of rotation is important in automotive seat design. The vertebral column consists of a series of curves in the saggital plane. When viewed from its posterior aspect, the spine is convex at its thoracic and sacral regions, and concave at its cervical and lumbar regions. Many seats have been designed in an attempt to fit the normal contour of the torso to distribute load more evenly. If the centers of rotation of the torso and the seat back differ, the relationship between the torso and seat back can change as the seat back angle changes. Andersson et al (1979) postulated that if the center of rotation of the torso were located at the ischial tuberosities, a change in seat back angle from 90° to 105° would move a lumbar support 4.5 cm upward along the lumbar spine. The result may be the loss of optimal support to the individual's back by the seat back. The pelvic-sacral support has been recommended to counteract the rearward rotation of the pelvis in seating (Kottke, 1961; Zacharkow,

1988). If the support is aligned too low on the torso, the buttocks will be pushed forward in the seat.

Estimation of Pelvic Landmark Locations: A method to estimate the location and orientation of the pelvis within the seat was presented. From the coordinates of the pelvic plate spark gaps, the locations of pelvic landmarks of one subject were estimated using pelvic spatial geometry data. The relationship of the pelvic plate contact points with the subject's pelvis was not known, therefore assumptions of soft tissue thickness were made. Pelvic landmark locations were calculated using 1.0 cm and 2.0 cm soft tissue thickness over the pubic symphysis to determine what variation would occur in the results. A pelvic-horizontal angle of 27.1° was calculated using a 1.0 cm estimate of soft tissue thickness over symphysion. This angle was found to be similar to Andersson et al's (1979) mean pelvic horizontal angle 21.6°. The AIIS-ASIS / horizontal angle may be of use to determine if a particular seat belt system will be effective in restraining the pelvis in the event of a crash. The smaller the angle, the less likely the seat belt will restrain the body through the pelvis. A 6° difference in both angles was noted between a 1.0 and 2.0 cm estimate of soft tissue thickness over the pubic symphysis. Investigation of the actual tissue thickness is needed to provide a more accurate estimation of pelvic landmarks.

The calculated distance of ischiale to the seat pan was 2.5 cm which is within the range of measured soft tissue

thickness under ischiale (Daniel and Faibisoff, 1982). They performed autopsies of six adult males with an average weight of 63 kg and found a range of 0.5 cm to 6.0 cm of subcutaneous tissue between the ischial tuberosities and the skin. The capability of this method of determining pelvic landmark locations is promising, however further study of its accuracy as well as refinement of the method is needed.

Two primary areas of study are necessary to improve and determine the accuracy of this method. First, the relationship of the contact areas of the plate with the actual pelvic landmarks must be investigated. The plate measurements of the ASIS breadth and pubic symphysis to ASIS were similar to that measured with an anthropometer. However, variability is expected to exist among individuals in the fit of the pelvic plate as well as in pubic symphysis soft tissue thickness. Second, the match between estimated and actual pelvic geometry of test subjects must be examined. The pelvic geometry was scaled to the ASIS breadth. Scaling to two or three dimensions may provide a more accurate representation of the pelvis. Further study is also needed to determine the variability in pelvic geometry found among individuals and the effect of variability on the predictions of pelvic location and orientation.

Preferred Seat Geometry: When subjects were asked to select seat geometries best suited for their driving, they were found to be relatively consistent with their choices.

Only knee angle and foot-X differed significantly between trials. There was a tendency for the sample to increase their knee angle with each successive trial. In the sample of five tested without the plate, the knee angle reached its maximum by the third trial of preferred seating. Thus, the mean knee angle of 122.6° found in trial 3 may best represent the preferred knee angle of the sample.

The mean chosen seat back angle in this study of 110.7° was within Rebiffe's (1975) predicted comfort range of 110° to 120°. The mean seat back angle was almost identical to the mean of 111.7° reported by Lay and Fisher (1940) in a survey of 250 adults. The mean seat pan angle of 8° was also similar to Lay and Fisher's report a range of 6°- 7° selected most frequently. The mean knee angle selected by the subjects of 122.6° was within Rebiffe's predicted range of 95° to 135° in his biomechanical model. However, the range of preferred knee angles in this study was 10° higher, ranging from 105° to 145°.

Only length of the lower extremities, as represented by trochanterion height, positively correlated with any of the seating parameters. As expected, subjects with longer lower extremities preferred seat geometries with more leg room in agreement with Schneider et al (1980). There was also some indication that these subjects preferred higher seats.

In agreement with Verriest and Alonzo (1986), the findings of the present study indicate that seating postures are reproducible. The only comparable parameter reported by

Verriest and Alonzo was knee angle. Verriest and Alonzo found the total range of knee angles of their sample to be three times higher than the average range for a subject. In the present study, the total range was eight times higher than the average range. In the remaining parameters, the total range was five to eight times higher than the average range. Differences in methodology were present between the two studies. Verriest and Alonzo allowed subjects control of lumbar and thoracic support and also had subjects use a steering wheel.

Because the test seat lacked many of the features contained in an automobile such as cushioning, a steering wheel and the act of driving, the seat geometry chosen may not have been representative of the subjects' actual preferred geometry for driving. The subjects hands were not positioned on a steering wheel as they would in driving. The steering wheel would have interfered with sound transmission from the pelvic plate spark gaps to the microphones. There is some evidence to validate the use of a hard seat under non-driving conditions as a viable method to predict preferred driving postures. UMTRI (1983) found the location of the pelvis to be almost identical in soft and hard seats. Schneider et al (1980) found little difference between the horizontal seat positions selected under non-driving and driving conditions.

Wearing the pelvic plate may have influenced the posture of the subjects. During the test procedure, all

subjects reported that they could sit comfortably in the seat while wearing the plate. Several of the subjects openly voiced their opinion that they did not feel the plate altered their sitting posture. In the analysis of the preferred seat geometries of five subjects tested with and without the plate, there is no indication that wearing the plate influences the subject's preferred seat geometry.

In conclusion, this research can be summarized as follows:

1) The pelvic plate can be used for tracking the pelvis in seating postures.

2) The pelvis rotates rearward primarily as a function of seat back angle. Large seat back angles should probably be avoided to ensure the safety of the occupant in the event of a crash.

3) The center of rotation of the seat back should be as close as possible to the center of rotation of the torso to optimize the support of the occupant's back.

4) A method for estimating pelvic landmark locations has been developed. Further research is necessary before this method can be implemented as a research tool.

5) Seating postures in a hard seat are reproducible.

Appendix 1

SUBJECT ANTHROPOMETRIC DATA

SUB	AGE	HGT	SIT HGT	BM	ASIS HGT	TROCH HGT
1	24	191.3	96.4	82.9	110.8	106.7
2	34	173.6	89.0	64.5	99.8	95.0
3	28	188.5	94.2	79.2	110.5	102.4
4	29	179.9	91.9	68.8	101.2	92.2
5	29	181.7	92.1	75.5	99.3	94.2
6	31	178.0	95.5	77.4	104.8	97.4
7	28	165.1	85.1	67.4	93.1	87.5
8	21	178.4	96.1	69.9	95.9	93.5
9	22	174.1	89.4	67.4	99.3	91.8
10	25	190.2	96.9	96.0	110.8	104.1
11	25	170.3	89.4	62.5	95.4	89.9
12	24	186.5	94.5	86.5	110.1	102.3
13	22	191.5	92.5	99.3	112.2	102.7
14	23	181.4	92.6	73.7	102.9	96.5
15	31	168.9	86.8	62.9	96.2	89.5
16	22	187.4	96.0	78.4	106.3	101.0
17	24	182.9	95.6	88.0	102.0	92.7
18	27	184.3	94.3	82.6	105.3	99.9
19	24	191.7	98.2	96.8	110.9	104.7
20	26	182.3	90.8	77.6	106.6	97.8
21	23	189.7	94.7	85.2	107.1	100.1
22	25	181.8	91.0	80.4	105.3	98.8
23	29	183.4	94.9	91.3	105.0	98.0
24	23	177.8	94.5	75.2	98.3	90.1
MIN	21	162.2	85.1	62.5	93.1	87.5
MAX	34	189.3	98.2	99.3	112.2	106.7
MEAN	25.8	179.4	93.0	78.7	103.7	97.0
SD	3.4	7.6	3.3	10.7	5.7	5.4

SUB = subject no., HGT = height from floor to top of head with shoes in cm, SIT HGT = sitting height from SRP to top of head in cm, BM = body mass in kilograms, ASIS HGT = height from floor to left ASIS with shoes in cm, TROCH HGT = height of left hip greater trochanter with shoes in cm.

SUB	TIB HGT	SPH HGT	PEL WTH	PEL DTH	ASIS-PS	WST C
1	53.8	11.0	23.3	16.2	15.2	102.0
2	46.8	9.2	21.9	16.3	13.8	91.8
3	50.2	11.7	23.5	14.5	15.2	100.8
4	48.2	10.2	25.2	13.6	15.6	91.9
5	48.0	7.8	21.6	14.7	12.9	97.3
6	50.8	9.8	23.2	14.7	12.9	98.4
7	48.8	10.3	23.7	13.0	13.8	93.4
8	46.9	9.7	22.7	13.6	13.5	95.9
9	47.0	10.3	21.1	13.7	13.3	93.7
10	54.6	11.3	24.2	16.5	14.2	106.5
11	47.1	10.8	22.8	13.0	13.8	91.4
12	53.0	8.7	27.0	14.2	16.1	102.7
13	54.3	11.0	22.1	14.7	15.0	106.5
14	50.6	10.2	23.3	14.9	13.7	95.5
15	48.1	9.4	19.3	14.6	13.0	86.7
16	52.5	10.1	21.4	16.5	13.7	95.3
17	51.2	11.0	23.2	16.3	14.4	105.6
18	52.0	9.0	22.5	15.9	14.2	102.3
19	58.7	9.8	21.2	16.5	14.0	102.7
20	53.7	10.0	23.3	15.3	12.3	98.5
21	51.3	9.8	20.9	16.8	14.0	102.2
22	52.6	11.1	21.0	14.3	13.2	100.8
23	51.8	10.1	25.1	16.7	14.7	102.7
24	48.4	10.8	21.1	15.6	13.0	96.6
MIN	46.8	7.8	19.3	13.0	12.3	86.7
MAX	58.7	11.7	27.0	16.8	16.1	106.5
MEAN	50.9	10.1	22.7	15.1	14.0	98.4
ST DEV	3.0	0.9	1.7	1.2	0.9	5.3

TIB HGT = height from floor to tibiale with shoes in cm, SPH HGT = height from floor to spherion with shoes in cm, PEL WTH = pelvic width from left ASIS to right ASIS in cm, PEL DTH = pelvic depth from left PSIS to ASIS in cm, ASIS-PS = distance from left ASIS to pubic symphysis in cm, WST C = waist circumference around the greater trochanters in cm.

SUB	THIGH C	CALF C	KNEE ANG
1	56.5	38.6	147
2	49.7	32.0	136
3	52.0	38.9	135
4	48.5	37.5	124
5	51.6	37.0	138
6	51.0	35.1	138
7	52.9	37.8	144
8	49.0	32.6	145
9	52.4	33.3	118
10	58.0	37.6	154
11	47.8	33.0	120
12	53.2	36.6	139
13	57.3	36.2	136
14	52.0	37.8	141
15	51.6	34.7	135
16	52.8	35.6	127
17	60.0	36.3	136
18	54.6	37.0	138
19	63.2	42.1	124
20	50.8	35.3	142
21	55.7	35.9	131
22	52.2	36.8	138
23	57.8	37.8	125
24	55.3	36.7	140
MIN	47.8	32.0	118
MAX	63.2	42.1	154
MEAN	53.6	36.3	135.5
ST DEV	53.6	2.2	9.8

THIGH C = thigh circumference in cm, CALF C = calf circumference in cm, KNEE ANG = left knee angle from hamstring length test in degrees.

Appendix 2

INFORMED CONSENT STATEMENT

I, ____________________________________, consent to serve as a subject in the reseach project, "The Influence of Seat Height and Seat Back Angle on Pelvic Orientation in Automobile Seating." I have been thoroughly informed of my participation, instrumentation, procedure, and purpose of the project in which I am participating. I have been advised that all work, will be conducted under the supervision of a licenced Physical Therapist. Further, I understand that I am free to withdraw from this experiment at any time and for any reason of my choice.

I understand that if I am injured as a result of participation in this reseach project, Michigan State University will provide emergency medical care if necessary, but these and any other medical expenses must be paid from my own health insurance program. My consent to serve as a subject is given freely and without coercion.

DATE:____________________

____
Subject's Signature

____
Street Address

____
City and Zip Code

____
Telephone

____
Witness Signature

Appendix 3

QUESTIONNAIRE

Subject number:____________ Date:_____________
Name:______________________________
Occupation:__________________
Birthdate:____________________________________
Sex:______________
Phone Number:_________________________________

A. Driving Informatiion
   1) How many years have you been driving?
      less than 5_____ 5-14_____ 15-25_____ more than 25____
   2) How many hours do you spend driving in a typical week?
      less than 10_____ 10-20_____ more than 20_____
      How many hours as a passenger?
      less than 10_____ 10-20_____ more than 20_____
   3) Check the type of vehicle you presently drive most frequently.
      compact car _________ sports car ________
      mid-size car_________ pickup truck________
      large car _________ van ________
      other _________ truck ________
   4) Check the style which best describes your driver's seat?
      bench ________ split bench (60/40) ________
      bucket________ other (please explain)________
   5) Special Features of Driver's Seat.
      Can you change your seat position?
         horizontally_______ 6-way movement (power) ______
         vertically ________ other (please explain)______
      ____
      Can you adjust your seat back angle for comfort?
         yes____ no____
      Headrests?
         adjustable______ continuous with seat back_______
   Built in lumbar support?
      adjustable_____ fixed_____not present_____
   Do you use any additional lumbar support?
      yes_____ no_____
   Do you use any additional seat cushions?
      yes_____ no_____

(Do not fill out sections B and C)

B. Past and/or Current Medical History
   1) Have you ever had an injury to the following areas?
      (Explain when, how, and type of injury for each.)
      Neck:____
      ____

Back: ____
____
Hip: ____
____
Knee: ____
____
Ankle: ____
____
Foot: ____
____

Did you seek medical attention? yes_____ no_____

If yes, check what type of treatments you received?

medication	________	cast	________
surgery	________	brace	________
manipulation	________	heel lift	________
physical therapy	________	cane/crutches	________

How long were you affected or limited by the injury? (explain) ____
____

2) Are you currently having pain?

neck	________	back	________
hip	________	buttock	________
thigh	________	knee	________
leg	________	ankle/foot	________

experiencing no pain at this time__________

C. General Health

1) Do you or have you had any medical problems which affects your sitting? ____
____

2) Are you currently under a physician's or chiropractor's care? yes________ no________

For what problem? ____
____

What type of treatment have you received? (medication, surgery, ...) ____
____

3) Do your joints hurt, swell or feel stiff? yes____ no____

If yes, please explain. ____
____

D. Activity Level

1) Have you increased or decreased your activity level recently? yes________ no________. If yes, please explain? ____
____

2) What percentage of your daily activities involve the following?

standing________ sitting (including driving)________

walking________

3) What sports or recreational activities do you participate in and for how many hours per week?________
____

4) Do you consider yourself an exerciser or non-exerciser?

____

If you consider yourself an exerciser, how many days per week do you exercise? (circle one) 1/2/3/4/5/6/7

Appendix 4

ANTHROPOMETRIC AND FLEXIBILITY TESTING

Handedness: Right______ Left______ Both______
Footedness: Right______ Left______ Both______

---------------------------standing-------------------------

1) Weight: ______________________
2) Height: ______________________
3) ASIS Height: _________________
4) Trochanterion ________________
5) Tibiale ______________________
6) Spherion: ____________________
7) ASIS to PSIS: Left: ________ Right: ________
8) Hip Circumference: ______________________________
9) Thigh Circumferenc: __________
10) Calf Circumference: _________
11) Forward Bending: ____________
12) Backward Bending: ___________
13) Range of Motion Screen
    Hip Flexion/Extension: WNL________ Limited________
    Knee Flexion/Extension: WNL________ Limited________
    Ankle Dorsiflexion/Plantarflexion: WNL________
    Limited________

----------------------------supine--------------------------

1) ASIS to ASIS: ___________________
2) ASIS to pubic symphysis: Left________ Right________
3) Knee extension ROM with hip flexed at 90 degrees:
   Left________ Right________
4) Post positions on pelvic plate: P1_____ P2_____
   P3_____

----------------------------sitting-------------------------

1) Height (seat back at 108 degrees)_________________

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