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The Effects of Lumbar Support Prominence and Vertical Adjustability on Driver Postures

FINAL REPORT

Matthew P. Reed
Lawrence W. Schneider
Bethany A. H. Eby

University of Michigan
Transportation Research Institute
Biosciences Division
2901 Baxter Road
Ann Arbor, Michigan 48109-2150

Submitted to:

Lear Seating Corporation
21557 Telegraph Road
Southfield, MI 48034

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16. Abstract: An appropriately contoured lumbar support is widely regarded as an essential component of a comfortable auto seat. Most recommendations for lumbar supports are based on research concerning stresses on the lumbar spine. Laboratory experiments have demonstrated that lumbar intervertebral disc pressure is lower when the spine is in an extended posture (lordosis) than when the spine profile is flat. These findings have led researchers to recommend longitudinally convex seatback contours that are intended to maintain or induce lordosis in the lumbar spine.

In the present study, laboratory experiments were conducted to investigate the effects of changes in seatback contour on driver posture. The primary goal of the research was to identify preferred driving postures for a range of seatback contours. Preferred postures were examined to determine if drivers respond to longitudinally convex lumbar supports in auto seats by sitting with lumbar lordosis.

In the first part of the study, 48 male and female subjects from four stature/gender groups operated an interactive laboratory driving simulator for three one-hour sessions with the lumbar support of a test seat adjusted to produce prominences of 0, 10, and 25 mm, respectively. Prior to each session, the standing posture of the subject was recorded. Posture and subject back contour data were collected by means of a sonic digitizing system. Changes in posture over the one-hour simulations were found to be small.

Based on the results from the first phase of testing, a second phase was conducted using short-duration sitting sessions to measure driver posture over a wider range of lumbar-support prominences. Eight subjects from each of the four stature/gender groups in the original pool of 48 subjects were recruited (32 subjects total). Postures were measured after a two-minute driving simulation with lumbar-support prominences of 0, 25, 35, and 45 mm. Sessions were conducted in which the subject could adjust the vertical position of the support as well as with the support fixed. Posture was also measured in sessions for which the subject's sitting procedure was prescribed to maximize the subject's lumbar lordosis in a manner similar to that used in previous studies of the effects of lumbar support.

Increasing the prominence of the lumbar support from 0 to 45 mm changed sitter-selected postures only slightly. Subject postures in sessions with the prescribed sitting procedure showed significantly more lumbar lordosis than in the preferred-posture conditions, indicating that the test conditions did not preclude postures with greater lordosis. Even when the sitting procedure was prescribed to maximize lordosis, the change in lumbar spine curvature with an increase in lumbar-support prominence was smaller than expected. These findings indicate that relatively large changes in the longitudinal contour of an automobile seat backrest do not result in similar changes in subject spine curvature. An analysis of changes in pelvis angle and leg posture with varying lumbar-support prominence and sitting procedure suggests that the extended-knee posture required with the typical automobile seat heights and pedal locations are key factors that prevent substantially lordotic postures in this environment.

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EXECUTIVE SUMMARY

An appropriately contoured lumbar support is widely regarded as an essential component of a comfortable auto seat. Most recommendations for lumbar supports are based on research concerning stresses on the lumbar spine. Laboratory experiments have demonstrated that lumbar intervertebral disc pressure is lower when the spine is in an extended posture (lordosis) than when the spine profile is flat. These findings have led researchers to recommend longitudinally convex seatback contours that are intended to maintain or induce lordosis in the lumbar spine.

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Differences among subjects in preferred postures were found to be much larger than changes in posture induced by increases in lumbar-support prominence. However, small but highly significant changes in posture associated with increases in lumbar-support prominence were noted. Averaging over all 32 subjects in Phase-2 testing, increasing the lumbar-support prominence from 0 to 45 mm

- reduced pelvis angle (more upright) by 3 degrees,
- increased thorax angle (more reclined) by 3 degrees,
- increased torso angle (more reclined) by 2 degrees,
- increased lumbar lordosis by 9 mm, and
- decreased net thoracolumbar spine flexion by 6 degrees.

Relative to the standing posture, average thoracolumbar spine flexion was 45 degrees, with 53 degrees of rearward pelvis rotation and 8 degrees of rearward thorax rotation. Average torso recline relative to the standing posture was 20 degrees. Comparison between preferred postures voluntarily selected by subjects and prescribed postures induced with a specified sitting procedure indicated that the test conditions did not preclude postures with significantly more lordosis than was preferred.

In test conditions for which subjects were allowed to adjust the vertical position of the lumbar support, the mean preferred lumbar support apex location was 152 mm above the sitter's hip joint centers, or about 159 mm above the H-point of the seat. The distribution of preferred lumbar support apex locations was approximately normal, with a standard deviation of 23 mm.

The results of this study suggest that, for seats that provide firm support for flat-spine or lordotic postures, increases in lumbar-support prominence have, on average, only a small effect on spine posture. For most subjects, longitudinally convex lumbar supports did not produce spine postures approximating the standing spine posture. An analysis of the relationships between leg posture and pelvis angle suggests that the auto seating environment, which requires extended knees, effectively prohibits substantially lordotic postures for many subjects through the effect of hamstring tension on hip range-of-motion. However, no relationship was found between scores on a simple hip-flexibility test and pelvis orientation, suggesting other confounding factors.

These findings suggest that lumbar supports in auto seats should not attempt to induce postures with considerable lumbar lordosis, because such postures are unusual even when the seat is designed to support them, and because such supports will result in inappropriate distributions of support force for most sitters. Instead, automotive lumbar supports should provide support for postures with the least spine flexion that subjects find comfortable and will voluntarily select. These postures are characterized by, on average, about 11 mm of lumbar lordosis. About 80 percent of the subjects preferred postures with between 0 and 25 mm of lordosis. The remaining subjects were more likely to prefer kyphotic postures than postures with more than 25 mm of lordosis. The back contour curves, preferred lumbar support positions, and posture data from this study can be used to design seats that are more likely to be comfortable for a large percentage of the population than seats designed using the previous physiologically based lumbar support design criteria.

1.0 INTRODUCTION

The appropriate design of lumbar support is the most frequently discussed issue in seating ergonomics. Åkerblom (1948), who is credited with beginning the modern study of seating, cited more than 70 previous works related to the subject. Åkerblom formulated chair design recommendations after extensive investigations of spine anatomy, muscle activity, and force balance in sitting. Since Åkerblom's work, hundreds of papers have been published on seating ergonomics, many of which include recommendations for lumbar support that do not differ substantially from earlier recommendations (see Chaffin and Andersson 1991; Reynolds 1993; and Reed *et al.* 1994 for reviews).

In view of this body of work, one might question the need for further research on lumbar support. However, some research suggests that current lumbar support recommendations based on physiological considerations do not adequately take into account the behavior of the sitter in the driving environment (Reed *et al.* 1991). This report describes the procedures and results of a research project intended to determine the effects of changes in seatback contour on driver posture.

1.1 DEFINITION OF LUMBAR SUPPORT

An important preliminary issue is the definition of the term "lumbar support." For the purposes of this report, lumbar support is defined geometrically, using a method similar to that employed by Andersson and others (Andersson *et al.* 1974a, 1974b, 1974c, 1974d; Andersson *et al.* 1979; Porter and Norris 1987). Figure 1 shows the sagittal back contour (profile) of a seated person. The lumbar support reference line is tangent to the posterior curves of the buttocks and thorax. The lumbar-support prominence is defined as the maximum deviation of the profile curve from the reference line. If the resulting depressed seat contour is convex, as shown in the Figure 1, the lumbar-support prominence is positive. The construction is slightly more complicated for negative prominences. If the lumbar spine is kyphotic, then the lumbar reference line is constructed in the position it would occupy if the sitter's back were straight, and the (negative) lumbar-support prominence is the maximum deviation from the reference line in the low-back region. The height of the lumbar support is defined as the location of the apex of the support above the sitter's hip joint centers on the torso line connecting the hip joint center and the shoulder joint. As an approximation, the H-point location and/or torso angle determined using the SAE J826 manikin and procedures can be used. The reference points used to define the vertical position of the lumbar supports in this study are made clear in context.

Although this definition of lumbar support was originally developed by reference to seat geometry, it is actually a measurement of a sitter's posture. In a laboratory study on lumbar support, Andersson *et al.* (1974a) used a wooden chair with a flat seatpan and seatback. Each subject's hips were positioned as far to the rear on the seat as possible so that the buttocks or sacrum firmly contacted the seatback and the sitter's thorax was reclined until it contacted the upper part of the seatback. The plane of the seatback thereby represented the lumbar reference line depicted in Figure 1. When the position of the lumbar support was changed relative to the reference plane, the change in lumbar prominence was directly measurable, since the positions of the upper and lower tangent points and the apex of the lumbar curve were determined by the apparatus. In later studies on a car seat, Andersson *et al.* (1974d) used an identical definition for lumbar prominence, although the method used for determining the reference plane was not described.

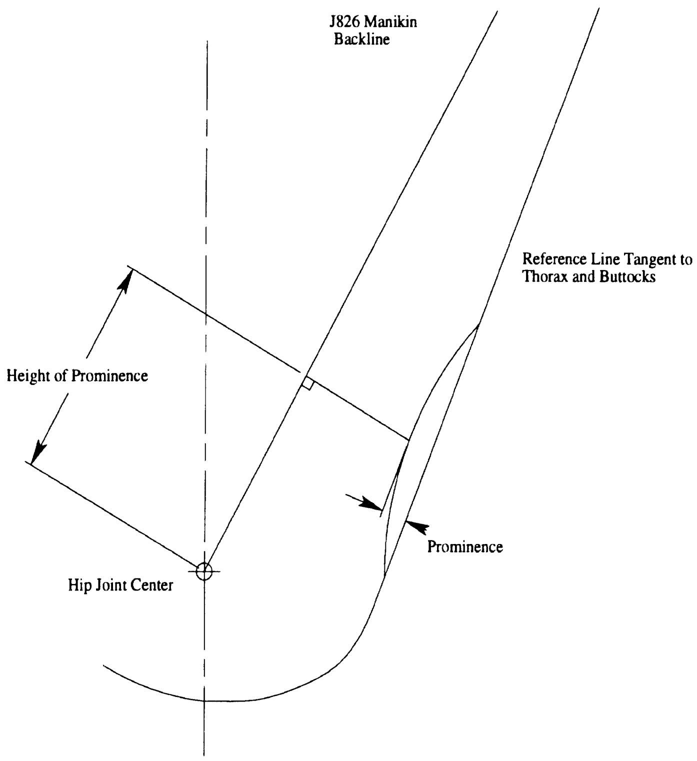


Figure 1. Geometric definition of lumbar support.

A primary problem in using this definition to design a backrest is that the accuracy of the lumbar support specification relies on prediction of the sitter's posture. Most auto lumbar support recommendations assume that the human hip joint centers are coincident in the sagittal plane with the SAE J826 H-point (SAE 1991), and that changes in the seatback contour alter the curvature of the sitter's lumbar spine, but do not change the hip joint center locations or the torso angle. If the manikin and human postures correspond in this manner, then the manikin back profile, which is flat in the lumbar area, provides the reference line. This is the method used by Robbins (1986), Hubbard and Reynolds (1984), and Maertens (1993) to specify lumbar support geometry. However, if the sitter's hip joint center locations relative to the seat are changed by the addition of a convex curve to the lower part of the seatback, then the original manikin-derived reference line will not correspond to the reference line that would be constructed from the sitter's actual posture. Consequently, the prominence of lumbar support measured using the sitter-based geometric definition described above would generally be smaller than that which would be obtained if the sitter sat with a back profile that matched the seatback curvature. In general, the geometric definition of lumbar support is useful only if the sitter's posture corresponds to the intended depressed contour of the seatback.

In defining test conditions for this study, the sitter's buttock and thorax positions were assumed to be unaffected by changes in the prominence of the lumbar support. Using this assumption, increases in the prominence of the physical support can be considered to translate into equivalent changes in the sitter's back profile, as they did in the studies of Andersson *et al.,* since the reference plane is assumed to remain fixed relative to the seatback. However, a central pretest hypothesis in the current study was that this assumption was generally not valid for auto seating, and that seated postures would change in response to increases in the prominence of the physical support in such a way that a new definition of appropriate lumbar support would be justified.

1.2 PURPOSE OF LUMBAR SUPPORT

Åkerblom (1948), Keegan (1953, 1964), Keegan and Radke (1964), and others recommended that a firm pad be located in the lower part of the seatback to restrain the lumbar spine from flexing excessively. Åkerblom recommended a firm support beginning at the height of the fourth or fifth lumbar vertebra, *i.e.*, at or below the top of the pelvis. Keegan suggested that seats be designed to produce a lumbar lordosis about midway between the typical standing lordosis and a flat contour. He recommended this posture because he found that people under treatment for low-back disorders were often more comfortable sitting in a reclined posture with lumbar lordosis than in an upright posture with a flat spine curvature. Both recommended an open space about 115 mm high below the lumbar support to allow the pelvis to shift forward and backward for different spine postures.

By the mid-1970s, most lumbar support recommendations were strongly influenced by physiological studies of the load on the lumbar spine. Andersson *et al.* (1974a, 1974b, 1974c, 1974d) used quantitative measurements of back extensor muscle activity and internal lumbar-disc pressure to assess spine loads for a range of postures. Andersson *et al.* found that disc pressure was lower in standing than in a wide range of seated postures, both unsupported and supported. Back extensor muscle activity was also low both in standing and supported sitting with reclined back angles. The experiments of Andersson and his coworkers suggested that lumbar intradiscal pressure is primarily affected by three factors: (a) quantity of body weight supported by the lumbar spine, (b) the tension exerted by the paraspinal musculature, and (c) the curvature of the spine.

In both standing and sitting with a vertical torso angle (*i.e.*, upright), the lumbar spine sustains an axial load that supports most of the weight of the upper body, contributing to the lumbar disc pressure. The back extensor muscles, notably the erector spinae, have lines of action largely parallel to the spine. Tension developed in these muscles adds to the axial load on the lumbar discs. As a person reclines, some of the upper body weight is supported by the seatback, reducing the axial load on the lumbar spine slightly. Reclining also moves the upper body masses rearward relative to the lumbar spine, reducing the extensor moment required of the back muscles and the muscle-tension contribution to axial spine load. Lumbar muscle activity is typically minimal when the sitter is reclined more than 20 degrees from the vertical for relaxed upper-body postures.

The curvature of the lumbar spine is the third important contributor to intradiscal pressure. Åkerblom, in his own work and in citations from previous researchers, identified a "natural form" for the spine. When the spine is excised with its ligaments intact, the unloaded lumbar spine assumes a posture Åkerblom describes as similar to the standing lordotic curvature. Keegan identified a similar spine posture, obtained by a recumbent subject with a torso-thigh angle of about 135 degrees, which he called the neutral spine posture. Andersson and others have noted that this "natural" spine curvature is produced by the wedge shape of the lumbar discs, which are taller anteriorly than posteriorly.

The paraspinal ligaments hold the discs in compression. Åkerblom reported that removing the ligaments, leaving only the discs between vertebrae, caused an increase in spine length of 37 mm in one preparation. The "natural" spine posture, therefore, represents a posture in which the forces and moments on the vertebral bodies due to tension in the ligaments and compression of the discs are in equilibrium. Keegan's studies show that a similar spine posture results from passive equilibrium when the musculature is included. Deviations from this posture (*i.e.*, flexion or extension of the spine) result in increased stress in the spine and paraspinal tissue.

The research of Andersson and his coworkers shows that the disc pressure changes from standing to supported sitting result from alterations of spine posture as well as from changes in the amount of body weight supported by the spine and tension in the paraspinal musculature. When the seatback is reclined 20 degrees from the vertical, the back extensor muscles are virtually inactive, and therefore do not contribute significantly to the intradiscal pressure. However, at all seatback angles, including 20 degrees, changes in the lumbar spine curvature affect the intradiscal pressure. Since the amount of upper body weight borne by the lumbar spine does not change substantially when the lumbar curvature is varied, the reduction of disc pressure with increased lumbar-support prominence is due primarily to the change in lumbar spine curvature. In general, Andersson and his coworkers found that, for reclined postures, increasing the lumbar lordosis toward the standing posture decreases lumbar intradiscal pressure. In subsequent experiments with a car seat, Andersson *et al.* (1974d) found the lowest levels of back extensor muscle activity and intradiscal pressure with a seatback angle of 30 degrees and a lumbar-support prominence of 50 mm. "Based on the assumption that low myoelectric activity and disc pressure are favourable ... ," he and his coauthors recommended these as target values for seat design (p. 133).

The substantial work of Andersson's research team, and other related research reported in the ergonomic and medical literature, led to recommendations that lumbar supports be constructed to preserve, to the extent possible, the standing lumbar lordosis in sitting, with the objective of reducing lumbar spine loads as measured by intradiscal pressure. These recommendations have been echoed by many others since (see Chaffin and Andersson 1991; Reynolds 1993; and Reed *et al.* 1994 for reviews). A lumbar support intended to preserve the standing lordosis will be located at approximately the apex of the standing curvature, around L3, and will be longitudinally convex to mate with the desired spine curvature.

1.3 ALTERNATIVE VIEWS

Porter and Norris (1987), noting that the lumbar support specifications in the literature are based primarily on physiological rationales, constructed a wooden laboratory seat to compare the lumbar support specifications recommended by Andersson *et al.* (1979) with sitter preferences. Plastic probes inserted from the rear of the seatback provided quantitative measurement of spine curvature. Thirty-seven male and 25 female subjects sat in the experimental chair adjusted to three conditions: (a) seatpan horizontal, seatback 90 degrees to seatpan; (b) seatpan inclined 15 degrees from horizontal, seatback 30 degrees rearward of vertical; and (c) same as (a) but with the knees extended to simulate a driving position. The seatpan and seatback angles in conditions (b) and (c) were taken from the recommendations in Andersson *et al.* (1974d). The lumbar support could be adjusted to 0-, 20-, or 40-mm prominence, and adjusted to any vertical position. Porter and Norris found that people preferred the 20-mm prominence to either of the other prominences in all test conditions. They also found that the preferred lumbar support height was about 120 mm above the hip joint center, although there was considerable variation among subjects. These experiments suggest that the postures that Andersson produced with a 40- to 50-mm lumbar prominence are not those that are preferred in an experimental chair with both reclined and vertical back angles. In general, postures with substantially less lordosis were preferred.

Some researchers have also questioned whether a lordotic lumbar spine posture is in fact desirable when seated. Adams and Hutton (1985) argue that the advantages of a flexed spine posture outweigh the disadvantages. They cite increased transport of disc metabolites with changing pressure levels as a factor in favor of flexed-spine postures.

The Porter and Norris research began to address an important issue in lumbar support design. Andersson and others have demonstrated apparent physiological advantages to sitting with substantial lumbar lordosis. Keegan has reported from clinical observations that patients treated for low-back disorders are more likely to be comfortable when sitting reclined with lumbar lordosis. However, an important question is whether lumbar support contours that are intended to produce or maintain lordotic spine postures are used by sitters in that way. Using a wooden laboratory chair generally unrepresentative of auto seating, Porter and Norris found that subjects preferred to sit with a maximum lumbar lordosis about half of that found in standing. This is close to Keegan's neutral posture, but less than Andersson's recommendation for minimal disc pressure.

In the current study, experiments were conducted to determine if drivers sit with different postures when the contour of the lower seatback is changed. If a sitter does not use a longitudinally convex support in the manner intended (that is, sitting with a lumbar lordosis), then the seat may provide substantially less support at the lower levels of the lumbar spine than it would if it more closely matched the shape of the sitter's back contour (Reed *et al.* 1991). Further, geometric definitions of lumbar support that rely on a correspondence between the sitter's spine profile and the intended depressed seat contour would need to be revised.

2.0 METHODS

The research presented in this report was conducted in two phases. In the first phase, driver posture and back contour were measured at 10-minute intervals during a one-hour laboratory driving simulation. The experiments were conducted with 0, 10, and 25 mm of lumbar support. In the second phase, posture and contour measurements were made during five-minute sitting sessions with a subset of the subjects who participated in the first phase of testing. Phase-2 experiments were conducted using 0, 25, 35, and 45 mm of lumbar support. Each lumbar support was studied with three different posture-selection protocols (Fixed, Adjustable, and Prescribed) in four test conditions. In the first session (Fixed), the lumbar support was fixed at the mean height chosen by subjects with the 25-mm support prior to the one-hour driving simulations. In the second session (Adjustable), the subject was allowed to adjust the vertical position of the lumbar support. In the third and fourth sessions (Prescribed), subjects followed a prescribed sitting procedure similar to the procedure used by Andersson *et al.* (1974a). This procedure was designed to illustrate the maximum lordosis that subjects could produce with each lumbar-support prominence.

2.1 SUBJECT ANTHROPOMETRY

Twelve subjects* were recruited in each of four stature-gender groups, as shown in Table 1. Subject age ranged from 19 to 72 years with a mean age of 40 years. Nineteen standard anthropometric measures collected from each subject are summarized in Appendix A. Two measures of hip and spine flexibility were also recorded. Combined hip and spine flexibility was measured using a toe-touch test. Subjects in stocking feet stood on the edge of a 200-mm-high platform and performed a straight-knee toe-touch. The exercise was scored by recording the distance from the subject's fingertips to the platform surface. Positive values indicate reach past the toes, while negative values indicate that the subject did not reach his or her toes.

Table 1
Phase 1 - Subject Anthropometry

Group	Gender	n	Stature Min-Mean-Max (mm)	Stature Min-Mean-Max (%ile by gender)*	Weight Min-Mean-Max (kg)
1	female	12	1533–1561–1595	6–14–29	49–55–64
2	female	12	1595–1614–1640	29–40–57	51–58–66
3	male	12	1726–1751–1775	33–47–61	60–78–96
4	male	12	1776–1833–1866	62–88–95	72–85–100

*Based on normal approximations to data from Gordon *et al. (1989)*.

*The rights, welfare, and informed consent of the volunteer subjects who participated in this study were observed under guidelines established by the U.S. Department of Health, Education, and Welfare Policy (now Health and Human Services) on Protection of Human Subjects and accomplished under medical research design protocol standards approved by the Committee to Review Grants for Clinical Research and Investigation Involving Human Beings, Medical School, The University of Michigan.

Hip flexibility was measured separately with the subject lying supine on a large flat table. The experimenter placed an inclinometer against the subject's right tibia, parallel to the long axis of the bone, and raised the subject's leg with knee straight until firm passive resistance was encountered. The resulting angle relative to the horizontal was recorded as a measure of hip flexibility. Higher values indicate greater flexibility. Flexibility data are summarized in Appendix A.

For Phase-2 testing, 32 of the original 48 subjects were recruited. The resampling of subjects within groups was based on the availability of the subjects. The first eight subjects from each group that agreed to participate were selected.

2.2 SEATING BUCK AND DRIVING SIMULATOR

A laboratory seating buck was constructed to reproduce the seat, steering wheel, accelerator pedal, and brake pedal positions and orientations of a contemporary minivan. Figure 2 shows the seating buck. The seating reference point (SgRP) is located 781 mm rearward and 334 mm above the accelerator heel point (AHP) in the flat lumbar support condition with the seat in the full-rear position. The center of the front surface of the steering wheel is located 465 mm rearward and 721 mm above the AHP. The seatpan angle was 13.5 degrees, measured using the modified H-point procedure developed by Roe and reported in Manary *et al.* (1994). The instrument panel in the laboratory buck was located about 100 mm forward of its position in the vehicle to facilitate digitization of driver posture. The accelerator pedal, brake pedal, and steering wheel were instrumented and connected to a computer driving simulator program (MacAdam *et al.* 1993). The simulated road scene was projected onto a screen approximately 10 feet in front of the driver's eye point, providing a field of view measuring approximately 44 degrees horizontally and 20 degrees vertically.

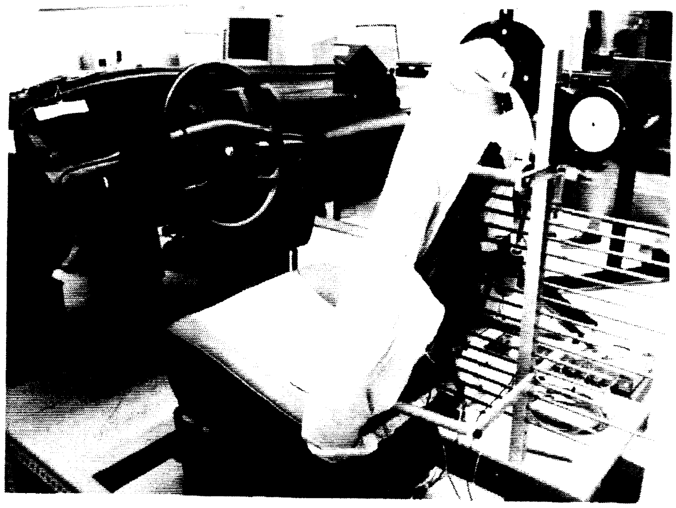


Figure 2. Laboratory seating buck.

2.3 SEAT

A minivan seat was extensively modified for use in testing, as shown in Figure 3. All of the foam and covering material on the seatback was removed. Part of the metal frame that supported the headrest was cut away to reduce the prominence of the headrest. An adjustable lumbar support supplied by Schukra North America was installed in the seatback. The front surface of the Schukra support frame was covered with a 2-mm-thick

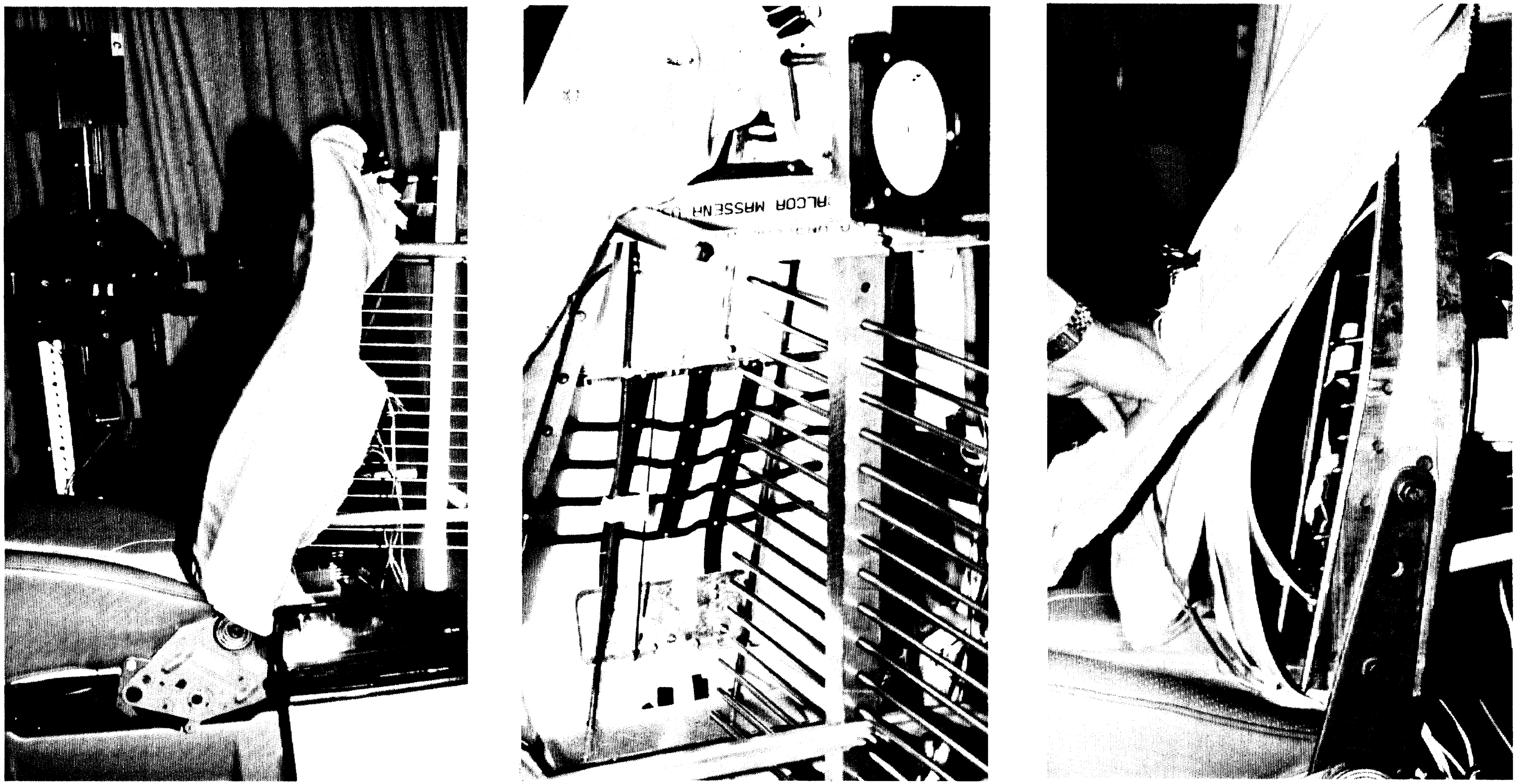


Figure 3. Test seat showing adjustable lumbar support and back contour measurement rods.

sheet of Teflon. A second layer of Teflon was cut to fit within the seatback frame and installed over the lumbar support. A soft, 15-mm foam sheet was laid over the outer Teflon sheet and covered with a thin fabric. A motorized adjustment mechanism provided approximately 120 mm of vertical lumbar support travel centered about 150 mm above the H-point on the J826 manikin backline (see Section 2.4). The experimenter adjusted the lumbar prominence by hooking different-length retaining rods between the top and bottom edges of the lumbar support frame.

Back-contour measurement rods were mounted in a frame attached to the seatback, after the manner of Porter and Norris (1987). The 6.4-mm-diameter, 424-mm-long steel rods were installed on 25-mm pitch approximately 25 mm to the right of the seatback centerline since a central rib in the Schukra support prevented placement on the centerline. Sixteen rods were located at 25-mm intervals along the rack, although usually only 12 rods were used because of lumbar support frame interference (depending on the vertical position of the support). During data collection, the rounded tip of each rod was pressed firmly against the seat foam, which was accessible through a slit in the Teflon sheet supporting the foam. The soft foam was readily compressed to a uniform thickness against the seated subject.

2.4 H-POINT CALIBRATION

SAE J826 (SAE 1991) provides a guide to the recommended methods and tools for measuring the interior dimensions of the vehicle that are related to occupant accommodation. The J826 manikin, or H-point machine, is a three-dimensional tool intended to represent the shape and mass distribution of a midsize male (Kaptur and Myal 1961). The location of the H-point of a seat (a standard reference point intended to approximate the hip joint center location of a typical sitter) is determined by placing the manikin in the seat using the prescribed procedure. The manikin is frequently used to verify that a vehicle seat and package layout, as constructed, is consistent with the original design drawings. Roe (1994) presents a summary of the current uses of the H-point manikin in vehicle design.

Because the H-point manikin was developed in the early 1960s using vehicle seats that were generally softer and less contoured than current seats, human factors practitioners in the auto industry have expressed concern that the manikin no longer accurately or consistently represents driver posture and positioning. In particular, the rigid back shell presents a flat lumbar spine contour that has been suggested to be inconsistent with driver postures in seats with firm, prominent lumbar supports. To address these concerns, the performance of the H-point manikin was investigated recently by Manary *et al.* (1994). The hip joint center locations of 40 drivers from a range of anthropometric groups were estimated using data collected as they sat in three different vehicle seats. The seats were chosen to span a range of firmness and lumbar support contour. The subject's hip joint center (HJC) locations were found to be consistently forward and above the manikin H-point by 8 to 13 mm. The offset between the human HJC and the manikin H-point did not vary consistently with amount of contouring in the seatback, indicating that, for the seats tested, the H-point manikin provided a reasonably accurate and consistent estimate of average hip joint center location.

The H-point manikin was used in the current study to measure the vehicle package geometry and to provide a seat reference point to compare with the subject's preferred hip joint center locations. An attempt was made to use the H-point machine and the SAE recommended procedure with all five lumbar-support prominences used in testing, but the machine and procedure were found to be poorly suited for use when the lumbar-support prominence exceeded 25 mm.

The procedures for use of the H-point manikin call for the manikin to be placed on the seat without the weights installed. Metal weights are added to the buttock/thigh and torso areas, following a prescribed procedure. The manikin is then manipulated in the seat by rocking back and forth and pressing the torso section against the seatback with prescribed force. During this manipulation, the buttock/thigh portion of the manikin is to be restrained from sliding forward on the seat.

With the test seat used in the current study, the firm lumbar support produced manikin movement that prevented accurate measurements of H-point with this procedure. With the 35- and 45-mm lumbar supports, adding weight to the torso of the manikin caused the torso section of the manikin to pivot around the apex of the lumbar support, thrusting the buttock/thigh section of the manikin forward. Even if the manikin were initially restrained, the sliding motion would begin as soon as the experimenter removed his hands from the machine. The magnitude of the sliding motion varied considerably from trial to trial, and, consequently, a consistent estimate of H-point location could not be made, even if some of the manipulation steps in the recommended procedure were not performed.

The 25-mm lumbar support condition was the most prominent for which a reasonably precise measurement of H-point location could be made. Table 2 shows the H-point locations relative to the seat pivot point for LS Prominences A, B, and C. Measurements were made with the lumbar support in the middle of its vertical travel about 150 mm above the H-point along the manikin backline. The seat was adjusted to the rearmost detent in the seat track travel and the manikin's heels were fixed at the buck accelerator heel point. The tests were iterated so that the H-point measurements could be made with a 21-degree manikin-measured seatback angle. The physical seatback angle required to obtain this angle was more upright for LS Prominence C than for the other two prominences. H30 is a standard SAE measure of the vertical distance between the horizontal plane of the accelerator heel point and the seating reference point, which is the seat H-point obtained when the seat is in the design position. H30 is the measure most commonly referred to as seat height in the automotive context. Table 2 demonstrates that the H-point location moves forward on the seat as the lumbar-support prominence is increased. Increasing the lumbar prominence 25 mm moved the H-point forward on the seat by 13 mm while the manikin back angle was constant at 21 degrees.

Table 2
SAE J826 H-Point Location re Seat Pivot Point
(mm)

LS Prominence	X	Z	H30
A (0 mm)	138	90	334
B (10 mm)	142	90	334
C (25 mm)	151	94	338

2.5 SONIC DIGITIZER

Posture and contour data were collected using a Science Accessories Corporation GP8-3D sonic digitizer. This and similar systems have been used extensively at UMTRI and other biomechanics labs for collection of spatial data. In the current study, two sonic emitters were mounted collinear with the tip of a hand-held probe. The emitters produce a wide-band sound pulse when an electric current arcs across a spark gap. An orthogonal array of four microphones receive the sound. An interface unit calculates the sound transit time to each microphone, applies a conversion factor to obtain distance, and sends these values via a serial connection to a computer. The three-dimensional location of each emitter is calculated trigonometrically from the three smallest microphone distances recorded for that emitter. The location of the probe tip is calculated from the locations of the two probe emitters. Figure 4 shows the probe being used to collect posture data on a seated subject.

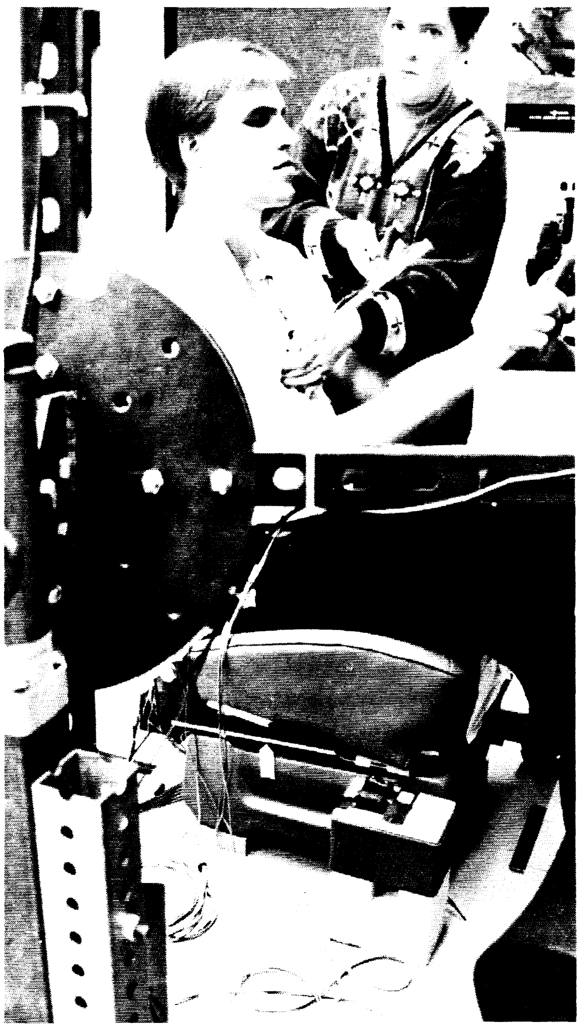


Figure 4. Digitizing a seated subject.

Prior to each test session, a single emitter located a known distance from one microphone was sampled 10 times. The calculated distance from emitter to microphone was compared with the nominal value to obtain a calibration factor accounting for changes in sound conduction velocity due to temperature and humidity fluctuations. This calibration factor was applied to all subsequent measurements. Immediately prior to testing, a transformation matrix was obtained. Three points defining two perpendicular axes in a horizontal plane located on the seating buck or the stabilization frame used for standing posture measurement were digitized with the sonic probe ten times each. Average values were used to compute a transformation matrix to convert microphone coordinates to buck or standing frame coordinates. The accuracy and precision of the system were then checked by redigitizing each of the three axes points five times each. The transformation was accepted only if all five sampled values lay within 2.5 mm of their nominal positions. During subsequent data collection, the calculated distance between the probe emitters, nominally 200 mm, was monitored. Data were rejected if the value differed from the nominal value by more than 2 mm. Section 3.9.3 contains an analysis of measurement errors associated with using the digitizer.

2.6 TEST CONDITIONS

Five lumbar-support prominences were used in testing. Each was defined by the displacement of the most prominent point on the lumbar support frame relative to the supporting structure. For lumbar support (LS) Prominence A, the support frame was allowed to flatten under loading by the subject to produce an approximately flat surface. For LS Prominence B, a metal retaining rod was used to hold the top and bottom edges of the Schukra support such that the point of maximum prominence was 10 mm forward of its position in LC Condition A. For LS Prominences C, D, and E, metal retaining rods were used to adjust the point of maximum prominence to 25, 35, and 45 mm forward of its position in Condition A, respectively. Table 3 shows the test conditions.

As noted above in Section 1.1, these test conditions do not necessarily correspond to 0, 10, 25, 35, and 45 mm of lumbar support under the definition used by Andersson *et al.* and Porter and Norris because the reference plane cannot be determined without identifying a particular posture. Instead, these conditions represent relative levels of lumbar support. Higher prominences should provide the opportunity for supported spine postures that are more lordotic. These prominences span the range of recommendations found in the ergonomic literature, if the reference plane is assumed to remain fixed relative to the seatback.

Table 3
Lumbar Support Prominences Used in Testing

Lumbar Support Condition	Prominence (mm)	Used In Phase 1 (Long-Duration)	Used In Phase 2 (Short-Duration)
A	0	x	x
B	10	x	
C	25	x	x
D	35		x
E	45		x

2.7 TEST PROTOCOL

2.7.1 Phase 1: Long-Duration Testing

Each lumbar-support prominence (*i.e.*, A, B, and C) was tested on a different day with each subject and the order of test conditions was counterbalanced. At the start of testing, the subject changed into form-fitting tights and a loose-fitting shirt to facilitate palpation of body landmarks. The subject was trained to locate the pubic symphysis landmark by reference to a skeleton and full-size replica of a pelvis. To digitize the point, the subject palpated the anterior-superior margin of the pubic symphysis and pressed the digitizer probe tip firmly against that point, compressing the underlying tissue.

The standing posture of the subject was recorded prior to each driving simulation session. The subject was instructed to stand erect in front of a stabilization frame, holding the hand grips on the frame to reduce body sway. Figure 5 shows a subject during measurement of standing posture. The investigator palpated the body landmarks listed in Table 4 and recorded their locations with the sonic digitizer probe. Fixed emitters were attached to the subject's body or clothing at the ankle, left trochanter, left acromion, C7, and suprasternale. These emitters were fired in sequence each time a landmark was digitized with the probe. The data from the trochanter and acromion landmarks were used to correct the body landmark data for body sway that might occur between measurements.

Figure 5. Digitizing standing posture.

Table 4
Body Landmarks

Landmark	Definition
GLABELLA	Undepressed skin surface point at the most anterior prominence on the brow on the midsagittal line.
TOP HEAD	Undepressed skin surface point at the most superior point on the head.
OCCIPUT	Undepressed skin surface point at the most posterior point on the occipital prominence.
C7, T1–T12, L1–L5	Depressed skin surface point over most posterior point on corresponding spinous process.
ASIS(L), ASIS(R)	Depressed skin surface point over anterior-superior iliac spine. Located by palpating at trunk-thigh junction to locate the most anterior point on the ilium.
PSIS(L), PSIS(R)	Depressed skin surface point over posterior-superior iliac spine. Located by palpating at the posterior margin of the ilium adjacent to the sacrum. Location of this landmark was aided by reference to the previously palpated L5 spinous process.
PUBIC SYMPHYSIS (PS)	Anterior-superior margin of the pubic symphysis. Subject is trained, using a model skeleton, to locate point with probe. Subject is instructed to compress the tissue toward the bone to the extent comfortable.
TOP STERNUM	Undepressed skin surface point at the most superior margin of the jugular notch of the manubrium in the midline of the sternum.
BOTTOM STERNUM	Undepressed skin surface point at the most inferior margin of the manubrium in the midline of the sternum.
LATERAL FEMORAL CONDYLE (LFC)	Undepressed skin surface point at the most lateral prominence of the right femoral condyle.

Prior to each test session, the experimenter fixed the lumbar support at the appropriate prominence, placed the seat track in its full-rear position, located the seatback recliner at a nominal 20-degree angle, and set the steering wheel angle adjustment to a neutral position. The lumbar support was initially positioned at the center of its 120-mm vertical range.

After the standing posture was recorded, the subject was instructed to sit in the test buck. Subjects were told to choose a "comfortable driving posture," such as they might choose on a "long drive" and to then manually adjust the seat track, seatback recline angle, and steering-wheel tilt for maximum comfort. Subjects were also told to adjust the vertical position of the lumbar support using a switch mounted to the right of the seat. The subject was encouraged by the experimenter to try a range of different seat and lumbar support positions and to find the most comfortable combination of adjustments. When the subject had adjusted the seat and steering wheel satisfactorily, the experimenter activated the driving simulator. The lights were dimmed during simulator operation to improve the visibility of the road scene and the experimenter provided instruction on operating the simulator. In general, the subjects readily followed instructions to keep the simulated vehicle in the right lane of a two-lane winding road, and to maintain an 88 km/h speed (displayed on the screen with a simulated head-up display as 55 mph).

After two minutes of operating the simulator, the experimenter instructed the subject to maintain his or her current posture while the simulator was paused and the lights brought up. The experimenter used the digitizer probe to record the subject's back contour and posture. First, each of the back contour probes in turn was pressed firmly against the subject's back, bottoming out the thin foam layer of the seatback against the subject's back, and the location of the rear of the probe was digitized. Next, two points on the contour-probe rack were recorded to define a projection plane perpendicular to the probes. These points also provided a precise measure of the selected seatback angle. The seatback pivot was also digitized to provide a reference point that is fixed relative to the seatpan.

The body landmarks listed in Table 4 were then digitized, with the exception of the spinous processes below C7 and the PSIS points, which are not accessible with the subject seated. Without moving the pelvis, the subject located the pubic symphysis landmark using the procedures learned previously. The contour and body landmark digitization typically required two minutes. The simulator was then restarted, and the subject drove until 10 minutes had elapsed from the time the simulator was previously paused. The simulator was again paused and data collection was performed as before. The total test time was one hour, providing seven data collection intervals at 0, 10, 20, 30, 40, 50, and 60 minutes. The actual time the subject was seated was approximately three minutes greater because of adjustment time and the two-minute initial drive.

Subjective comfort evaluations were obtained prior to and following the long-duration driving sessions. Subjects reported discomfort in their upper-back, lower-back, buttock, and thigh areas by marking open-scale lines anchored by the words "No Discomfort" and "Unbearable Discomfort." The questionnaire is included in Appendix B.

2.7.2 Phase 2: Short-Duration Testing

After Phase-1 testing and preliminary results of analyses with all 48 subjects had been completed, Phase-2 testing was begun, using a similar protocol. For each subject, posture and back contour were measured 16 times, using four lumbar-support prominences in four consecutive sessions. Total test time was about 90 minutes per subject.

Session 1: Fixed Lumbar Support Condition

In this session, each subject was tested with each of four lumbar-support prominences (A, C, D, and E) in counterbalanced order.

For each, the vertical position of the lumbar support was fixed at the mean position selected by the first 24 subjects in Phase-1 testing with the 25-mm lumbar support. This placed the apex of the support approximately 156 mm above the H-point of the seat obtained in LS Prominence A (flat). The seating buck was initially configured by the experimenter as described above for Phase-1 testing. The subject was instructed to sit in the seat with a "comfortable" driving posture, adjusting the seat track, recliner, and steering wheel tilt to desired positions. The subject then drove the simulator for two minutes. The experimenter stopped the simulator after instructing the subject to maintain his or her posture. The sonic digitizer was used to record the same posture and back contour data collected in the long-duration testing.

After completion of each condition, the subject stepped behind a curtain in the laboratory while the experimenter readied the buck for the next prominence condition.

Session 2: Adjustable Lumbar Support Condition

The second set of four tests was identical to those of the first session except that the subject was allowed to adjust the vertical position of the lumbar support for Conditions C, D, and E. LS Prominence A is flat, so the vertical adjustment was not used in that condition. The LS Prominences were presented for each subject in the same order as in the first session (counterbalanced among subjects).

Sessions 3 and 4: Prescribed Posture Condition

In the third session, the seatback angle was set by the experimenter to the mean value selected by subjects of the corresponding stature group in the long-duration testing. Seatback angles were 21, 22, 24, and 25 degrees for the small-female, midsize-female, midsize-male, and large-male groups, respectively. These angles are referenced to the physical orientation of the seatback when the J826 manikin seatback angle was 21 degrees with LS Prominence A. The subject-selected seat track position from the last test of Session 2 was maintained for Sessions 3 and 4. The vertical position of the lumbar support was fixed at the same position used in the first (Fixed) session, and the steering wheel angle remained as it was set by the subject in the last test of the second session.

The subject was instructed to sit using a prescribed procedure in an attempt to induce the subjects to produce maximally upright pelvis orientations and back contours matching the lumbar-support curvature as much as possible. The subject first sat in the seat and leaned forward, flexing at the hips as much as possible. The subject was then told to slide his or her buttocks rearward on the seat as far as possible while continuing to lean forward from the hips. The subject was then instructed to recline his or her upper body to find a "comfortable driving posture" against the seatback without moving the pelvis. Subjects maintained a comfortable grip on the steering wheel with their hands at approximately the 10-o'clock and 2-o'clock positions.

In Session 3, the lumbar-support prominences were tested for each subject in the same order as in Sessions 1 and 2. In Session 4, identical tests were performed as in Session 3, except that the order of testing was reversed (*i.e.*, A, C, D, E became E, D, C, A) for each subject.

2.8 DATA REDUCTION

2.8.1 Statistical Representation of Posture and Back Contour

For each test session, the digitizer control software produced a data file containing the laboratory coordinates of each point recorded. For each seated measurement interval, the contour and posture data were extracted and translated to an XZ (sagittal) plane origin at the seat pivot point so that postures from different subjects at different seat track positions could be directly compared. Most posture data analyses presented here are restricted to the sagittal (XZ) plane. The buck X axis (fore-aft) was constructed parallel to the seat and vehicle package centerline. The sitter's sagittal plane was assumed to be parallel to the buck XZ plane, so only X and Z coordinates were used to describe the location of most body landmarks. Pelvis data were analyzed in three dimensions to determine the rotation of the pelvis around vertical and lateral axes. However, only small deviations from sagittally symmetric postures were found, so planar data were used for most analyses of pelvis orientation.

Two joint-center locations used to define posture, but not directly measured, were calculated as described in Table 5. Shoulder (glenohumeral) joint location was estimated using the torso geometry for midsize males reported by Schneider *et al.* (1985) as shown in Figure 6. Hip joint center location was calculated using the method described by Manary *et al.* (1994), using pelvis proportions from Bell *et al.* (1990) and Reynolds *et al.* (1981). Figure 7 shows the calculation procedure schematically in which the coordinates of the left and right hip joint centers in a pelvis coordinate system are expressed as percentages of the distance between the anterior-superior iliac spines.

Table 5
Calculated Body Landmarks

Landmark	Definition
SHOULDER	An approximation to the location of the glenohumeral joint in the midsagittal plane. The relationships among TOP STERNUM, C7, and the glenohumeral joint for the midsized male in Schneider *et al.* (1985) were used to estimate the shoulder joint location. See Figure 6.
HJC	Sagittal position of mean of hip joint centers. Hip joint center locations calculated from ASIS(L), ASIS(R), and PUBIC SYMPHYSIS using method of Bell *et al.* (1989, 1990) and Reynolds *et al.* (1981) as adapted by Manary *et al.* (1994). See Figure 7.

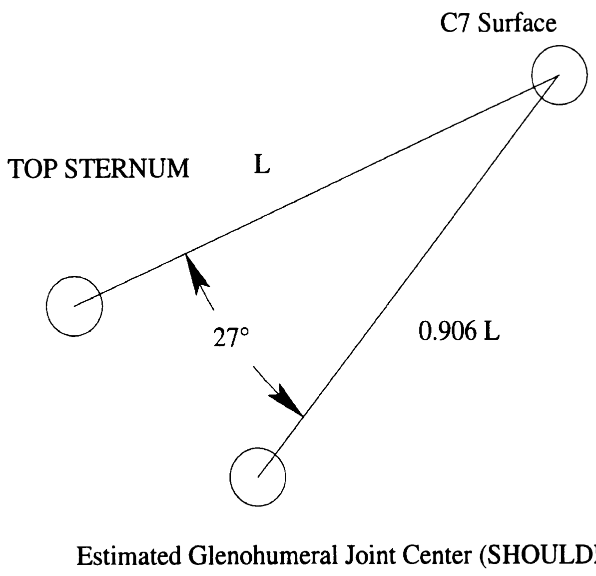
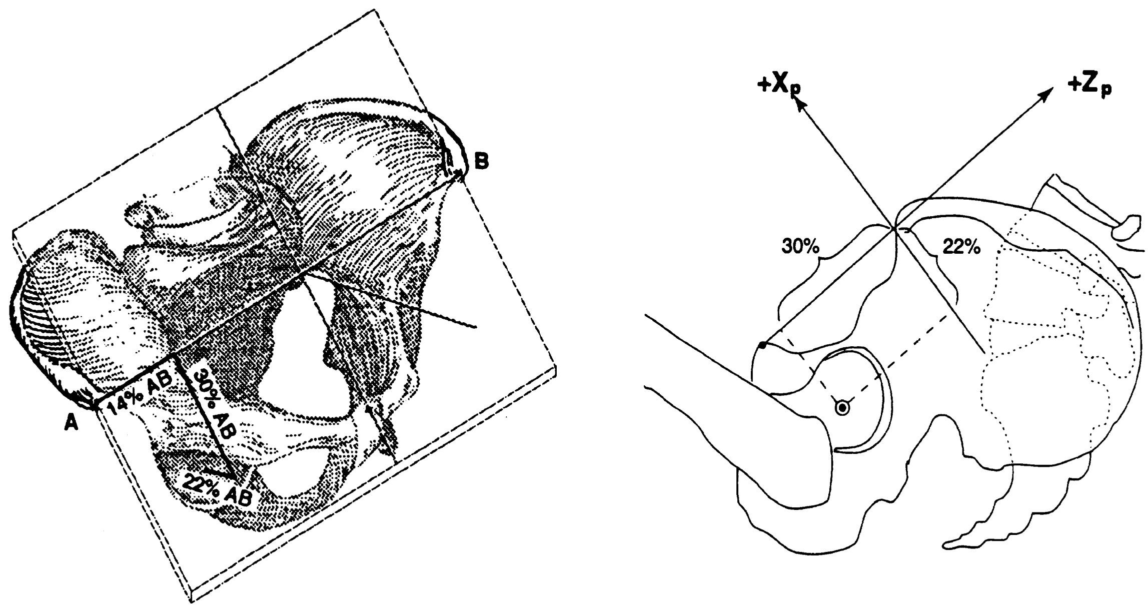


Figure 6. Method of estimating shoulder joint location in the sagittal plane.



Perspective View   Side View

Figure 7. Method of estimating hip joint center location, after Manary *et al.* (1994), adapted from pelvis proportions given by Bell *et al.* (1989, 1990) and Reynolds *et al.* (1981).

The posture variables listed in Table 6 and shown in Figure 8 were calculated for each measurement interval. Linear interpolation was used to obtain 12 equally-spaced contour points from the unevenly spaced back contour data (some probes were obstructed by the lumbar support mechanism). Two measures of back contour were obtained that are similar to the definition of lumbar support discussed in the introduction. The lumbar lordosis was defined as the largest deviation from a reference line constructed through the lowest point in the contour and tangent to the thorax. The height of the lumbar lordosis was defined as the projection of this point onto a line through the mean hip joint center angled rearward from vertical by the J826 manikin-referenced seatback angle. Figure 9 shows the calculation procedure schematically.

Table 6
Posture Variables

Variable	Definition (All angles are measured in sagittal plane. Body landmarks are described in Tables 4 and 5.)
Head Angle	Angle wrt horizontal of line formed by GLABELLA and OCCIPUT landmarks. Larger angles indicate more rearward head orientation.
Thorax Angle	Angle wrt vertical of line from TOP STERNUM to C7. Larger angles indicate more reclined thorax orientation.
Sternum Angle	Angle wrt vertical of line from BOTTOM STERNUM to TOP STERNUM. Larger angles indicate more reclined sternum orientation.
Pelvis Angle	Angle wrt vertical of line from PUBIC SYMPHYSIS to the mean of ASIS(R) and ASIS(L). Larger angles indicate more rearward pelvis rotation.
Torso Angle	Angle wrt vertical of a line from HJC to SHOULDER. Larger angles indicate more reclined torso orientation.

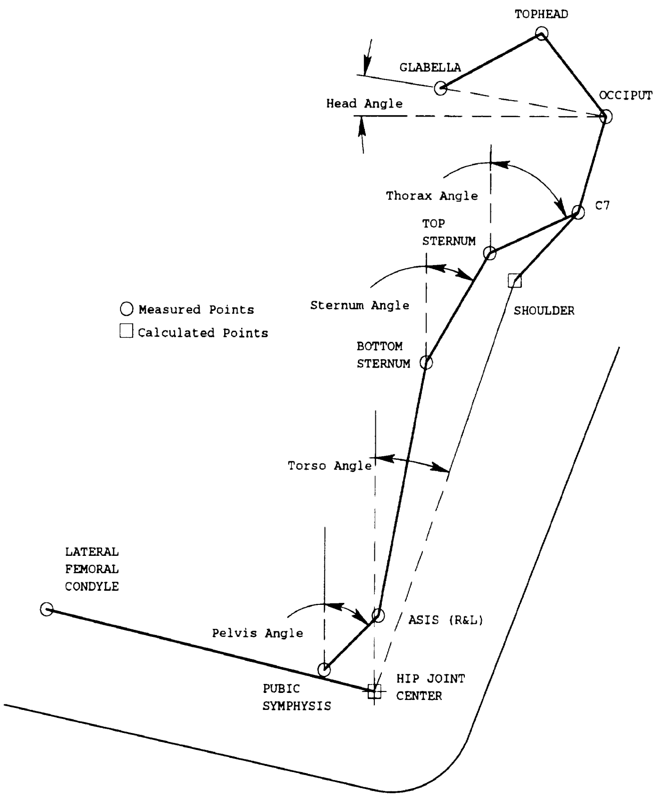


Figure 8. Body landmarks and posture variables.

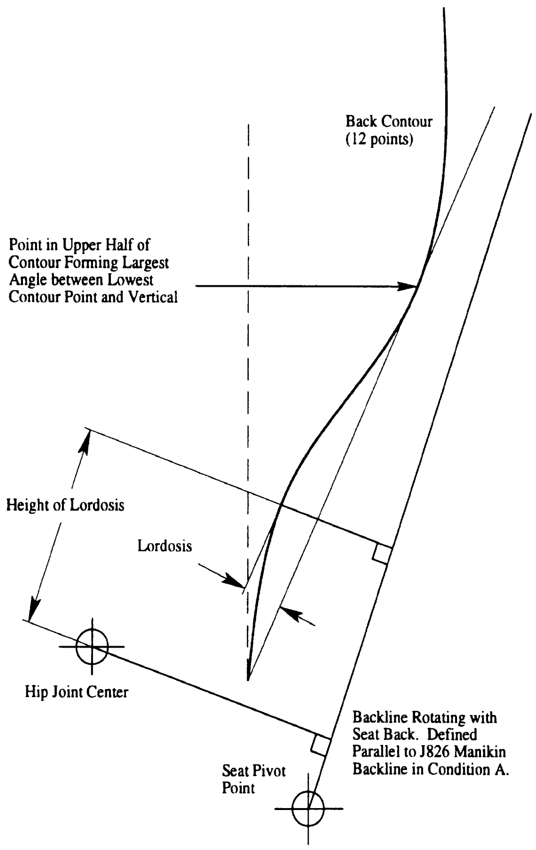


Figure 9. Schematic of calculation of lordosis and height of lordosis.

In addition to measures of torso posture, the right lower extremity (leg and thigh) orientation of sitters was analyzed in an effort to understand more fully the potential restrictions on posture imposed by the lower limb posture. Figures 10a and 10b show the definition of knee angle, thigh angle, and spread angle. The hip joint center location was calculated as described above. The location of the ankle could not be measured in the seating buck because the center console of the instrument panel interfered with the sonic digitizing system. However, a single mean ankle joint location was estimated from data in Schneider *et al.* (1994a unpublished). In a study of postural responses to changes in accelerator-pedal characteristics, Schneider *et al.* measured the right heel positions and foot orientations of 48 drivers in three different vehicle packages. Using data from that study, an estimated ankle joint center location for the present study was calculated based on the package geometry of the current seating buck. The mean ankle joint center location was estimated to lie 57 mm rearward of the AHP, 144 mm to the right of the seat centerline, and 108 mm above the horizontal plane containing the AHP (the buck floor).

Knee joint center location was estimated by first constructing a plane through the right lateral femoral condyle (LFC) surface landmark, the estimated ankle joint location, and the right hip joint center location. The knee joint center was estimated to lie 60 mm from the plane on a perpendicular to the plane through the LFC landmark. Figure 10a shows the calculation procedure schematically.

Three angles relating to leg posture were defined, as shown in Figure 10a and 10b. Knee angle is the included angle between the line segments connecting the ankle, knee, and hip joint centers. Thigh angle is the angle in the sagittal plane, relative to the horizontal, of the line connecting the right hip joint center with the right knee joint center. Spread angle is the angle of the right femur segment in the transverse (horizontal) plane, and is a measure of leg splay.

Prior to each of the three Phase-1 driving-simulation sessions, the subject's standing posture was recorded, as described above. The variable values obtained for each standing dataset were averaged to obtain a single representation of standing posture for each subject. Posture variables were calculated in a manner identical to that used with seated data, except for pelvis angle. Confidence in the accuracy of the pubic symphysis landmark for the standing data was not as high as for the seated data because subjects frequently made fairly large movements in the process of palpating the pubic symphysis landmark while standing. Consequently, pelvis angle was estimated using the relationship between the mean PSIS and the mean ASIS, rather than mean ASIS and pubic symphysis. According to data from Reynolds *et al.* (1981), the plane formed by the pubic symphysis and ASIS is vertical when the sagittal-plane line connecting mean ASIS and mean PSIS forms an angle of 5 degrees with the horizontal. Since the surface-landmark line defining the pelvis angle is angled about 5 degrees with respect to the underlying bone points, an angle of 100 degrees was assumed between the mean-ASIS-to-mean-PSIS and mean-ASIS-to-PS vectors. The pelvis angle was estimated using this relationship as illustrated in Figure 11.

Two measures of standing lumbar spine contour were also calculated using a method similar to that described in Figure 9 for seated back contour characterization. Using a sagittal plane analysis, a reference line was constructed from the mean PSIS tangent to a linear interpolation through the thoracic spinous process points. The lumbar lordosis was defined as the maximum perpendicular deviation of the line connecting the spinous process landmarks from this reference line. The height of the lordosis above the mean hip joint center was also calculated.

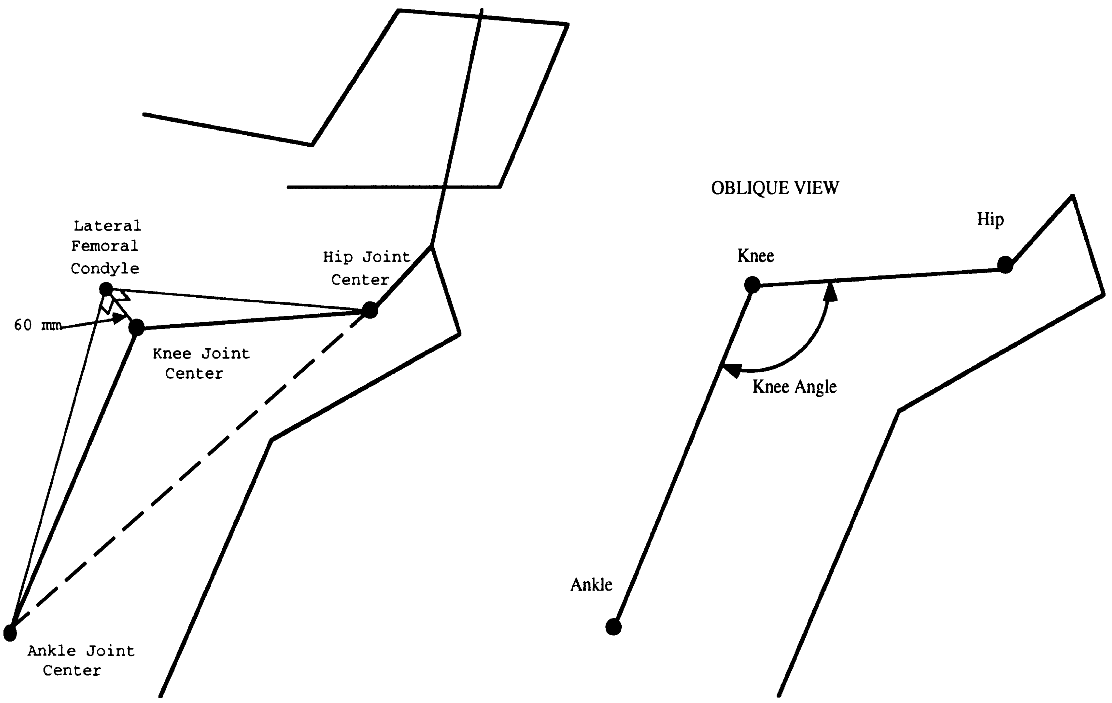


Figure 10a. Illustration of leg posture variable calculations.

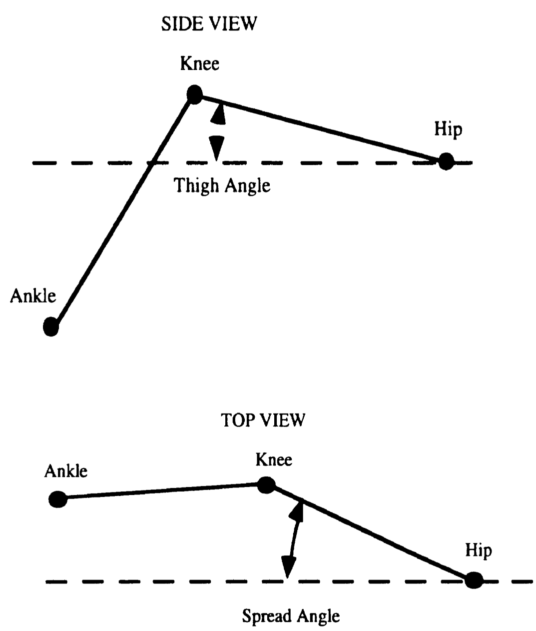


Figure 10b. Illustration of leg posture variable calculations.

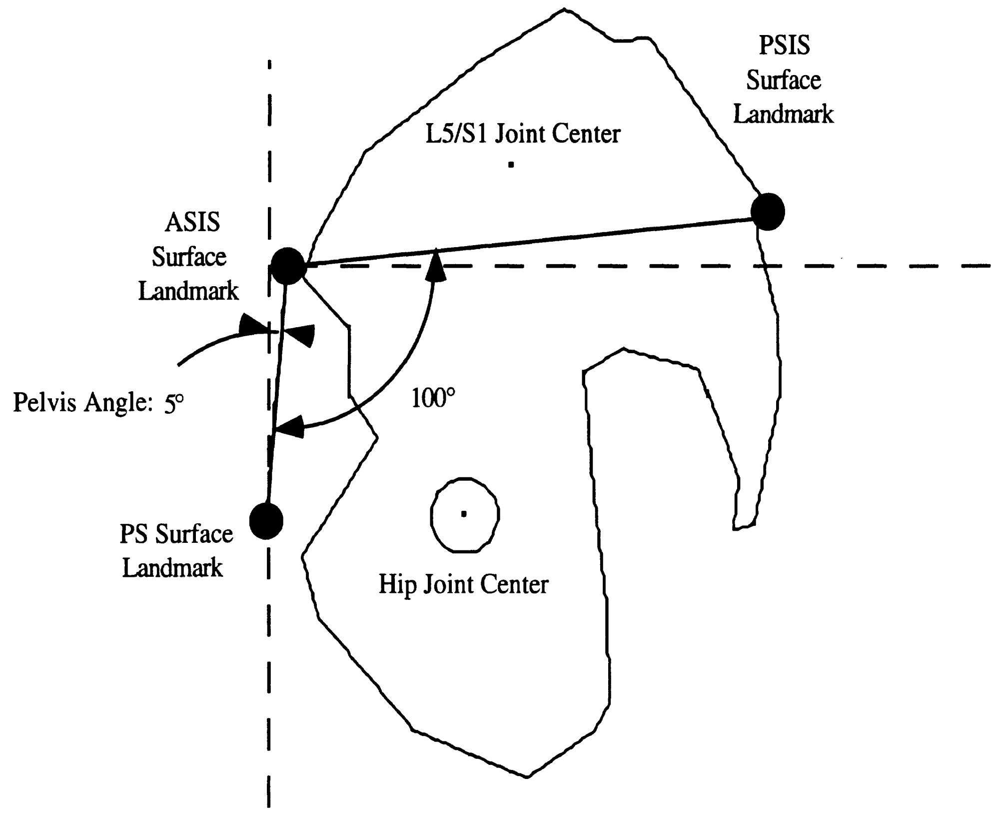


Figure 11. Schematic of calculation of pelvis angle for standing data.

2.8.2 Variable Selection and Goals of Analysis

A primary hypothesis that influenced the design of this study was that changes in lumbar support contour have little or no effect on the seated posture in the auto environment, and, more specifically, that longitudinally convex lumbar supports do not produce matching lordosis in sitters. A negative hypothesis (a hypothesis of no effect) is difficult to study, because a failure to observe a statistically significant difference between conditions may be due to poor equipment or experimental technique, rather than to a true lack of effect. With these potential pitfalls in mind, considerable attention was paid to the accuracy and precision of the measuring equipment and the consistency of the experimental procedures. Also, a relatively large number of subjects were tested to ensure adequate statistical power to discriminate among test conditions.

In this study, data collection and analyses focused on torso posture, that is, the relative position and orientation of the pelvis, thorax, and head. The orientations of these body segments largely determine the curvature of the spine. As noted in the introduction, most recommendations for lumbar support are based on the belief that the lumbar support design can influence the curvature of the sitter's spine. Therefore, examination of spine posture is an appropriate way to determine if lumbar supports have the desired effect.

The posture variables of primary interest are the pelvis angle, thorax angle, sternum angle, and head angle (see Table 6 and Figure 8). The pelvis forms the lower segment in the torso linkage comprised of the pelvis, the flexible lumbar spine, the relatively inflexible thoracic spine and ribcage, the highly flexible cervical spine, and the head. Pelvis angle is the angle with respect to vertical of a line in the sagittal plane from the pubic symphysis landmark to the mean sagittal location of the anterior-superior iliac spine landmarks. (Note that these are compressed-flesh landmarks, and not points on the underlying bone.) Large pelvis angles indicate that the pelvis is tilted more rearward, which is accompanied by increased flexion of the lumbar spine if the orientation of the thorax (ribcage) remains constant. In contrast, smaller, more upright pelvis angles are an indication of reduced lumbar spine flexion, if the thorax orientation remains constant. Smaller pelvis angles would be expected with increasing lumbar-support prominence if an increase in lumbar-support prominence has the intended effect of reducing lumbar spine flexion.

Thorax angle and sternum angle are both measures of the orientation of the upper torso. The thorax, which is approximately delineated by the ribcage, is frequently assumed to be rigid for purposes of biomechanical analysis, because the range of motion of the thoracic spine is considerably less than lumbar or cervical spine. However, some motion can be expected in the lower thoracic spine (T8 to T12), particularly for the vertebrae attached to ribs that do not connect to the sternum (T11 and T12).

Thorax angle is the angle relative to the vertical of a line from the top of the sternum to the C7 spinous process. A plane through C7 and the top of the sternum can be used as an upper segmentation plane for the thorax, and the prominent C7 process is frequently used as a marker for the location of the upper part of the thoracic spine. Sternum angle is the angle relative to the vertical of a line connecting the upper and lower ends of the sternum. If the ribcage remains rigid, changes in sternum angle and thorax angle should be the same.

Flexion or extension of the thoracic and lumbar spine can be tracked by monitoring the relative orientations of the pelvis and thorax. According to the currently prevailing theories of lumbar support, increasing the lumbar-support prominence should result in a decrease in lumbar spine flexion, which should be evident as increases in thorax angle and sternum angle and/or a decrease in pelvis angle.

The relationship of head angle to thorax angle in auto seating has not been studied extensively. The analyses in this report are intended to determine if changes in the lumbar support result in either changes in head angle or changes in the relative angle between the head and thorax, indicating changes in net cervical spine flexion.

Back contour measurements provide a secondary method for determining the effect of increased lumbar-support prominence on spine flexion, but this method is less precise than analysis of pelvis and sternum angles. The back contour is influenced to a greater extent by the variable deformation of soft tissues, particularly the lower-back and buttock musculature and overlying fat pads. Increasing the lumbar-support prominence could alter the contour of the subject's back by changing the pattern of soft-tissue deflection without producing a different spine curvature. A kinematic model of the torso linkage was used in these analyses to visualize the possible effects of the measured changes in pelvis and thorax orientation on the curvature of the spine profile, and to compare these estimates of changes in spine curvature with measured changes in longitudinal back contour.

3.0 ANALYSES AND RESULTS

3.1 OVERVIEW OF ANALYSES

Preliminary data analysis conducted after six subjects in each stature/gender group (24 total) had completed Phase-1 testing is summarized in Reed *et al.* (1995). The results indicate that, on average, subjects changed posture only slightly over the one-hour driving simulation. This finding provided a justification for using short-duration sitting sessions in Phase 2.

In the data from Phase-1 testing, few differences in posture or contour between LS (lumbar support) Prominences A and B (0- and 10-mm lumbar support) were found, while many significant differences were observed between LS Prominences A and C (0-mm and 25-mm lumbar support). Consequently, the report of Phase-1 findings deals only with LS Prominences A and C. The small size of the posture and contour differences between the two conditions indicates that no conclusions of substance are overlooked by neglecting the data from LS Prominence B.

The aggregate data from Phase 1 and Phase 2 were analyzed in several steps. The results of these analyses can be found in the following report sections:

Section 3.2: The long-duration test data (Phase 1) were studied to determine if the conclusion from the preliminary analysis that there are no substantial time-related effects is upheld in the larger data set.

Section 3.3: Data from short-duration testing (Phase 2), which represent a wider range of test conditions than the long-duration testing, were analyzed extensively to determine the effects of the lumbar-support prominence on posture.

Section 3.4: The postures obtained in long-duration testing with LS Prominences A and C were compared with those observed in short-duration testing to verify the representativeness of the short-duration tests.

Section 3.5: The posture data collected with the subjects standing were analyzed to characterize body segment orientations in a standard reference posture.

Section 3.6: The data from Phase 2 were normalized by subtracting the standing posture variable values from the seated values for each subject. These normalized variables represent the change in posture from the standing reference position. Additional statistical analyses were performed with these normalized variables.

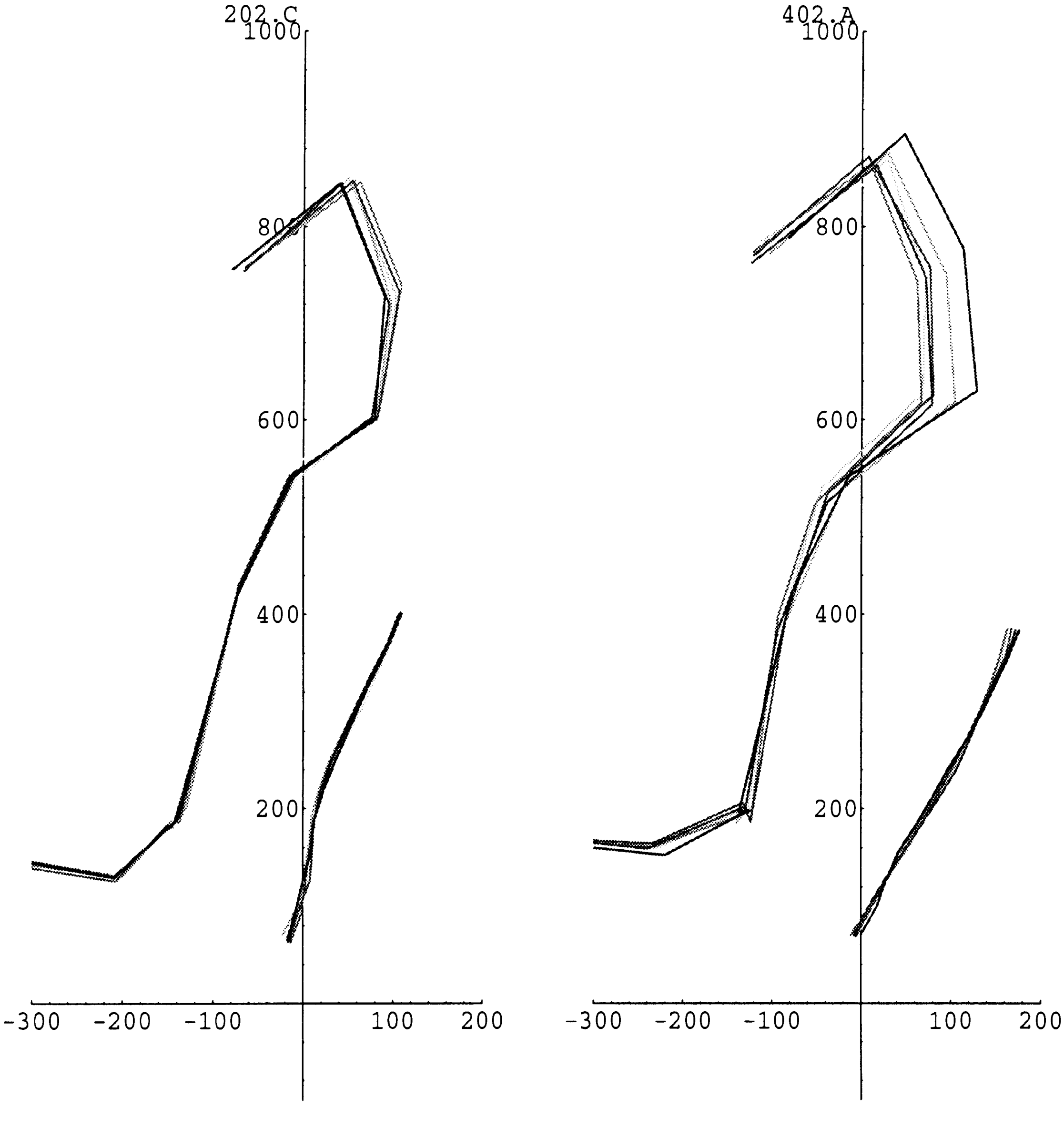
Section 3.7: Data from back contour measurements in Phase 2 were analyzed further to determine typical back contours for each subject group and test condition.

Section 3.8: A kinematic model of the torso was exercised to illustrate the changes in posture attributable to increases in lumbar-support prominence.

Section 3.9: Several additional analyses are presented in this section. Comfort data collected in Phase-1 testing were analyzed to determine if comfort differed significantly among the lumbar-support prominences. The hip joint center locations in Phase-2 testing were compared with the H-point locations measured with the SAE J826 H-point manikin. A post-hoc analysis of palpation and digitization errors was performed to assess the precision of measurement.

3.2 CHANGES IN POSTURE OVER TIME IN LONG-DURATION TESTING

One of the primary purposes of the one-hour driving simulation was to determine if there were any systematic changes in posture over time. For all but four of 48 subjects, who showed gradual movement, there was little difference between subsequent measurements. Figure 12 shows data from all seven measurement intervals for two subjects. One subject's data are virtually indistinguishable from one measurement interval to the next. This pattern of repeatability was typical of most subjects. The data from the other subject illustrated in Figure 12 show systematic movement during the one-hour simulation.



A B

Figure 12. Typical posture data points from the one-hour driving simulation, in mm, relative to the seat pivot point. Each plot shows data from seven measurement intervals (0, 10, ... , 60 minutes) . Darker lines connect data points from later measurements. The lines in each plot connect, in order, the glabella, top of head, occiput, C7, top of sternum, bottom of sternum, ASIS(R), ASIS(L), and lateral femoral condyle landmarks (lateral femoral condyle is not shown). Plot A shows data points from LS Prominence C for a midsize-female subject, demonstrating typical consistency between measurement intervals. Plot B shows data points from LS Prominence A for a large-male subject, one of four subjects who showed obvious movement trends during the simulation.

A statistical procedure was used to determine if systematic changes in posture occurred during the driving simulation. Using the data for LS Prominences A and C, a least-squares regression line was fit to the seven data values of each posture variable for each test session. No difference was found between the mean regression slopes for the two lumbar-support prominences, using a paired comparison, so the slopes for the two conditions were averaged within subject. The mean value of the average slope is significantly different from zero, or nearly significant, for sternum angle, thorax angle, and pelvis angle, but not for head angle. Table 7 shows the mean within-subject slope (degrees/minute), the standard deviation, and Student's t value testing the hypothesis that the slope is equal to zero. Table 7 indicates that none of the primary posture variables show a substantial linear trend. The trends that are significant indicate average changes of less than 2 degrees over the one-hour session. Examination of the data from individual tests shows five or fewer subjects out of 48 for whom the linear trend resulted in a change of more than 5 degrees in any posture variable over the one-hour session.

Table 7
Test of Linear Time Effect

Variable	Mean Slope* (degree/minute)	Student's t Value†	Change in 60 Minutes (deg)
Pelvis Angle	0.021	3.19	1.26
Sternum Angle	0.018	3.05	1.08
Thorax Angle	0.013	1.98	--
Head Angle	0.010	1.43	--
Torso Angle	0.018	4.67	1.08

* Average slope of least-squares linear fit to variable vs. time across subjects and LS Prominences.
† Absolute Student's t values greater than $T_{(0.025, 47)} = 2.01$ indicate significance in a two-tailed test with alpha = 0.05.

There was also a significant, but small, linear effect of time on the horizontal location of the subject's mean hip joint center ($t_{(47)} = -3.18$; $p = 0.002$). On average, subjects' hip joint centers moved forward about 4 mm during the 60-minute test session, as shown in Figure 13.

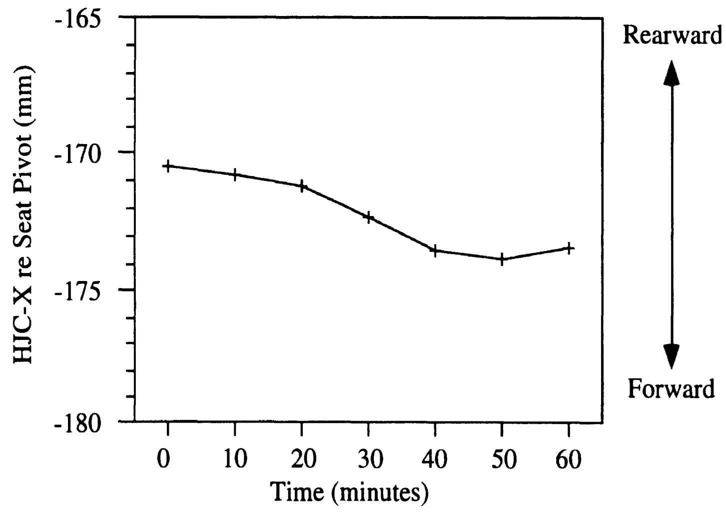


Figure 13. Horizontal position of mean hip joint center by measurement interval for Phase 1, averaged over LS Prominences A and C. The positive X direction is rearward on the seat.

These findings are consistent with those obtained in preliminary analyses with data from 24 subjects and justify the conclusion that, for the test conditions in this study, initial postures are reasonably representative of postures selected during a one-hour driving simulation. In view of this finding, the focus of the analysis was shifted to data from the Phase 2 short-duration testing.

3.3 EFFECTS OF LUMBAR SUPPORT PROMINENCE ON POSTURE

Four lumbar-support prominences were investigated in Phase-2 short-duration testing (LS Prominences A, C, D, and E) nominally representing 0, 25, 35, and 45 mm of lumbar-support prominence under the geometric definition given in Section 1.1. Each subject sat in the seat adjusted to each prominence under three test conditions. In the Fixed test condition, the vertical position of the lumbar support was fixed 156 mm above the mean hip joint center obtained with the first 24 subjects in long-duration (Phase-1) testing. This lumbar support position was the mean location chosen by the first 24 subjects in Phase-1 testing with the 25-mm lumbar support. In the Adjustable test condition, the subject was allowed to adjust the vertical position of the support over a 120-mm range centered at about the L3 level. In tests with both fixed and vertically adjustable lumbar supports, subjects were free to choose their preferred posture while adjusting the seatback recline angle, seat track position, and steering wheel angle to his or her preferred positions. These postures are referred to as "preferred" to contrast them with the "prescribed" postures obtained using a specified sitting procedure. In the Prescribed test condition, subjects were instructed to sit in a manner intended to maximize lumbar lordosis (see Section 2.7.2).

Figure 14 shows typical Phase-2 data from one subject. Both posture and contour data from lumbar-support prominences A, C, D, and E are shown for each test condition.

ANOVA techniques were used to investigate the effects of lumbar-support (LS) Prominence, stature/gender Group, and test condition (Fixed, Adjustable, and Prescribed) on postures and back contour. Unless otherwise indicated, effects were considered to be statistically significant when an *F*-test indicated that the probability of Type-I error (α) associated with rejecting the null hypothesis of no effect was less than 0.01.

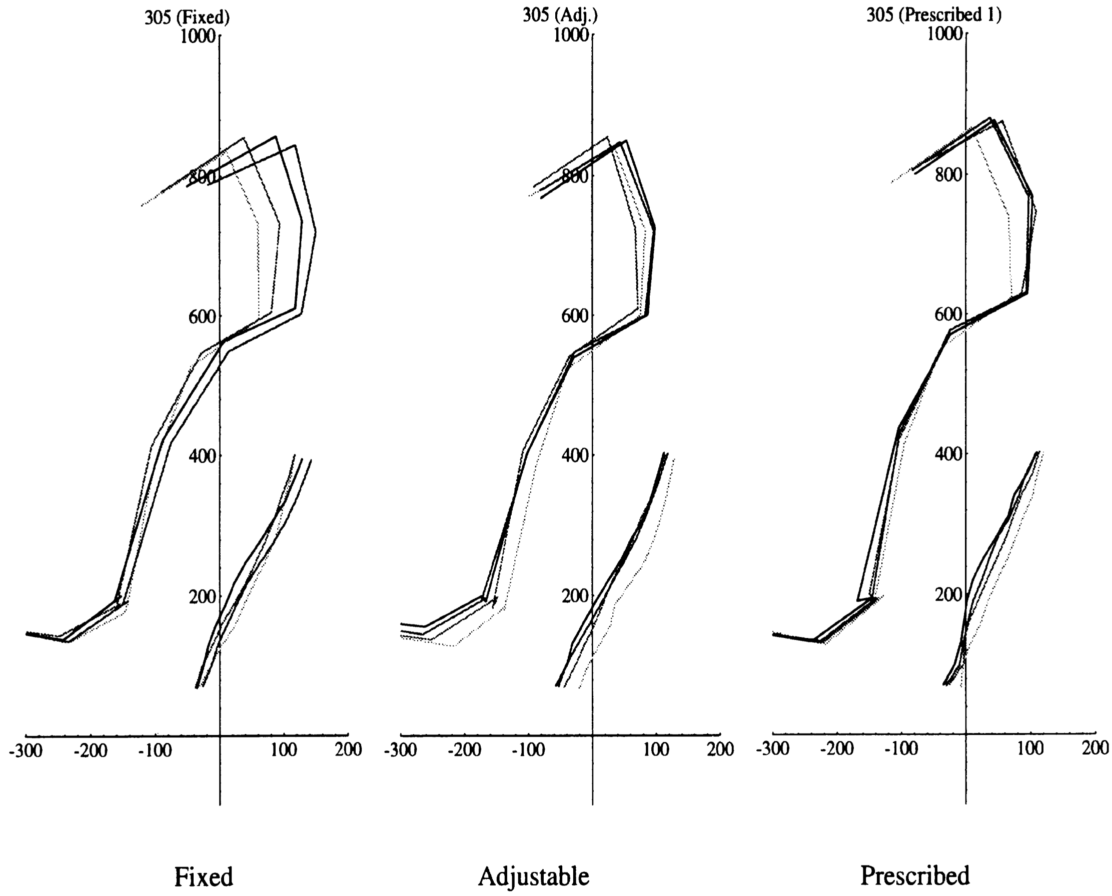


Figure 14. Typical data from Phase-2 testing. Posture and contour data for one midsize-male subject from Fixed, Adjustable, and Prescribed Conditions are shown. Origin is seat pivot point. Lines connect the same posture data points illustrated in Figure 12. LS Prominences A, C, D, and E are shown for each test condition with darker lines for larger lumbar-support prominences. Only data from the first set of prescribed-posture measurements are shown.

3.3.1 Intersubject Variability

One of the most important observations to be made from these data is that the variance among subjects on the important postural variables is much larger than the variance attributable to changes in lumbar-support prominence. For example, Figure 15 shows a plot of pelvis angle by subject for the Fixed and Adjustable Conditions. The angle measures are grouped fairly tightly within subject, even though four different lumbar-support prominences are represented for each subject. In contrast, the differences among subject means are large. The standard deviation of subject means for pelvis angle is 12 degrees, while the average standard deviation within subject is only 3.4 degrees. This finding of large intersubject variability is consistent across most posture variables. In general, the differences among subjects are large compared to within-subject differences among test conditions.

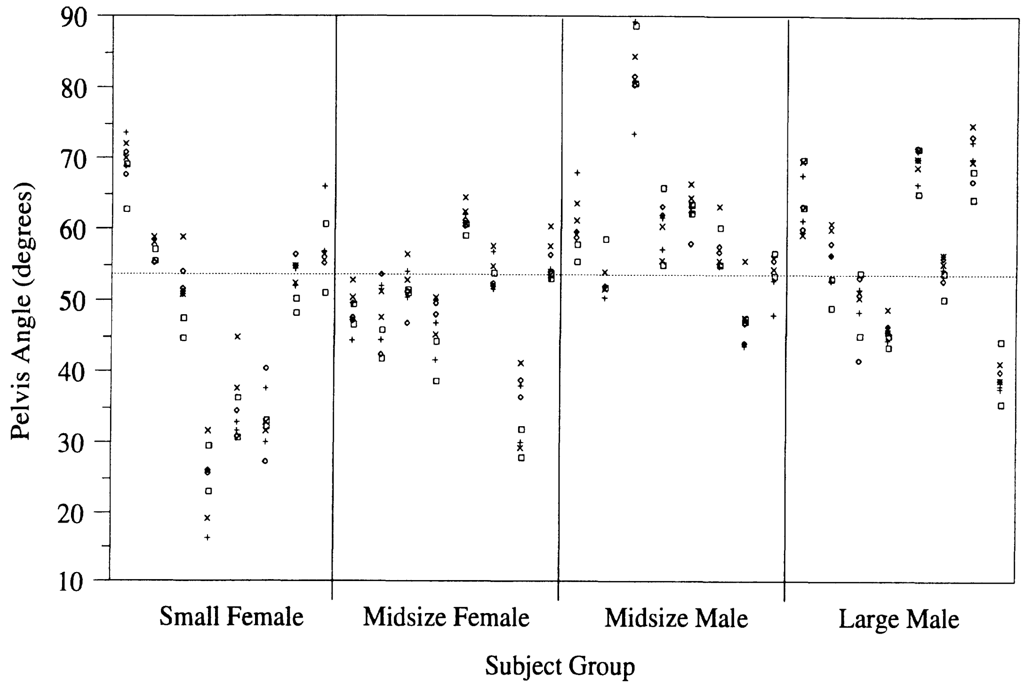


Figure 15. Pelvis angle by subject in Phase-2 testing, Fixed and Adjustable Conditions. LS Prominences A, C, D, and E are shown with symbols X, ◇, +, and □, respectively. Overall mean = 53.6 degrees. Range of subject means = 24 to 83 degrees. Standard deviation of subject means = 12 degrees. Average standard deviation within subject = 3.4 degrees.

3.3.2 Pelvis Angle

Pelvis angle is one of the most important posture variables relating to lumbar spine posture because it represents the orientation of the lower end of the torso kinematic chain. Smaller pelvis angles (*i.e.*, more upright pelvis orientations) with constant or larger thorax angles indicate decreasing lumbar flexion.

Preferred Posture

Figure 16 shows mean pelvis angle by LS Prominence and Condition (Fixed, Adjustable, and Prescribed). There is no difference between preferred-posture conditions (Fixed and Adjustable) for any of the lumbar-support prominences. However, the LS Prominence effect is highly significant ($p \leq 0.001$). Averaging across the Fixed and Adjustable Conditions, the pelvis angle means are 55.3, 53.5, 53.2, and 52.4 degrees for LS Prominences A, C, D, and E, respectively. The mean pelvis angle for LS Prominence C is not significantly different from LS Prominence D, and LS Prominence D is not significantly different from LS Prominence E, but all other paired comparisons are significant ($p < 0.05$). Overall, increasing the lumbar-support prominence 45 mm from a flat contour decreased mean pelvis angle by 2.9 degrees.

Prescribed Posture

Pelvis angles are significantly smaller (more upright pelvis orientation) in the Prescribed Conditions than in the Preferred Condition. The Condition*LS Prominence interaction is not significant, indicating that the effect on pelvis angle of changing the lumbar-support prominence is approximately the same for the Fixed, Adjustable, and Prescribed Conditions. The difference in pelvis angle between the preferred and prescribed postures is about 10 degrees regardless of the lumbar-support prominence. This finding was unexpected, because one pretest hypothesis was that the difference between preferred and prescribed postures would be largest for larger lumbar-support prominences and small or nonexistent with a flat seatback (LS Prominence A). However, these data show that subjects were able to sit with their pelves about 10 degrees more upright than they did in their preferred postures, regardless of the prominence of the lumbar support.

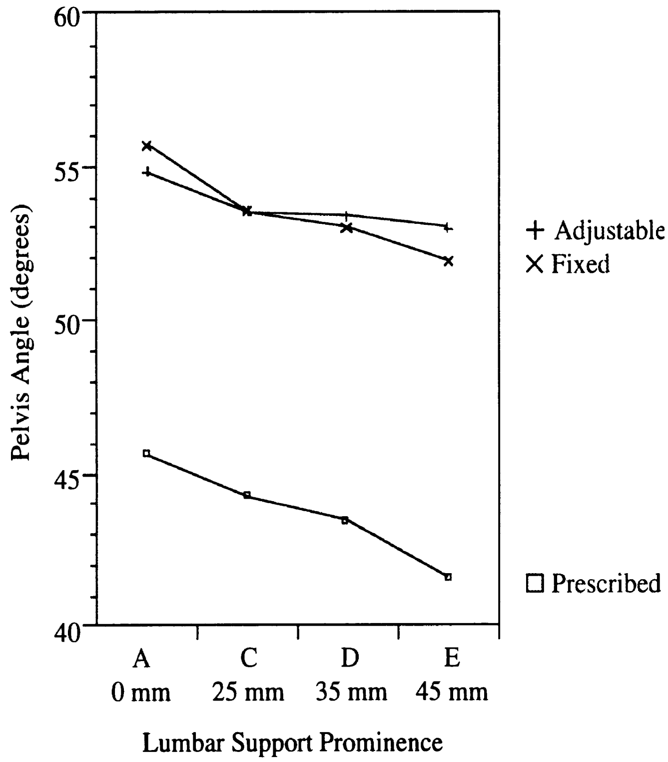


Figure 16. Mean pelvis angle by LS Prominence and Condition for Phase-2 testing (32 subjects).

3.3.3 Thorax Angle

Thorax angle measures the orientation of the sitter's ribcage and upper thoracic spine. Larger thorax angles (more reclined), along with constant or smaller pelvis angles, indicate reduced flexion in the thoracic and lumbar spine.

Preferred Posture

Figure 17 shows thorax angles by LS Prominence and Condition. As with pelvis angle, there are no differences in thorax angle between the Fixed and Adjustable preferred-posture Conditions overall, although thorax angles are significantly different in LS Prominence D ($t_{(31)} = 2.75$, $p \leq 0.01$). Thorax angles increase with increasing lumbar-support prominence, consistent with decreasing lumbar spine flexion. Averaging across Conditions (Fixed and Adjustable), the mean thorax angles are 53.5, 54.5, 56.2, and 56.6 degrees for LS Prominences A, C, D, and E, respectively. The mean thorax angle for LS Prominence A is not significantly different from that for LS Prominence C, and the mean for LS Prominence D is not significantly different from the mean for LS Prominence E, but all other comparisons are significant ($p<0.05$). Overall, increasing the lumbar-support prominence 45 mm from a flat contour increased mean thorax angle by 3.1 degrees.

Thorax angles in preferred position also differ significantly among stature/gender groups. Figure 18 shows the mean thorax angle across LS Prominences and preferred-posture conditions by group. Thorax angles for midsize males are significantly larger than for the other groups.

Prescribed Posture

Thorax angles in prescribed postures are similar to thorax angles in preferred postures. The Condition*LS Prominence interaction is significant (p=0.03), but the differences in LS Prominence effects between conditions are small, as shown in Figure 17.

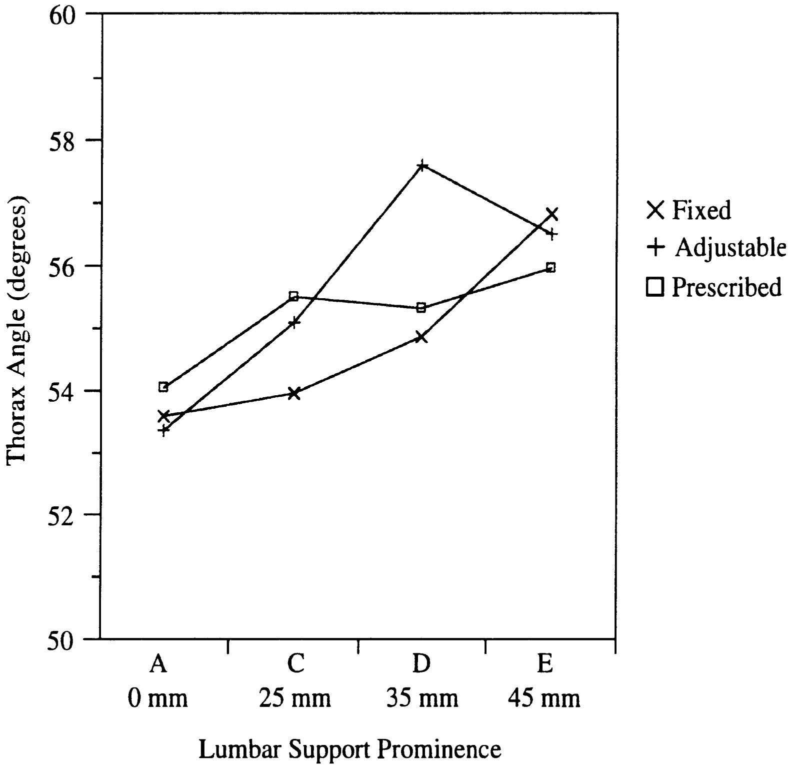


Figure 17. Mean thorax angle by LS Prominence and Condition for Phase-2 testing (32 subjects).

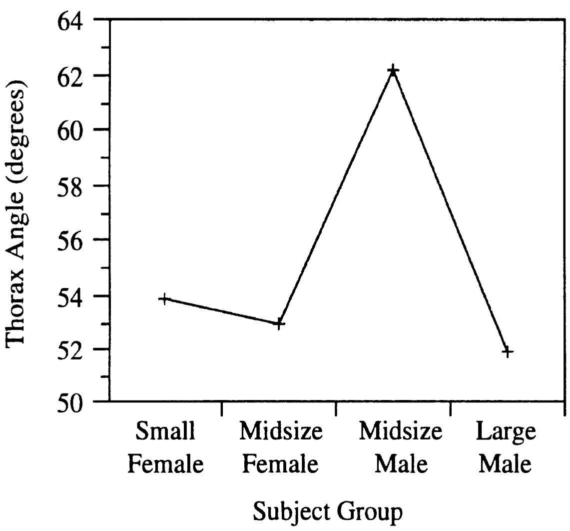


Figure 18. Mean thorax angle by stature/gender Group for Fixed and Adjustable Conditions in Phase-2 testing (32 subjects).

3.3.4 Sternum Angle

Like thorax angle, sternum angle is related to the orientation of the sitter's ribcage and upper thoracic spine. Larger sternum angles, along with constant or smaller pelvis angles, indicate reduced flexion in the thoracic and lumbar spine.

Preferred Posture

Figure 19 shows sternum angle by LS Prominence and Condition. There is no overall difference for sternum angles between the Fixed and Adjustable Conditions in the preferred postures, and no significant difference between Conditions for any individual LS Prominence. Sternum angles increase with increasing lumbar-support prominence, consistent with decreasing lumbar spine flexion. Averaging across Conditions (Fixed and Adjustable), the sternum angle means are 22.3, 24.7, 25.1, and 26.1 degrees for LS Prominences A, C, D, and E, respectively. The mean sternum angle for LS Prominence C is not significantly different from the mean for LS Prominence D, and the mean for LS Prominence D is not significantly different from the mean for LS Prominence E, but all other comparisons are significant ($p<0.05$). Overall, increasing the lumbar-support prominence 45 mm from a flat contour increased mean sternum angle by 3.8 degrees. Unlike thorax angles, sternum angles are not significantly different among stature/gender Groups, although the trends are similar.

Prescribed Posture

Sternum angles are not significantly different in the preferred- and prescribed-posture conditions. This is consistent with the findings for thorax angle.

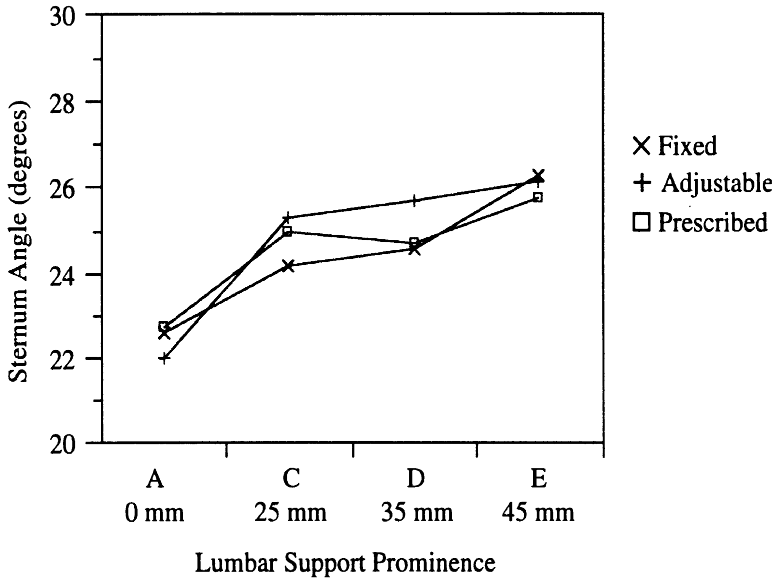


Figure 19. Mean sternum angle by LS Prominence and Condition for Phase-2 testing (32 subjects).

3.3.5 Head Angle

Preferred Posture and Prescribed Posture

Head angles are not significantly different among Groups, Conditions, or LS Prominences. The overall mean head angle in the preferred-posture conditions is 10 degrees.

3.3.6 Torso Angle

Torso angle is defined as the angle relative to vertical of a sagittal-plane line connecting the mean hip joint center (the midpoint of a line connecting the two hip joint centers) and the mean shoulder (glenohumeral) joint center. Both of these points are calculated from digitized body landmarks (see Table 5 and Figures 6 and 7). Any particular torso angle can be achieved with a wide range of spine flexions, and hence a wide range of pelvis and thorax angles. The torso angle is a measure of the recline angle of the subject's trunk without regard to the curvature of the spine. Figure 20 shows mean torso angles by LS Prominence and Condition.

Preferred Posture

Torso angles are not significantly different across subject groups or preferred-posture conditions. There are, however, significantly different mean torso angles for different lumbar-support prominences such that torso angle tends to increase with greater prominence. Averaging across Conditions (Fixed and Adjustable), the mean torso angles are 23.0, 23.6, 24.2, and 24.6 degrees for LS Prominences A, C, D, and E, respectively. Differences between mean torso angles for adjacent LS Prominences are not significant (*i.e.*, the mean torso angle for LS Prominence A is not significantly different from the mean torso angle for LS Prominence C), but all other comparisons are significant ($p<0.05$). Overall, increasing the lumbar-support prominence 45 mm from a flat contour increased mean torso angle by 1.6 degrees.

Prescribed Posture

In the prescribed-posture condition, torso angle remained constant with increasing lumbar-support prominence. The mean torso angle in the Prescribed Condition is significantly lower than in the preferred posture conditions at 20.6 degrees, compared with 23.9 for all preferred-posture conditions. The difference in torso angle between preferred and prescribed postures is about 2.5 degrees for the flat LS Prominence and about 4 degrees for the 45-mm LS Prominence. An important distinction between the Preferred and Prescribed test conditions is that subjects did not adjust the seatback angle in the Prescribed sessions. Instead, the experimenter set the seatback angle to 21, 22, 24, and 25 degrees for the small-female, midsize-female, midsize-male, and large-male groups, respectively. See Section 3.3.12, below, for further discussion of seatback angle.

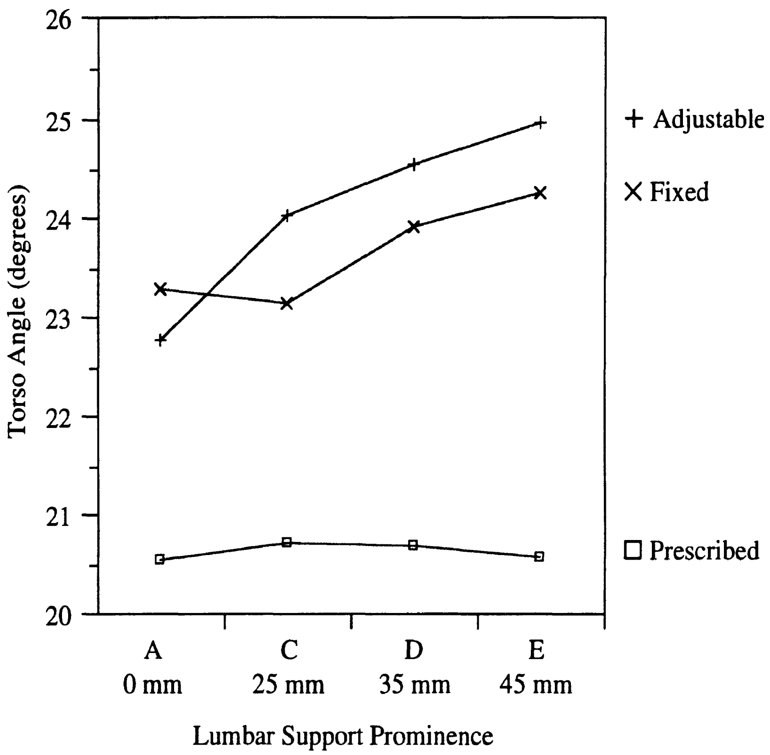


Figure 20. Mean torso angle by LS Prominence and Condition for Phase-2 testing (32 subjects).

3.3.7 Pelvis Angle – Sternum Angle

Subtracting sternum angle from pelvis angle gives a measure of the amount of flexion in the thoracic and lumbar spine by expressing the relative orientations of the thorax and pelvis. Although the absolute values of the measure have little meaning, contrasting the values obtained in different lumbar-support prominences gives an indication of the relative level of spine flexion in each of the conditions.

Preferred Posture

Figure 21 shows a plot of pelvis angle – sternum angle by LS Prominence and Condition. The data have been normalized by assigning the value of zero to the mean value obtained with LS Prominence A for the Fixed Condition. Positive values indicate spine extension (more rearward bending) relative to the flat-seatback condition.

Subject Group and Condition effects (Fixed vs. Adjustable) are not significant for the preferred postures. Relative to the flat lumbar-support (LS Prominence A), LS Prominences C, D, and E produced average reductions in thoracolumbar spine flexion of 4.2, 4.9, and 6.7 degrees, respectively, using the pelvis angle – sternum angle measure. All paired comparisons except LS Prominence C vs. D are significant ($p<0.05$).

Prescribed Posture

Values of pelvis angle – sternum angle for the prescribed-posture condition are consistently 10 degrees less than comparable values for the preferred posture conditions across LS Prominences. This observation reflects that pelvis angles are about 10 degrees smaller in prescribed postures, while sternum angles are not significantly different between preferred and prescribed postures.

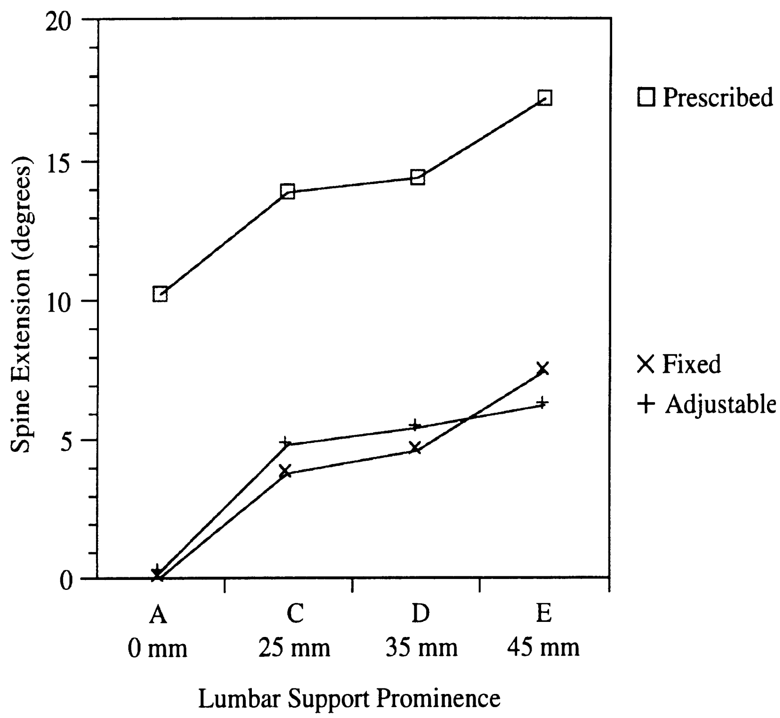


Figure 21. Mean values of pelvis angle minus sternum angle by LS Prominence and Condition for Phase-2 testing (32 subjects). Data have been normalized by assigning zero to the mean value of pelvis-sternum observed in the Fixed Condition with LS Prominence A. Positive values indicate spine extension (increasing lordosis) relative to the flat-seatback condition, in degrees.

3.3.8 Pelvis Angle – Thorax Angle

Subtracting thorax angle from pelvis angle gives another relative measure of thoracolumbar spine flexion. Figure 22 shows mean values by LS Prominence and Condition, normalized in the same manner as the data in Figure 21. The results are very similar to those obtained by subtracting sternum angle from pelvis angle.

Preferred Posture

Subject Group and Condition effects are not significant. Relative to LS Prominence A, the net reductions in thoracolumbar spine flexion for LS Prominences C, D, and E are 2.8, 4.8, and 6.0 degrees, respectively, in the preferred postures. All paired comparisons between LS Prominences except D vs. E are significant. Considering together the results from analyses with pelvis angle – sternum angle and pelvis angle – thorax angle, the effect of increasing the prominence of the lumbar-support 45 mm from a flat contour is to decrease thoracolumbar spine flexion by about six degrees, on average.

Prescribed Posture

As with pelvis angle – sternum angle, the values of pelvis angle – thorax angle in the Prescribed Condition are about 10 degrees less than for the Preferred Conditions, reflecting the fact that pelvis angles are about 10 degrees smaller in prescribed postures than in preferred postures, but thorax angles are similar. The net effect on pelvis angle – thorax angle of increasing the lumbar-support prominence by 45 mm in prescribed postures is about 6 degrees, similar to the effect for the preferred postures.

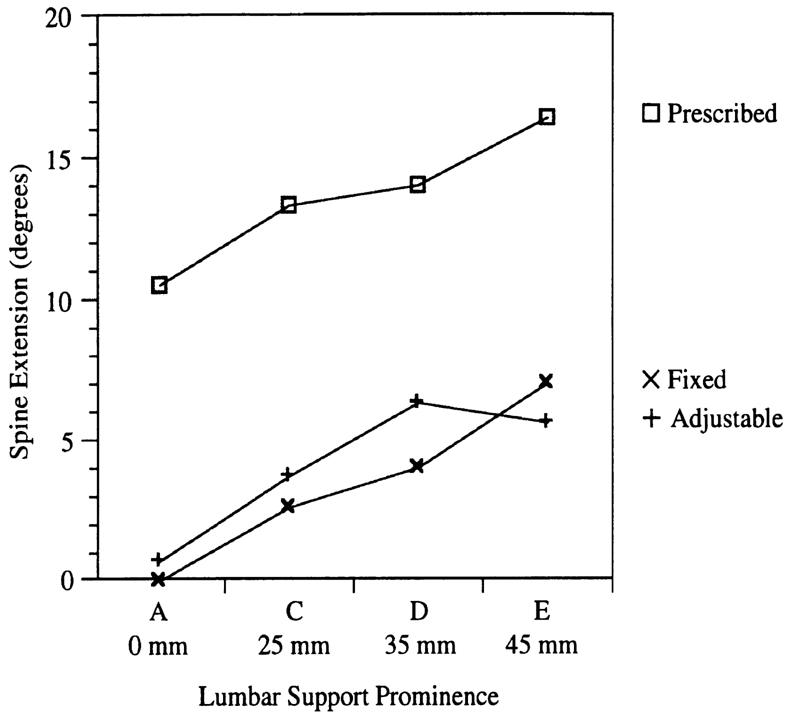


Figure 22. Mean values of pelvis angle minus thorax angle by LS Prominence and Condition for Phase-2 testing (32 subjects). Data have been normalized by assigning zero to the mean value of pelvis-thorax angle observed in the Fixed Condition with LS Prominence A. Positive values indicate spine extension (increasing lordosis) relative to the flat-seatback condition, in degrees.

3.3.9 Mean Hip Joint Center Position re Seat

The mean hip joint center (HJC) location was calculated as described in Table 5 and Figure 7. The mean HJC is a useful measure of the fore-aft and vertical position of the subject's pelvis relative to the seatpan. Figure 23 shows the mean HJC-X (fore-aft) location by Condition and LS Prominence. The data are normalized relative to mean HJC-X in LS Prominence A for the Fixed Condition. Increasing values indicate more forward positions on the seat.

Preferred Posture

There are no differences between the Fixed and Adjustable Conditions. All paired comparisons among LS Prominences are significant for the preferred-posture conditions. Increasing the lumbar-support prominence shifted the mean HJC forward. Relative to the mean HJC-X location for LS Prominence A, the mean HJC is shifted forward 7, 11, and 16 mm for LS Prominences C, D, and E, respectively. The Group effect is also highly significant. Figure 24 shows mean HJC-X values for the preferred posture conditions by subject group and LS Prominence. The male subjects' HJC locations are further forward than the female subjects' for all LS Prominences. The LS Prominence*Group interaction is close to being significant ($p = 0.07$), with the trends indicating that larger subjects may move forward slightly more in response to an increase in lumbar-support prominence.

The mean value of HJC-Z for the preferred-posture conditions increased by 5.4 mm from LS Prominence A to LS Prominence E (see Figure 25). HJC-Z, the mean vertical HJC location, differed by only 1.5 mm between the Fixed and Adjustable Conditions, with the mean HJC-Z being lower for the Adjustable Condition. Though significant ($t_{(31)} = -2.5$, $p \leq 0.01$), this difference is very small.

Prescribed Posture

As expected, subjects sat with their hip joint centers considerably more rearward in the prescribed-posture condition relative to the positions chosen in preferred postures. The difference increased with increasing lumbar-support prominence, from 19 mm with LS Prominence A to 29 mm with LS Prominence E. The net forward shift from LS Prominence A to LS Prominence E was 7 mm for prescribed postures, compared to 16 mm for preferred postures. However, the vertical HJC position remained approximately constant over the LS Prominences in prescribed postures, in contrast with the 5.4 mm increase in HJC-Z observed in preferred postures.

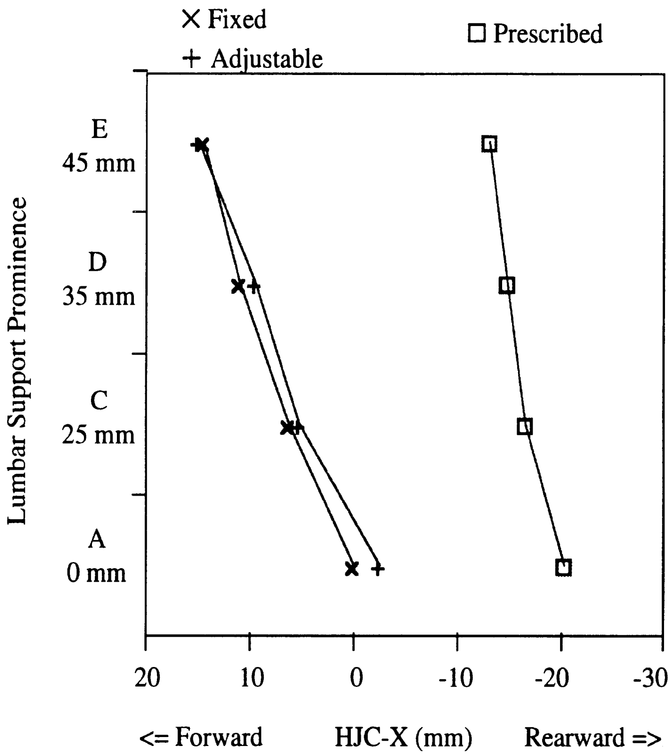


Figure 23. Mean values of HJC-X (fore-aft) by LS Prominence and Condition for Phase-2 testing (32 subjects). Data have been normalized by assigning zero to the mean value of HJC-X observed in the Fixed Condition with LS Prominence A. Positive values indicate forward pelvis movement relative to the flat-seatback condition, in mm.

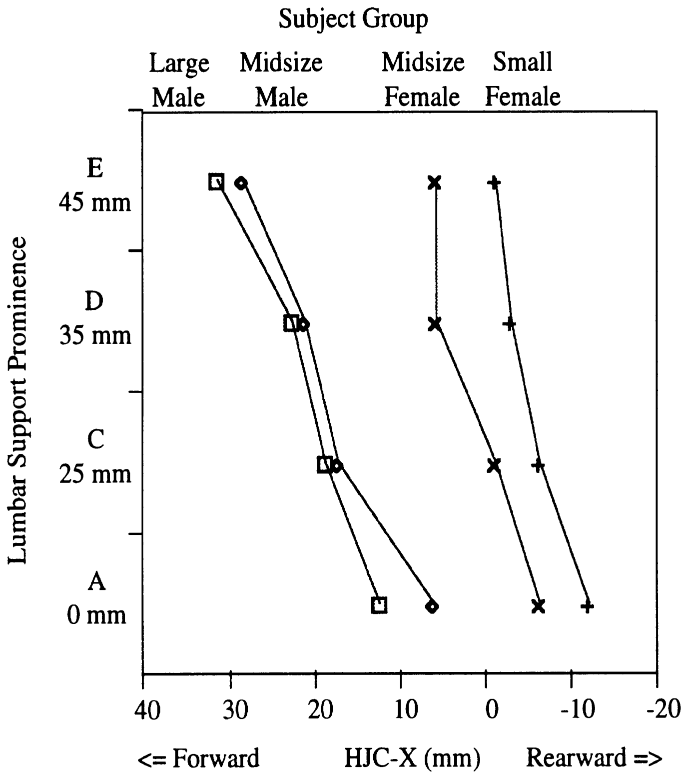


Figure 24. Mean values of HJC-X by Group and LS Prominence for Phase-2 testing (32 subjects) in Fixed and Adjustable (preferred-posture) Conditions, normalized as in Figure 23.

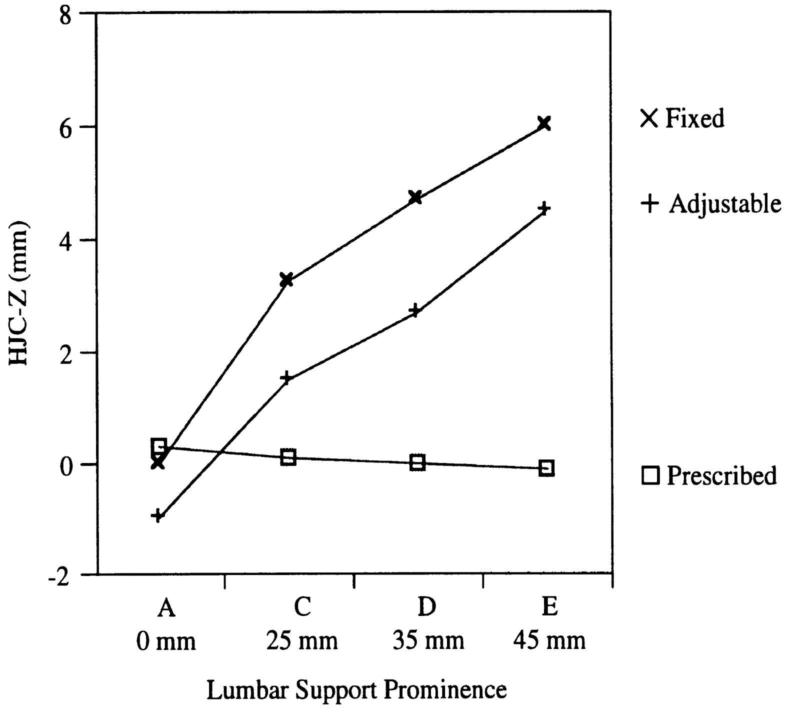


Figure 25. Mean values of HJC-Z (vertical) by LS Prominence and Condition, normalized as in Figure 23. Large values indicate higher positions (mm).

3.3.10 Lumbar Lordosis

Figure 9 shows the procedure for calculating lumbar lordosis. Figure 26 shows the lordosis by LS Prominence and Condition.

Preferred Posture

For preferred postures, subject Group and Condition effects are not significant. All paired comparisons between lumbar-support prominences are significant ($p \leq 0.05$). The mean lumbar contour lordoses are 2, 5, 7, and 11 mm for LS Prominences A, C, D, and E, respectively.

Prescribed Posture

Lumbar lordosis, as measured by the maximum prominence of the lumbar back contour, is significantly larger in prescribed postures with an average difference in lordosis between preferred and prescribed postures, across LS Prominences, of 9 mm. The differences between preferred and prescribed postures do not differ across LS Prominences. This is consistent with the observations regarding net thoracolumbar spine flexion (see Sections 3.3.7 and 3.3.8).

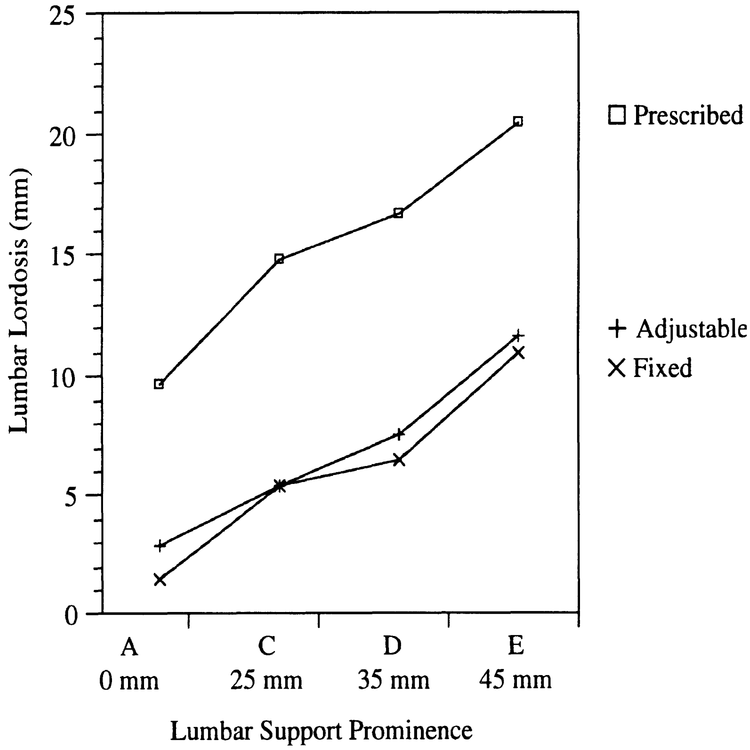


Figure 26. Mean values of lumbar lordosis by LS Prominence and Condition for Phase-2 testing (32 subjects).

3.3.11 Height of Lumbar Lordosis

The height of the lumbar lordosis was calculated as shown in Figure 9. Figure 27 shows the height of the lumbar lordosis above the subject's mean hip joint center along the manikin-referenced backline by Condition and LS Prominence.

Preferred Posture

Only the Condition*LS Prominence interaction approached significance in the ANOVA (p=0.07). The overall mean in preferred-posture conditions is 144 mm above the HJC.

Prescribed Posture

The lumbar lordosis is located significantly higher relative to the sitter's hip joint centers in the prescribed-posture condition than in the preferred-posture conditions. On average, the lumbar lordosis is located 15 mm higher in LS Prominence E than in LS Prominence A. The Condition*LS Prominence interaction is significant, but largely because of differences in the LS Prominence effect between the Fixed and Adjustable Conditions. Averaging the two preferred-posture conditions together, the mean difference in the height of the lumbar lordosis between the prescribed and preferred postures is 18 mm. The overall mean for the prescribed-posture condition is 163 mm versus 144 mm for the preferred-posture conditions.

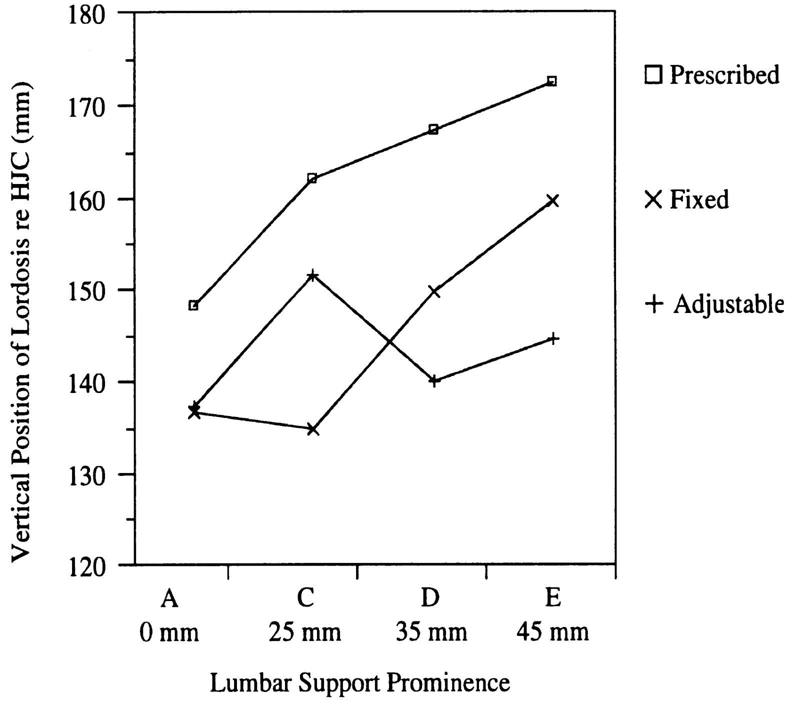


Figure 27. Mean values of the height of the lumbar lordosis above the mean HJC by LS Prominence and Condition for Phase-2 testing (32 subjects).

3.3.12 Seatback Angle

Seatback angle was calculated from two reference points on the seat contour-measurement frame that were digitized at each measurement interval. The line formed by these two points is 18 degrees more upright than the J826-manikin-measured seatback angle for the flat lumbar-support condition with a nominal seatback angle of 21 degrees. Therefore, subject-selected seatback angle was calculated by adding the 18-degree offset to the angle formed by the two reference points, regardless of LS Prominence. This measure of seatback angle varies one-to-one with the orientation of the seatback frame, but does not necessarily represent the back angle that would be produced by an H-point measurement with the seatback at the sitter-selected back angle, particularly for the more prominent lumbar supports (see Section 2.4 for a discussion of H-point measurements).

Preferred Posture

Seatback angles are not significantly different among Conditions, Groups, or LS Prominences. The overall mean seatback angle is 22.5 degrees in preferred-posture conditions. Figure 28 shows the mean seatback angles by LS Prominence and Condition.

Prescribed Posture

Seatback angles in the prescribed-posture conditions were set by the experimenter according to subject group. Manikin adjusted seatback angles were set to 21, 22, 24, and 25 degrees for the small-female, midsize-female, midsize-male, and large-male groups, respectively. Consequently, seatback angles for the Prescribed Condition do not represent data but rather test conditions. Comparison between the seatback angles for the preferred and prescribed conditions can show if the seatback angles chosen for the prescribed conditions are reasonable, given the seatback angles chosen by the subjects in the preferred-posture conditions.

Figure 29 shows the mean seatback angles by Condition and Group. Seatback angles do not differ as much among groups in the preferred-posture conditions as do the experimenter-set seatback angles in the prescribed posture conditions. One important observation is that the mean subject-selected seatback angles are not smaller than the experimenter-selected back angles except for the small-female group, where the mean difference is about one degree. If the experimenter-set seatback angles were smaller than those preferred by subjects, excessive restriction of upper-body posture might have occurred. Given these findings, the experimenter-selected seatback angles appear to have been reasonable.

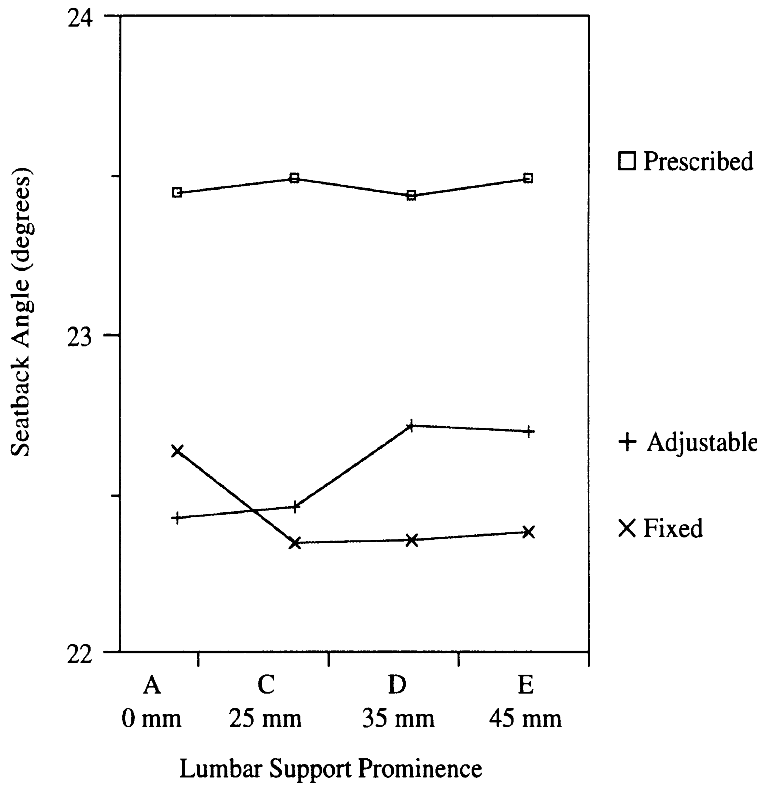


Figure 28. Mean values of seatback angle by LS Prominence and Condition for Phase-2 testing (32 subjects).

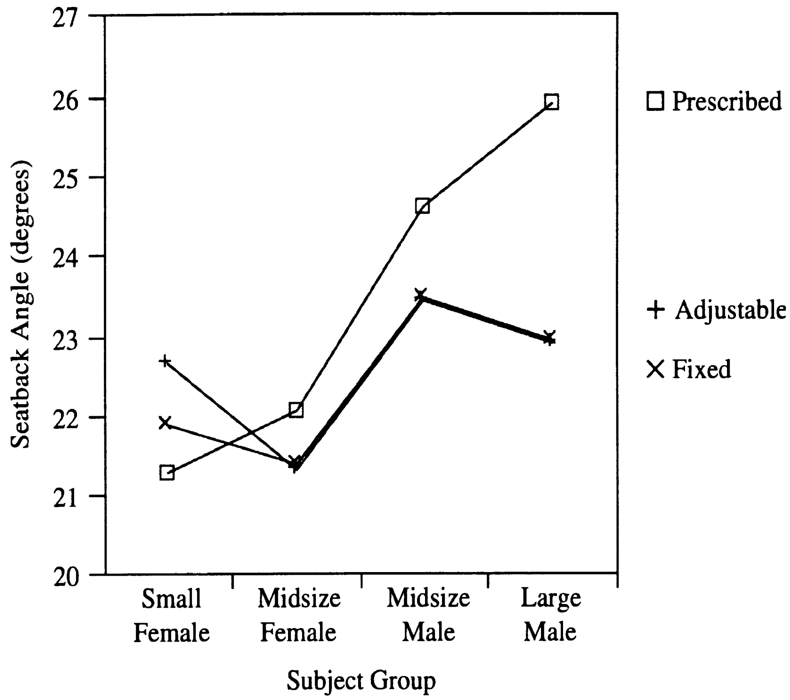


Figure 29. Mean values of seatback angle by Condition and Group for Phase-2 testing (32 subjects).

3.3.13 Subject-Selected Vertical Lumbar Support Position

In Session 2 of short-duration testing, subjects adjusted the vertical position of the lumbar support. This subject-selected lumbar support position is expressed relative to the mean hip joint center location along the backline, analogous to the calculation of the height of the lumbar lordosis. The data do not show censoring (data points stacking up at the ends of the travel), indicating that the adjustment limitations did not substantially affect the results. Figure 30 shows preferred lumbar support apex positions by LS Prominence. Figure 31 shows the subject-selected vertical lumbar support position by subject group, and Figure 32 shows the distribution of preferred lumbar support positions for LS Prominences C, D, and E.

Preferred Posture

For prescribed postures, subjects chose slightly lower positions with larger lumbar-support prominences. The mean subject-selected lumbar support heights relative to the hip joint center are 158, 152, and 146 mm for LS Prominences C, D, and E, respectively. The overall mean is 152 mm above the HJC, 8 mm higher than the mean height of the lumbar lordosis. The average standard deviation within LS Prominence is 23 mm. The ANOVA Group effect was not significant (p=0.14), but Figure 33 shows that, on average, taller subjects chose lower lumbar support positions. One midsize-male subject positioned the support at the top of its range with LS Prominence E, but most placed it at or below the center of the 120-mm travel. A linear regression between the subject-selected position of the lumbar support and the location of the lumbar lordosis did not show a significant relationship. The correlation coefficient is 0.16.

Prescribed Posture

The vertical position of the lumbar support was set by the experimenter rather than the subject in the prescribed-posture condition (see Section 2.7), so no analysis of subject-selected lumbar support position in prescribed postures was possible.

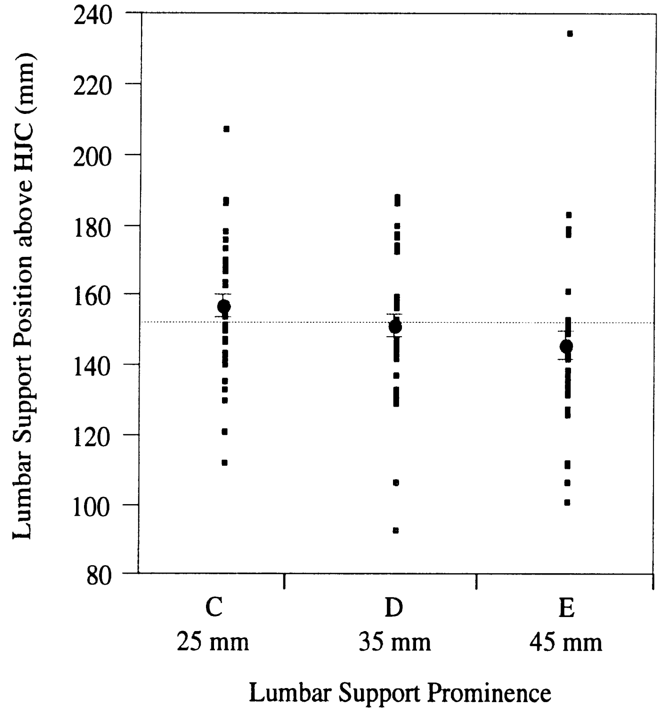


Figure 30. Subject-selected vertical lumbar support position relative to HJC along manikin-referenced backline, by LS Prominence for Phase-2 testing (32 subjects). Large dots are means within LS Prominence. Lateral bars indicate ± 1 standard error.

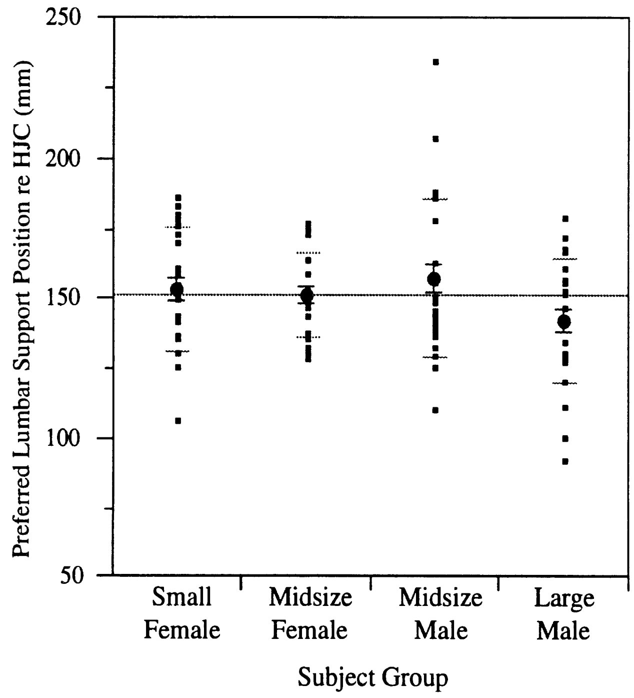


Figure 31. Subject-selected vertical lumbar support position relative to HJC along manikin-referenced backline, by subject group, for Phase-2 testing (32 subjects). Large dots are means within LS Prominence. Lateral bars indicate ± 1 standard error.

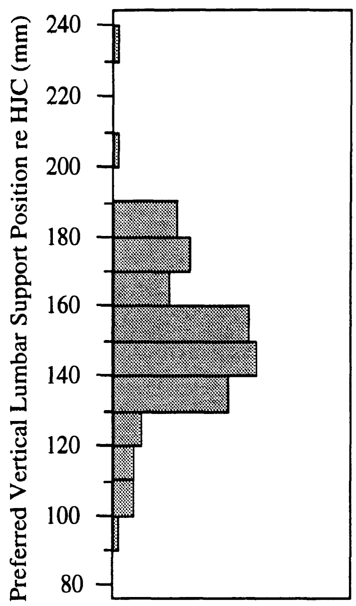


Figure 32. Distribution of subject-selected vertical lumbar support position relative to HJC along manikin-referenced backline for LS Prominences C, D, and E in Phase-2 testing (32 subjects).

3.3.14 Knee Angle

Preferred Posture

Figure 33 shows the average knee angles by LS Prominence and Condition. Knee angles did not differ significantly among LS Prominences. The average knee angle in preferred postures was 113.8 degrees. The standard deviation of knee angles across subject groups and preferred-posture test conditions is 5 degrees. There were large intergroup differences in knee angle. Figure 34 shows knee angle by Group and Condition. Large male subjects sat with significantly smaller knee angles (more knee flexion) than the other subjects. Figure 35 shows knee angles by subject group for preferred-posture conditions.

Prescribed Posture

Knee angles in prescribed postures were an average of 4 degrees larger (more extended) for all LS Prominences. The differences between the preferred- and prescribed-posture knee angles do not differ significantly among subject groups.

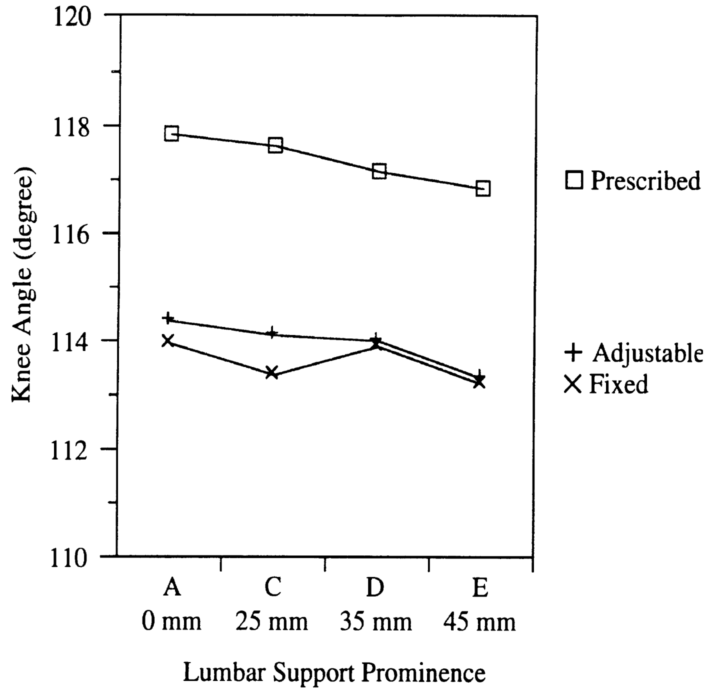


Figure 33. Mean values of knee angle by LS Prominence and Condition for Phase-2 testing (32 subjects).

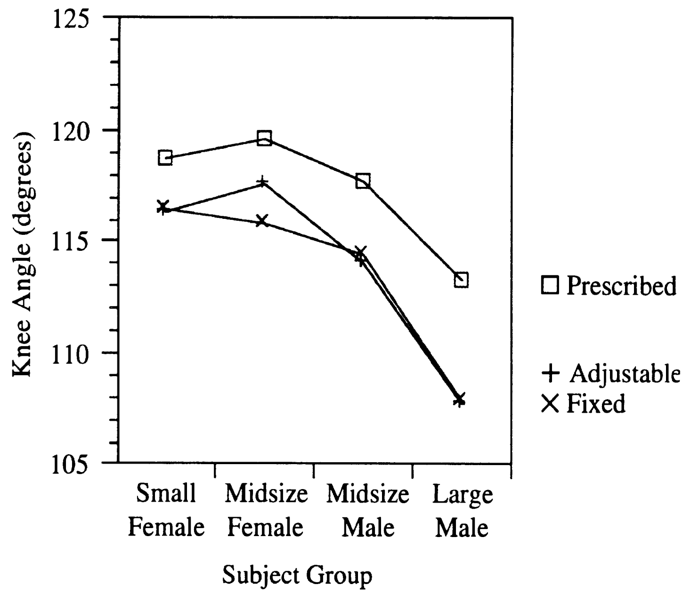


Figure 34. Mean values of knee angle by Condition and Group for Phase-2 testing (32 subjects).

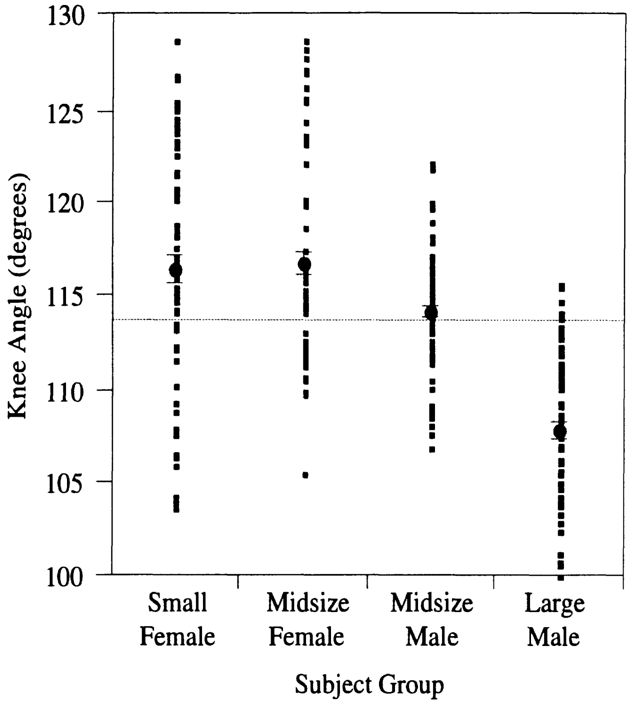


Figure 35. Knee angles by subject Group. Large dots are Group means. Lateral bars are ± 1 standard error.

3.3.15 Thigh Angle

Thigh angle is a measure of the inclination of the subject's right femur relative to the horizontal in the sagittal plane.

Preferred Posture

Thigh angles in preferred postures do not differ significantly among LS Prominences or Conditions. There are significant differences among subject groups, however. Figure 36 shows mean thigh angles by Condition and Group. Male subjects, particularly large males, sat with significantly larger thigh angles than female subjects. Group means are 8.8, 9.5, 14.0, and 16.6 degrees for the small-female, midsize-female, midsize-male, and large-male groups, respectively. Post-hoc comparisons show that the thigh angles of the two male groups are significantly different from each other and from the two female groups.

Prescribed Posture

Thigh angles in prescribed postures do not differ significantly from those measured in preferred postures.

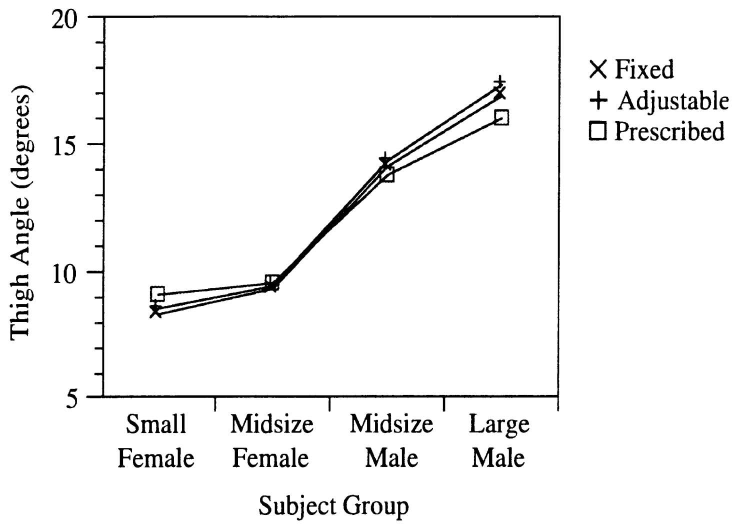


Figure 36. Thigh angle by Group and Condition.

3.3.16 Spread Angle

Spread angle is the angle of the femur segment with respect to the X axis (straight ahead) in the transverse (XZ) plane. Spread angle is a measure of leg splay. Figure 37 shows mean spread angles by Condition and Group.

Preferred Posture

Spread angles do not differ significantly among LS Prominences or Conditions. However, there are large, significant differences in spread angles between male and female subjects. Spread angles for female subjects were 0.9 degrees compared with 11.7 degrees for male subjects.

Prescribed Posture

Spread angles in prescribed postures do not differ from those measured in preferred postures across LS Prominences, Conditions, and Groups.

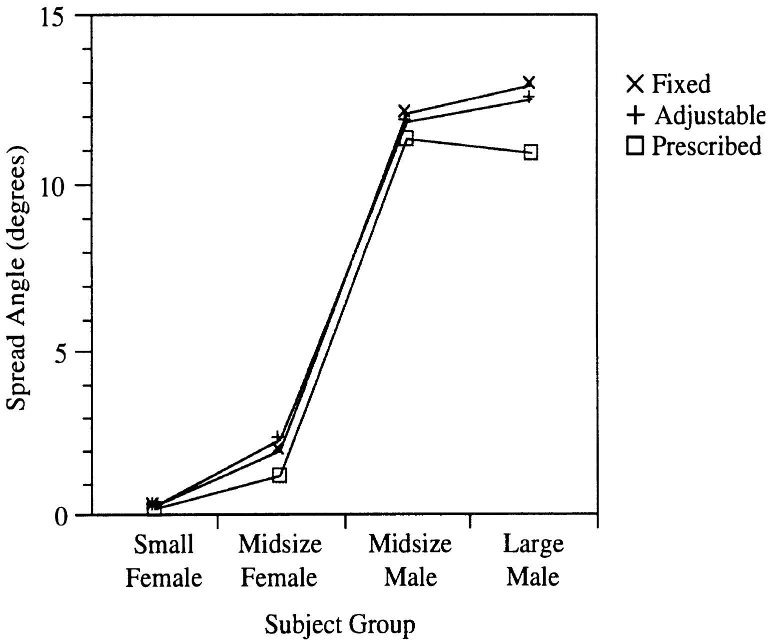


Figure 37. Spread angle by Group and Condition.

3.3.17 Subject-Selected Seat Position

Preferred Posture

Figure 38 shows the subject-selected seat position as measured by the location of the seat pivot point rearward of the accelerator heel point, a package reference point. Large-male subjects (85th- to 95th-percentile male by stature) were substantially censored in their seat track selection. A linear regression suggests that the large-male subjects might have used an additional 20 to 40 mm of seat track travel if it were available. Although it is not unusual for tall subjects to be censored in seat track travel (Schneider *et al.* 1994b, unpublished), the increase in lumbar-support prominence increased the need for rearward seat movement, since the subjects responded to the increased prominence by sitting further forward on the seat.

Figure 39 shows the mean sitter-selected seat position by LS Prominence and Condition. For the preferred-posture trials, the subjects selected slightly more rearward seat positions, on average, with increasing lumbar-support prominence. Combined with the forward movement of the HJC relative to the seat (see Section 3.3.9), these data suggest that, on average, subject's hip joint centers remained in approximately the same location in vehicle space as the LS Prominence was increased. An increase in LS Prominence from 0 to 45 mm caused a mean rearward shift in seat position of about 7 mm. This is less than half of the 16-mm forward movement of HJC relative to the seatpan. This difference may result from the seat track censoring of the large-male subjects, who could not move the seat further rearward as the LS Prominence was increased.

Prescribed Posture

Since the seat track was not adjusted between prescribed-posture trials, comparisons among LS Prominences for prescribed posture are not meaningful.

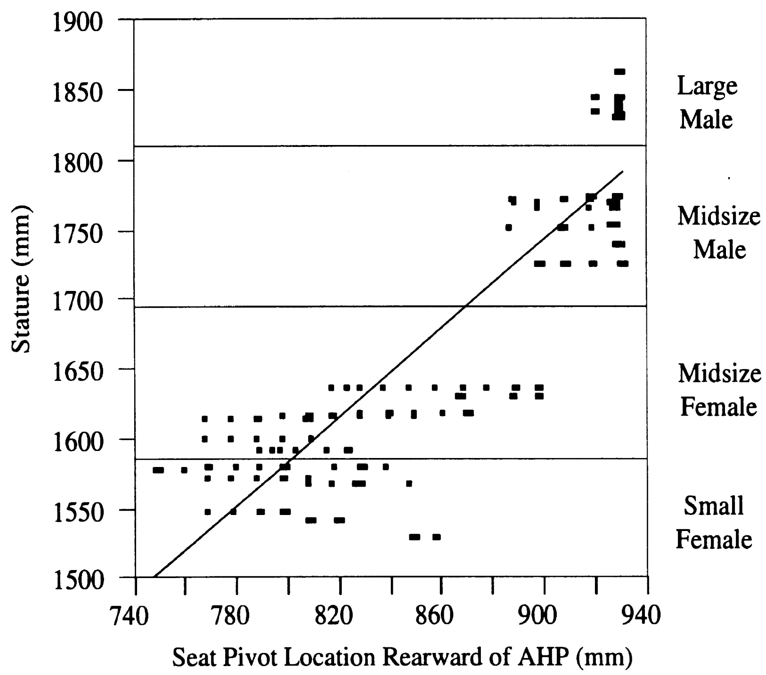


Figure 38. Seat pivot location rearward of accelerator heel point by subject stature showing the effect of stature on fore/aft seat positioning. Diagonal line is linear regression.

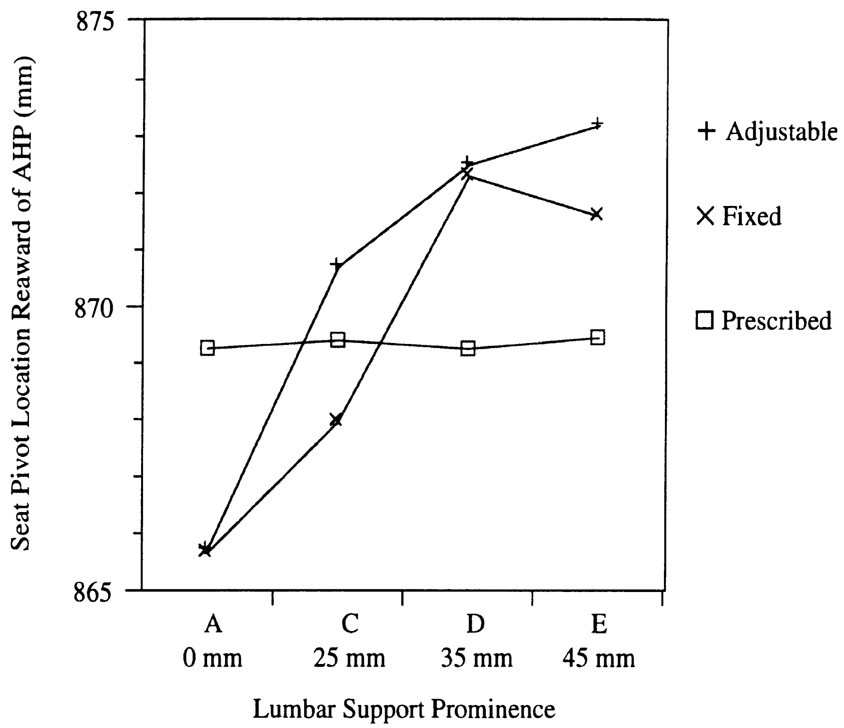


Figure 39. Seat pivot location rearward of accelerator heel point by LS Prominence and Condition.

3.3.18 Summary of Results of Short-Duration Testing

Table 8 shows the mean posture and contour variable values obtained in preferred-posture Conditions by LS Prominence. The overall mean for each variable is shown, along with the average standard deviation within LS Prominence.

Table 9 presents the findings with regard to the effect of LS Prominence on posture in a slightly different way. The table shows the mean change in posture and contour variables between the flat LS Prominence (A) and the 45-mm LS Prominence (E). As shown in the preceding analysis and Table 8, most of the posture variables change approximately linearly in response to increasing lumbar-support prominence. Table 9 also shows the mean difference between the preferred and prescribed posture conditions. Where an interaction between Condition and LS Prominence was found, the table shows the range of the Prescribed–Preferred Condition effect from LS Prominence A to LS Prominence E.

As shown in Table 9, increasing the lumbar-support prominence decreased spine flexion pelvis - thorax) about 6 degrees by approximately equal and opposite changes in the orientations of the top and bottom of the thoracolumbar spine. The increase in lumbar-support prominence of 45 mm also caused subjects to sit with their hips about 16 mm further forward on the seat, with an increase of about 9 mm in lumbar lordosis as measured by the prominence of the lumbar back contour. Only a small difference in vertical hip joint center location was found between preferred-posture conditions with fixed and vertically adjustable lumbar supports. Other variables showed no difference.

Table 8
Posture and Contour Summary Statistics for Preferred Postures by LS Prominence
N = 64 in each cell (32 subjects x 2 Conditions)
(Units are degrees unless otherwise indicated.)

Variable	A (0 mm)	C (25 mm)	D (35 mm)	E (45 mm)	Overall Mean	Std. Dev.*
Pelvis Angle	55.3	53.5	53.2	52.5	53.6	12.4
Thorax Angle	53.5	54.5	56.2	56.6	55.2	7.5
Sternum Angle	22.3	24.7	25.1	26.2	24.6	8.0
Head Angle	10.0	10.4	10.6	9.3	10.1	6.1
Torso Angle	23.0	23.6	24.2	24.6	23.9	5.8
Spine Extension † (pelvis-sternum)	0.0	4.2	4.9	6.7	3.9	13.8
Spine Extension † (pelvis-thorax)	0.0	2.8	4.8	6.0	3.4	13.7
HJC-X †	0.0	7.1	11.7	16.2	8.7	21.7
HJC-Z †	0.0	2.9	4.2	5.7	3.2	12.7
Lordosis (mm)	2.2	5.3	6.9	11.3	6.4	7.1
Height of Lordosis re HJC (mm)	137.0	143.3	144.9	152.1	144.3	39.3
Seatback Angle (subject-selected)	22.5	22.4	22.5	22.5	22.5	3.6
LS Position above HJC ** (subject-selected, along J826-referenced backline)	n/a	158.0	151.8	146.3	152.0	22.9

* Average standard deviation within LS Prominence.
† Normalized to LS Condition A = 0.
** Means for Adjustable Condition only. No adjustment was permitted with LS Prom. A.

The prescribed sitting procedure induced subjects to sit with their hips as far to the rear on the seat as possible. The net reduction in thoracolumbar spine flexion with the prescribed sitting procedure was about 1.5 times the size of the reduction in flexion that resulted from the addition of 45 mm of lumbar support when subjects were allowed to choose their posture freely (*i.e.*, 10 degrees versus 6 degrees). This reduction in spine flexion resulted almost entirely from a change to more upright pelvis angles (-10 degrees) accompanied by a rearward shift of the hips. The mean change in pelvis angle from preferred to prescribed postures was about 10 degrees, regardless of the lumbar-support prominence. Similarly, the increase in the lordosis from preferred to prescribed postures was about 9 mm, regardless of lumbar-support prominence.

Table 9
Summary of Effects of LS Prominence and Prescribed Posture

Variable	Net Change with Addition of 45 mm of LS in Preferred Postures	Net Change from Preferred to Prescribed Posture
Pelvis Angle	–2.9°	–10°
Thorax Angle	+3.1°	n.s.*
Sternum Angle	+3.8°	n.s.
Head Angle	--	n.s.
Torso Angle	+1.6°	+2.5° to +4°
Spine Flexion (pelvis-sternum)	–6.7°	–10°
Spine Flexion (pelvis-thorax)	–6.0°	–10°
HJC-X	16 mm (forward)	19 to 29 mm (rearward)
HJC-Z	5.4 mm (up)	0 to 5 mm (down)
Lordosis	+9 mm	+9 mm
Height of Lordosis	n.s.	+18 mm
Seatback Angle (subject-selected)	Ns.	Ns.
Vertical LS Position (subject-selected)	–12 mm (C-E)	n/a

* Ns. indicates no significant difference.

Figure 40 shows the distributions of values obtained by subtracting the average variable value over the preferred-posture tests for LS Prominence A from the corresponding values for LS Prominence E. Figure 40 illustrates considerable variability among subjects in their responses to increasing lumbar-support prominence. For example, six of 32 subjects actually sat with larger (more reclined) pelvis angles in LS Prominence E than in LS Prominence A. The differences are all less than 3 degrees, indicating that, essentially, their pelvis orientations were the same in spite of the addition of 45 mm of lumbar support. No subject showed a reduction in pelvis angle of more than 10 degrees in LS Prominence E. Two subjects, using the pelvis-sternum measure, or four subjects, using the pelvis-thorax measure, apparently *increased* their spine flexion in response to increased lumbar-support prominence, although the mean response was a net reduction in flexion of about 6 degrees. Two subjects sat with decreased lumbar lordosis in LS Prominence E compared with LS Prominence A. Only three subjects increased their lumbar lordosis more than 15 mm in response to an increase of 45 mm in lumbar-support prominence, and none increased prominence more than 20 mm.

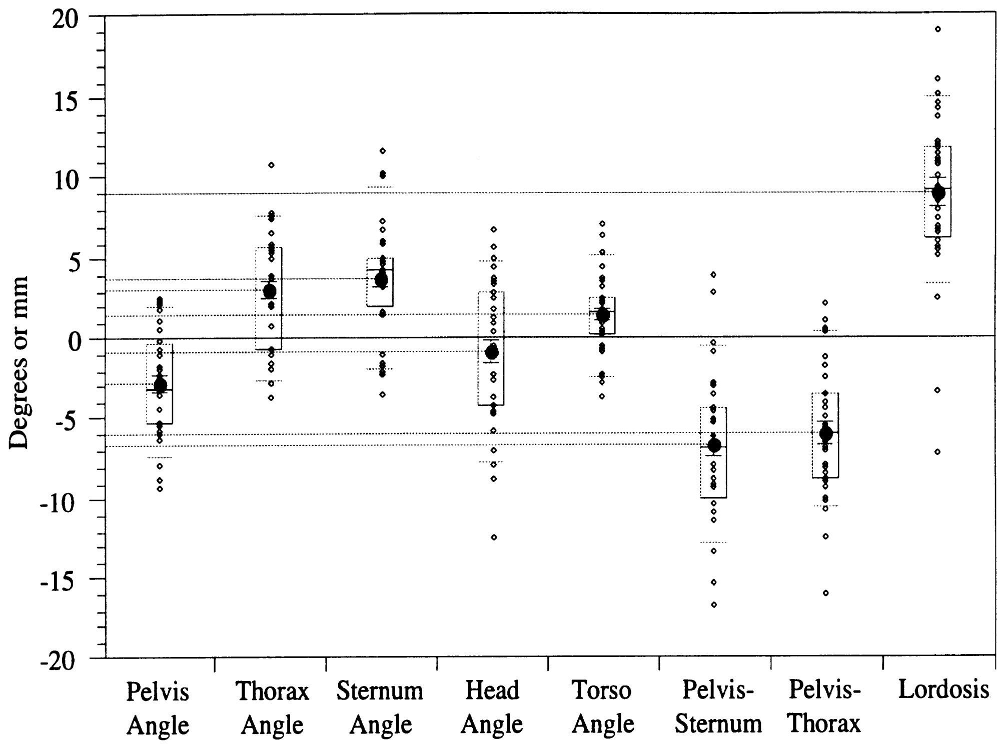


Figure 40. Distributions of the change in posture variables from LS Prominence A to LS Prominence E in preferred postures for 32 subjects in Phase-2 testing. Posture variables were averaged across Fixed and Adjustable Conditions for each subject and LS Prominence. Each subject is represented as one data point for each variable. Larger dots are mean values with standard error bars. Boxes and horizontal lines show 10th-, 25th-, 50th-, 75th-, and 90th-percentile estimates. Light lines illustrate mean values on vertical axis, which are the same as the mean values shown in Table 9.

3.4 COMPARISON OF LONG-DURATION AND SHORT-DURATION POSTURE RESULTS

In Phase 1 of this study, 48 subjects participated in one-hour driving simulations with lumbar-support prominences A, B, and C, comprising 0, 10, and 25 mm of lumbar support, respectively. Analyses of the first 24 subjects (six in each stature/gender group) were reported in Reed *et al.* (1995). The preliminary analyses demonstrated that the posture variables of interest do not change substantially over time, indicating that a short-duration sitting session is likely to produce postures that are reasonably representative of longer-duration sitting. In light of this finding, plans to test a total of 60 subjects using the driving-simulation protocol were modified to allow short-duration testing of a wider range of lumbar support contours. Subsequent analyses of data from all 48 Phase-1 subjects (see Section 3.2) showed that the preliminary conclusions regarding systematic time effects were accurate.

The magnitudes of the difference between Phase-1 and Phase-2 postures are small. In general, these differences can be explained by the small but significant time effects discussed in Section 3.2. Data for the 32 subjects who participated in Phase-2 testing were extracted from the Phase-1 data for comparison. Data from the first measurement interval in the long-duration testing were compared to data from the short-duration tests with vertically adjustable lumbar support.

Only two significant posture effects involving the short- vs. long-duration term were found. The lumbar lordosis was about 3 mm larger in LS Prominence C during long-duration testing than in short-duration testing, as shown in Figure 41. Also, head angle was about 5 degrees larger in Phase 1 than in Phase 2, an unexpected finding. No explanation for this observation has been found. As noted above, head angle is not influenced by lumbar-support prominence, and the amount of simulator driving before measurement was the same in Phase 1 and Phase 2 (two minutes), suggesting that differences in task demands do not account for the difference.

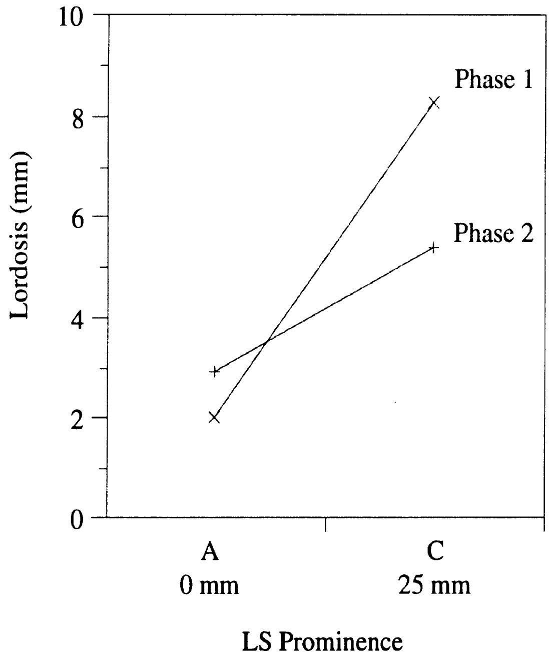


Figure 41. Comparison of mean lordosis obtained in the Adjustable Phase-2 sessions and in the first measurement made in the Phase-1 testing, taking only the 32 subjects who participated in both test phases.

Similar ANOVAs were conducted comparing data from the last measurement interval of Phase-1 testing (elapsed time = 60 minutes) with the data from the Adjustable Condition of Phase 2. Due to the small time effects described in Section 3.2, some additional significant differences were observed. Sternum angle was larger at the end of Phase 1 than in Phase 2 by about 1.3 degrees. Head angle was greater in Phase 1 by 5.9 degrees, and HJC-X, the fore-aft position of the mean hip joint center, was about 6 mm further forward in the 60-minute Phase-1 measurement than in the Phase-2 measurement (see Figure 13 for a description of the time-related trend in HJC location). There was also a significant difference in the lumbar lordosis for LS Prominence C, virtually identical to that observed in data from the first measurement interval of Phase-1 testing, which is illustrated in Figure 41. In general, however, the findings from the short-term sitting sessions were consistent with those from the one-hour driving simulation trials.

3.5 STANDING POSTURE RESULTS

Standing posture was measured before each Phase-1 test. Figure 42 shows typical standing posture data from a midsize-male subject. Averages for each of the posture variables were computed from the three measurements for each subject prior to analysis. Table 10 shows means, minimums, maximums, and standard deviations for posture variables calculated from the standing data for the 48 Phase-1 subjects.

Table 10
Summary Statistics for Standing (S) Posture Variables, N=48
(Units are degrees unless otherwise noted.)

Variable	Mean	Std. Dev.	Min	Max
Pelvis Angle (S)	0.0	7.3	-16	23
Thorax Angle (S)	47.5	5.9	32	62
Sternum Angle (S)	16.1	5.3	6	28
Head Angle (S)	3.8	6.9	-12	18
Torso Angle (S)	3.7	2.7	-4	10
Lumbar Lordosis (S) (mm)	23.8	7.3	9	42
Height above HJC of Lumbar Lordosis (S) (mm)	183	32	107	261

Standing pelvis angle varied significantly by gender, with male subjects having, on average, standing pelvis angles 6 degrees larger (more rearward tilt) than female subjects ($p<0.01$). Head angle also varied among subject groups, as shown in Figure 43. All intergroup comparisons are significant ($p<0.05$) except that midsize-male head angles are not significantly different from midsize-female or large-male head angles.

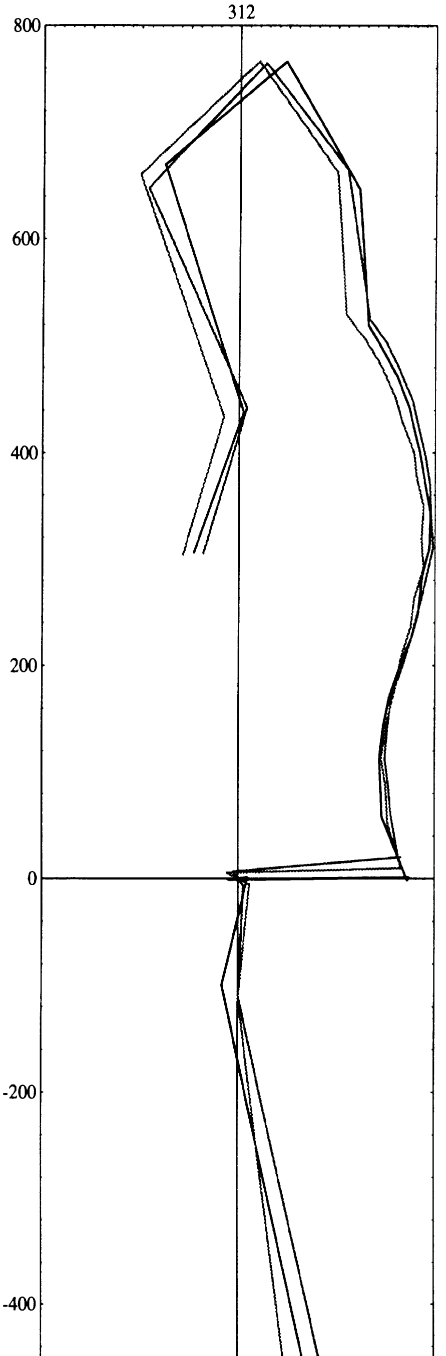


Figure 42. Typical standing posture data from a midsize-male subject, in mm. Three sets of measurements are shown. Line connects bottom sternum, top sternum, glabella, top head, occiput, spinous processes C7–L5, PSIS(R), PSIS(L), ASIS(R), ASIS(L), pubic symphysis, and lateral femoral condyle landmarks.

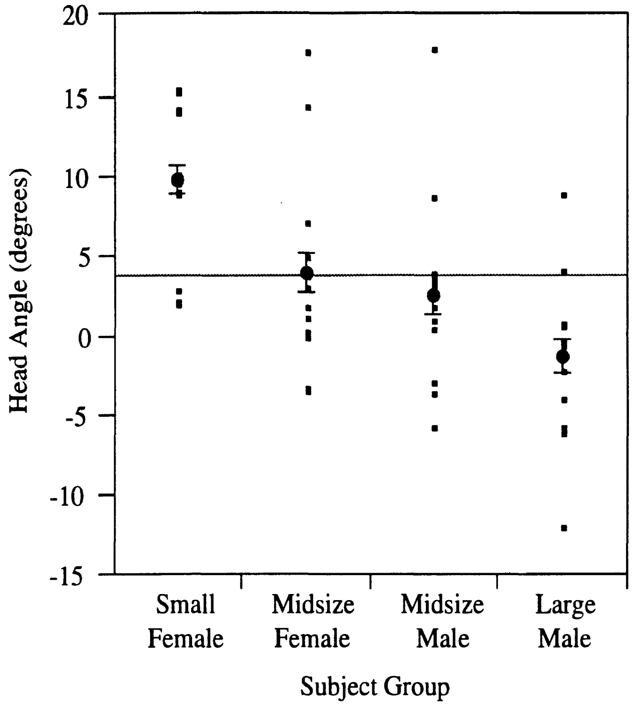


Figure 43. Standing head angle by subject Group for Phase-1 subjects (N=48).

3.6 ANALYSIS OF NORMALIZED POSTURE DATA

Data from Phase-2 testing were normalized by subtracting the values obtained for each subject while standing in Phase 1, thus expressing the posture variables in terms of the change in orientation relative to the standing posture. Figure 44 shows the distributions of these normalized variables for all Phase 2 preferred-posture sessions (32 subjects x 4 LS Prominences x 2 Conditions (Fixed and Adjustable) = 256). Table 11 lists the summary statistics.

Table 11
Summary Statistics for Normalized (norm) Posture Variables (N=32)
(Seated minus Standing within Subject)
Phase-2 Preferred-Posture Conditions (LS Prominences A, C, D, and E)

Variable	Mean	Std. Dev.	Min	Max
Pelvis Angle (norm)	53.3	14.2	19	88
Thorax Angle (norm)	8.3	7.4	-15	35
Sternum Angle (norm)	8.2	6.5	-11	23
Head Angle (norm)	6.5	7.8	-15	29
Torso Angle (norm)	20.2	5.9	6	32
Pelvis–Sternum (norm)	45.1	15.2	6.5	84
Pelvis–Thorax (norm)	44.9	15.3	-0.7	82

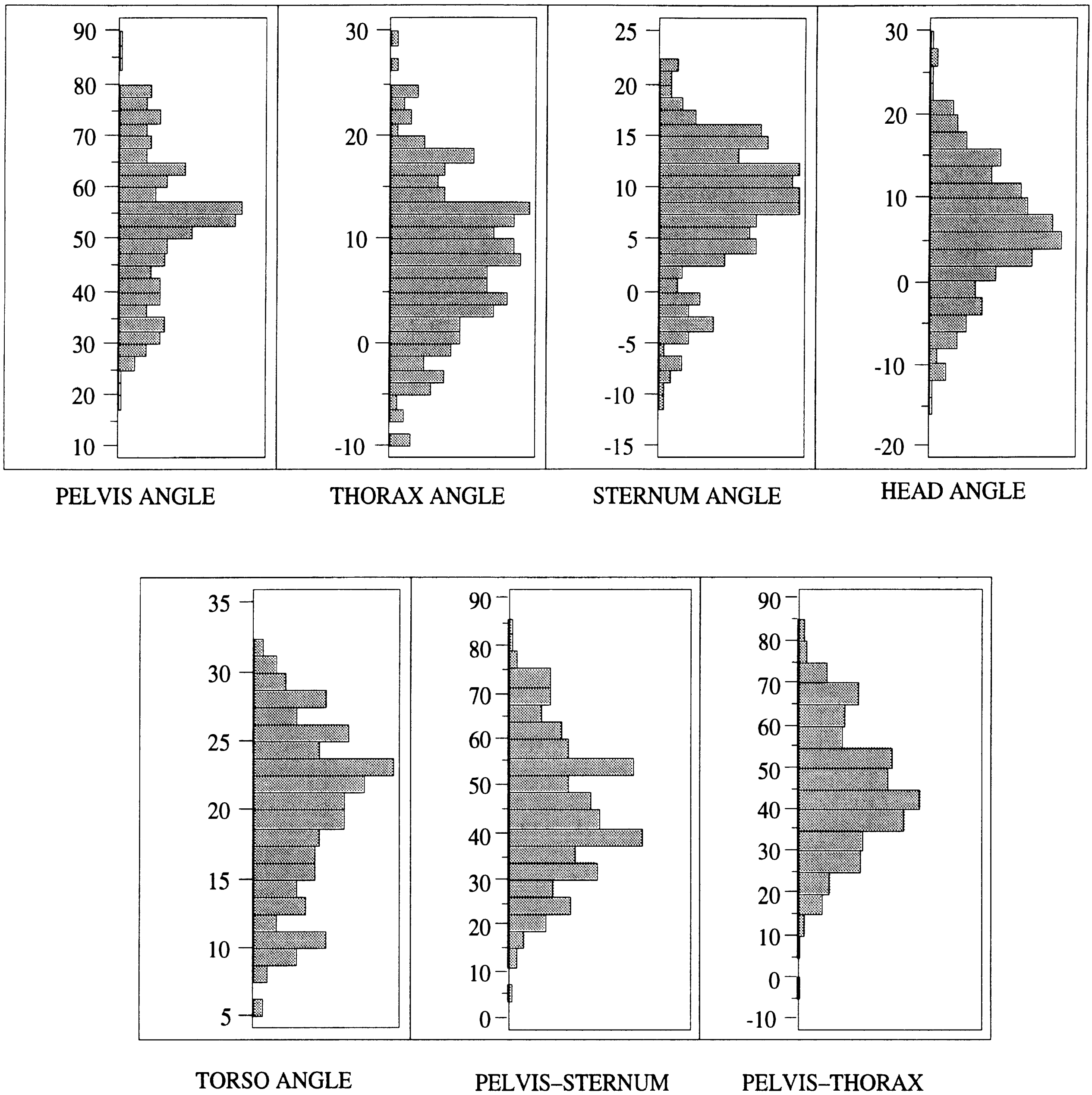


Figure 44. Frequency distributions of normalized posture variables for all Phase-2 preferred-posture test conditions (LS Prominences A, C, D, and E, with both fixed and vertically adjustable lumbar supports). Vertical axes are in degrees. Horizontal axis is count axis for histogram. Values indicate the change in the posture variable from standing to sitting. Means and standard deviations for the displayed distributions are listed in Table 11.

The normalized posture variables provide a useful illustration of sitting behavior referenced to a standard posture (standing). In considering Figure 42 and Table 11, it is important to keep in mind that all four lumbar-support prominences tested in Phase 2 are included, so the effects of changes in lumbar-support prominence on these posture variables contribute to the spread of the distributions shown. In general, however, the magnitudes of those effects are small relative to the intersubject variance.

In Phase 2, seated subjects rotated their pelves rearward an average of 53 degrees from the standing orientation. For comparison, the average effect on pelvis angle of a 45-mm increase in lumbar support was about 3 degrees, or 6 percent of the mean rearward rotation from the standing orientation (compare Table 9 with Table 11). Normalized thorax and sternum angles show that, on average, the ribcages of seated subjects are reclined about 8 degrees in sitting compared to standing. The subjects' heads are tilted rearward an average of 6.5 degrees from standing to sitting. Combining the sternum/thorax angle and head angle findings, subjects experienced an average of only about 1.5 degrees of neck flexion moving from standing to sitting.

Since the subjects' ribcages reclined only 8 degrees while their pelves rotated rearward by 53 degrees, the net flexion of the thoracolumbar spine averaged 45 degrees from standing to sitting. For comparison, the average reduction in flexion produced by a 45-mm increase in lumbar-support prominence is about 6.5 degrees, or 14 percent of the average spine flexion associated with sitting. The average change in spine flexion resulting from the prescribed sitting procedure was 10 degrees, or about 22 percent of the average spine flexion in preferred postures.

Torso angle increased an average of 20 degrees from standing to sitting, which is about 2.5 times larger than the increase in sternum and thorax angles. Thus, torso recline in this seating environment was accomplished primarily by flexion of the thoracolumbar spine, which results in a forward displacement of the hips relative to the thorax, rather than by equivalent simultaneous changes in the orientations of the thorax and pelvis. The torso does not recline as a unit in this seating situation, even with prominent lumbar supports.

There are also significant subject-group differences in normalized posture variables for thorax angle, sternum angle, and head angle. Figure 45 shows plots of normalized variable values by subject group. In general, for male subjects, and particularly the midsize-male subjects, the ribcage was more reclined than for female subjects. Male subjects' head angle changes relative to the standing posture are also generally larger than those of female subjects.

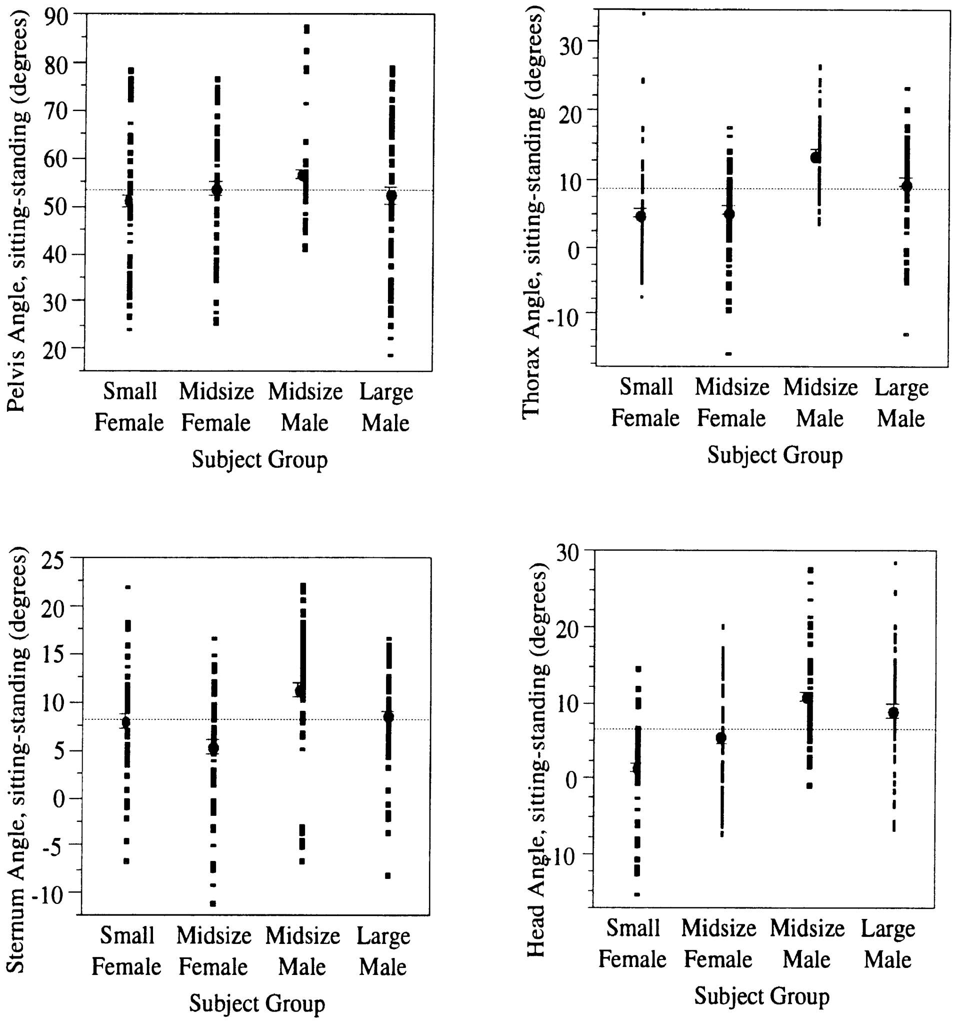


Figure 45. Selected normalized posture variables, showing subject group differences. Large dots are group means. Error bars are plus/minus one standard error.

Table 12 shows the mean values of the normalized variables by LS Prominence, averaged across the Fixed and Adjustable preferred-posture Phase-2 Conditions, and allows direct comparison of the effects of increasing lumbar lordosis with the overall change in posture from standing to sitting. Back contour measures are included in Table 12. The negative values for the normalized lumbar lordosis indicate that, on average, subjects exhibit considerably less lordosis when they sit than when they stand, even in a seat equipped with a 45-mm lumbar support. The lumbar lordosis ratio is the ratio of the lordosis measured sitting to that measured standing, and can be read as the fraction of the standing lumbar lordosis preserved in sitting. For the 45-mm prominence, less than half of the standing lordosis was preserved, on average. The height of the lumbar lordosis above the hip joint center decreased in sitting by an average of about 45 mm. This measurement was made vertically for standing postures and along the manikin-referenced backline for seated postures. The differences were smaller for more prominent lumbar supports.

Table 12
Means of Normalized Posture Variables
(Seated-Standing Values within Subject)
Phase 2 Preferred-Posture Conditions by LS Prominence

Variable	A (flat)	C (25 mm)	D (35 mm)	E (45 mm)	Change A to E†
Pelvis Angle (norm)	54.9	53.2	52.9	52.1	5.1%
Thorax Angle (norm)	6.6	7.7	9.3	9.8	-48.5%
Sternum Angle (norm)	5.9	8.3	8.7	9.8	-66.1%
Head Angle (norm)	6.5	6.8	7.1	5.7	12.3%
Torso Angle (norm)	19.3	19.9	20.5	20.9	-8.3%
Pelvis–Sternum (norm)	49.0	44.8	44.1	42.3	13.7%
Pelvis–Thorax (norm)	48.3	45.5	43.5	42.4	12.2%
Lordosis (mm) (norm)	-22.2	-19.1	-17.5	-13.2	40.5%
Lordosis Ratio*	0.06	0.21	0.28	0.45	--
Height of Lordosis (mm) (norm)	-52.0	-45.7	-44.1	-37.0	28.8%

† The change from LS Prominence A to E as a percentage of the net change from standing to LS Prominence A: 100 x (A–E)/A.

* Defined as the lumbar lordosis obtained in the test divided by the lordosis measured with the subject standing.

Figure 46 shows the distributions of spine extension ratios in Phase-2 testing. The spine extension ratio is the change in spine flexion from LS Prominence A to LS Prominence E divided by –1 times the change in spine flexion from standing to sitting. The ratio is positive when the increase in lumbar-support prominence resulted in a decrease in spine flexion, *i.e.*, a change to a posture more like the standing spine posture. A ratio of 0.5, for example, would indicate that a subject sat with only half as much spine flexion with LS Prominence E as with LS Prominence A, relative to the standing posture. Figure 46 demonstrates that no subject reduced his or spine flexion by more than 50 percent when the LS Prominence was increased 45 mm, while several subjects actually increased their spine flexion (negative values) in response to increased lumbar-support prominence (see also Figure 40 and Table 12).

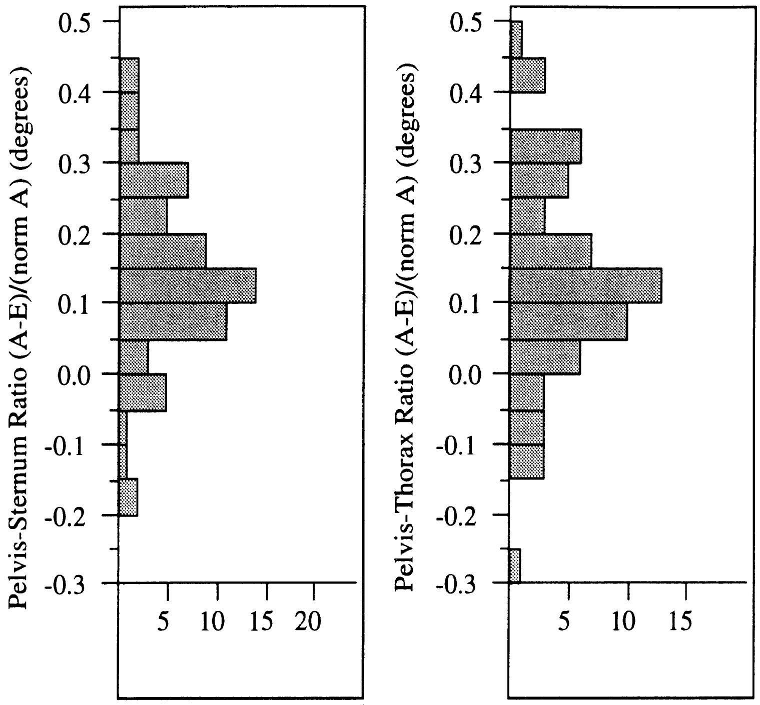


Figure 46. Distributions of spine flexion ratios. Vertical axis is dimensionless, horizontal axis is count axis. The left plot shows the result of calculations using data from the pelvis angle–sternum angle measure, while the right plot shows the result of calculations using data from the pelvis angle–thorax angle measure. The ratios represent the change in spine flexion from LS Prominence A to E divided by the total change in spine extension from standing to sitting, within subject. Data for both the Fixed and Adjustable Conditions are shown, for 32 Phase-2 subjects. Means are 0.14 for each measure.

3.7 BACK CONTOUR ANALYSIS

Additional analyses of the back contour data were performed to determine how the distribution of contours was influenced by lumbar-support prominence. The contour measurement apparatus contained 16 probes, covering 375 mm of the lower seatback. Depending on the lumbar support position, the access of four or five probes to the seatback surface was obstructed by the lumbar support mechanism. In most tests, 12 probe points were available. A standardized data set was created for each set of measurements by using a linear interpolation to distribute 12 points evenly between the highest and lowest measured points. These evenly spaced points were used for all subsequent analyses. The probe rack was located parallel to the long axis of the seatback, approximately 25 mm to the right of the seat midline. The probes could not be located on the midline because a central rib of the lumbar support frame obstructed access to the sitter's back. This lateral offset prompts an important caution regarding the interpretation of these data, as described below.

3.7.1 Representations of the Shape of the Interface Between the Sitter's Back and the Seat

It is customary to treat longitudinal back contours as though they represent the profile of the sitter's spine, *i.e.*, a curve connecting the spinous process surface landmarks. However, there are at least four "back curvatures" of interest in a supported seated posture, and each can be different. Figure 47 illustrates the lower torso of a seated subject, with four longitudinal curves. Three are on or in the sitter's body and one is on the seat.

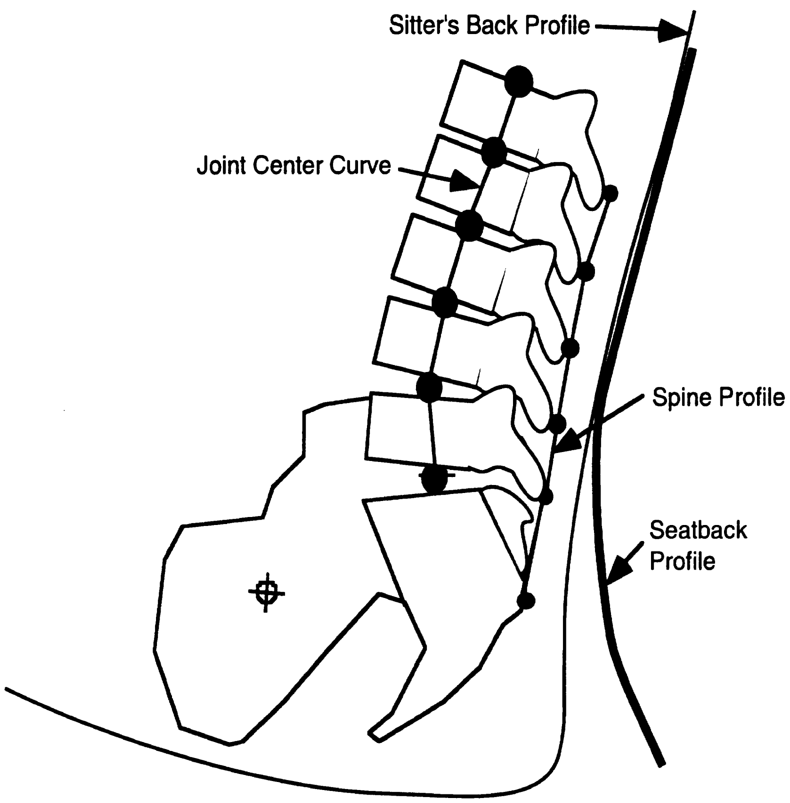


Figure 47. Schematic illustration of several curves that can be used to describe the interaction between the sitter's lower back and the seat.

One curve of interest connects the joint centers of the spine. Such a curve gives the best representation of the orientation of the vertebral bodies, but is generally not constructed unless accurate internal data can be obtained, *e.g.*, by radiography. The spine profile is a curve connecting the spinous process surface landmarks. In seated postures, this curve is usually flatter at the L4/L5/S1 levels than the curve joining the joint centers. Since there is generally less soft tissue directly over the spine than adjacent to it, spinous process landmarks can often be reliably palpated and their locations recorded.

The sitter's back profile represents the most rearward projection of the back tissue, as viewed from the side, and is frequently rearward of the spine profile in the lumbar area, particularly for lordotic spine postures, because of the lateral contour of the back. The standing back profile of a person is generally defined by the musculature and other soft tissue in the lumbar area, rather than the spinous processes, because the lumbar extensor muscles "bridge" the concavity in the lumbar spine profile, creating a back profile that has less inward curvature than the spine profile. The same situation occurs in sitting when the spine posture is lordotic, although the effect is lessened by the compression of the soft tissues that results from the pressure between the seatback and sitter.

The seatback profile is generally defined on the midline of the seat, although it could be defined to be the profile of the most rearward point on the backrest surface at each vertical level. The seatback profile is usually coincident with the sitter's back profile in the areas where the sitter's back is in contact with the seat.

In some studies, *e.g.*, Porter and Norris (1987), the design of the test chair is such that the spine profile can be measured with the subject seated. This procedure, using probes pushed into contact with the skin over the spinous processes, gives a reasonably accurate measurement of the location of the spine, but may not coincide with the back profile or seatback profile, particularly for substantially lordotic spine postures or subjects with considerable soft tissue in the lower-back area. In the current study, the sitter's contour measurement was made slightly to the right of the seat midline. Depending on the lateral positioning of the sitter, this measurement could be on the spine, corresponding to the spine profile depicted in Figure 47, or adjacent to the spine over the soft tissue, corresponding to the sitter's back profile. The lateral position of the subject's back probably varied between tests, since the sitters stood up and then repositioned themselves for each new test condition. Averaging contours over subjects and test conditions is likely to combine measurements made on the spine with those made adjacent to the spine over the soft tissue.

If the sitter's postures were substantially lordotic, the soft-tissue bridging phenomenon described above would tend to flatten the average curve obtained, relative to the true mean spine profile. However, the posture data from this study show sitters in preferred driving postures with an average spine flexion of 45 degrees (relative to the standing posture), which for most subjects will result in a nearly flat spine profile. The flat contours that predominate in the data from this study are therefore probably accurate measures of both spine profile and the sitter's back (flesh) profile, because these two contours have approximately the same shape when the spine is straight. If considerably less spine flexion was observed in the seated posture data, then more caution would be required in interpreting the back contour data, because differences in the lateral positioning of the subject would be expected to result in larger differences in the measured contour.

3.7.2 Averaging Back Contours Across Subjects

A consistent way of representing contours was needed to facilitate a statistical description of the back contours. Contours differed across tests because of intersubject differences in body shape, posture, and seatback angle. To remove the effects of seatback angle, the standardized contour points for each test were rotated to a nominally vertical orientation. This was accomplished by rotating the contour points around the seat pivot point by the selected or specified seatback angle, which was calculated as described in Section 3.3.12. The resulting contours were approximately vertical, and well aligned across subjects and tests. Linear interpolation of the rotated contours at 10-mm increments was used to obtain values at the same set of Z-coordinates for each contour. Mean contours were then calculated by averaging the X-coordinate values at each Z-coordinate level across the desired data set.

One important consideration is whether the average contours obtained by this method adequately represent the underlying data. A variety of statistical and graphical techniques were used to examine the distribution of contours within subject groups, conditions, and lumbar-support prominences. In general, the averaged contours were found to give a good representation of the central tendencies of the contour distributions. Figure 48 shows the back contours for the midsize-male subjects in the Fixed Condition by LS Prominence, along with the mean contours calculated for each condition. The variances in these data are typical of other subject groups and conditions. The averaged contours are seen to capture the typical contour shapes very well.

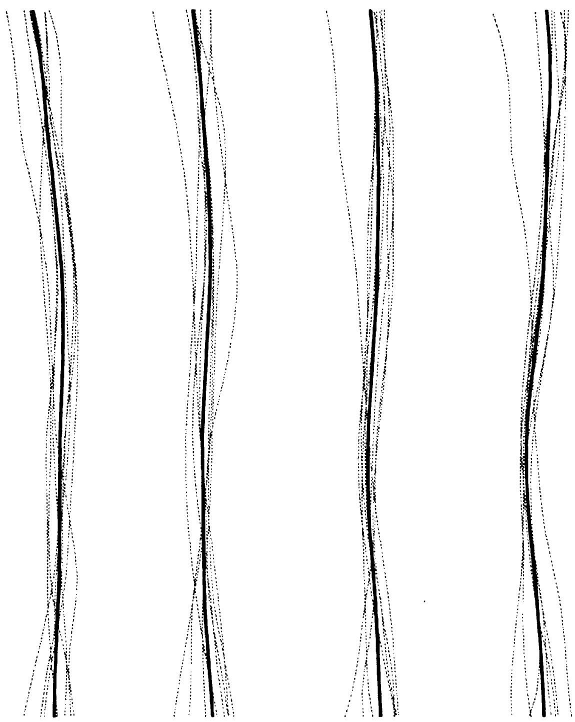


Figure 48. Individual back contours and means for midsize males in Fixed Conditions. Contours are rotated as described in text. Dark line is mean contour, light lines are individual contours.

Figures 49, 50, and 51 show the average back contours plotted by subject group, lumbar-support prominence, and condition. In the Fixed Condition, the large-male subjects deflected the lower part of the seatback more than the other groups, particularly in LS Prominences A and C. The test seat was constructed with a thin foam pad to minimize differences in seat contour for subjects with different body weight, but the lumbar support frame deflected slightly for larger subjects. In the Adjustable Condition, the effect of greater body weight is compounded by the tendency of the male subjects to position the lumbar support lower than the female subjects (see Section 3.3.13). The result is a difference in back contour between the groups, even with the more prominent lumbar supports.

These graphical depictions of the body contours support the findings from postural and quantitative contour analyses. Increasing lumbar-support prominence increased the curvature of the subjects' lower backs, particularly in the fixed lumbar support condition. When the subjects were allowed to adjust the vertical position of the lumbar support, the average change in curvature was not as pronounced, particularly for the male subjects. For example, compare the Fixed and Adjustable plots in Figures 49 and 50 for LS Prominence E. With the lumbar support position fixed, the large-male subjects deflected the seatback slightly more than the other subjects, but, in general, the back contours for all of the subjects show lordotic curves with similar apex locations. In the Adjustable Conditions, the apexes of the low-back curves for male subjects are lower than for female subjects, consistent with the findings in Section 3.3.11. The result is that, when the contours are averaged over all subjects, the contours for high-prominence conditions are flatter in the Adjustable Condition than in the Fixed Condition.

The contours for the Prescribed Conditions shown in Figure 51 demonstrate the increased lordosis that subjects were able to produce when sitting with the prescribed procedure. All subject groups produced lordotic mean contours, even with a flat lumbar support. The relative alignment of the top and bottom ends of the contour curves for the preferred- and prescribed-posture conditions (seen in the contours averaged over all subjects in Figure 51) reflects the fore-aft positioning of the subject's hips. As illustrated in Figure 23 in Section 3.3.9, the subjects positioned their hips further forward on the seat in response to increased lumbar-support prominence, but that forward movement was smaller in prescribed-posture conditions than in preferred-posture conditions.

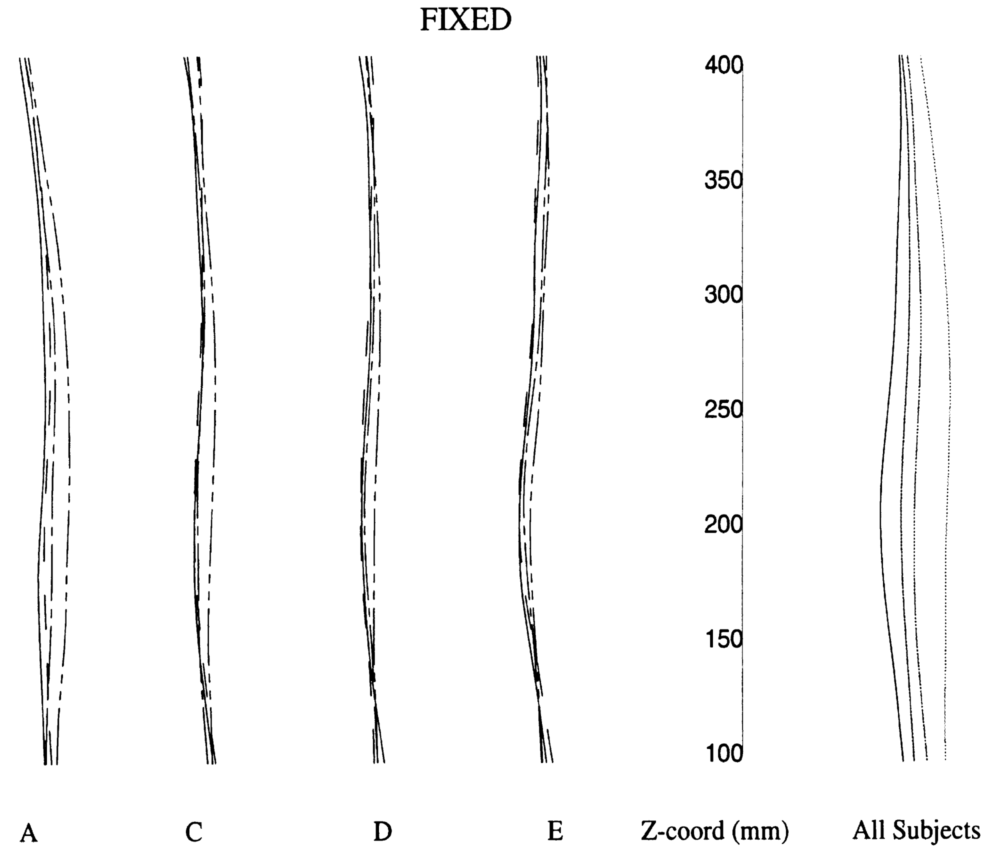


Figure 49. Back contours in Phase-2 testing by subject group and lumbar-support prominence for the Fixed test condition. The plots on the left side of the figure show average contours for each subject group within each lumbar-support prominence. (Small Females: —; Midsize Females: — —; Midsize Males: — - —; Large Males: — - - —.) The plots on the right side of the figure show the contours averaged over all subjects by lumbar-support prominence (A, C, D, and E). Contours from larger-prominence conditions are shown with darker lines.

In Figure 48, variance perpendicular to the seatback is smallest in the low-back area, and larger at the top and bottom of the contours. This reflects the range of postures chosen by the subjects. In the preferred-posture conditions, with lumbar supports from 25 to 45 mm, the contours below the lumbar support are generally not restricted by the seat surface. This can be seen by comparing the prescribed-posture contours in Figure 51 with the preferred contour distributions in Figures 49 and 50. The average prescribed contour is rearward of the most rearward preferred contour at the low end of the seatback, indicating that the preferred contours at the base of the seat are probably not restricted by the seat surface. In contrast, the influence of the upper seatback skews the distributions of the upper part of the contours. Since the seatback potentially restricts the rearward movement of the sitter's thorax, contours that deviate substantially from the mean contour at the upper end are always further forward, rather than rearward. These deviations, although accurately reflecting sitter preferences and anthropometry, tend to pull the averaged contour forward, away from the seatback. The implications of these effects in applying the contours to seat design are discussed in Section 4.

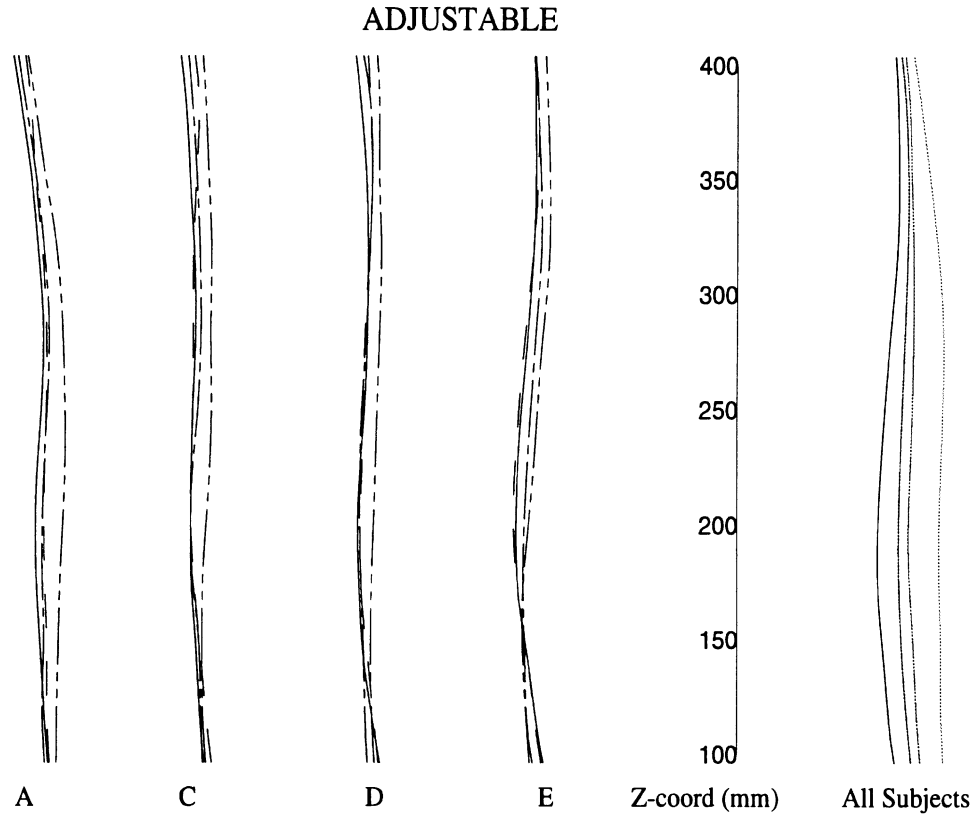


Figure 50. Back contours in Phase-2 testing by subject group and lumbar-support prominence for the Adjustable test condition. The plots on the left side of the figure show average contours for each subject group within each lumbar-support prominence. (Small Females: —; Midsize Females: — —; Midsize Males: — - —; Large Males: — - - —.) The plots on the right side of the figure show the contours averaged over all subjects by lumbar-support prominence (A, C, D, and E). Contours from larger-prominence conditions are shown with darker lines.

It is useful to examine the back contours with reference to body landmarks. Figures 52, 53, and 54 show the contours for the four lumbar-support prominences by subject group, aligned at the mean hip joint center location for each group, for the Fixed, Adjustable, and Prescribed Conditions, respectively. The contour for each group has been rotated around the seat pivot point by the mean seatback angle for the Group and LS Prominence. These subject-selected seatback angles average 22.5 degrees across groups and LS Prominences. The hip joint centers of the female subjects were much closer to the back contour than those of the male subjects. This is most likely an effect of pelvis size, although the larger pelvis angles produced by the male subjects also increase slightly the distance between the back contours and the hip joint centers.

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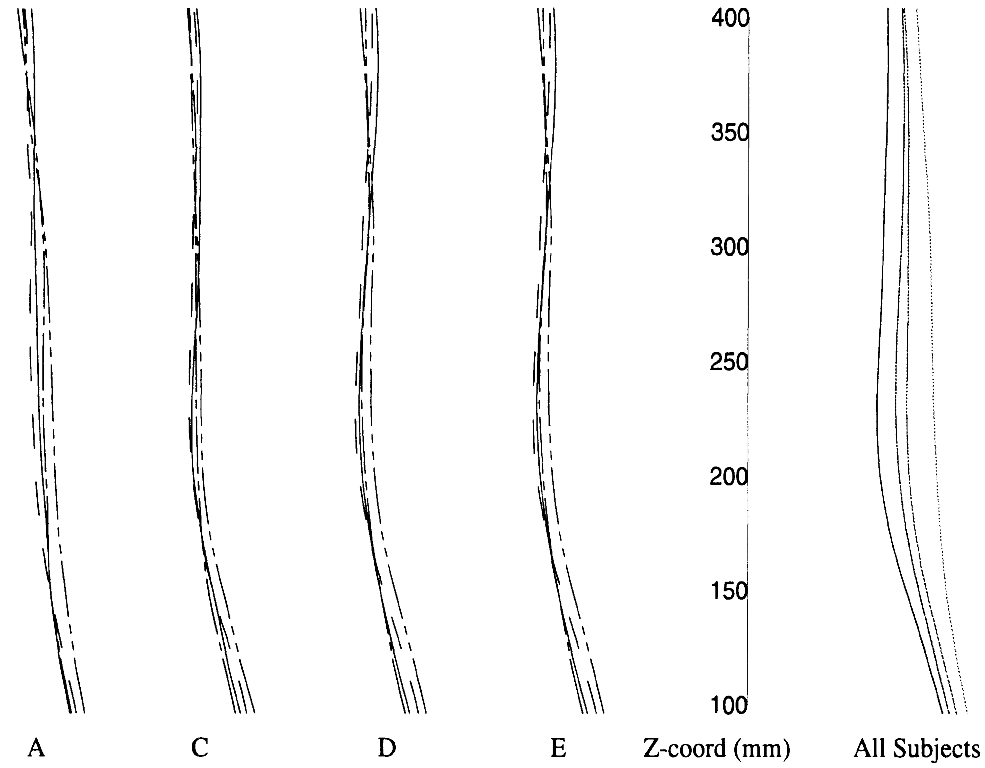

Figure 51. Back contours in Phase-2 testing by subject group and lumbar-support prominence for the Prescribed test condition. The plots on the left side of the figure show average contours for each subject group within each lumbar-support prominence. (Small Females: —; Midsize Females: — —; Midsize Males: — - —; Large Males: — - - —.) The plots on the right side of the figure show the contours averaged over all subjects by lumbar-support prominence (A, C, D, and E). Contours from larger-prominence conditions are shown with darker lines.

Superimposed on each plot in Figures 52, 53, and 54 are lines depicting the approximate location of the lumbar spine for small females and large males. Robbins (1986), using data from Schneider *et al.* (1985) and Robbins *et al.* (1985a, 1985b), estimated the locations of the L5 and T12 spinous process landmarks for large males (LM), approximately 95th-percentile male by stature and weight, and small females (SF), approximately 5th-percentile female by stature and weight. The locations of L5-SF, L5-LM, T12-SF, and T12-LM are 77, 90, 190, and 251 mm, respectively, above the hip joint center along the manikin-measured backline. These locations are depicted on a 22.5-degree backline.

The differences among groups in postural adaptation to increases in lumbar-support prominences can be seen in the contours from the Fixed and Adjustable Conditions of Figures 52 and 53, respectively. In particular, the male subjects sat with flatter back contours than the female subjects, even at the higher prominence levels. These differences are present, but not as apparent, in the Prescribed Conditions shown in Figure 54. The differences in contours between the preferred- and prescribed-posture conditions demonstrate clearly that subjects, on average, could have chosen more lordotic back postures in the preferred conditions than they did.

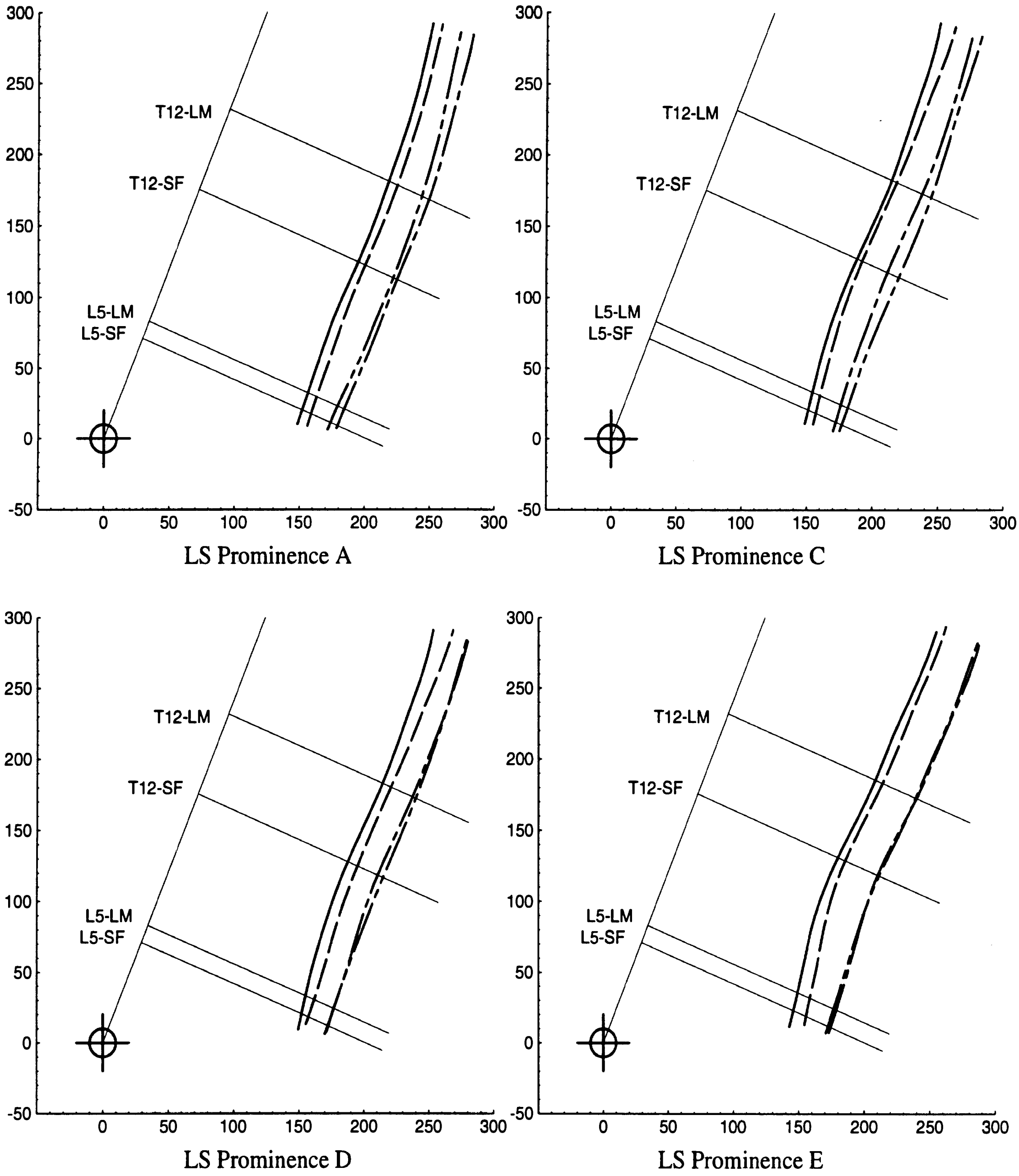

Figure 52. Mean back contours by subject group and lumbar-support prominence for the Fixed Conditions, aligned on mean group hip joint center location. Dimensions in mm.
(Small Females: —; Midsize Females: — —; Midsize Males: — - —; Large Males: — - - —.)
See text for explanation of body landmarks.

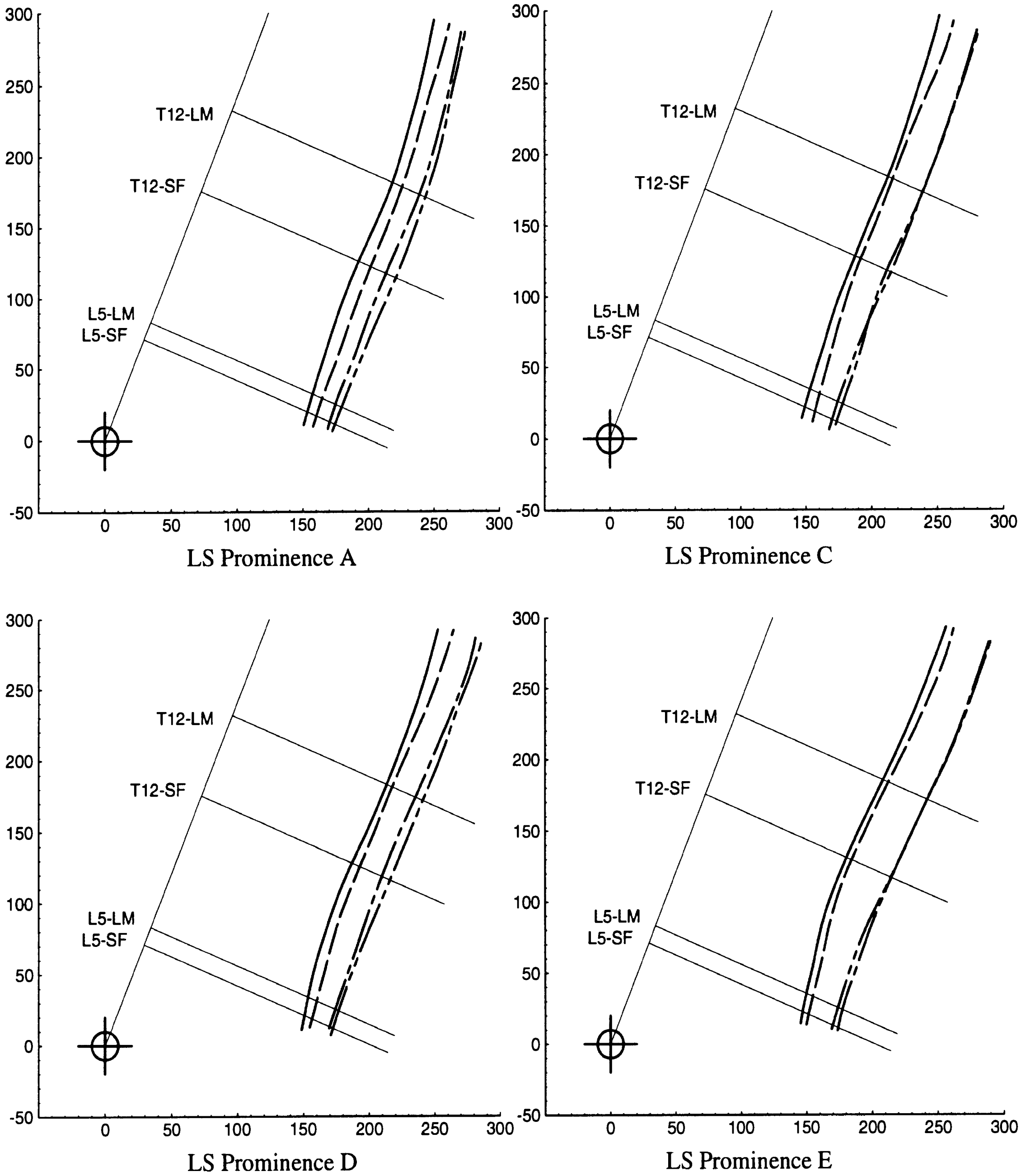

Figure 53. Mean back contours by subject group and lumbar-support prominence for the Adjustable Condition, aligned on mean group hip joint center location. Dimensions in mm.
(Small Females: —; Midsize Females: — —; Midsize Males: — - —; Large Males: — - - —.)
See text for explanation of body landmarks.

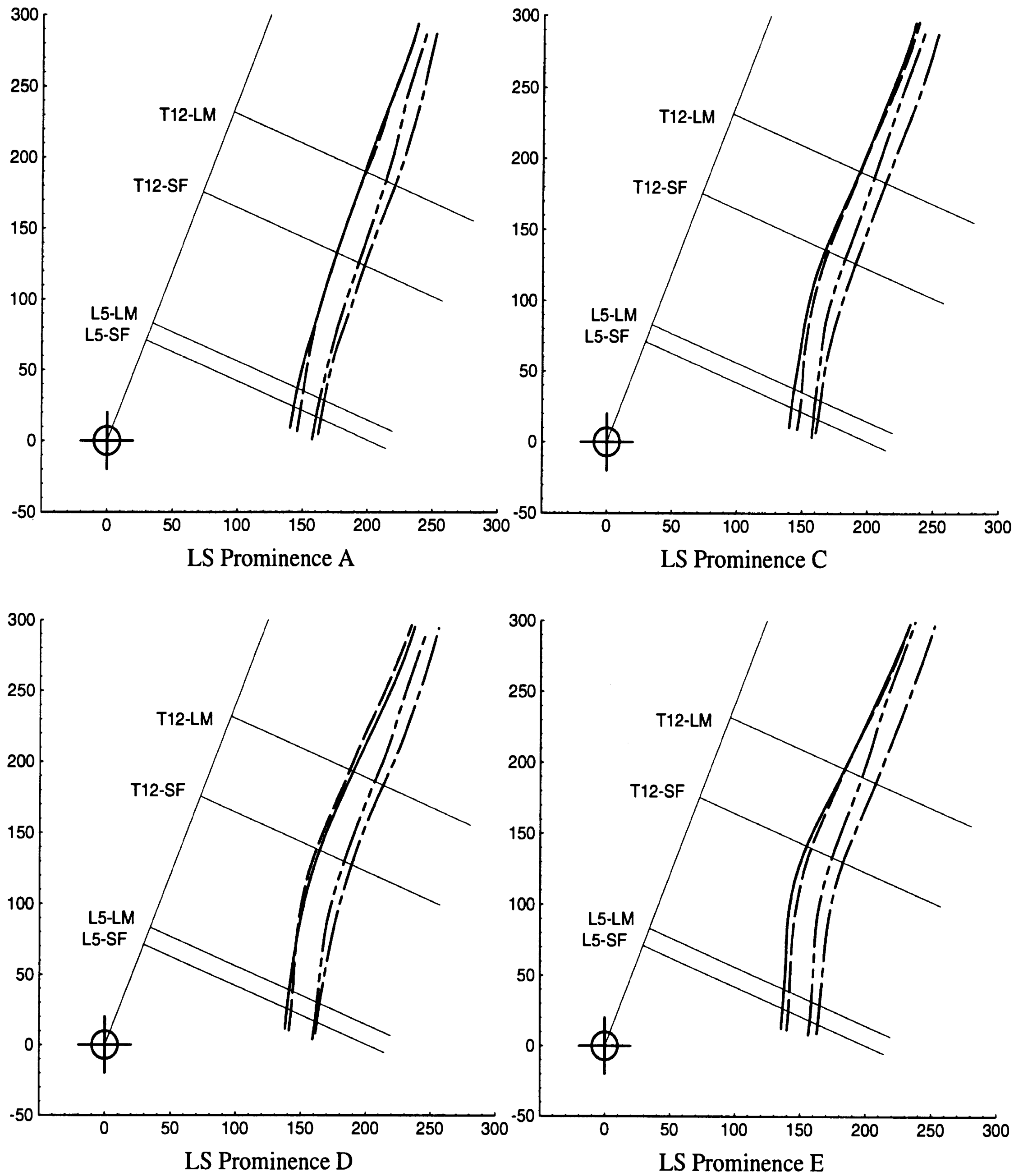

Figure 54. Mean back contours by subject group and lumbar-support prominence for the Prescribed Conditions, aligned on mean group hip joint center location. Dimensions in mm.
(Small Females: —; Midsize Females: — —; Midsize Males: — - —; Large Males: — - - —.)
See text for explanation of body landmarks.

3.8 KINEMATIC MODELING OF TORSO POSTURE

A planar kinematic model of the human torso was used to visualize the postures measured with subjects. The model is based largely on work by Haas (1989), Hubbard *et al.* (1993), and others at Michigan State University, although the original data sources for the MSU model were consulted extensively in the development of the current model, including Schneider *et al.* (1985) and Robbins *et al.* (1985a and 1985b) for driver anthropometry, Reynolds *et al.* (1981) for pelvis geometry, and Snyder *et al.* (1972) for lumbar-spine geometry and posture.

The model used here is based on midsize-male anthropometry and consists of a pelvis and 17 vertebrae linked by revolute (pin) joints. The model spine can be flexed or extended by distributing the net change in orientation between the top and bottom of the spine among the 17 intervertebral joints (T1/T2 to L5/S1). For the present illustrations, spine motion is distributed evenly among the six lumbar joints (T12/L1 to L5/S1), following the recommendations of Hubbard *et al.* (1993). No thoracic spine mobility is included. In general, more spine motion is expected at the base of the spine (L5/S1) than higher in the spine, but the assumption of even distribution of motion in the lumbar spine is made for simplicity and because it results in larger predicted changes in back contour when the net spine flexion is changed. The assumption of a fixed motion distribution in the spine reduces the kinematic degrees of freedom (dof) to four. The spine can be flexed or extended (1 dof), the entire model can be rotated in the plane (1 dof), and the model can be translated on the X and Z axes (2 dof).

The model was initially configured to a "neutral" starting posture, and then was adjusted to simultaneously represent the mean values of pelvis angle, sternum angle, thorax angle, and back contour obtained with Phase-2 subjects with LS Prominence A for the preferred-posture conditions (Fixed and Adjustable). These mean values can be found in Table 9. Figure 55 shows the model configured to match these values. The shoulder and hip joint centers are illustrated, along with the flesh-plane line connecting the mean ASIS and pubic symphysis points, which define the pelvis angle. A reference line is constructed from the PSIS tangent to the thoracic spine. Although the pelvis profile shown in the figure is a reasonably accurate representation of midsize-male pelvis and sacrum geometry, the vertebrae are depicted as simple polygons and accurately represent only the positions of the joint centers and spinous processes. Figure 56 shows the model moved in five steps from the neutral posture to a standing posture, demonstrating the articulation of the lumbar spine.

The model was adjusted to simulate the mean preferred postures for the four LS Prominences studied in Phase 2. Figure 57 shows the model adjusted from the neutral posture depicted in Figure 55 to match the mean values of spine extension (calculated from pelvis angle – sternum angle), torso angle, HJC-X, and HJC-Z for LS Prominences A, C, D, and E. The mean values used are shown in Table 9. Figure 58 shows an overlay of the four posture simulations. Postures for larger lumbar-support prominences are shown with darker lines.

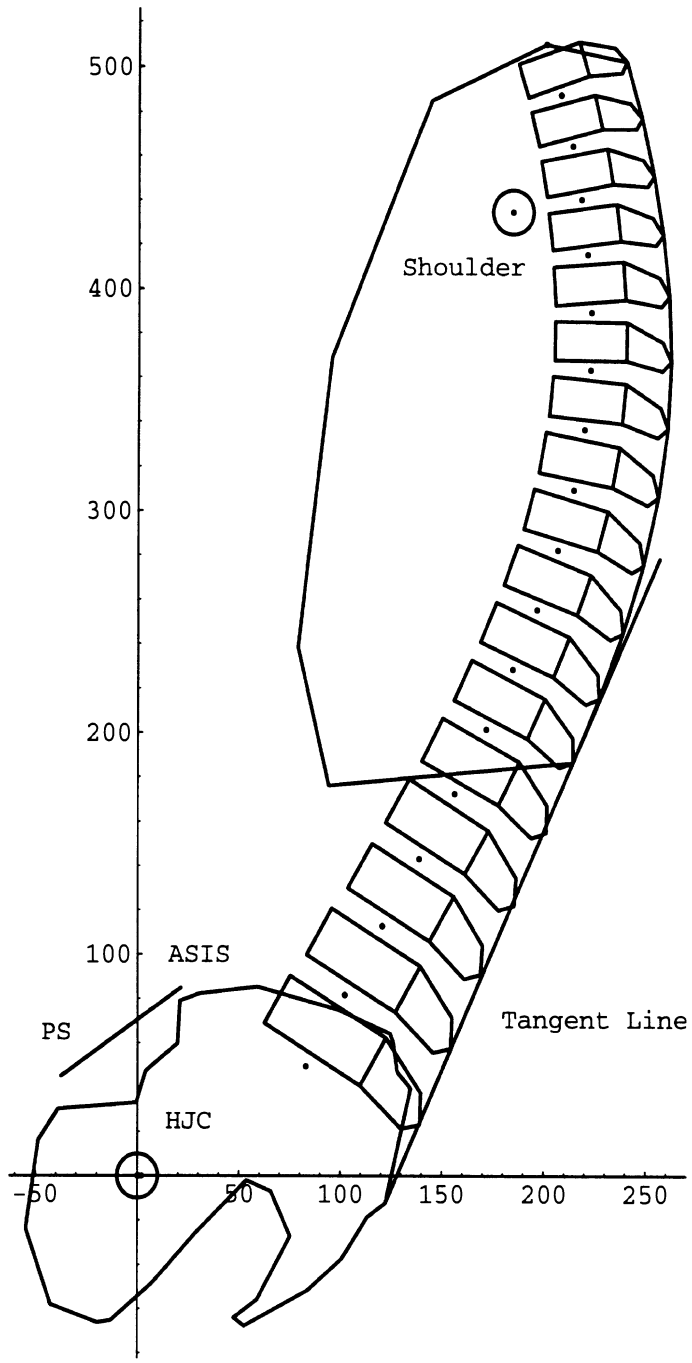

Figure 55. Kinematic model adjusted to illustrate the mean values of pelvis angle, sternum angle, thorax angle, torso angle, and lordosis obtained with the 32 Phase-2 subjects in LS Prominence A (flat) in the Fixed and Adjustable Conditions. Dimensions along axes are in millimeters. See text for additional description of model.

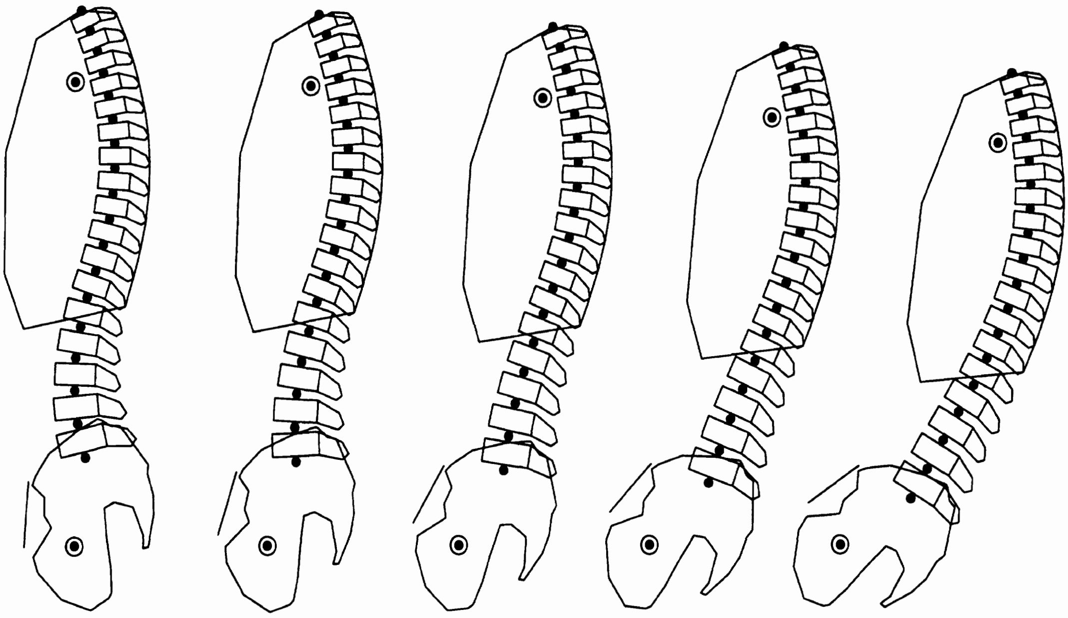

Figure 56. Simulation sequence showing the mean change in posture from standing (left) to sitting (right, LS Prominence A), demonstrating the articulation of the model lumbar spine. Shoulder and hip joint centers are shown. Net lumbar spine flexion is 45 degrees.

Figures 57 and 58 demonstrate that a primary effect of increasing lumbar-support prominence is to shift the subjects forward on the seat. The lordosis in the model simulations is measured as the maximum perpendicular deviation of a lumbar spinous process point from a reference line constructed through the PSIS tangent to the thoracic spinous processes. The lordosis measured by this method increased by 3.4 mm in response to the 6.7-degree reduction in spine flexion associated with the mean change in posture from LS Prominence A to LS Prominence E. In contrast, the mean increase in lordosis measured on the subjects was 9 mm. The difference may be related to an inconsistent relationship between the back contour and spine profile (see Section 3.7.1). The greater pressure concentration associated with the more prominent lumbar supports may have compressed the soft back tissue to a greater extent than with smaller prominences, increasing the apparent lordosis more than the actual change in spine curvature. However, the small increase in the prominence of the spine profile observed with the model may be an accurate representation of the mean response of the subjects. When the model spine profile is relatively flat (*i.e.*, flexions from the neutral posture of less than 30 degrees), there is an approximately linear relationship between spine extension and lumbar lordosis as measured here, with a slope of about 0.54 mm/degree. As noted in Sections 3.5 and 3.6, the average standing lordosis was 23.8 mm. The average reduction in spine flexion produced by a 45-mm increase in lumbar-support prominence was about 14 percent of the spine flexion with LS Prominence A, relative to the standing posture. Assuming a linear relationship between lordosis and spine flexion, 14 percent of 23.8 mm is 3.3 mm, approximately the increase in lordosis observed with the model.

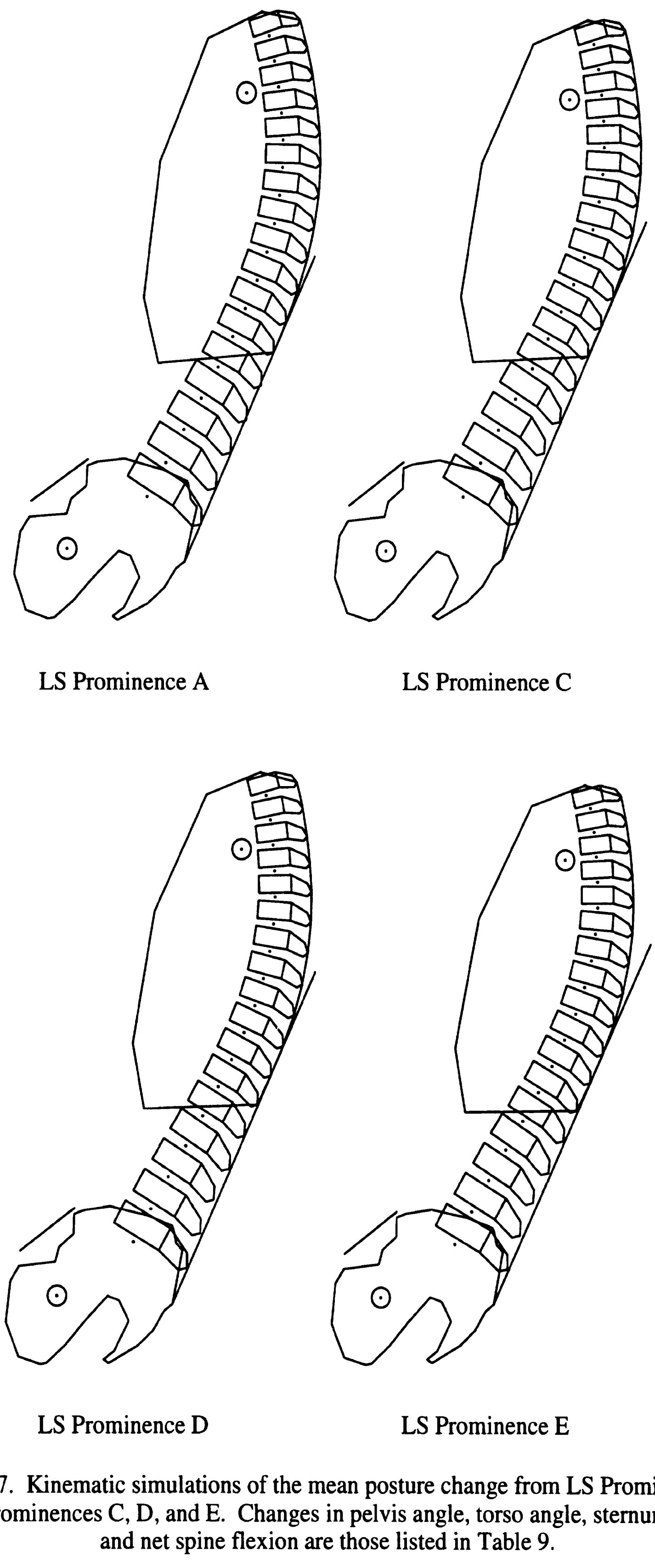

Figure 57. Kinematic simulations of the mean posture change from LS Prominence A to LS Prominences C, D, and E. Changes in pelvis angle, torso angle, sternum angle, and net spine flexion are those listed in Table 9.

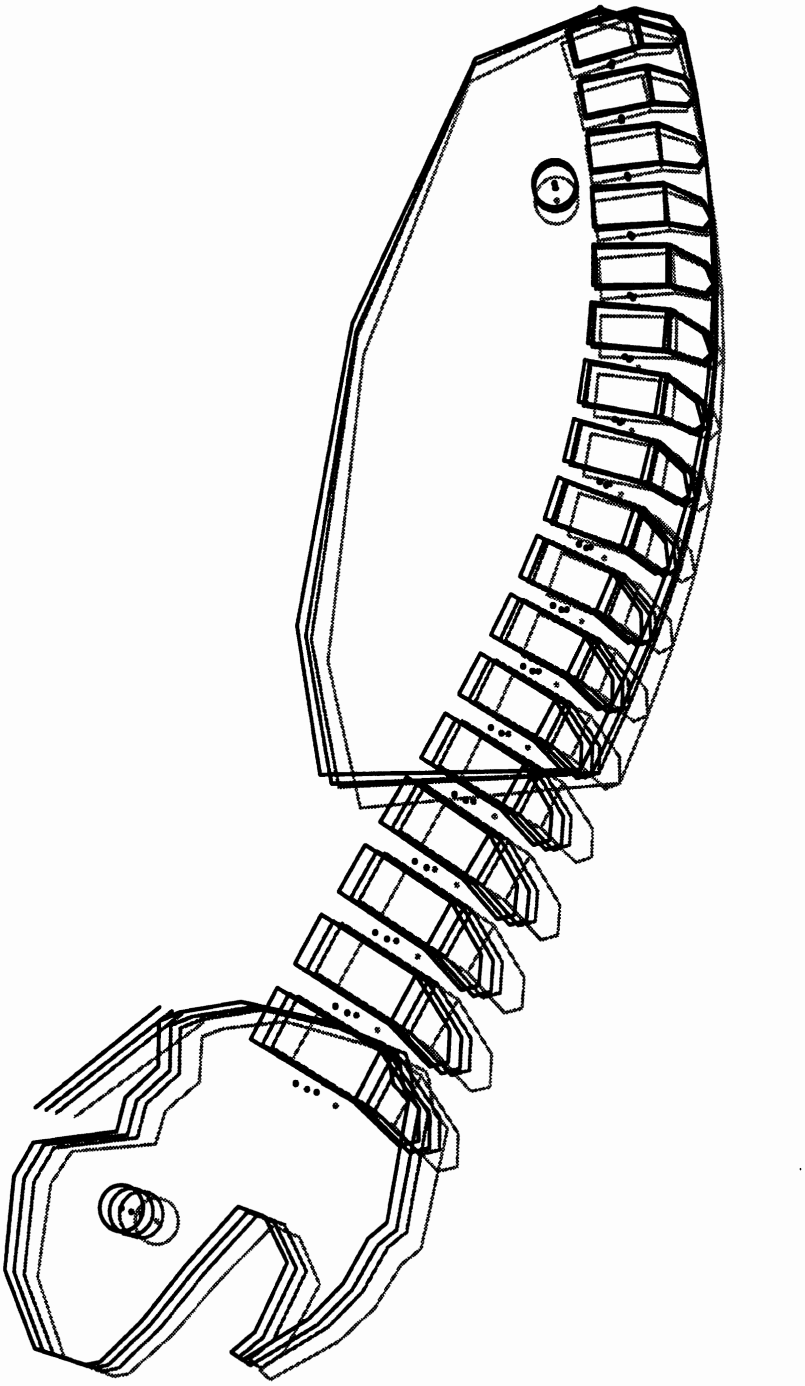

Figure 58. Overlay of kinematic simulations for LS Prominences A, C, D, and E, representing mean postures from Phase-2 testing. Larger lumbar-support prominences are shown with darker lines.

3.9 ADDITIONAL ANALYSES

3.9.1 Comfort in the Long-Duration Driving Simulation

In Phase-1 testing, subjects completed a questionnaire at the beginning and end of each one-hour driving simulation, indicating their discomfort in the upper back, lower back, buttocks, and thighs by making a mark on an open-scale line anchored by No Discomfort and Unbearable Discomfort. Subjects also reported overall discomfort by the same technique. Discomfort responses were scored by measuring the distance in millimeters from the left edge of the line (No Discomfort) to the subject's mark. The scores were standardized within subject by subtracting off the mean of the subject's responses and dividing by the standard deviation. Differential scores were obtained by subtracting the initial standardized score from the final standardized score. ANOVA was performed using Body Region and LS Prominence as fixed effects.

Figure 59 shows the initial standardized scores by LS Prominence and body area for all 48 Phase-1 subjects. Over all body regions, subjects reported significantly more discomfort with LS Prominence C than with the other prominences. Initial discomfort responses were highest in the lower-back region. Figure 60 shows the final standardized scores, indicating relative discomfort after the one-hour driving simulation. Again, discomfort was significantly greater in the lower back than in the other body regions. Discomfort scores for LS Prominence C are significantly higher than for the other prominences in the lower back area and overall. Figure 61 shows the change in standardized discomfort score (final – initial) over the one-hour simulation. The increase in discomfort was significantly larger for the lower back than for other body areas, but post-hoc tests did not show significant differences among LS Prominences.

These discomfort findings should be interpreted cautiously, because the test seat was unrepresentative of production seats in several respects. In particular, the padding on the lumbar support was much thinner than would normally be used. The resulting pressure peaks in the lumbar area may have resulted in discomfort evaluations that are significantly different from those that would be obtained in testing with more realistic seats with comparable lumbar support prominence. The most important aspect of these data is that, although there were differences in initial discomfort evaluations, there were no significant differences among lumbar support prominences in the magnitude of the change in discomfort over the one-hour simulation, suggesting that none of these prominences was sufficiently uncomfortable that concern regarding the effect of discomfort on posture selection is warranted.

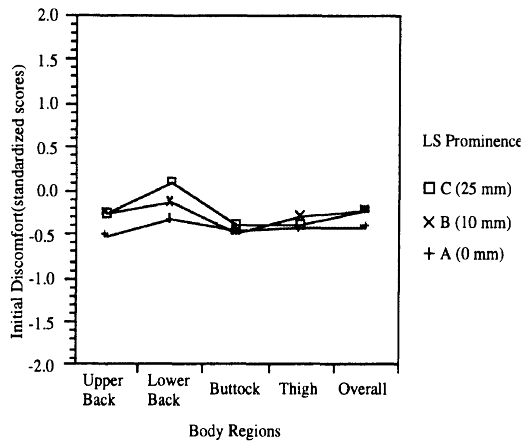

Figure 59. Initial standardized discomfort scores by lumbar-support prominence and body region. Higher scores indicate greater discomfort.

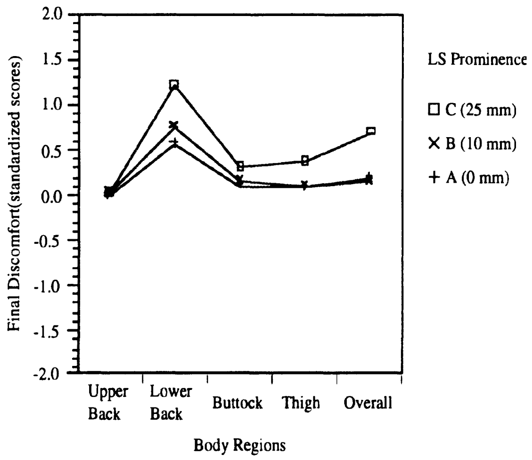

Figure 60. Final (one-hour) standardized discomfort scores by lumbar-support prominence and body region. Higher scores indicate greater discomfort.

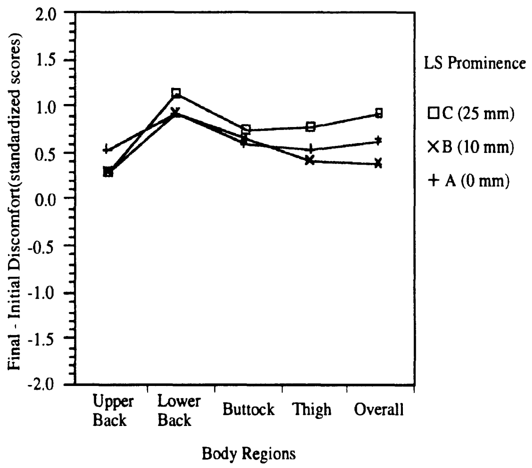

Figure 61. Change in standardized discomfort scores (final–initial) by lumbar-support prominence and body region. Higher scores indicate larger increases in discomfort over the one-hour driving simulation.

3.9.2 Comparison Between HJC and H-Point Locations

Comparisons were made between the calculated human HJC locations and the H-point locations measured with the J826 manikin (see Section 2.4). Because the H-point manikin results were not reliable with LS Prominences D and E, comparisons are made for LS Prominences A and C only. Figures 62 and 63 show the HJC locations relative to the H-point for LS Prominences A and C, respectively, using data from the Fixed Condition for the 32 Phase-2 subjects. The mean HJC location for LS Prominence A is 31 mm forward of and 7.5 mm above the H-point. For LS Prominence C, the mean HJC location is 25 mm forward of and 7 mm above the H-point.

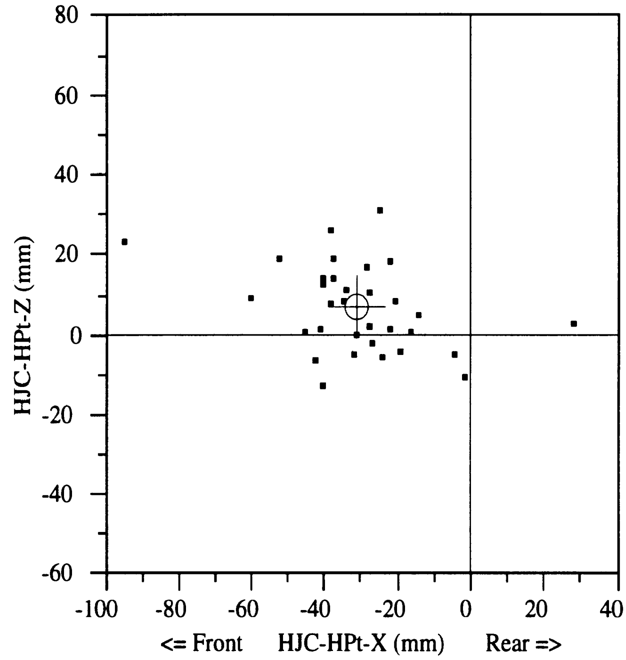

Figure 62. Comparison of calculated HJC location with J826 manikin H-point for LS Prominence A (0 mm).

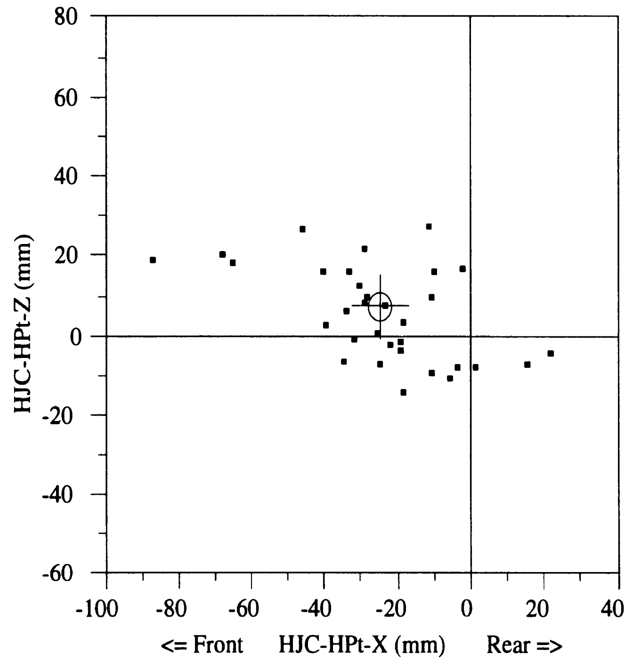

Figure 63. Comparison of calculated HJC location with J826 manikin H-point for LS Prominence C (25 mm) in the Fixed Condition (N=32).

The variance in HJC location relative to H-point is larger horizontally than vertically. Most of this variance can be explained by variations in pelvis angle. Figure 64 shows the horizontal distance between the H-point and HJC for the Fixed Condition, taking data from LS Prominences A and C, plotted against pelvis angle. Pelvis angle explains 72 percent of the variance (r^2), based on a linear regression analysis.

Figures 65 and 66 show the HJC location relative to H-point for the Prescribed Condition. The slope of the regression line is –1.45, suggesting that a reduction in mean pelvis angle of about 19 degrees would bring the HJC and H-point together for these LS Prominences where the mean reduction in pelvis angle in the Prescribed Condition was about 10 degrees, relative to the preferred posture trials. The mean HJC is 11 mm forward of and 8 mm above the H-point for LS Prominence A and 2 mm rearward of and 4 mm above the H-point for LS Prominence C. As noted in Section 3.3.9, the prescribed sitting procedure results in more rearward hip joint center locations, and these locations correspond more closely to the H-point than do preferred HJC locations.

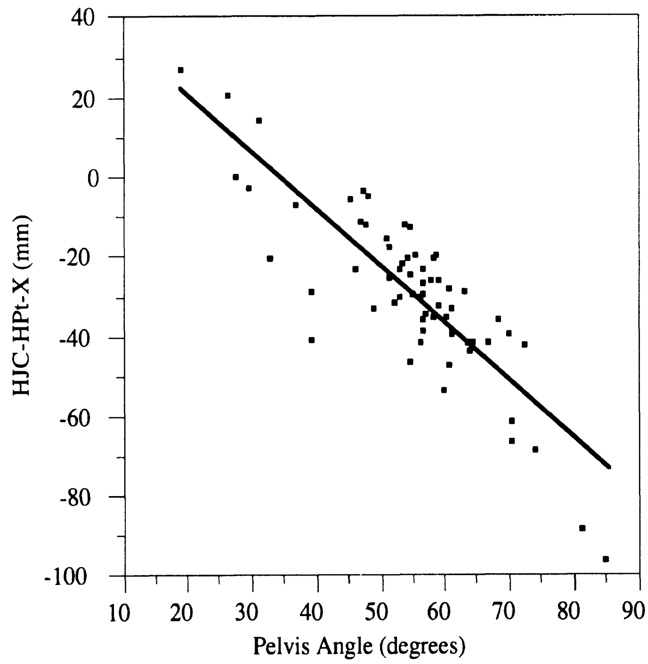

Figure 64. Relationship between horizontal HJC location and pelvis angle for the Fixed Condition with LS Prominences A and C. Least-squares regression line is shown.

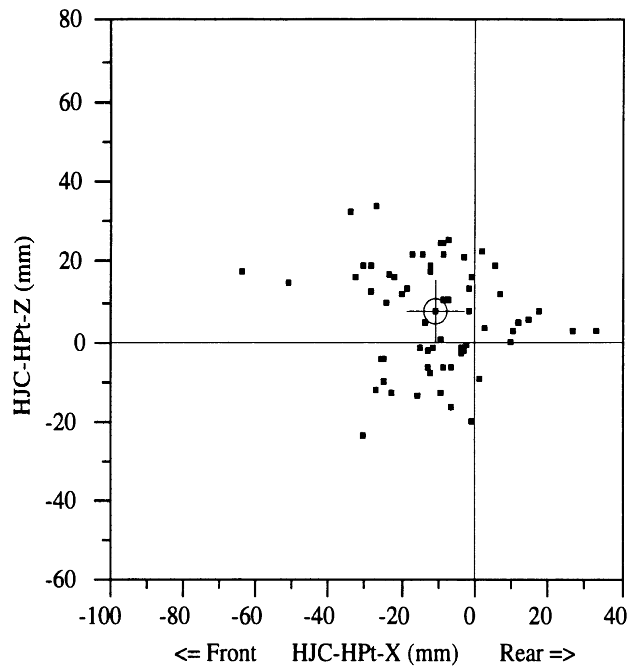

Figure 65. Comparison of calculated HJC location with J826 manikin H-point for LS Prominence A (0 mm) in the prescribed-posture condition.

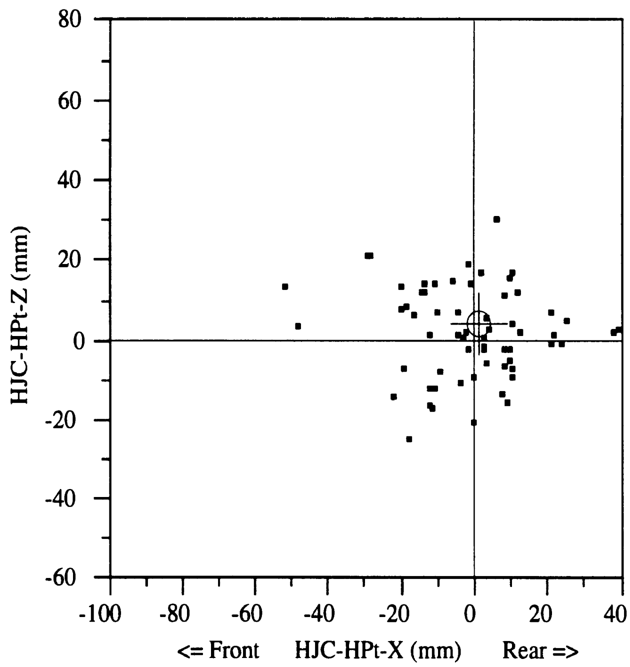

Figure 66. Comparison of calculated HJC location with J826 manikin H-point for LS Prominence C (25 mm) in the prescribed-posture condition.

3.9.3 Post-Test Assessments of Measurement Precision

The precision of the sonic digitizing system was reassessed after testing was complete by examining the distribution of repeated measurements of the same point. During each one-hour Phase-1 test, the seat pivot point location was recorded seven times while the point remained stationary relative to the seating buck. Figure 67 shows the distribution of the 96 sets of seven measurements (all Phase-1 tests with two lumbar support conditions), after subtracting off the mean from each set. Over all Phase-1 tests, the mean square errors for the measurement of the seat pivot point are 0.80, 0.36, and 0.97 mm for the X, Y, and Z axes, respectively. These estimates include the errors inherent in the digitizer, as well as the precision with which the experimenter can locate a fixed point on the seat frame. The errors shown in Figure 67 are approximately normal and are smaller along the Y axis, which is perpendicular to the surface on which the digitized point lies.

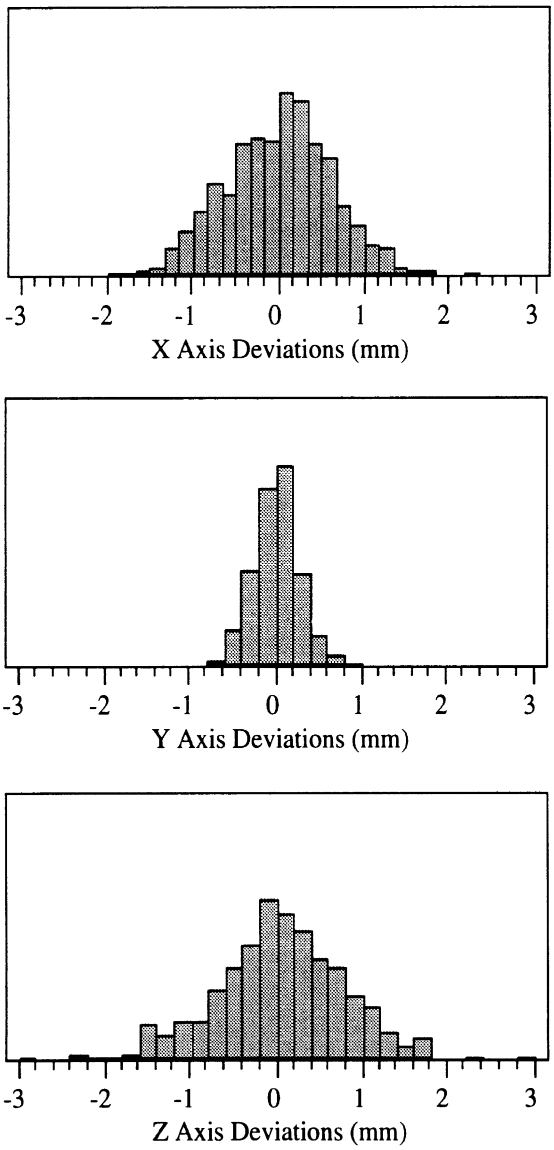

Figure 67. Histograms demonstrating the precision of the sonic digitizing apparatus. Each plot shows deviations from the mean for 96 sets of seven repeated measurements of the same point. Deviations are smaller on the Y axis because the Y axis is perpendicular to the surface on which the digitized point lies.

Figure 67 demonstrates the precision with which a fixed, hard-surface point was digitized during testing. Palpating and digitizing body landmarks is less precise, because of the difficulty in accurately and reliably locating body landmarks and positioning the probe on them. During testing of each Phase-2 subject, the left and right anterior-superior iliac spine (ASIS) landmarks on the subject's pelvis were digitized 16 times, once in each trial. The actual distance between these two landmarks remains constant between measurements, so ideally the measure of the inter-ASIS distance obtained from the digitized data will also be constant within subject.

The distribution of inter-ASIS distance measurements reflects errors in the measurements of the two points. Figure 68 shows the inter-ASIS distances for 512 Phase-2 measurements (32 subjects x 16 measurements), after subtracting off the mean for each subject. The mean square error (square root of the average within-subject variance) for the inter-ASIS distance measurement is 5.6 mm. The average inter-ASIS distance is 217 mm, giving a coefficient of variation of 5.6/217 = 2.6 percent.

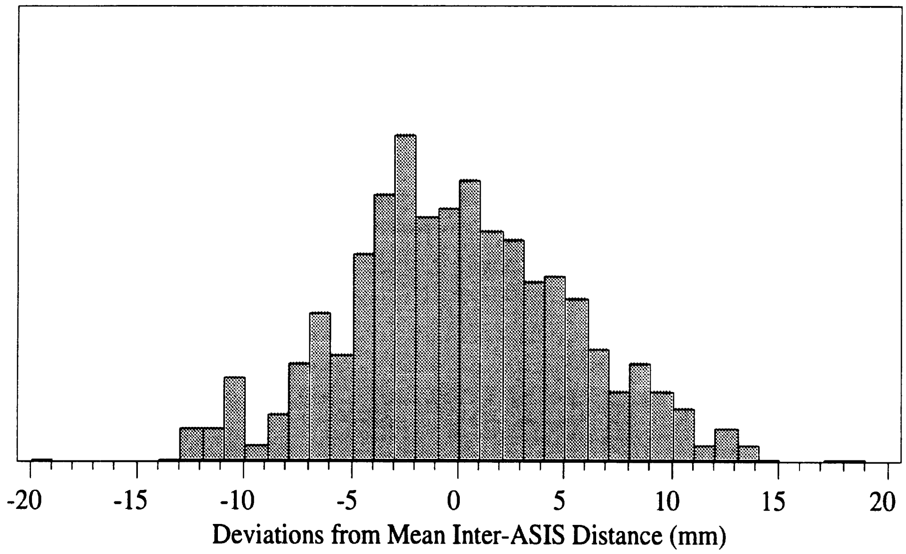

Figure 68. Measurements of inter-ASIS distance using sonic digitizer from Phase-2 data. Values have been standardized by subtracting each subject's mean from the values for that subject. 512 values are plotted (32 subjects x 16 measurements).

If the variance in the measurement of the two ASIS points along the line connecting the two points can be considered to be independent, then the average variance associated with measuring a single point is one-half the variance in the inter-ASIS distance. By this method, the variance along an axis in palpating and digitizing a single point is estimated to be $(1/2)*(5.6)^2 = 15.7\ mm^2$. The standard deviation of the digitization of the ASIS landmark on any axis is thereby estimated to be the square root of 15.7 mm^2, or 4.0 mm. Since the errors are approximately normally distributed, about 95 percent of the digitized body landmark data can be expected to lie within 8 mm of the actual locations. This dimension compares favorably with the geometry of the body landmarks being recorded, *e.g.*, ASIS, spinous processes, and lateral femoral condyle. It should be noted that the ASIS landmark is more difficult to locate accurately than most of the other landmarks used in this study (*e.g.*, the sternum, C7, and head points).

Figure 67 illustrates that the variance can be expected to be smaller on an axis perpendicular to the surface on which the point to be digitized lies, because contacting the surface with the probe tip restricts the range of errors. When substantial soft tissue must be compressed to make a measurement, this restriction may not significantly reduce the variance, but, for most of the body landmarks measured, the underlying bone is close to the surface and little soft tissue is compressed in making the measurement. In this study, most of the primary analysis variables are calculated from the sagittal plane locations of body landmarks. Since the body surfaces on which most of the digitized points lie are perpendicular to the sagittal plane, the observed reduction in variance perpendicular to the surface probably improved the precision of measuring body landmark locations in the sagittal plane beyond the level implied by the 3- to 4-mm standard-deviation estimates calculated above.

Using the estimated distributions of digitization errors, the potential effects of these errors on posture variables can be examined. When the two points used to define a posture angle are located relatively close together, the effect of digitization errors on the calculated angle is larger than if the points are farther apart. The two points used to define thorax angle were measured to be 131 mm apart, on average, for the 32 Phase-2 subjects. The estimated standard deviation for palpation and digitization errors at the TOP STERNUM and C7 landmarks is 3.2 mm, using the calculation technique previously used with ASIS data. If the errors are assumed to be independent and uniform on all axes, then the variance in the angular variable due to measurement error is

$$\sigma_a^2 \text{ (radians)} = \frac{2\,\sigma_e^2}{d^2}$$

where σ_e is the standard deviation of error distribution (mm) and d is the nominal distance between the points (mm). For thorax angle, measurement error is estimated to produce a standard deviation of about 2 degrees. For repeated measurements of a sitter's thorax angle, about 95 percent of the calculated angles would be expected to lie within 4 degrees of the true value.

Accurate and precise measurement of the pubic symphysis landmark is particularly important because the data were used to calculate pelvis angle and locate the hip joint center. In this case, however, the subject palpated the landmark and positioned the probe tip. Because of the difficulty in locating this landmark, errors were expected to be greater than for the more accessible landmarks located by the experimenter.

Following the same analysis procedure as described above for the ASIS measurements, the distances between the digitized pubic symphysis point and the left and right ASIS landmarks were calculated. The mean PS-to-ASIS distance was 144 mm, with an average within-subject standard deviation of 7.4 mm (variance = $(7.4)^2 = 54.9$). Using the 15.7 mm^2 variance estimate calculated previously for the ASIS measurements, the standard deviation associated with measurement of the pubic symphysis landmark was estimated to be

$$\sqrt{(54.9 - 15.7)} = 6.3 \text{ mm}$$

This is considerably more variance than for the experimenter-measured points, but still a reasonable magnitude. It is particularly important to note that the pubic symphysis landmark is difficult to locate precisely. The upper margin of the symphysis is rounded and covered with a layer of soft tissue that varies substantially in thickness among subjects. It is reasonable to assume, however, that the digitization errors perpendicular to the surface of the symphysis will be smaller than the errors in other directions (*e.g.*, laterally), because of the surface-resistance effect noted in Figure 67.

Conservatively, however, the 6.3-mm standard deviation estimate of error for the pubic symphysis may be used to approximate the error in pelvis angle that would result. Assuming equal, independent variance on each axis, the pelvis angle variance due to measurement error is estimated to be

$$\sigma_{pa}^2 = \frac{\sigma_{e1}^2 + \sigma_{e2}^2}{d^2} = \frac{(6.3)^2 + (4)^2}{(100)^2} = 20 \text{ degrees}^2$$

The estimated standard deviation of pelvis angle due to measurement error is 4.5 degrees. Since the errors are approximately normally distributed, 95 percent of the pelvis angle measurements would be expected to lie within 9 degrees of the true value.

Another way to assess the repeatability of pelvis angle measurements is to examine the data from Phase-1 (long-duration) testing. A linear model was fit to the pelvis angle data for LS Prominences A and C (48 subjects), using time as a continuous covariate, LS Prominence as a fixed effect, and Subject as a random effect. All effects were significant with $p<0.001$. The residuals from the resulting least-squares fit represent the subject's pelvis angle measurements with the linear effects of LS Prominence, Time, and subject mean response removed. Standard deviations from the 14 within-subject residuals were then calculated. The standard deviations for the 48 subjects were approximately normally distributed, with a maximum of 7 degrees, a minimum of 1.4 degrees, and mean of 3.1 degrees. This estimate is slightly less than the more conservative estimate made above, suggesting that about 95 percent of the measured pelvis angles lie within 6.2 degrees of the true value. The actual precision is probably even better, since this estimate includes other sources of variance, such as unsystematic subject movements between measurements.

4.0 DISCUSSION

4.1 METHODOLOGICAL ISSUES

4.1.1 Measurement

One of the hypotheses that influenced the design of this study was that relatively large changes in shape of the seatback would have only a small effect, or no effect, on the postures of the sitters. This hypothesis was prompted by data from a number of studies conducted at UMTRI (*e.g.*, Reed *et al.* 1991; Manary *et al.* 1994), and also from anecdotal observations that lordotic driving postures are rare. From an experimental perspective, a hypothesis of no effect is difficult to support with data, because great care must be taken to demonstrate that the statistical power of the experiment was sufficient to detect the smallest effect that would be of practical interest.

Because of these potential pitfalls, considerable emphasis was placed on the development of the test apparatus, software, and procedures to ensure that the data would be as free as possible from experimental errors. In addition, a relatively large number of subjects were tested, with repetitions of key trials, to increase the statistical power.

The analyses in Section 3 of this report indicate that these efforts were highly successful. Post-test assessment of palpation and digitization errors, using conservative assumptions, indicate that the precision of the digitized measurements compare favorably with the physical dimensions of the landmarks targeted. Measurement errors were approximately normally distributed with an estimated standard deviation between 3 and 4 mm. Errors of that magnitude are estimated to produce distributions of angular variables with standard deviations of around 2 to 3 degrees. This measurement precision contributed to the statistical power that allowed significant results with small magnitudes to be observed.

4.1.2 Constraints of Laboratory Testing

One important qualification of the findings from this study is that the postures were observed in a laboratory mockup of a vehicle under static, simulated-driving conditions. It is possible that drivers would have selected different postures in a similarly configured vehicle on the road. However, other research at UMTRI has indicated that driver positions in properly configured seating bucks are similar to positions chosen while driving actual vehicles. One vehicle component that has been demonstrated to have a small effect on posture, but that was omitted from the vehicle mockup used in this study, is the header or headliner. A low header may cause tall subjects to select more reclined seatback angles than they would otherwise. Because only a small effect of header on posture and positioning has been demonstrated, the lack of a header in this study was felt to be justified by the resulting increased ease in digitizing body landmarks.

One surprising finding from this study is that very little posture change occurred during the one-hour driving simulation. Although the driving behavior during the simulations was subjectively "normal," the lack of vibration and movement of the seating buck, compared with an actual vehicle, may have reduced the amount of posture change. Additional study of posture in the on-road environment should be conducted to determine if more posture change occurs on the road than in the laboratory. It is difficult, however, to make accurate measurements of the type made in this study in an actual vehicle, even one that is stationary.

4.2 DISCUSSION OF FINDINGS

This study led to primary findings in three areas:

1. quantitative descriptions of driver postures and back contours in a high-seat-height passenger vehicle package,

2. quantitative assessments of the changes in postures and back contours that result from an increase in lumbar-support prominence, and

3. subject preferences for lumbar-support locations.

4.2.1 Driver Posture

The driving postures observed in this study are similar to those that have been observed in other studies of driver posture and positioning (*e.g.*, Schneider *et al.* 1985, Reed *et al.* 1991, Manary *et al.* 1994). One of the most important observations is that there are considerable differences among subjects on most of the posture variables examined. In particular, pelvis angles ranged over about 70 degrees. Although some of this variance may be due to differences in the subjects' pubic-symphysis palpation techniques, analysis of the errors that might be attributable to that source suggests that most of the observed variation in pelvis angle is not due to measurement errors. Visual examination of the subject driving postures through video tapes made of Phase-1 testing also confirm that subject pelvis postures differed greatly. It is particularly important to note that the differences in posture among subjects are generally much larger than the differences attributable to changes in the seatback curvature, even with the relative large changes in curvature introduced in this study.

The normalized data values presented in Section 3.6, obtained by subtracting the standing variable values from each subject's seated data, demonstrate that the variance in standing pelvis angles is about one-third of the variance in seated pelvis angles, while the variance for measures of thorax orientation is about the same sitting and standing. More of the variance in the amount of spine flexion in sitting can be attributed to differences in seated pelvis angles than to differences in thorax angle. The correlation between pelvis angles in preferred- and prescribed-posture conditions in Phase-2 data is 0.86, indicating that the differences among subjects are consistent even when each subject was instructed to sit using the same procedure.

On average, subjects sat with only about 1.5 degrees of neck flexion relative to the standing posture. The postures of the upper ribcage and head were, in general, similar to the standing postures, with only 8.3 degrees of mean rearward thorax recline and 6.5 degrees of rearward head rotation. Femur orientation changed an average of about 102 degrees from standing to sitting, while pelvis angle changed about 53 degrees, giving a net hip flexion of about 47 degrees. The average spine flexion from standing to sitting was about 45 degrees, indicating that subjects sat with about as much hip flexion as spine flexion, relative to the standing posture.

Another interesting finding was that torso angles did not differ among subject groups (*i.e.*, by gender and stature), while seatback angles did. This finding indicates that larger subjects select larger seatback angles while maintaining the same average torso angle as smaller subjects. This observation has important implications for modeling driver posture, because it suggests that driver stature is not an important determinant of torso angle, although driver-selected seatback angles are affected.

4.2.2 Effects of Changes in Lumbar-Support Prominence on Posture

In general, changes in lumbar-support prominence produced statistically significant but small changes in subject posture. As noted above, these within-subject changes were generally much smaller than the differences among subjects. Increasing the lumbar-support prominence by 45 mm from an approximately flat contour reduced spine flexion on average by about 6 degrees, by opposite-direction rotations of the thorax and pelvis of about 3 degrees. This average spine extension is only 6.5/45 or about 14 percent of the average spine flexion associated with sitting. There is considerable variability in subject's postural responses to the increase in lumbar-support prominence, from a 2- or 3-degree *increase* in flexion to a 17-degree decrease. However, no subjects showed a reduction in spine flexion with a 45-mm increase in lumbar-support prominence result greater than 50 percent of the net spine flexion associated with moving from standing to sitting with a flat lumbar support (see Figure 47).

The kinematic model illustrations of the mean posture variable values showed that the most visually apparent response to an increase in lumbar-support prominence was a forward movement of the subject's hips on the seat. The increase in lordosis as measured by the change in the back contour measurement is about 9 mm. However, the kinematic model simulations suggest that the average change in spine profile is probably less, approximately 3 or 4 mm. The difference is probably due to increased compression of soft tissue in the lumbar area with the more prominent lumbar support, since the back contour measurement may not directly measure spine profile (see Section 3.7).

The increase in lumbar-support prominence caused subjects to sit with more reclined ribcages (3 degrees on average), and also slightly larger torso angles (1.6 degrees on average). The mean change in torso angle is small compared to the standard deviation of torso angles among subjects across LS Prominences of 5.6 degrees.

The prescribed sitting procedure was intended to determine if postures with substantially more lordosis than the preferred postures were possible with these test conditions. A surprising finding was that subjects sat with an average of 10 degrees less spine flexion in the Prescribed Condition for all four lumbar-support prominences. The pretest hypothesis was that the prescribed postures would be about the same as preferred postures when the lumbar support was flat, but that they would be increasingly different as the lumbar-support prominence was increased.

The 10-degree average reduction in spine flexion with the prescribed sitting procedure is considerably larger than the 6.5 degree reduction in flexion associated with prominent lumbar supports in preferred postures, but it still represents only 22 percent of the mean spine flexion relative to standing that sitters produced with the flat lumbar support in preferred postures. Few sitters were able to reduce their seated spine flexion by more than 50 percent, even when provided with a prominent lumbar support and using a sitting procedure intended to minimize spine flexion. The conclusion from these observations is that postures with lordosis of even 50 percent of the standing lordosis are not possible for most sitters in this automotive environment.

One reason for this inability to produce spine extension in sitting is probably the restriction on hip-joint flexion imposed by the action of the two-joint posterior muscles of the thigh. These "hamstring" muscles are primarily the long head of biceps femoris, semimembranosus, and semitendinosis. Each muscle is attached to the ischial tuberosity of the pelvis and also to either the tibia (semimembranosus and semitendinosus) or to the fibula (biceps femoris), thus spanning both the hip joint and the knee joint. Because of passive tension in these muscles during automotive sitting, hip flexion can be influenced by knee flexion. When the knee is extended (*i.e.*, the leg is straighter), the hip flexion range-of-motion is reduced.

Many ergonomic researchers have proposed that knee extension increases rearward pelvic tilt in sitting through the action of these hamstring muscles (*e.g.,* Stokes and Abery 1980, Boughner 1991). Data on the relationship between knee extension and hip flexion restriction are sparse, however. Recently, the Large Male, Small Female and 6-Year-Old Dummies Task Group of the SAE Human Biomechanics and Simulation Standards Committee (1995) published data linking passive hip flexion to knee angle for 52 male and female subjects. With the subjects lying supine, the experimenter maximally flexed the subject's hip with the knee flexed by pressing the thigh toward the subject's chest. The subject's knee was then extended until resistance was felt, while holding the thigh in place. The knee angles measured in this posture represent the maximum knee angle that can be obtained without restricting hip flexion. Male and female subjects had about the same maximum hip flexion of about 122 degrees. However, the maximum knee extension possible with the hip maximally flexed was smaller for males than for females. Mean maximum knee extension angles at maximal hip flexion were 118 degrees and 128 degrees for males and females, respectively. The average within-gender standard deviation was 16.2 degrees. Knee angles and hip angles were distributed approximately normally.

In the present study, mean seated knee angles averaged about 114 degrees in preferred postures. Knee angles were about 4 degrees larger in prescribed-posture conditions. These means are close to the average maximum knee extension that can be tolerated without restricting hip flexion. The average hip flexion in preferred seated postures was about 47 degrees, considerably less than the maximum of 122 recorded in the SAE Committee data. In prescribed postures, the mean hip flexion was larger by about 10 degrees. An important question is whether the 57 degrees of hip flexion and a 118 degree knee angle, or the deviations from those mean values observed in these data in the prescribed postures, represent a situation in which the pelvis angle is constrained by the action of the hamstring muscles.

Boughner (1991) investigated the action of the hamstring muscles on the pelvis with four male subjects during a dynamic exercise. Starting from an erect standing posture, the subject flexed maximally from the hips while keeping the legs straight. The subject then slowly bent his knees while maintaining maximal hip flexion. Upon reaching maximum knee flexion, the subject reversed direction, slowly extending the knees while maintaining maximal hip flexion. Boughner presents hip angle versus knee angle plots for three trials with each subject. The subject's maximum hip flexion with a 120-degree knee angle was determined from these plots. Subject means were 52, 54, 64, and 75 degrees, with an overall mean of 61 degrees. If the Boughner data are representative of the hamstring extensibility of the sample population in the current study, then the prescribed-condition posture, which included an average of 57 degrees of hip flexion and a 118-degree knee angle, probably represents hamstring-limited hip flexion.

Comparison of data from the current study with the SAE Committee data and the data from Boughner suggest that pelvis angles were restricted by hamstring tension. The 10-degree difference between preferred and prescribed postures probably represents the average difference between comfortable and maximal extension of the hamstring muscles.

Hip flexion range of motion was measured in this study (see Appendix A), but no significant relationships between hip flexibility and pelvis angle were observed. Attempts were made to construct linear models relating knee angle, hip flexibility, and the interaction of the two to pelvis angle, but these models did not explain significant fractions of the variance in pelvis angle in either preferred- or prescribed-posture conditions. So, while the trends in the hip- and knee-flexion data, and a biomechanical consideration of the seated posture suggest that the postures are limited by hamstring extensibility, the hip flexibility measurements on the subjects in this study did not show significant relationships with pelvis angle. Other researchers (*e.g.*, Stokes and Abery 1980) have demonstrated that hamstring-limited hip flexibility affects seated pelvis angle, but have not shown statistically significant relationships. The lack of clear functional relationships between hip flexibility and seating behavior is probably due to an inexact correspondence between the hip flexibility measurements and the seated situation (*i.e.*, straight legs in the hip-flexibility test versus some knee flexion in sitting), and differences among subjects in the amount of hamstring tension that they are willing to tolerate.

If seated postures in this study do represent hamstring-limited postures, then substantially lordotic postures will be even less likely with lower seat heights. H30 for the seating buck in the current study is 334 mm, considerably higher than a typical passenger car H30 of 270 mm. Schneider *et al.* (1994a, unpublished) measured knee angles for 48 subjects from a range of anthropometric groups with three different seat heights. Mean knee angles in preferred postures were 120, 125, and 129 degrees for seat heights (H30) of 360, 270, and 180 mm, respectively, using a range of seatpan angles at each seat height. These data demonstrate that knee angles can be expected to be larger with lower seat heights, which should have the effect of restricting hip flexion to a larger extent than was observed in the current study. Such restriction will result in greater rearward pelvis rotation, and greater spine flexion, unless the additional rearward pelvis rotation is accompanied by equivalent thorax recline. Since thorax recline is limited by visibility and reach requirements, as well as comfortable neck flexion, lordotic spine postures are probably less likely for seat heights lower than the one used in the current study.

4.2.3 Subject Preferences for Lumbar Support Location

In Phase-1 testing, and in the Adjustable Condition of Phase-2 testing, subjects adjusted the vertical position of the lumbar support to the most comfortable position. The data on their preferred lumbar support positions are presented in Section 3.3.13. On average, subjects preferred the apex of the lumbar support 152 mm above the mean hip joint center location for lumbar-support prominences of 25, 35, and 45 mm. The vertical position of the lumbar support is measured along the H-point manikin-referenced backline. The value obtained by this calculation is approximately the same as that obtained by measuring along the subject's torso line. As noted in Section 3.9.2, the subjects' mean hip joint center locations were, on average, forward of and above the manikin measured H-point. The vertical offset was about 7 mm for the 25-mm lumbar-support prominence, making the average preferred lumbar support position about 159 mm above the H-point of the seat along the manikin backline. There was no significant correlation between the location of the lumbar lordosis and the placement of the lumbar support ($r = 0.16$). The lack of relationship between these two measures is probably a result of the largely flat spine postures that were observed. Because the lumbar lordosis values were small, variability in the measurement of the location of the lumbar lordosis was large.

There was considerable variance in preferred position of the lumbar support apex. The average standard deviation for each lumbar-support prominence was 23 mm. A Wilks-Shapiro test of normality failed to reject the null hypothesis that the distribution is normal. A linear regression analysis did not show a significant relationship between stature and preferred lumbar support position. Since stature, the stratification variable used in subject selection, did not show a relationship with preferred lumbar support height, 23 mm is probably a good estimate of the population standard deviation in preferred positions. Using a normality assumption, the range of lumbar support locations required to satisfy a desired percentage of the population can be estimated. These data suggest that 95 percent of the driving population's preferred lumbar support apex locations lie between 113 and 205 mm above the H-point along the manikin backline. Using lumbar spine location estimates from Robbins (1986) presented in Section 3.7, these data suggest that drivers prefer the lumbar-support prominence to be located over a wide range of the lumbar spine. Irrespective of stature, some subjects preferred the lumbar support in the upper part of the spine, at the L2 level, while others placed the support considerably lower, near the L4-L5 level.

4.3 IMPLICATIONS FOR SEAT DESIGN

The geometric definition of lumbar support presented in Section 1.1, which has been dominant in the ergonomic literature, accurately represents the interaction between the sitter and the seat only if the sitter conforms to desired depressed seatback contour. Robbins (1986), Maertens (1993), and others have suggested that the appropriate seatback contour be generated by starting with the flat depressed seatback contour produced by the J826 H-point manikin and adding a convex curvature in the lumbar spine region. The findings of this study suggest that the effect of such a change in the seat will be to shift the average hip joint center location forward on the seat, thus inducing larger torso angles without changes in the physical seatback angle, and to reduce slightly the average spine flexion of the sitters. Neither the resulting average back contour or depressed seat surface contour is likely to look like the intended contour because of these postural reactions to the change in seat geometry.

The physiological studies of Andersson and others have demonstrated that lordotic spine postures result in reductions in stresses in the spine, as represented by lumbar intradiscal pressure. However, the findings from the current study show that sitters do not voluntarily select substantially lordotic lumbar spine postures in an auto seat even when provided with a prominent, longitudinally convex lumbar support. Adding a lumbar-support prominence equal to the largest recommendations in the ergonomic literature, and larger than the largest standing lordosis measured among these subjects, produced an average reduction in net spine flexion relative to the standing posture of only about 13 percent. This large difference between the recommended posture and preferred postures suggests an important question:

> In light of the observed postural reactions of sitters to prominent, longitudinally convex lumbar supports, how should seats be designed to reduce stress on the lumbar spine to the extent possible, with the goal of decreasing discomfort and the potential for pathology?

The average spine flexion relative to the standing posture associated with the most prominent lumbar support and the prescribed sitting procedure was about 29 degrees, while the corresponding flexion for the flat lumbar support condition in preferred postures was about 45 degrees. About 20 of the 29 degrees of flexion in the prescribed postures resulted from rearward pelvis rotation relative to standing. Subjects were apparently not able, on average, to sit with their pelvis in the standing orientation, even using a sitting procedure intended to produce the most upright pelvis angles possible. The discussion presented above suggests that the sitter's resting hamstring length restricts pelvis angles sufficiently to prevent postures approaching the standing lordosis for most sitters.

The back contours presented in Section 3.7, along with the kinematic-model illustrations of the mean posture results, indicate that preferred back contours in an auto seat are fairly flat in the lumbar area for most sitters. With lumbar-support prominences of 25 mm or greater, negative lordosis (kyphosis) was rare, suggesting that few sitters would prefer concave depressed seat contours. These contour results are consistent with the findings of the posture analyses. Consequently, seatback designs that result in relatively flat or slightly convex depressed seat contours in the area of the lumbar spine are likely to match well with drivers' preferred postures.

It is important to emphasize that the *depressed* seat contour, that is, the contour when the subject is sitting in the seat in a comfortable posture, should be flat or slightly convex to mate well with the subject's back contour. The undepressed contour necessary to produce the desired depressed contour will likely be quite different. For typical driving postures, the pressure against the seatback is greatest in the area of the lumbar spine, and drops off rapidly further up the seatback. To maintain a flat profile in this area, a constant-density foam must be considerably thicker in the lumbar area than higher on the seatback. Undepressed profiles that appear similar to the standing spine curvature may provide the appropriate distribution of resistance to deformation to produce a nearly flat contour when loaded by a sitter, but experimentation is necessary to verify that a particular seatback design produces the desired depressed contours.

As noted in Section 3.7, large, heavy subjects will tend to deform a padded seatback to a larger extent than lighter subjects, particularly in the lower back area. Fortuitously, however, larger (generally male) subjects also prefer flatter back contours, and are less likely to sit with more than 10 mm of lordosis. Consequently, the fact that lighter subjects will not deflect a padded seatback as much, and will therefore experience a more convex back contour than heavier subjects, may not substantially reduce the correspondence between the depressed seat contour and the sitter's preferred back contour. The data from this study suggest that the difference between large and small subjects in the prominence of the depressed seatback contour should not exceed about 20 mm, particularly because small, light subjects who prefer to sit with a flat spine profile may find the depressed seat contour convexity too prominent.

In view of the body of research demonstrating the physiological advantages of lordotic postures, a seat should be designed to *allow* those sitters who are capable of sitting with such postures to choose them if they so desire, but without precluding appropriate back support for the majority of sitters who prefer to sit with a flat back profile. If a seat is designed so that the depressed back contour presents a convexity intended to mate with a large lordosis, as many have been, then the sitters who sit with largely flat back contours, including the majority of those in this study, will not receive appropriate support from the seatback.

In considering what support is appropriate, it is necessary to return to the discussion of the purposes of lumbar support begun in the Introduction. Åkerblom, and later Keegan, suggested that the purpose of the lumbar support is to prevent excessive rearward rotation of the pelvis, thereby restricting lumbar spine flexion. When information about the spine loading associated with flexed-spine postures became available (*e.g.*, Andersson 1974a), recommendations for convex lumbar supports were justified by the observation that lumbar intervertebral disc pressures were lower with lordotic spine postures.

The findings presented in this report suggest that, for auto seating, the prevailing lumbar support recommendations should be modified. Returning to Åkerblom's original recommendations, the purpose of the lumbar support should be to restrict rearward pelvis rotation to the minimum required for comfort, thereby restricting spine flexion to the minimum that is necessary. Controlling pelvis angle requires firm support as low as the L5 spine level for all sitters (about 15 to 20 mm below the most superior margin of the iliac crest). If the posterior aspect of the subject's pelvis is not supported by the seatback, then the pelvis is constrained to rotate rearward only by the action of the muscles and ligaments that cross the sacroiliac and L5/S1 joints. These muscles and ligaments, and the surrounding tissues, are implicated in the majority of low-back pain. When sitting without pelvis support, these muscles and ligaments are stressed considerably more than they would be with pelvis support. In the absence of voluntary muscle activity, these joints will flex to the maximum allowed by the tension in the paraspinal tissues. Although Andersson *et al.* (1979) have demonstrated that the vertical position of lumbar support does not have a significant effect on the resulting spine curvature, the distribution of support can have an important effect on the internal distribution of stress.

Previous attempts to induce lordosis by the provision of firm, prominent, longitudinally convex lumbar supports in auto seats may have inadvertently increased the stress on sitters' lumbar spines by failing to mate well with their preferred postures. If a driver sits with a flat spine profile against a firm, longitudinally convex lumbar support located at the L3 level, the back of the pelvis may receive no support at all (Reed *et al.* 1991). In this case, the pelvis is free to rotate maximally against the muscles and ligaments that act across L5/S1 and the sacroiliac joint.

An appropriate lumbar support design will minimize or eliminate the situation of an unsupported pelvis. At the same time, the seatback must not interfere with the sitter's buttocks in such a way that the sitter is prevented from sitting with the minimal desired rearward pelvis rotation. These potentially conflicting requirements are addressed in the seatback design schematic depicted in Figure 69. The flat depressed seatback contour is brought down to about 115 mm above the H-point before curving rearward away from the subject. About 90 percent of the preferred lumbar support positions recorded in this study lie above this line. Pressure against the sitter's back should remain relatively high down to this line. The seatback should then curve sharply away from the sitter to provide buttock clearance. Although no data are available on the population distribution of buttock shapes in sitting, at least a 50-mm clearance space (fore-aft) below the apex of the curve should be provided. The vertical height of the clearance space should be at least 100 mm, following the 114-mm recommendation of Keegan (1964). This clearance allows a person who is able to sit with considerable lumbar lordosis to obtain appropriate support for such a posture by sliding his or her pelvis rearward on the seat. The back contours in prescribed postures demonstrate that the center of the back curvature in maximally lordotic postures is between the L3 and L5 level, so sitters who prefer lordotic postures should be accommodated by this design. This is essentially the lumbar support strategy recommended by Åkerblom for office chairs. Most contemporary auto seat designs do not have sufficient clearance space below the lumbar support, and, as a consequence, sitters with large buttocks cannot sit sufficiently far enough to the rear on the seat to benefit from the lumbar support.

The recommended lumbar support design represents a clear departure from contour recommendations that rely on the geometric definition of lumbar support presented in Section 1.1. As noted throughout this report, the geometric definition relies on a correspondence between the sitter's posture and the intended depressed contour of the seat. This study did not find such a correspondence. Since sitter's postures remained approximately the same as the seatback contour was changed considerably, changes in seatback geometry are a poor measure of the changes in lumbar support that the sitter experiences.

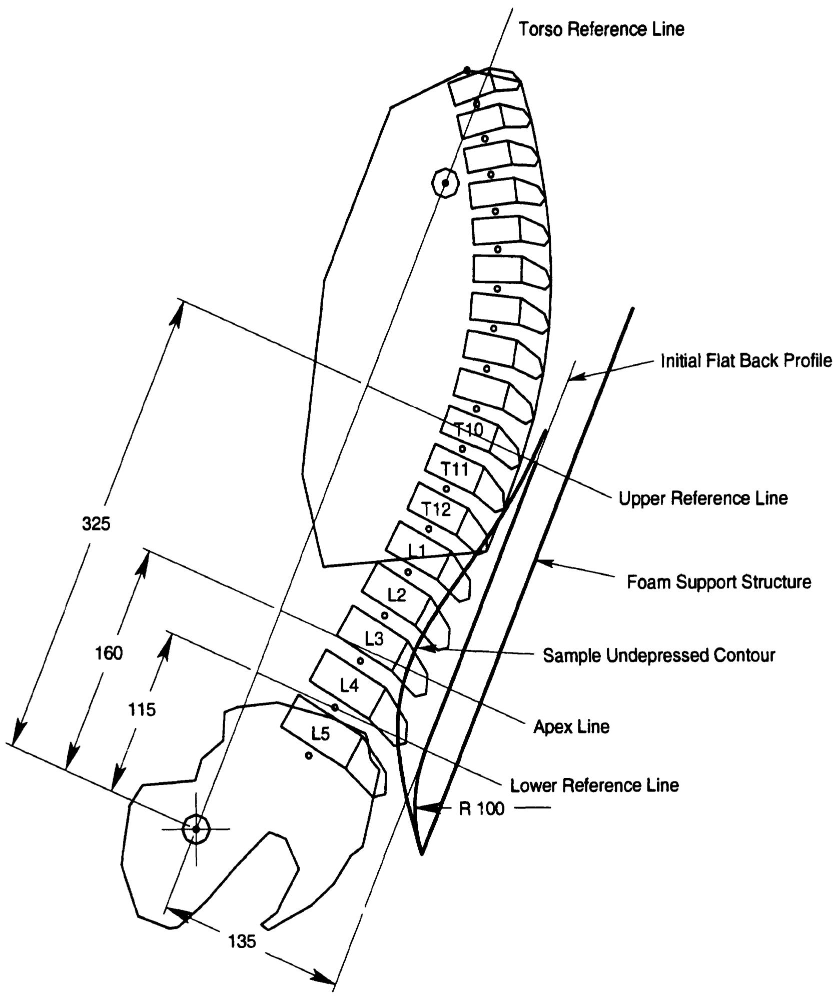

Figure 69. Lumbar support design recommendations.

Instead of measuring changes in seatback geometry relative to a static representation of a sitter, the distribution of support forces relative to sitters' bodies should be measured, along with the sitters' back contours. A measurement of the pressure distribution between the sitter and backrest, referenced to body landmarks and the H-point of the seat, will demonstrate whether support forces are appropriately distributed when the sitter is in a comfortable posture. The "amount" or "level" of lumbar support provided by a particular seat should be expressed in relation to the ratio of the pressure in the lower-back area to the overall pressure on the seatback. A seat with a high level of lumbar support will have a larger proportion of the seatback support force directed at the lower-back area than a seat with less lumbar support. The level of support that is appropriate, as measured by this metric, should be determined by subjective comfort evaluations. As noted above, a primary consideration is that the support forces be directed sufficiently low on the back. Although a lack of support at the bottom of the spine may not result in unfavorable short-term comfort evaluations, the long-term discomfort is likely to be greater because of higher stress levels. The subject's posture should be assessed when sitting in a seat with a candidate backrest design, but the result should not be expected to vary much among reasonably comfortable designs. On average, a flat spine profile should be observed when a sitter is presented with a good lumbar support design, based on the findings of the current study.

Adjustable lumbar supports are frequently recommended (*e.g.*, Reynolds 1993). The findings from this study provide some guidelines for the vertical range of adjustability that might be desirable. If the subject pool is taken as representative of the population, and the distribution of preferred lumbar support apex positions is assumed to be normal, then ± 2 standard deviations from the mean location should accommodate the preferences of about 95 percent of the population. This would require a vertically adjustable lumbar support with about 23*4 = 92 mm of vertical travel centered about 159 mm above the H-point. Because the support in this study was very thinly padded, subjects may have been more particular about the position of the support than they would have if the support had been better padded and more representative of a production seat. With a more padded support, a smaller range of travel centered at the same point would likely suffice.

Prominence adjustment is a more common feature of adjustable lumbar supports in auto seats than vertical adjustability. This adjustment is usually accomplished by inflating an air bladder lying in or under the foam padding in the low-back area or by adjusting the contour of the underlying support structure, as with the Schukra support. These findings suggest that only a small change in the shape of the depressed seat contour, perhaps 10 to 15 mm, is necessary to accommodate most preferred driving postures. One key is that these results apply to the depressed contour. If a seat is thickly padded in the lower-back area, then large sitters will depress the seat surface considerably more than small sitters and experience a flatter or even kyphotic seat contour in the area of the lumbar spine. As noted above, thin padding over the lumbar support gives the seat designer more control over the depressed seat contour, because the differences in contours between large and small people are smaller than with thicker foam. However, if thick foam is required for styling or other reasons (*i.e.,* foam that shows a range of depression greater than about 20 mm between the largest and smallest sitters), an adjustable-prominence support located beneath the foam will aid heavier sitters in restoring the depressed seatback contour to the approximately flat shape preferred by most sitters. Additionally, the few sitters who prefer to sit with substantial lordosis will be able to obtain appropriate support in that posture. However, as noted above, the recommended seatback design is intended to allow a sitter to adjust the effective prominence of the lumbar support by shifting his or her pelvis rearward on the seat while tilting it more upright. When this freedom of movement is provided, the need for an adjustable-prominence lumbar support may be reduced or eliminated. An accompanying report (Reed *et al.* 1995) contains a more detailed presentation of seat design recommendations based on the findings of this study.

4.4 RECOMMENDATIONS FOR FURTHER RESEARCH

The most important limitation of these findings is that they were obtained with a single vehicle seating package. Although substantially lordotic postures are probably less likely with lower seat heights, because of the restriction on hip flexion with knee extension, verification of these results in other vehicle packages and seatpan angles is desirable.

Further research regarding the factors that result in the subjects' preference for flat-spine postures is also warranted. Some vehicle package variables under the control of auto designers, such as steering wheel to pedal horizontal distance, may influence the spine posture of sitters. Similarly, the design of the upper part of the seatback should be investigated to determine if changes in that area can increase the amount of lordosis with which subjects are able to sit. If the mechanisms by which vehicle and seat design parameters influence preferred postures can be determined, then seat and vehicle designers will be more effective in their efforts to produce comfortable seats.

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APPENDIX A

SUBJECT ANTHROPOMETRY AND FLEXIBILITY MEASURES

Table A1
Subject Anthropometry

Subject	1 = Phase-2 Subject	Age	Stature (mm)	Weight (lb)	Heel Height (mm)	Arm Reach (mm)	Arm Length (mm)	Forearm Length (mm)	Sitting Height (mm)	Eye Height (mm)	PSIS Height (mm)	Knee Height (mm)	Poplit. Height (mm)	Butt. – Knee Length (mm)	Butt. – Poplit. Length (mm)	Should. Breadth (mm)
101	0	59	1548	110	24	784	335	406	815	725	160	472	357	566	479	378
102	1	58	1544	114	17	774	320	410	807	715	124	488	374	542	455	380
103	0	23	1534	140	13	755	335	401	805	698	168	493	368	590	500	410
104	1	34	1582	108	27	835	329	426	877	765	172	466	364	529	446	388
105	1	24	1533	135	34	844	334	443	820	714	146	505	377	560	494	424
106	0	32	1595	117	13	761	338	429	876	763	145	488	365	528	456	398
107	1	33	1582	116	16	805	358	426	842	735	154	483	379	565	486	404
108	1	39	1581	129	24	749	338	408	859	746	156	495	376	548	470	419
109	1	63	1574	110	20	762	345	413	854	742	152	483	366	550	461	381
110	1	38	1571	117	18	736	330	420	852	742	148	477	373	565	470	386
111	0	48	1538	125	20	745	330	421	811	716	140	486	365	548	469	383
112	1	25	1550	121	30	796	348	436	816	716	160	492	384	563	486	401
201	1	27	1640	130	12	818	354	434	873	764	177	510	402	579	490	386
202	1	52	1639	136	20	759	352	443	878	776	125	526	407	576	494	398
203	1	31	1595	132	25	340	423	787	854	750	139	494	381	567	482	409
204	0	24	1605	133	14	798	336	431	843	723	135	510	384	562	490	385
205	0	38	1597	111	15	807	364	435	850	746	164	515	410	568	455	397
206	1	52	1602	113	28	825	348	430	868	773	160	487	362	557	476	409
207	1	24	1619	116	20	780	339	428	860	743	152	491	373	569	482	402
208	0	44	1603	116	9	810	347	443	849	747	132	504	378	561	480	379
209	0	21	1595	134	15	798	346	446	875	747	185	505	381	560	474	415
210	1	43	1622	141	22	783	350	434	842	738	154	517	383	567	491	381
211	1	42	1618	123	18	775	342	417	892	711	146	491	387	541	462	412
212	1	22	1634	146	5	806	360	440	855	739	150	530	408	588	503	424
301	1	61	1756	174	32	879	392	504	894	778	179	570	437	614	530	465
302	0	19	1727	151	19	868	387	485	899	783	137	542	417	593	503	465
303	1	64	1776	180	22	939	397	504	903	783	181	574	440	620	507	479
304	1	23	1729	189	28	848	373	477	917	806	135	554	420	605	512	494
305	1	24	1769	170	26	926	370	502	918	815	147	568	436	610	521	461
306	1	67	1742	158	30	898	385	492	881	770	150	562	446	623	531	407
307	0	25	1760	157	30	844	372	457	943	834	157	544	421	590	500	401
308	1	62	1773	170	20	866	404	515	878	781	110	574	444	624	538	461
309	0	57	1769	212	27	938	396	496	919	811	135	568	423	643	549	462
310	0	41	1726	132	20	871	379	454	907	799	145	533	425	584	509	418
311	1	54	1728	167	20	923	402	490	862	742	144	568	436	633	545	512

Table A1. (continued)

Subject	1 = Phase-2 Subject	Age	Stature (mm)	Weight (lb)	Heel Height (mm)	Arm Reach (mm)	Arm Length (mm)	Forearn Length (mm)	Sitting Height (mm)	Eye Height (mm)	PSIS Height (mm)	Knee Height (mm)	Poplit. Height (mm)	Butt. – Knee Length (mm)	Butt. – Poplit. Length (mm)	Should. Breadth (mm)
312	1	56	1755	195	25	870	379	471	915	799	123	574	429	607	516	456
401	0	26	1833	187	16	886	390	509	950	837	143	607	476	509	509	473
402	1	21	1834	217	20	919	402	500	970	862	172	575	443	632	527	512
403	1	24	1842	158	28	923	394	489	947	834	135	590	460	635	531	458
404	0	49	1826	215	38	928	392	508	954	823	161	578	447	623	530	517
405	1	59	1847	173	39	895	375	507	952	813	156	577	436	618	518	454
406	1	72	1835	188	26	951	427	517	912	790	150	586	451	655	520	455
407	1	33	1845	220	27	940	390	503	962	815	145	588	443	653	542	529
408	1	28	1775	162	16	889	407	500	904	781	190	547	417	651	545	467
409	0	25	1824	183	26	907	393	508	948	820	128	565	436	640	567	476
410	1	29	1866	184	35	907	395	505	980	850	148	590	456	643	536	466
411	0	32	1831	188	25	891	390	495	999	868	160	575	441	620	509	489
412	1	57	1838	178	25	985	430	525	950	827	145	590	463	657	519	467

Table A1. (continued)

Subject	1 = Phase-2 Subject	Hip Breadth (mm)	ASIS Breadth (mm)	Inter-Pupil (mm)	Inter-Corner Eye (mm)	ASIS – PSIS Depth (mm)	Xiph. – T9 Depth (mm)	Back Flex (mm above floor)	Ham. Flex (deg from horiz)
101	0	329	201	52	78	137	186	n/a	n/a
102	1	328	241	62	80	155	161	-19	77.5
103	0	433	227	50	74	201	185	n/a	n/a
104	1	342	255	51	84	143	159	158	72.5
105	1	345	196	54	77	172	187	-6	82
106	0	403	244	49	72	165	150	298	55.5
107	1	363	230	56	87	155	169	-11	69
108	1	411	242	57	77	144	174	203	70
109	1	365	237	48	74	157	186	146	69.5
110	1	394	215	53	80	163	156	94	72
111	0	363	229	55	75	180	185	-3	75
112	1	365	225	55	77	150	170	55	72.5
201	1	372	231	57	80	148	187	117	65
202	1	394	247	55	76	158	185	206	59
203	1	355	210	50	72	175	165	12	74.5
204	0	380	230	55	79	165	186	n/a	n/a
205	0	343	215	55	77	131	187	n/a	n/a
206	1	340	225	51	70	148	180	352	66
207	1	330	213	50	70	141	170	-11	84
208	0	344	231	52	72	146	175	n/a	n/a
209	0	363	269	54	77	170	182	137	61
210	1	401	243	60	84	165	185	84	72.5
211	1	380	244	52	77	150	187	-46	82.5
212	1	403	225	54	74	168	185	-39	82
301	1	368	247	56	80	142	228	171	61
302	0	348	223	55	71	155	207	n/a	n/a
303	1	386	235	60	78	183	232	247	45.5
304	1	387	237	69	81	180	218	261	60
305	1	366	215	54	75	184	223	64	69
306	1	369	278	58	72	158	240	21	83
307	0	371	246	61	81	160	196	44	67
308	1	347	237	58	78	160	205	24	73
309	0	421	254	57	77	205	250	199	47.5
310	0	347	240	55	72	167	195	274	70
311	1	371	230	54	74	164	213	7	69.5

Table A1. (continued)

Subject	1 = Phase-2 Subject	Hip Breadth (mm)	ASIS Breadth (mm)	Inter-Pupil (mm)	Inter-Corner Eye (mm)	ASIS – PSIS Depth (mm)	Xiph. – T9 Depth (mm)	Back Flex (mm above floor)	Ham. Flex (deg from horiz)
312	1	401	244	57	79	175	240	159	62
401	0	379	236	54	80	161	186	166	61
402	1	395	240	57	82	151	255	16	53
403	1	362	222	56	78	139	190	155	66.5
404	0	411	243	58	77	172	242	n/a	n/a
405	1	390	264	59	75	159	197	289	66
406	1	410	261	63	82	203	233	96	63
407	1	401	270	52	86	185	255	140	51
408	1	363	232	60	87	182	187	-13	69
409	0	373	250	60	80	166	200	-90	67.5
410	1	365	260	57	75	160	205	-131	84.5
411	0	395	244	53	70	162	210	-109	86
412	1	399	243	58	74	175	218	114	55

Table A2
Subject Anthropometry: Group and Overall Means by Project Phase

		Age	Stature (mm)	Weight (lb)	Heel Height (mm)	Arm Reach (mm)	Arm Length (mm)	Forearm Length (mm)	Sitting Height (mm)	Eye Height (mm)	PSIS Height (mm)	Knee Height (mm)	Poplit. Height (mm)	Butt. – Knee Length (mm)	Butt. – Poplit. Length (mm)	Should. Breadth (mm)
Phase 1																
Small Female	Mean	39.7	1561.0	120.2	21.3	778.8	336.7	419.9	836.2	731.4	152.1	485.7	370.7	554.5	472.7	396.0
	Std. Dev.	14.1	22.0	10.2	6.6	35.0	10.0	12.8	26.9	20.8	12.9	10.6	7.7	17.4	16.7	15.8
Midsize Female	Mean	35.0	1614.1	127.6	16.9	758.3	355.1	464.0	861.6	746.4	151.6	506.7	388.0	566.3	481.6	399.8
	Std. Dev.	11.6	17.0	11.5	6.6	133.1	22.9	102.0	15.6	18.7	18.0	14.0	15.3	11.9	13.6	14.6
Midsize Male	Mean	46.1	1750.8	171.3	24.9	889.2	386.3	487.3	903.0	791.8	145.3	560.9	431.2	612.2	521.8	456.8
	Std. Dev.	18.4	19.5	21.3	4.6	34.3	11.9	19.2	22.0	24.1	20.4	14.2	9.9	17.7	16.6	33.3
Large Male	Mean	37.9	1833.0	187.8	26.8	918.4	398.8	505.5	952.3	826.7	152.8	580.7	447.4	628.0	529.4	480.3
	Std. Dev.	16.8	21.4	20.3	7.6	29.5	15.8	9.5	25.9	26.1	16.7	15.1	15.3	39.9	16.6	25.7
Overall	Mean	39.7	1689.7	151.7	22.5	836.2	369.2	469.2	888.3	774.1	150.4	533.5	409.3	590.2	501.4	433.2
	Std. Dev.	15.5	110.7	33.0	7.3	98.7	29.3	60.2	49.7	43.9	16.9	41.2	33.7	38.9	29.2	43.2
Phase 2																
Small Female	Mean	39.3	1564.6	118.8	23.3	787.6	337.8	422.8	840.9	734.4	151.5	486.1	374.1	552.8	471.0	397.9
	Std. Dev.	14.2	19.4	9.3	6.6	39.3	12.2	12.5	24.3	18.2	13.7	11.8	6.6	12.9	16.7	17.0
Midsize Female	Mean	36.6	1621.1	129.6	18.8	735.8	358.5	476.6	865.3	749.3	150.4	505.8	387.9	568.0	485.0	402.6
	Std. Dev.	12.2	16.5	11.6	7.3	161.5	26.9	125.7	15.8	21.5	15.2	17.2	16.6	14.3	12.5	14.1
Midsize Male	Mean	51.4	1753.5	175.4	25.4	893.6	387.8	494.4	896.0	784.3	146.1	568.0	436.0	617.0	525.0	466.9
	Std. Dev.	17.7	19.0	12.1	4.5	33.0	13.0	14.8	20.9	22.9	24.7	7.0	8.3	9.7	13.2	30.9
Large Male	Mean	40.4	1835.3	185.0	27.0	926.1	402.5	505.8	947.1	821.5	155.1	580.4	446.1	643.0	529.8	476.0
	Std. Dev.	19.3	26.4	23.0	7.4	31.7	18.6	11.0	26.6	27.7	17.7	14.7	15.0	13.7	10.6	28.3
Overall	Mean	41.9	1693.6	152.2	23.6	835.8	371.6	474.9	887.3	772.3	150.8	535.1	411.0	595.2	502.7	435.8
	Std. Dev.	16.3	110.2	32.2	7.0	113.4	31.1	68.7	45.5	40.5	17.7	42.5	33.3	38.9	28.6	42.8

Table A2. (continued)

		Hip Breadth (mm)	ASIS Breadth (mm)	Inter-Pupil (mm)	Inter-Corner Eye (mm)	ASIS – PSIS Depth (mm)	Xiph. – T9 Depth (mm)	Back Flex (mm above floor)	Ham. Flex (deg from horiz)
Phase 1									
Small Female	Mean	370.1	228.5	53.5	77.9	160.2	172.3	91.5	71.6
	Std. Dev.	33.5	17.5	3.9	4.3	17.8	13.5	108.0	6.9
Midsize Female	Mean	367.1	231.9	53.8	75.7	155.4	181.2	90.2	71.8
	Std. Dev.	25.1	16.8	3.0	4.2	13.4	7.4	130.6	9.6
Midsize Male	Mean	373.5	240.5	57.8	76.5	169.4	220.6	133.7	64.3
	Std. Dev.	22.4	15.9	4.2	3.6	16.8	18.0	104.3	10.9
Large Male	Mean	386.9	247.1	57.3	78.8	167.9	214.8	57.5	65.7
	Std. Dev.	17.9	14.3	3.2	5.0	16.9	25.6	133.4	11.4
Overall	Mean	374.4	237.0	55.6	77.2	163.2	197.2	93.4	68.1
	Std. Dev.	25.7	17.3	4.0	4.4	16.8	27.0	118.4	10.1
Phase 2									
Small Female	Mean	364.1	230.1	54.5	79.5	154.9	170.3	77.5	73.1
	Std. Dev.	27.4	18.3	4.2	4.2	9.6	11.7	86.0	4.5
Midsize Female	Mean	371.9	229.8	53.6	75.4	156.6	180.5	84.4	73.2
	Std. Dev.	27.8	14.1	3.6	4.9	11.8	8.4	138.4	9.3
Midsize Male	Mean	374.4	240.4	58.3	77.1	168.3	224.9	119.3	65.4
	Std. Dev.	16.5	18.0	4.8	3.1	14.8	12.6	103.5	11.0
Large Male	Mean	385.6	249.0	57.8	79.9	169.3	217.5	83.3	63.5
	Std. Dev.	19.3	17.2	3.2	5.1	20.8	27.6	126.2	10.9
Overall	Mean	374.0	237.3	56.0	78.0	162.3	198.3	91.1	68.8
	Std. Dev.	23.5	18.1	4.3	4.6	15.6	28.6	110.9	9.9

NOTES TO ANTHROPOMETRIC TABLES

- Measures not described here were recorded as described in Gordon *et al.* (1989).
- Subject numbers beginning with 1, 2, 3, and 4 denote small-female, midsize-female, and large-male subjects, respectively.
- Stature is measured in stocking feet.
- Weight is with normal indoor clothing, without shoes.
- Heel height is the height of the heels on the shoes worn by the subject during testing, measured between the inner sole and the floor.
- PSIS Height is the height of the posterior-superior iliac spine landmark above the reference seat surface. The reference seat is a standard flat table used for anthropometric measurements (see Gordon *et al.* 1989).
- Xiphoid – T9 depth is the horizontal depth of the chest at the level of the xiphoid process, which is approximately at the level of the 9th thoracic vertebrae. The measurement was made after normal expiration.
- Back flexibility was measured with the subject performing a maximal straight-legged, standing toe-touch exercise. The measure is the distance between the standing surface and the subject's finger tips. Negative values indicate reach below the standing surface.
- Hamstring flexibility was measured with the subject lying supine on a table. The experimenter lifted the subject's right leg at the ankle, holding the knee straight, until substantial passive resistance was felt. The measurement is the angle of the anterior, longitudinal edge of the tibia in this position with respect to the vertical. Larger values indicate a larger range of hip flexion with the leg straight.

APPENDIX B

COMFORT QUESTIONNAIRE

Subject ______________
Trial ______________

COMFORT QUESTIONNAIRE

Make an "X" on the line to indicate your level of discomfort.

	No Discomfort	Unbearable Discomfort
Upper Back	______________________________	
Lower Back	______________________________	
Buttock Area	______________________________	
Thigh Area	______________________________	
Overall	______________________________	