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ABSTRACT

An appropriately contoured lumbar support is widely regarded as an essential component of a comfortable auto seat. A frequently stated objective for a lumbar support is to maintain the sitter's lumbar spine in a slightly extended, or lordotic, posture. Although sitters have been observed to sit with substantial lordosis in some short-duration testing, long-term postural interaction with a lumbar support has not been documented quantitatively in the automotive environment. A laboratory study was conducted to investigate driver posture with three seatback contours. Subjects† from four anthropometric groups operated an interactive laboratory driving simulator for one-hour trials. Posture data were collected by means of a sonic digitizing system. The data identify driver-selected postures over time for three lumbar support contours. An increase of 25 mm in the lumbar support prominence from a flat contour did not substantially change lumbar spine posture.

INTRODUCTION

The appropriate design of lumbar support is the most widely discussed issue in seating ergonomics. The concept of support for the lower back in sitting is certainly not new. Åkerblom is widely credited with beginning the modern study of seating with his 1948 monograph (1*), but he 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, there have been hundreds of papers published on seating ergonomics, many of which include recommendations for lumbar support configuration that do not differ substantially from earlier recommendations (2, 3, 4). 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 (5). This paper describes preliminary results from a series of experiments that are now under way to provide a new research basis for lumbar supports in auto seats.

DEFINITION OF LUMBAR SUPPORT – An important preliminary issue is the definition of the term "lumbar support." For the purposes of this paper, lumbar support will be defined geometrically, using a method similar to that employed by Andersson and others (6, 7, 8, 9, 10). Figure 1 shows the sagittal 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

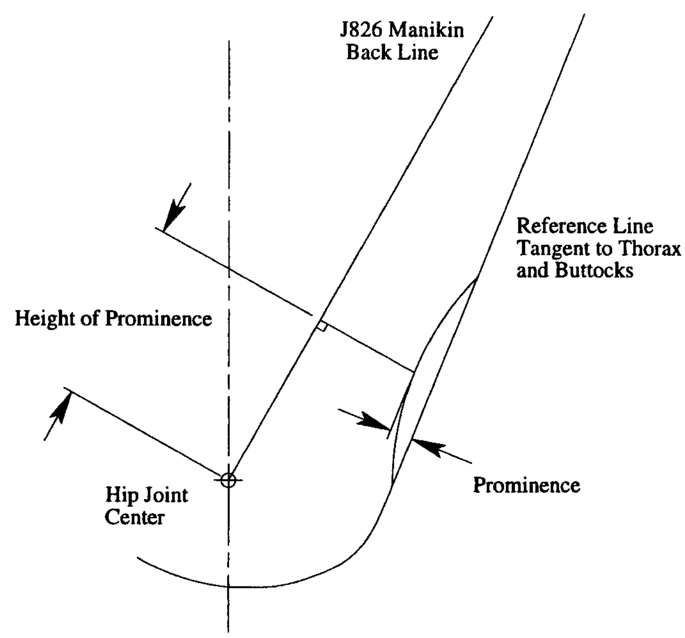


Figure 1. Geometric definition of lumbar support, adapted from Andersson (6).

† 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 (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.

* Numbers in parentheses signify references at the end of the paper.

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 prominence is the maximum deviation from the reference line in the low-back region. The height of the lumbar support is defined as the height along the SAE J826 manikin back line (11) of the point of maximum prominence above the sitter's hip joint centers. A laterally symmetric posture is assumed.

This method of defining lumbar support supposes a particular seated posture and a particular sitter. A different posture, or a different sitter, could produce a different measure of lumbar support. We would like lumbar support to be a quantitatively measurable property of the seat, yet we also desire a measure that reflects the manner in which the seatback design affects the experience of the sitter. A depressed contour must be used, but a depressed contour requires a sitter, whether a human or a weighted surrogate like the SAE J826 H-point manikin (11). The J826 manikin, which is the only available anthropomorphic tool for measuring auto seats, does not have an articulated spine and hence cannot respond to different seat designs with different torso curvatures. Consequently, in the absence of a standard sitter, the lumbar support characteristics of a seat must be described statistically, with reference to the sitting behavior of a particular population.

For some laboratory seats, the definition given above is readily applied. Andersson *et al.* (6) used a wooden laboratory chair with a flat seatpan and seatback. Each subject was instructed to sit with the hips as far to the rear on the seat as possible so that the buttocks firmly contacted the seatback, and with the back of the thorax touching 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 relative 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.* (9) used an identical definition for lumbar prominence, although they did not describe the method used for determining the reference plane. When the reference plane cannot be accurately determined, the absolute magnitude of the lumbar prominence cannot be determined, but relative measurements can be made if the reference plane is assumed to remain constant. In view of the findings of this study, this is probably not a generally valid assumption.

PURPOSE OF LUMBAR SUPPORT – Åkerblom (1), Keegan (12, 13, 14), 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.* (6, 7, 8, 9) 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 suggest 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. Consequently, 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 supplied by back muscles and the muscle-tension contribution to axial spine load. Lumbar muscle activity is typically near zero 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 spine 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 probably 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 posture. 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.* (9) 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.

The substantial work of Andersson's research team 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 (2, 3, 4). 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.

ALTERNATIVE VIEWS – Porter and Norris (15), 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.* (9) with sitter preferences. Plastic probes inserted from the rear of the seatback provided quantitative measurement of spine curvature. A total of 37 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.* (9). 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 show 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 are preferred.

Some researchers have also questioned whether a lordotic lumbar spine posture is in fact desirable when seated. Adams and Hutton (16) 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 prominence 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, an experiment is being conducted to determine if people sit with substantially different postures in a seat with a prominent, longitudinally convex lumbar support than they do when the seatback contour is flat. If a sitter does not use the convex support in the manner intended (that is, sitting with substantial lordosis), then the sitter may experience substantially less support at the lower levels of the lumbar spine than he or she would when sitting against a flat seatback (5). This paper presents preliminary results from 24 subjects tested in a one-hour driving simulation. The research is continuing with additional subjects participating in long-term sitting sessions as well as short-term testing of other seatback contours.

METHODS

OVERVIEW – Volunteer subjects participated in one-hour driving simulations using each of three lumbar support contours. At ten-minute intervals, a sonic digitizer was used to record the locations of body landmarks and the subject's longitudinal back curvature.

SUBJECTS – Six 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 were collected from each subject but are not reported here. Two measures of hip and spine flexibility were also recorded.

Table 1
Subject Anthropometry

Group	Gender	n	Stature Min-Mean-Max (in.)	Stature Min-Mean-Max (mm)	Stature Min-Mean-Max (%ile by gender)*
1	female	6	60.3–61.3–62.8	1533–1556–1595	6–14–29
2	female	6	62.8–63.5–64.6	1594–1613–1640	29–40–57
3	male	6	68.0–68.9–69.9	1727–1750–1776	33–46–62
4	male	6	71.9–72.3–72.7	1826–1836–1847	85–88–91

*Based on normal approximations to data from Gordon *et al.* *(17)*.

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 352 mm above the accelerator heel point (AHP), giving an H30 seat height of 352 mm. The center of the front surface of the steering wheel is located 465 mm rearward and 721 mm above the AHP. The instrument panel in the laboratory buck is 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 are instrumented and connected to a driving simulator program running on a Macintosh computer. The simulated road scene is 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.

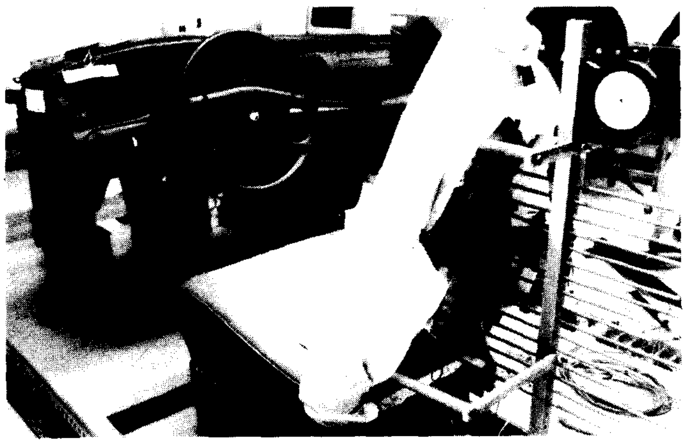


Figure 2. Laboratory seating buck.

SEAT – A minivan seat was extensively modified for use in testing. All of the foam and covering material on the seatback were 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 seat. The front surface of the support frame was covered with a 2-mm-thick 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 lumbar support adjustment provides approximately 120 mm of vertical travel. The experimenter adjusts the lumbar prominence by hooking varying-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 (15). 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. A central rib in the Schukra support prevented placement on the centerline. Sixteen rods are located at 25-mm intervals along the rack, although usually only 12 rods can be used because of lumbar support frame interference (depending on the vertical lumbar support position). During data collection, the rounded tip of each rod is pressed firmly against the seat foam, which is accessible through a slit in the Teflon sheet supporting the foam. The soft foam is readily compressed to a uniform thickness against the seated subject. Figure 3 shows a view of the seatback, including the adjustable lumbar support and the contour measurement rods.

Figure 3. Rear view of seatback, showing adjustable lumbar support and contour-measurement rods.

SONIC DIGITIZER – Posture and contour data are collected using a Science Accessories Corp. GP8-3D sonic digitizer. This and similar systems have been used extensively at UMTRI and other biomechanics labs for collection of spatial data (18). 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. Software written for this application applies a calibration factor to adjust for changes in temperature and humidity and calculates the three-dimensional location of the emitter using the three shortest microphone distances. The location of the probe tip is calculated from the locations of the two probe emitters.

TEST CONDITIONS – Three lumbar support contours were investigated. Each was characterized by the displacement of the most prominent point on the lumbar support (the point having the furthest forward location) relative to the supporting structure. In lumbar support (LS) Condition A, the support frame was allowed to flatten under loading from the subject to produce an approximately flat surface. In LS Condition 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 condition B. For LS Condition C, the point of maximum prominence was 25 mm forward of its position in Condition A.

These test conditions do not necessarily correspond to 0, 10, and 25 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 sitter and posture. Instead, these conditions represent relative levels of lumbar support. Condition C should provide the opportunity for supported spine postures that are substantially more lordotic than either condition A or B. In these preliminary data from one-hour driving simulation trials, there are few significant differences in posture and contour between the A and B conditions, while there are highly significant differences between the A and C conditions. Consequently, only results from LS Conditions A and C are discussed. Given the nature of the findings, no conclusions of substance are lost by neglecting the data from Condition B.

PROTOCOL – For each subject, each lumbar support condition is tested on a different day. At the start of testing, the subject changes into form-fitting tights and a loose-fitting shirt to facilitate access to body landmarks. The subject is trained to locate the pubic symphysis landmark. To digitize the point, the subject palpates the anterior-superior margin of the pubic symphysis and presses the digitizer probe tip firmly against that point.

Prior to testing, the experimenter fixes the lumbar support at the appropriate prominence (test condition), places the seat track in its full-rear position, locates the seatback recliner at a nominal 20 degree angle, and sets the steering wheel angle adjustment to a neutral position. The lumbar support is initially positioned at the center of its vertical travel.

The subject sits in the vehicle buck and manually adjusts the seat track, seatback recline angle, and steering-wheel tilt for maximum comfort. The vertical position adjustment for the lumbar support is motorized and controlled by the subject with a switch mounted to the right of the seat. The subject is encouraged by the experimenter to try a range of different positions to find the most comfortable combination of adjustments. When the subject has adjusted the seat and steering wheel satisfactorily, the experimenter activates the driving simulator. The lights are dimmed while the simulator is running to improve the visibility of the road scene. If necessary, the experimenter provides feedback and instruction on operating the simulator. In general, subjects readily follow instructions to keep the simulated vehicle in the right lane of a two-lane, winding road, and 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 instructs the subject to maintain his or her current posture while the simulator is paused and the lights are brought up. The experimenter uses the digitizer probe to record the subject's back contour and posture. First, each of the back contour probes in turn is pressed firmly against the subject's back, bottoming out the thin foam layer, and the location of the rear of the probe is digitized. Next, two fiduciary points on the contour-probe rack are recorded to define a projection plane perpendicular to the probes. These points also provide a precise measure of seatback angle. The seatback pivot is digitized to provide a reference point that is fixed relative to the seatpan. The body landmarks listed in Table 2 are then digitized. The subject locates the pubic symphysis landmark using the procedures learned previously. The contour and body landmark digitization typically requires two minutes. The simulator is then restarted, and the subject drives until 10 minutes have elapsed from the time the simulator was previously paused. The simulator is paused again and data collection performed as before. The total test time is one hour, providing seven data collection intervals (0, 10, 20, 30, 40, 50, and 60 minutes). The actual time the subject is seated is approximately 3 minutes greater, because of adjustment time and the two-minute initial drive.

Table 2
Body Landmarks

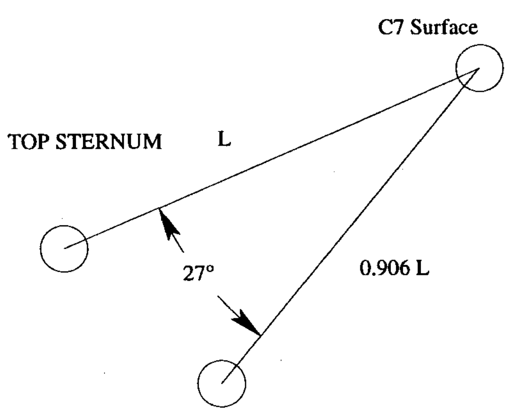
Landmark	Definition
GLABELLA	Undepressed skin surface point at the most anterior prominence on the brow on the midsagittal line.
TOP HEAD	Undepressed skin surface point at the most superior point on the head.
OCCIPUT	Undepressed skin surface point at the most posterior point on the occipital prominence.
C7	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.
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.

ANALYSIS

For each test, the digitizer control software writes a data file that contains the buck coordinates of each point recorded. At each measurement interval, the contour and posture data are extracted and translated to an XZ-plane origin at the seat pivot point so that postures from different seat track positions can be directly compared. Linear interpolation is used to obtain 12 equally-spaced contour points from the unevenly spaced contour data (some probes are obstructed by the lumbar support mechanism). Posture data analyses presented here are restricted to the sagittal (XZ) plane. Two additional points used to define posture are calculated as described in Table 3. Shoulder position is estimated using the torso geometry for midsize males reported by Schneider *et al.* (19) as shown in Figure 4. The posture variables listed in Table 4 and shown in Figure 5 are calculated for each measurement interval. Two measures of back contour are also obtained that are similar to the definition of lumbar support discussed in the introduction. Figure 6 shows the calculation procedure schematically.

Table 3
Calculated Body Landmarks

Landmark	Definition
HJC	Sagittal position of mean of hip joint centers. Hip joint center locations calculated from ASIS(L), ASIS(R), and PUBICSYMPHYSIS using method of Bell as adapted by Manary *et al.* (18).
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 midsize male in Schneider *et al.* (19) were used to estimate the shoulder joint location. See Figure 4.



Estimated Glenohumeral Joint Center (SHOULDER)

Figure 4. Method of estimating shoulder joint location in the sagittal plane.

Table 4
Posture Variables

Variable	Definition*
Head Angle	Angle wrt horizontal of line formed by GLABELLA and OCCIPUT landmarks. Larger angles indicate greater neck extension.
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.

* All angles are measured in sagittal plane. Body landmarks are defined in Tables 2 and 3.

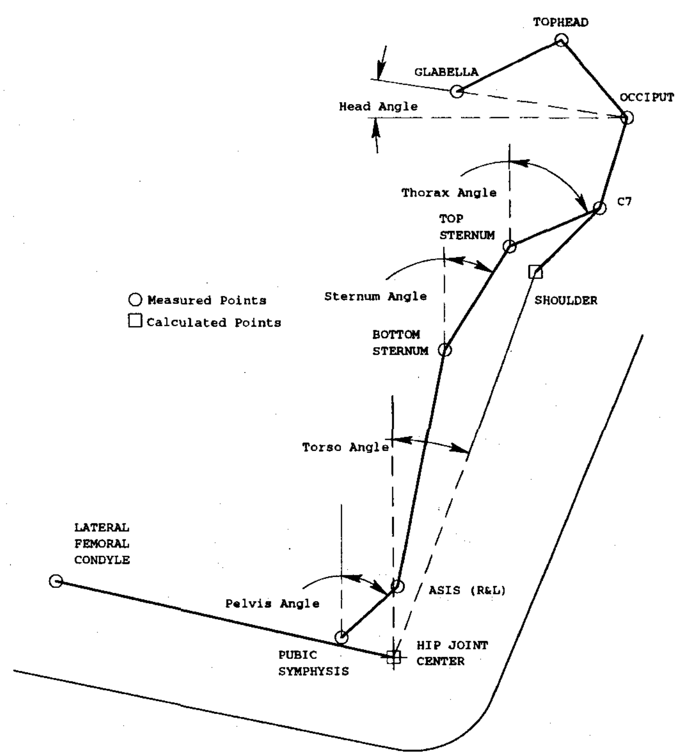


Figure 5. Body landmarks and posture variables.

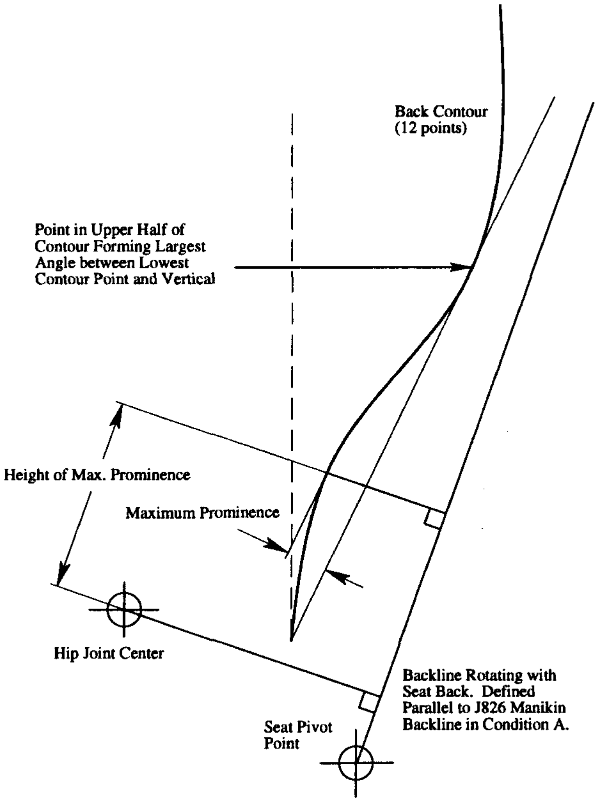


Figure 6. Schematic of calculation of maximum prominence and height of maximum prominence.

RESULTS

Large intersubject differences in sitting posture were found. Figure 7 shows seated pelvis angle by subject. All seven measurements from both the A (flat) and C (25-mm prominence) conditions are shown. Data for each subject are shown in a different position on the horizontal axis (14 data points for each subject). The mean pelvis angle by subject across conditions ranges from 39 to 72 degrees. The mean pelvis angle across all subjects and test conditions is 56.5 degrees. An important observation is that the points for each subject are fairly well grouped. The average standard deviation of pelvis angle within subject across test conditions is only 3.3 degrees, while the standard deviation of the mean pelvis angles by subject is 8.3 degrees. From Figure 7, it is apparent that any systematic, within-subject effect of test condition on pelvis angle is much smaller than the intersubject pelvis angle variance. Another observation is that there appear to be substantial differences between subject groups in pelvis angle. The group means are 58, 50, 64, and 54 degrees for the small females, midsize females, midsize males, and large males, respectively.

Figure 8 shows a similar plot of sternum angle by subject. As with pelvis angle, the data are well grouped within subject, and intrasubject differences between test conditions are generally smaller than intersubject differences. The overall mean is 24 degrees, with a range of subject means from 11 to 33 degrees. The standard deviation of subject means is 5.9 degrees, while the average within-subject standard deviation is 3.2 degrees. Head angle and thorax angle also show substantial intersubject variability.

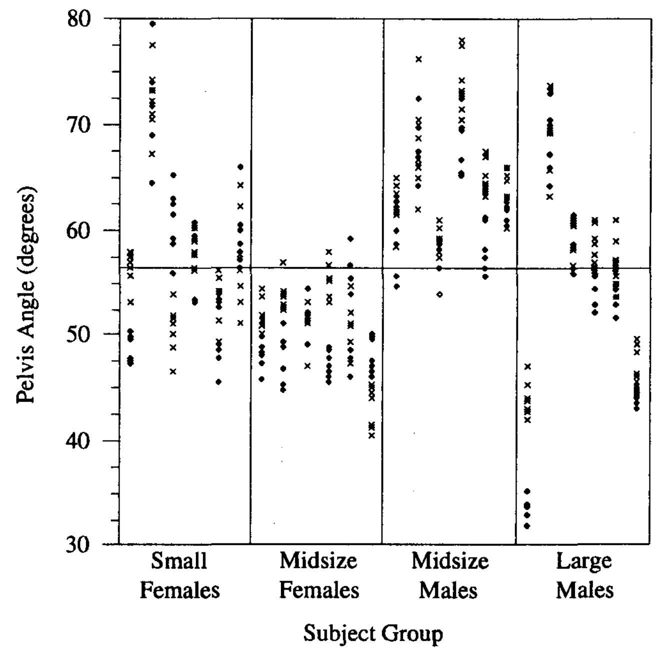


Figure 7. Pelvis angle by subject and group. Overall mean = 56.5°; Subject mean range = 39 to 72°. Condition A shown with **x** symbols, Condition C shown with ♦ symbols.

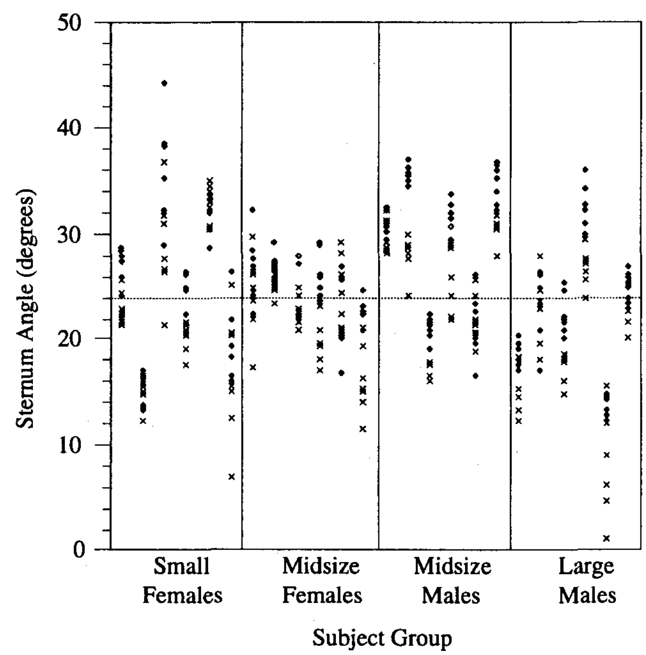


Figure 8. Sternum angle by subject. Overall mean = 24°; Subject mean range = 11° to 33°. Condition A shown with **x** symbols, Condition C shown with ♦ symbols.

TIME EFFECTS – The primary purpose of the one-hour driving simulation is to determine if there are any systematic changes in posture over time. Preliminary examination shows that, for all but a few subjects, there is little difference between subsequent measurements.

A least-squares line was fit to the seven data values of each variable for each trial. No difference was found between the mean slopes for the two LS Conditions, 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 5
Test of Linear Time Effect

Variable	Mean Slope* (degree/ minute)	Std. Dev. of Slope	Student's t Value†	Change in 60 Minutes (deg)
Head Angle	-0.002	0.048	–0.25	--
Thorax Angle	0.016	0.036	2.19	0.96
Sternum Angle	0.021	0.049	2.05	1.26
Pelvis Angle	0.024	0.053	2.02	1.44

* Average slope of least-squares linear fit to variable vs. time across subjects and LS conditions.
† Absolute Student's t values greater than $T_{(0.025, 23)} = 2.07$ indicate significance in a two-tailed test with alpha = 0.05.

Table 5 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 5 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 simulation. Examination of the data from individual trials shows few instances where the linear trend resulted in an estimated change over the trial of more than 5 degrees in any posture variable. There are also few instances in which substantially nonlinear trends are observed.

Since only small systematic changes in posture were found, the posture variable values for each trial were averaged and the means used in subsequent analyses. Analysis of variance (ANOVA) was used to investigate the effects of the lumbar support prominence on subject posture. The most salient finding, in keeping with the observations from Figures 7 and 8, is that intersubject variability accounts for most of the variance in the data. The variance percentages explained by Subject alone are 56%, 60%, 73%, and 63% for pelvis angle, thorax angle, sternum angle, and head angle, respectively.

LUMBAR SUPPORT EFFECTS – The change in lumbar support from Condition A to Condition C, a nominal increase in prominence of 25 mm, produced significant differences in pelvis angle and sternum angle ($F_{(1,20)} = 4.92$, $p = 0.038$; $F_{(1,20)} = 33.3$, $p < 0.001$). The LS Condition effect approaches significance for thorax angle ($F_{(1,20)} = 2.28$, $p = 0.147$), but is not significant for head angle ($F_{(1,20)} = 0.28$, $p = 0.60$).

The least-squares estimate of the A–C LS Condition effect on pelvis angle is 2.0 degrees, indicating that, on average, subjects sat with more upright pelvis angles in Condition C. The effect of LS Condition (A–C) on sternum angle is –3.4 degrees, indicating that, on average, the subjects sat with their sternums more reclined in Condition C.

A measure related to net spine flexion can be obtained by subtracting sternum angle from pelvis angle. Larger values of pelvis–sternum indicate greater spine flexion. The effect of LS Condition (A–C) on pelvis angle–sternum angle is highly significant ($F_{(1,20)} = 32.3$, $p < 0.001$). The least-squares estimate of the effect is 5.4 degrees, equivalent to the sum of the absolute effects of LS Condition on pelvis angle and sternum angle individually. In summary, one result of a nominal increase of 25 mm in lumbar support prominence is to reduce net flexion in the lumbar and thoracic spine an average of 5.4 degrees, if changes in sternum angle are assumed to reflect changes in the orientation of the sitter's thoracic spine.

Although the effect of LS Condition on thorax angle is not significant, the effect of LS Condition on pelvis angle minus thorax angle, another measure of net spine flexion, is significant ($F_{(1,20)} = 12.1$, $p = 0.002$). The least-squares estimate of the effect is 3.4 degrees, less than the estimate obtained using sternum angle.

Although both are intended to be measures of the orientation of the sitter's ribcage, the sternum and thorax angle results differ slightly. For some subjects, the sternum angle change from LS Condition A to C is positive when the thorax angle change is negative. Data from other subjects show the reverse. Across all subjects, the correlation between the mean sternum angle change and mean thorax angle change from LS Conditions A to C is 0.72, a weaker correlation than expected. This may be due in part to the small angle changes observed. A typical distance from C7 to TOP STERNUM is 138 mm. A net error (*e.g.*, positive on one point and negative on the other) perpendicular to the line of only 7 mm gives an angle measurement error of 3 degrees, which is the estimated magnitude of LS Condition effect. So, while the trends are consistent, measurement error as a percentage of the true angle difference may account for the lower-than-expected correlation between the two estimates of ribcage rotation.

SUBJECT GROUP DIFFERENCES – There are significant differences in pelvis angle between subject groups. The group means are shown in Table 6. Comparing all pairs of groups, using Tukey-Kramer HSD with alpha = 0.05, the mean pelvis angle for midsize males is significantly higher than for midsize females. Other comparisons are not significant. The other posture variables do not show significant group differences.

Table 6
Pelvis Angles by Subject Group

Group	Mean Pelvis Angle (degrees)	Std. Dev.
Small Females	57.9	7.8
Midsize Females	50.1	3.4
Midsize Males	64.0	5.2
Large Males	53.9	10.5

OTHER EFFECTS OF LS CONDITION – The lumbar support prominence also affected the horizontal position of the subject's hips. The left and right hip joint centers (HJCs) were calculated from the pelvis posture data using the method of Manary *et al.* (18). A mean HJC was calculated by averaging the left and right HJCs and used as a measure of subject hip position in the XZ plane. The mean HJC is further forward on the seat for LS Condition C than for condition A ($F_{(1,20)} = 6.26$, $p = 0.02$). The mean difference is estimated to be 11.4 mm. The mean HJC is also about 3 mm higher in the LS Condition C.

The fore-aft positions of the shoulder relative to the seat are not significantly different between subject groups or between the two LS conditions. However, shoulder joint height varies, as expected, with stature. Shoulder height also varies with LS Condition ($F_{(1,20)} = 10.8, p = 0.004$). On average, shoulder joint locations are 6.8 mm higher in Condition C.

Torso angle, measured as the angle from the vertical of a line from mean HJC to the estimated shoulder joint location (in the XZ plane), does not differ significantly among the subject groups. Torso angle is significantly different between LS conditions ($F_{(1,20)} = 8.97, p = 0.007$). On average, subjects sat about 1.8 degrees more reclined (larger torso angles) in Condition C than in Condition A. Means over all subjects are 23.3 degrees and 25.1 degrees for LS Conditions A and C respectively. Seventeen of the twenty-four subjects sat with a larger torso angle in Condition C. This observation is consistent with the 11-mm average forward shift in mean hip joint location with the more prominent support.

BACK CONTOUR – There are significant differences in back contour between the two LS conditions. The average maximum lumbar prominence for Condition A is 1.0 mm, indicating that, on average, subjects sat with a nearly flat low-back contour. For Condition C, the average maximum lumbar prominence is 8.9 mm. Standard deviations are 4.5 mm and 6.9 mm for LS Conditions A and C, respectively. The difference in prominence is highly significant ($t_{(23)} = 7.46, p < 0.001$). Some intergroup differences in lumbar contour prominence approach significance. Figure 9 shows the difference in maximum prominence between the two LS conditions for all subjects. Midsize female subjects show a larger effect of lumbar support prominence on back contour than do the other subjects. One small female subject sat with a flatter lumbar contour in Condition C than in Condition A. Only two subjects increased their lumbar contour prominence more than 15 mm in Condition C relative to Condition A.

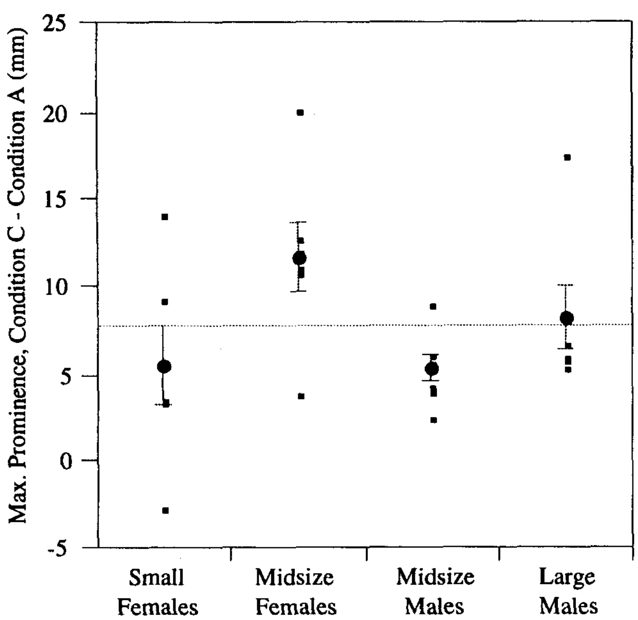


Figure 9. Difference in maximum lumbar contour prominence between LS Conditions A and C. Larger dots are group means. Error bars indicate ± 1 group standard deviation.
Horizontal line is overall mean.

The height of the maximum prominence of the lumbar contour does not differ between lumbar support conditions, largely because the maximum prominence was small in LS Condition A. However, in the data from LS Condition C, the mean height of the maximum prominence for large males is significantly lower than the other groups ($t_{(23)} = 2.18, p = 0.04$), as shown in Figure 10. Data from one subject substantially increased the variance in the large-male group. Subject 401, the subject contributing the upright pelvis angles shown in Figure 7, is an outlier relative to his group on many measures. For all subjects, the height of the point of maximum prominence above the HJC along the backline is 139 mm with a standard deviation of 24 mm (see Figure 6 for definition of backline).

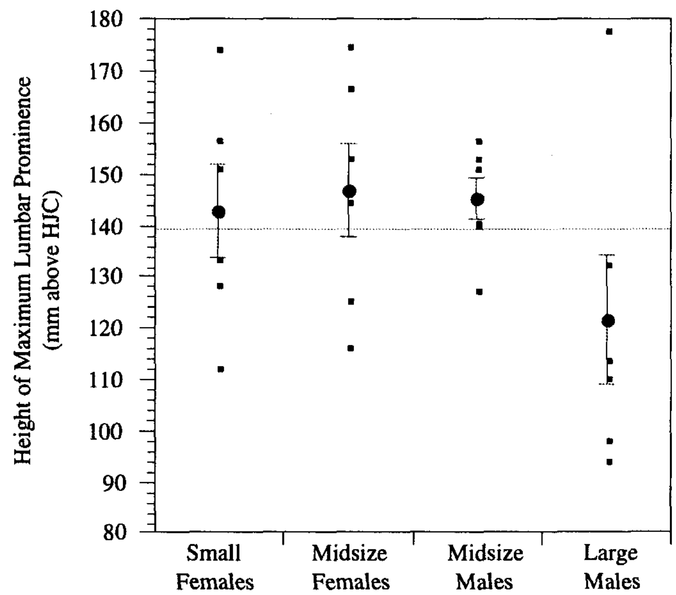


Figure 10. Maximum lumbar prominence height above HJC on back line for LS Condition C. Large dots are group means. Error bars indicate ± 1 group standard deviation.
Horizontal line is overall mean.

SEATBACK ANGLE – Seatback angle was calculated from fiduciary points on the contour-probe frame. This reference plane is angled 18 degrees more upright than the SAE J826 manikin back angle when the manikin is placed in the seat with LS Condition A. Consequently, this differential was added to the angle measured from the contour-probe frame to obtain a manikin-referenced back angle. Note that this is not the same as the torso angle, which is defined as the angle relative to vertical of a sagittal-plane line connecting the mean HJC and shoulder point.

The subject-selected seatback angle varies with both subject group and LS Condition. Figure 11 shows a plot of seatback angle versus LS Condition by Group. The interaction approaches significance ($F_{(3,20)} = 2.99, p = 0.055$). In general, larger subjects choose more reclined seatback angles than smaller subjects, but choose less reclined seatback angles with the more prominent lumbar support. Smaller subjects, in contrast, tend to choose slightly larger seatback angles with the more prominent support. The difference between groups was reduced in LS Condition C. The overall mean back angle across groups is 23 degrees. The seatback angle is not significantly different for LS conditions A and C.

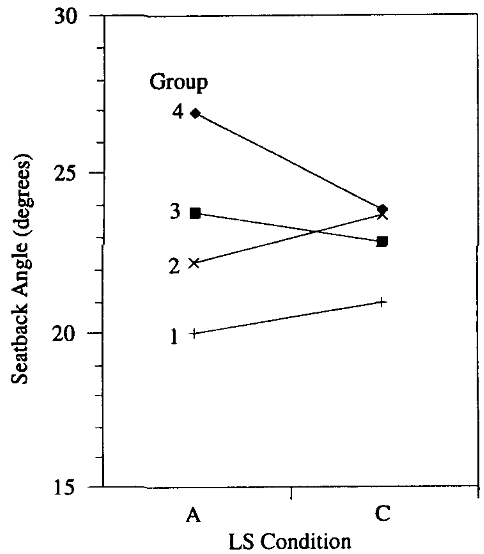


Figure 11. Seatback angle versus LS Condition by group.

There are significant differences between genders in the selected lumbar support position, as shown in Figure 12. In testing with LS Condition C, subjects are instructed to adjust the vertical position of the lumbar support vertically within a 120-mm range centered about 156 mm above the mean location of the sitters' hip joint centers. The vertical position of the lumbar support refers to the position of the apex of the curve of the lumbar support mechanism. Figure 12 shows that male subjects tend to select lower LS positions than do female subjects (means ± s.d: male = 121±18 mm, female = 147±15 mm). The gender difference is 26 mm ($F_{(1, 20)} = 13.7$, $p = 0.001$). The subject-selected vertical lumbar support position is moderately correlated with the height of the maximum lumbar prominence ($r = 0.58$). There is no significant difference between the mean lumbar support position (134 mm above HJC) and the mean height of the maximum lumbar contour prominence (139 mm).

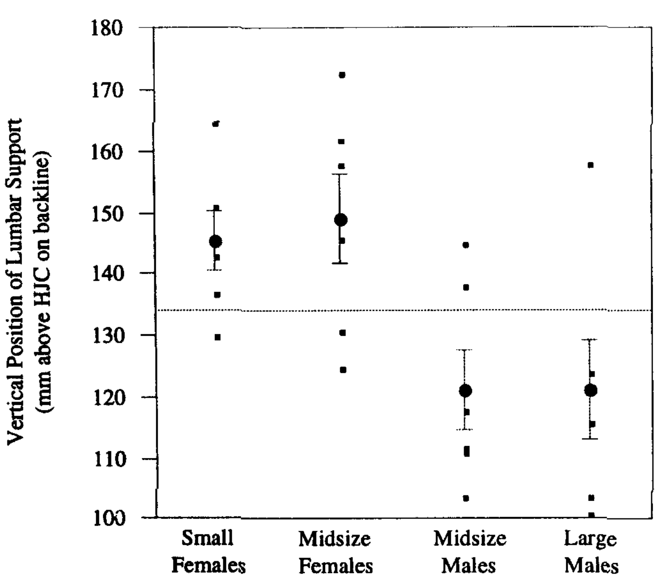


Figure 12. Subject-selected vertical lumbar support position, in millimeters above mean HJC location, measured along back line.

SUMMARY OF RESULTS – Although the analyses above show that the experiment was powerful enough to detect small within-subject differences in posture between lumbar support conditions, these differences were minor, particularly compared with the large intersubject variability. In this preliminary analysis of data from a larger study, the average effects of adding a vertically adjustable 25-mm lumbar support to a flat backrest contour are to:

- decrease pelvis angle by 2 degrees (more upright),
- increase sternum angle by 3.4 degrees (more reclined),
- decrease flexion of the thoracic and lumbar spine by 5.4 degrees,
- increase the maximum prominence of the lumbar lordosis by 8 mm,
- increase torso angle by 1.8 degrees, and
- shift the hip joint center forward by 11 mm.

These findings can be partially visualized by use of a kinematic model of the torso. A planar representation of the thorax, lumbar spine, and pelvis were developed based on the interpretation by Haas (20) of anthropometric data from Schneider *et al.* (19), Snyder *et al.* (21), and Reynolds *et al.* (22). The model is intended to represent the spine linkage of a midsize male, and consists of rigid links connected by pin joints located at the intervertebral joint centers from L5/S1 to T8/T9. The model was initially adjusted to produce a flat lumbar-spine posture, shown with light lines in Figure 13. The hip joint center of the model lies at the origin of the plot. Lines connect joint centers and spinous processes below T8. The lumbar spine was then extended 5.4 degrees, the mean spine extension produced by the 25-mm support, using the even distribution of lumbar motion recommended by Hubbard *et al.* (23). The pelvis of the model was rotated around the hip joint center to produce a pelvis angle 2 degrees more vertical than the flat-spine model. The model was translated forward 11.4 mm and upward 3 mm, to account for the difference between the two LS conditions in mean HJC location. The torso angle was also adjusted to approximate the mean torso angle in LS Condition C. The resulting representation of posture is shown in Figure 13 with dark lines. The lumbar extension of 5.4 degrees results in only a small lumbar lordosis, with a prominence close to the 9-mm average measured in testing. The illustration in Figure 13 is intended to assist in visualizing the findings, but should not be interpreted as representing any individual subject's postures.

DISCUSSION AND CONCLUSIONS

This paper presents preliminary results from a study of postural adaptation to seatback contour in auto seats. Findings are presented from analyses of data from 24 subjects. A total of 48 subjects will participate in testing similar to that described in this paper. Additional seatback contours, some with subject-controlled adjustments, will be tested.

The preliminary results show that preferred pelvis and thorax orientations are not changed substantially by a 25-mm increase in the prominence of the lumbar support when the subject is given control over the vertical location of the support. The increase in lumbar support prominence produces changes in back contour that are about one-third the magnitude of the support prominence increase, on average. A schematic visualization of the torso skeletal linkage shows that increased lumbar support

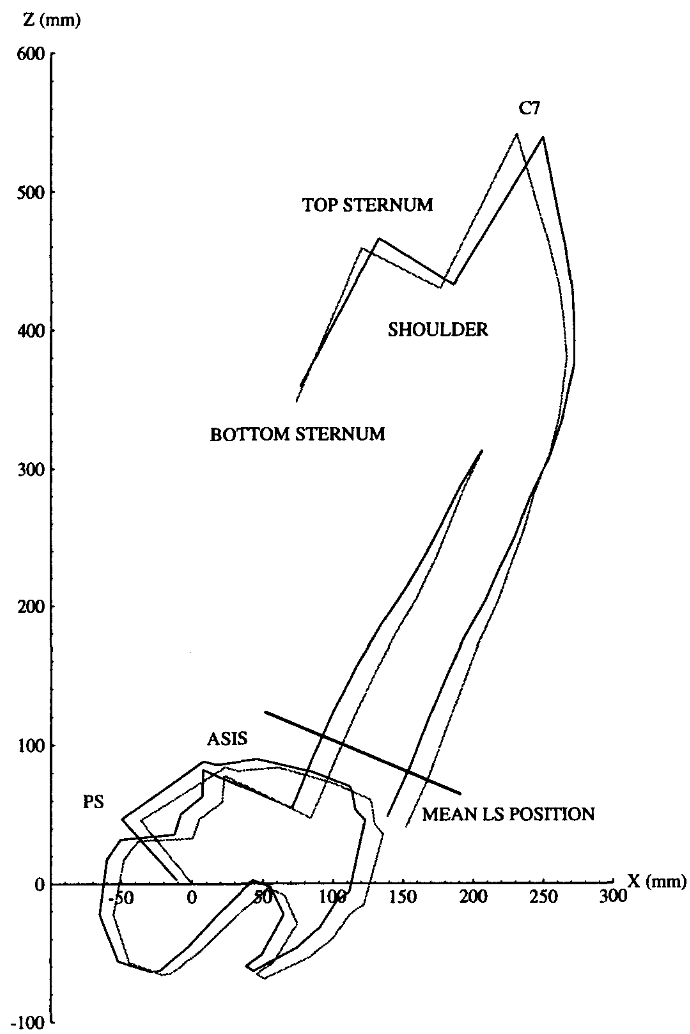


Figure 13. Schematic representation of the torso using a planar kinematic model. The sagittal-plane profile of the pelvis and sacrum are shown, along with a line connecting the sternum points, shoulder joint center, and spinous process surface points. Another line connects spine joint centers from T8/T9 to L5/S1. Light lines show a flat lumbar spine posture, illustrating the mean pelvis, thorax, sternum, and torso orientations obtained with lumbar support Condition A. The dark lines show the model translated forward to match the Condition C HJC location with the pelvis angle, sternum angle, thorax angle, and torso angle adjusted to match the mean data from Condition C. The dark line perpendicular to the spine indicates the mean subject-selected lumbar support position. The distance between the model back contours on that line is 15 mm.

prominence causes the subject to sit forward on the seat with only a small increase in lumbar lordosis.

It should be emphasized that these findings are preliminary and that more study of postural adaptation in auto seats is needed. The current data are limited by sample size and by the static laboratory conditions used in testing. Differences between postures chosen in an on-road environment and those measured in the laboratory are expected to be small, however, since the primary physical constraints affecting posture selection (vision requirements and control placement) are included in the laboratory seating buck design.

These findings are in agreement with earlier work. The flat lumbar spine profiles recorded by Schneider *et al.* (19) in a study of driver anthropometry have been criticized as unrepresentative of driving postures in present-day seats because of the lack of lumbar contour in the test seats. However, the preliminary results of the present study show that the addition of a 25-mm lumbar support does not substantially alter drivers' lumbar spine postures.

As noted in the introduction, current lumbar support design recommendations are strongly influenced by the goal of reducing lumbar disc pressure, which is related to the loads on the disc annulus and the surrounding ligaments. As Andersson and others have shown, lumbar lordosis generally results in reduced disc pressures. However, seated postures with substantial lumbar lordosis were not selected by the subjects in this study, even when the seat was configured to provide support for lordotic postures.

Among the factors that may contribute to the prevalence of flat-spine postures is the influence of the posterior thigh muscles in restricting forward pelvis rotation. The hamstring muscles connect the pelvis and leg across the knee and hip joints and produce a restriction on pelvis orientation that varies depending on knee angle (24, 25). When the knees are extended beyond 90 degrees, as is typical of automotive postures, the relatively erect pelvis angle necessary to produce substantial lumbar lordosis with a reasonable thorax orientation may not be possible for many sitters without discomfort in the backs of the thighs. Consequently, more reclined pelvis orientations may be selected, resulting in greater spine flexion and a flat lumbar spine contour. In the current study, a relatively high seat height was used (H30 = 352 mm), potentially reducing the influence of the hamstring muscles on pelvis posture by allowing less-extended knee angles than would be required with a lower seat height. For vehicles with lower seats, including most passenger cars, lumbar lordosis may be even less likely than for the seat height tested, although further research is necessary to verify this assumption.

The apparent physiological benefits of lumbar lordosis cannot be realized if sitters do not select such postures. If lordotic lumbar curvatures are not prevalent even when the seat is designed to accommodate them, then the purpose of lumbar supports in auto seats should be reconsidered. The preliminary findings from the present study suggest that seatbacks with fixed lumbar supports should provide support for nearly flat spine profiles, rather than for the standing spine curvature associated with lower disc pressure. Those people who prefer to sit with substantial lordosis can be accommodated by providing an adjustable-prominence support located approximately 140 mm above the hip joint center.

These investigations are continuing with a larger group of subjects and several additional test conditions. Subsequent reports will describe a general model of the postural effects resulting from changes in seatback contour. This research is expected to contribute to the formulation of a new rationale for lumbar support design.

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