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AN INVESTIGATION OF AUTOMOTIVE SEATING DISCOMFORT AND SEAT DESIGN FACTORS

FINAL REPORT

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16. Abstract

A study of automotive seating comfort and related design factors was conducted, utilizing subjective techniques of seat comfort assessment and objective measures of the seat/subject interaction. Eight male subjects evaluated two luxury and two sport seats during a short-term seating session and throughout a three-hour driving simulation. For the latter, subjects operated a static laboratory driving simulator with an interactive road-scene display, performing body-area discomfort evaluations at thirty-minute intervals. Cross-modality matching (CMM), a subjective assessment technique in which a stimulus is rated by matching to the level of another stimulus, was used during the long-term driving simulation to evaluate discomfort. Subject posture, muscle activity in the lower back and abdomen, and pressure levels at key support locations on the seat were monitored. In addition, a sonic digitizing system was used to record seat indentation contours and to characterize the subjects' spinal contours.

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SUMMARY

A study of automotive seating comfort and related design factors was conducted, utilizing subjective techniques of seat comfort assessment and objective measures of the seat/subject interaction. Eight male subjects evaluated two luxury and two sport seats during a short-term seating session and throughout a three-hour driving simulation. For the latter, subjects operated a static laboratory driving simulator with an interactive road-scene display, performing body-area discomfort evaluations at thirty-minute intervals. Cross-modality matching (CMM), a subjective assessment technique in which a stimulus is rated by matching to the level of another stimulus, was used during the long-term driving simulation to evaluate discomfort. Subject posture, muscle activity in the lower back and abdomen, and pressure levels at key support locations on the seat were monitored. In addition, a sonic digitizing system was used to record seat indentation contours and to characterize the subjects' spinal contours.

Cross-modality matching was shown to be an effective technique for assessing seating discomfort. CMM data and data collected using a traditional questionnaire were highly correlated, but CMM provided better differentiation between the test seats. Electromyography indicated a higher frequency of intense trunk muscle activity associated with the two sport seats than with the two luxury seats. Data from pressure sensors located on each seat indicated that seats with the highest reported discomfort during the driving simulations produced higher levels of pressure. Digitized contours of subjects' indentation patterns on each seat also showed marked differences between contours for the most and least comfortable seats. Seats that were reported to be more comfortable had broader areas of indentation with less localized indentation under the ischial tuberosities and at the lumbar spine. Posture tracking showed significant, systematic differences in subject posture between the seats. Analysis of thorax and pelvis orientations supported observations that subjects' lumbar curvatures were generally neutral or kyphotic during the driving simulations, even though two seats had prominent lumbar supports.

1.0 INTRODUCTION

This study[1] was undertaken with the primary and long-term objective of gaining a better understanding of the seat design factors which contribute to seating comfort during extended periods of driving. Prior to conducting the experimental phase of this project, two preliminary studies were conducted. First, a brief roadside survey of drivers was conducted to define further the problems of discomfort experienced by drivers of late-model vehicles. The results of this study are published separately (Schneider and Ricci 1989). Data collected were used in the formulation of the test procedures for the experimental portion of the study.

In conjunction with this roadside survey, an in-depth review and investigation of the literature concerned with seating comfort and the measurement of discomfort was conducted. A summary of selected studies and findings in these areas is presented in a separate report (Lee and Schneider 1990). In general, it was found that there is considerable disagreement among researchers regarding the issues of seat design and comfort and that there is little experimental evidence on which informed design decisions can be made. Many of the design guidelines currently in use are extrapolated from knowledge of anatomy and physiology (*e.g.*, spine intra-discal pressure relationships and blood flow considerations) but have not been demonstrated to be fully suitable for application to driver seats in passenger cars.

Subsequent to these field and literature surveys, an experimental research project was evolved with two primary goals. First, it was desired to develop, utilize, and evaluate reliable and applicable subjective and objective methodologies for assessing discomfort levels experienced by drivers. Second, data from an initial series of experiments were analyzed to gain further insight into the relationships between seat design factors and features and the comfort performance of automotive seats.

Section 2 of this report describes the test procedures and protocols used in this study. Section 3 presents the data analyses and findings for the different types of subjective and objective data collected. Section 4 presents an evaluation of the test methodologies, while Section 5 provides a discussion and interpretation of this exploratory laboratory work. Appendices A through F contain further details on the test methodologies and measurement tools used in the course of the study.

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[1] 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.

2.0 RESEARCH METHODOLOGY

2.1 GENERAL APPROACH

Three aspects of seating-comfort research were chosen as foci for this study:

1. identification of seat design parameters associated with long-term discomfort in test subjects,
2. application and evaluation of subjective discomfort-measurement techniques, and
3. measurement of objective factors associated with long-term discomfort.

The focus on long-term discomfort also provided the opportunity for comparison with short-term evaluations of the same seat design parameters.

The research strategy was to test volunteer subjects on four different seats, each of which presented a unique set of design parameters. Each subject made an initial evaluation of each test seat at a preliminary session, followed by four driving-simulation sessions (one for each test seat) during which the subject sat in a seat for a three-hour period while reporting levels of discomfort in various body areas at regular intervals. During the simulation, various objective measures were also monitored.

The test protocol provided for:

- a systematic, short-term assessment of each test seat,
- evaluation of discomfort during the driving simulation,
- continuous monitoring of related objective measures, and
- a final subjective assessment by the subject.

The experimental techniques can be divided into three groups. First, a comparison was to be made between short- and long-term evaluations of seat design factors. A questionnaire designed for a comprehensive, short-term evaluation was developed, based on the work of Iwasaki *et al.* (1988). This instrument contained two response sections which recorded the subject's assessment of a seat feature (*e.g.*, cushion width) and also his satisfaction with that feature. The questionnaire provided a comprehensive short-term evaluation of the test seats, which was then compared with the discomfort measures taken during and at the end of the driving simulation.

The second group of techniques was employed for the evaluation of discomfort during the long-term driving simulation. An open-scale questionnaire was chosen as a standard method, while cross-modality matching (CMM) was adopted as a promising assessment technique. CMM is a procedure by which a subject reports the level of a stimulus by matching the level of sensation with another stimulus, whose magnitude can be objectively measured. Researchers have suggested that matches will be more reliable if the stimuli to be matched are similar (Pepermans and Corlett 1983, Marks 1989). The roadside survey of driver discomfort conducted earlier in this study indicated that drivers frequently characterized their discomfort as burning, a dull ache, or numbing (Schneider and Ricci 1989). In an attempt to approximate those types of discomfort, the external reference stimuli were chosen to be heat, pressure, and cutaneous electro-vibration. The electro-vibration produces a stimulus like a mild electric shock, which can be described as a numbing feeling, increasing to a sharp pain as the magnitude of the stimulus is increased.

Objective techniques comprised a third group. These included physiological responses of the subject and interactions at the seat-subject interface. Electromyography (EMG) was chosen to monitor muscle activity associated with maintaining the driving posture, and also the frequency and severity of voluntary movement during the simulation. Considerable study has been made of the pressure distributions at the seat-subject interface (*e.g.*, Drummond 1982, Kadaba 1984). The majority of these investigations have focused on short-term, static pressure distributions, and many have involved significant modifications to the test seats, imposition of a sensing blanket between the subject and seat, or construction of test seats specifically designed for pressure distribution measurement.

For this research, focusing on extended-duration driving, it was essential to maintain the feel and performance of the seat. To monitor pressures unobtrusively, low-profile pressure sensors were mounted on the seat cushions and backrests. These provided a means to evaluate the pressure exerted on key body areas by the seat, indicated shifts in body weight distribution, and showed changing support demands made of the seat. Additionally, the posture that the subject assumed while driving was monitored with sonic digitizing apparatus. Sonic emitters located at body landmarks were tracked over the course of the driving simulation, allowing calculation and analysis of postural variables.

2.2 TEST APPARATUS

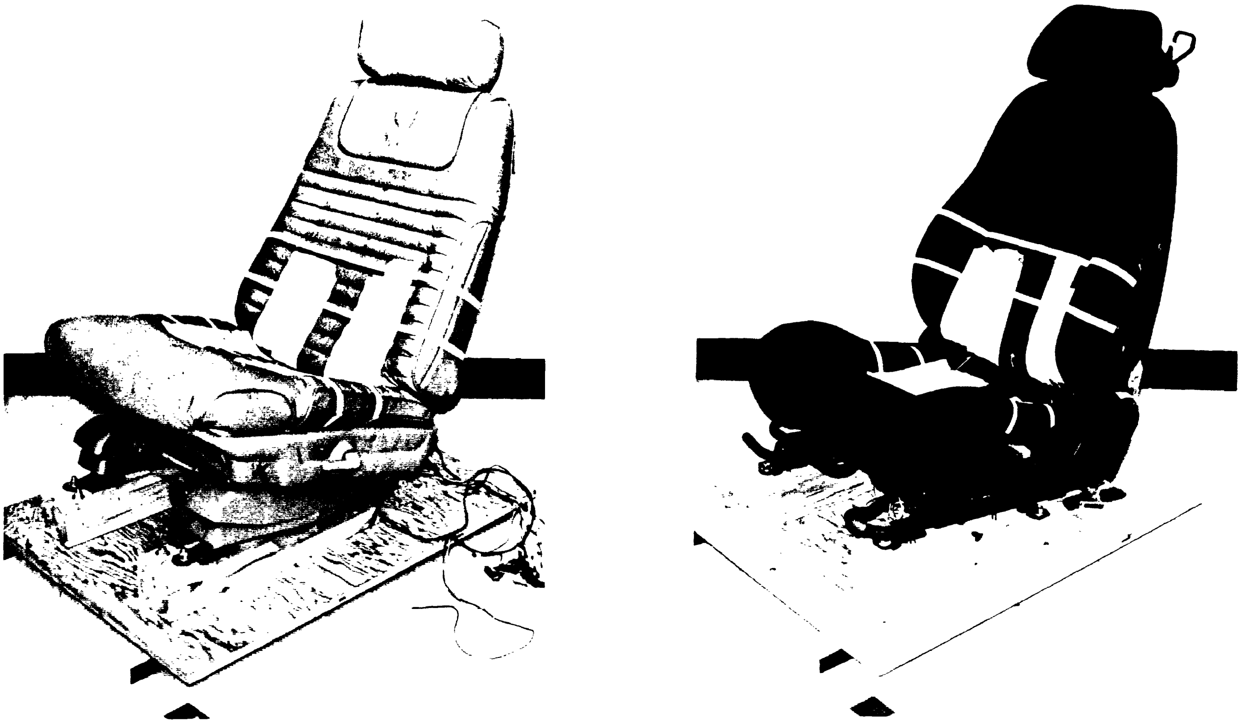
2.2.1 Selection of Seats. Four seats were selected for testing to fit an experimental matrix (see Table 1) configured to provide a range of production design styles. Two seats were selected from domestically produced cars and two from Japanese vehicles. From each of these categories, one luxury and one sport model were chosen. The U. S. models were manufactured by General Motors or its suppliers (Cadillac Seville and Chevrolet Camaro). The Japanese seats were manufactured for Nissan by Ikeda Bussan, Ltd. (Nissan Maxima and 240SX). Figure 1 shows photos of the four test seats.

TABLE 1

TEST SEAT MATRIX

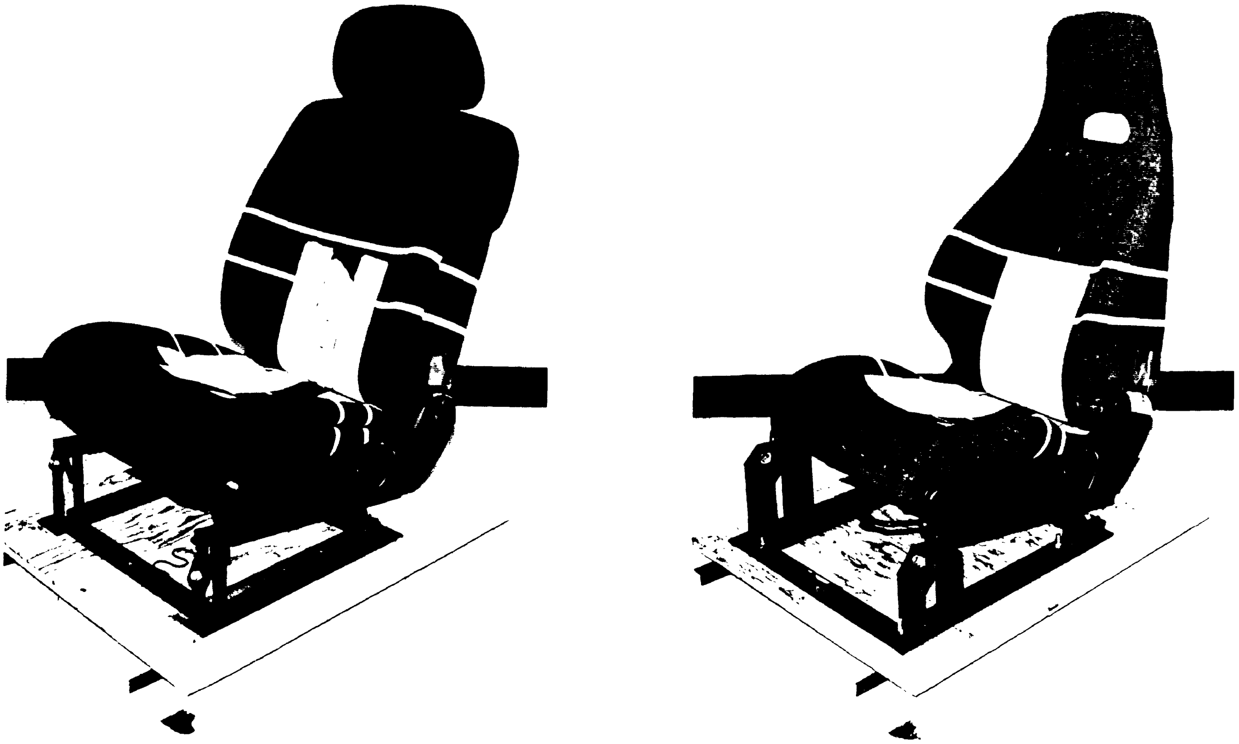
Manufacturer	Sport	Luxury
Japanese	Nissan 240 SX	Nissan Maxima
American	Chevrolet Camaro	Cadillac Seville

The two seats under each of the luxury/sport categories represent different styles. Both luxury seats are wide and soft, but the Maxima seat has a well defined lumbar support and slightly contoured cushion, while the Seville seat is a more traditional luxury model, with no ancillary support targeted to the lumbar area and a thicker, softer cushion than the Maxima seat. The Seville cushion is comprised of a thick foam pad supported by a basket of soft, longitudinal wires, while the Maxima seat has a much thinner pad supported by three lateral s-springs, with a metal pan supporting the thicker



Seat One: Cadillac Seville

Seat Two: Chevrolet Camaro



Seat Three: Nissan Maxima

Seat Four: Nissan 240SX

FIGURE 1. Photographs of the four test seats.

under-thigh padding. The Maxima seat relies largely on the s-springs for cushioning, as its cushion padding is the thinnest of the test seats. The backrest of the Maxima is a thin pad supported by lateral s-springs, with a formed metal lumbar support, while the Seville backrest is a formed foam pad supported by a metal frame. Of particular note on the Seville backrest is the presence of a metal rod along the bottom edge of the backrest padding, which stiffens the local resistance to indentation.

The Camaro and 240SX seats also reflected different design approaches to a similar seating segment. The 240SX cushion was short and firm, with little longitudinal contour, and had short side supports. The thin foam padding was supported by three longitudinal s-springs. By contrast, the Camaro cushion was long and heavily contoured, both laterally and longitudinally. Like the Seville, it was comprised of molded foam supported by a flexible basket of longitudinal wires. Most notable in the comparison of sport seats was the contouring of the Camaro cushion. The Camaro had a thick thigh support arising approximately 250 mm forward of the backrest surface and continuing to the front edge of the cushion. At its maximum height, the padding extended about 50 mm above the surface of the rear portion of the cushion. Also, the Camaro seat had prominent lateral supports in the cushion area, extending from the backrest to the front of the cushion. The backrest of the Camaro seat was formed of molded foam supported by a metal frame, like the Cadillac seat, but included a contoured plastic support in the lumbar area. The 240SX seat had a backrest of molded foam, which was supported by lateral s-springs. Appendix A summarizes selected design characteristics of the four seats.

The two U. S. seats, the Seville and the Camaro, were manufactured with adjustable features in addition to the seat track and seatback recliner included in the Japanese seats. The Seville seat included a motorized tilt mechanism, which would raise or lower the front and rear of the seat. The Camaro seat had electro-pneumatic adjustments for the lumbar support and backrest lateral support, as well as a small range of tilt in the cushion. To control test conditions, all adjustments other than the recliner and seat track were fixed prior to the test. The tilt settings were determined by reference to the manufacturers' package drawings, using the "design" positions. For the Camaro seat, pneumatic supports were disconnected, leaving the seat in an unenhanced configuration. Because of the practical necessity of limiting the adjustment of these seats, their configurations for these tests did not represent actual conditions of use, where drivers could further adjust the seats for their comfort. However, they were tested at "design" positions and effectively represent a particular combination of design parameters.

Additional information on their physical characteristics is contained in the report sections on Indentation Contour (Section 3.8) and Appendix E, Static Force-Deflection Testing. For the purposes of this report, the test seats will be referred to by assigned number, as follows.

Seat 1: Cadillac Seville
Seat 2: Chevrolet Camaro
Seat 3: Nissan Maxima
Seat 4: Nissan 240SX

2.2.2 Seating Buck. An adjustable test apparatus, known as a "seating buck," was designed and constructed to simulate important dimensional features of the vehicles for which the test seats were manufactured. Six parameters were matched to those of the vehicle package. Steering wheel location and angle, accelerator pedal location, footrest location (left foot), dashboard height, and headliner position were made adjustable to conform to each vehicle layout. The test seats were mounted to platforms, preserving their design positions, which were then mounted in the seating buck as appropriate. Figure 2 shows a view of the buck with a test seat mounted and Figure 3 shows a detail of a dimensioned elevation view of the buck layout.

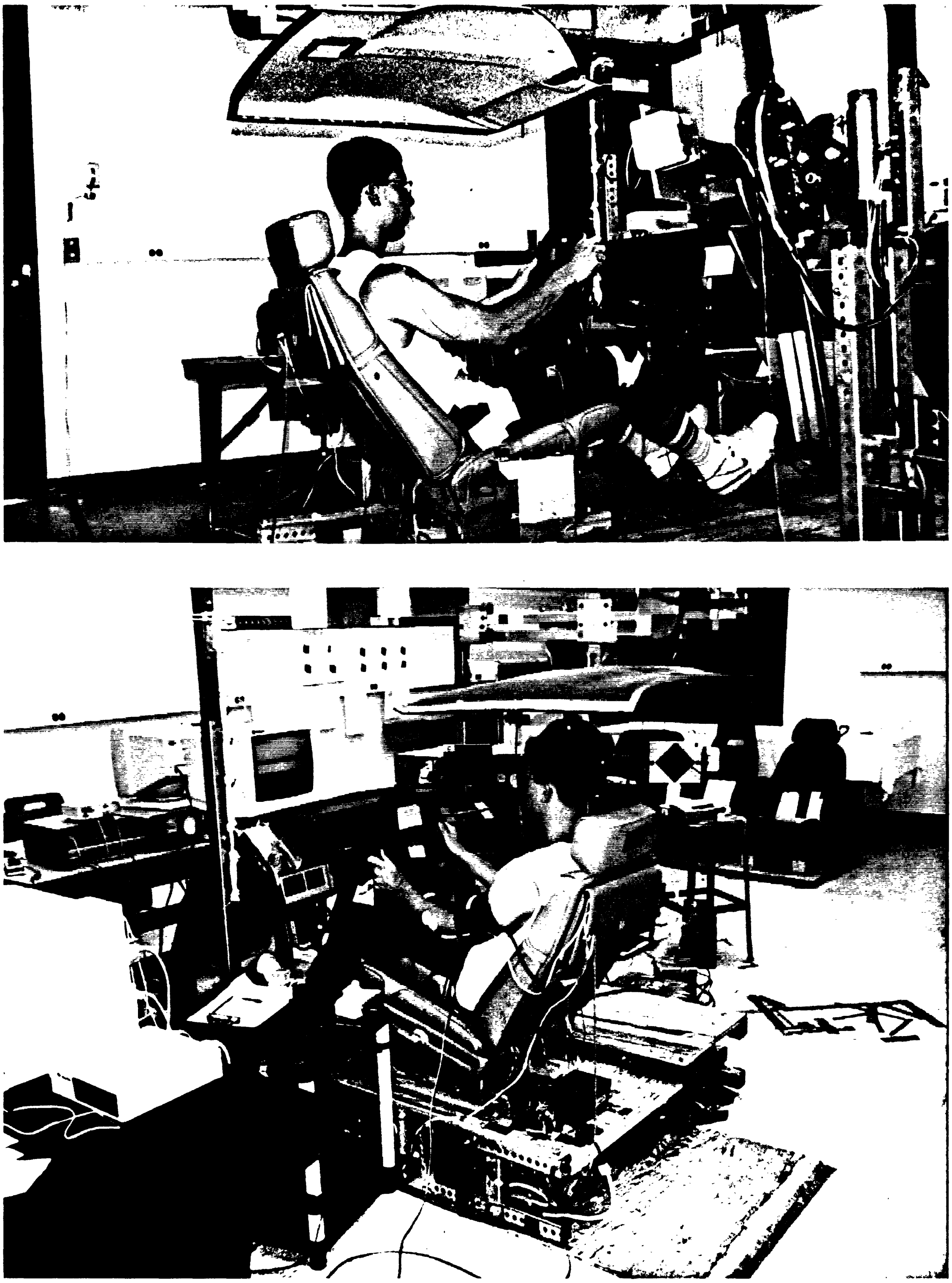


FIGURE 2. Seating buck with test seat mounted.

SEATING BUCK DIMENSIONAL LAYOUT

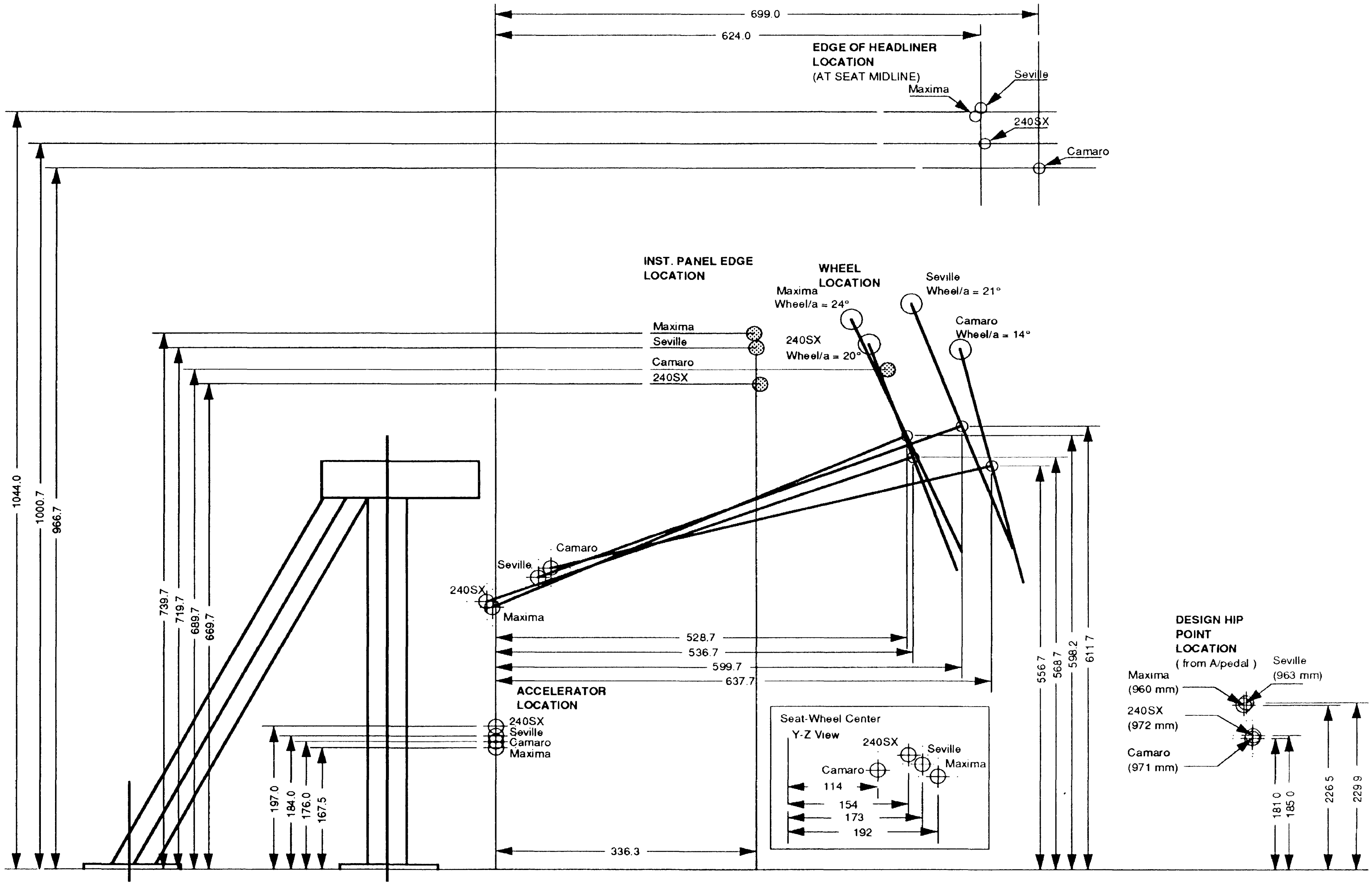


FIGURE 3. Detail of dimensioned buck layout.

2.2.3 Simulator. Simulation of long-distance driving was provided by a symbolic, computer-generated driving scene displayed on a video monitor directly in front of the dashboard. The steering wheel and accelerator pedal were instrumented to provide feedback to software running on a personal computer, which generated a road scene of random curves and hills. The computer displayed a representation of a speedometer, and reacted with color and sound to encourage the subject to remain within "legal" limits. A running score was tabulated and displayed for each test, to help retain the concentration of the subject. Points were awarded at a steady, slow rate for maintaining proper tracking and staying within the required speed range. Deviations from the "road" or speed violations resulted in rapid loss of points. This device was effective in keeping the subjects' attention. The subjects reported that the simulator task was easily mastered, yet required constant attention, conditions substantially similar to rural freeway driving.

2.2.4 Tracking of Body Landmarks. During the driving simulation, each subject's posture was monitored with a Science Accessories Corporation GP8-3D sonic digitizer. Using an eight-channel multiplexer to sample multiple targets, the system reported the three-dimensional locations of eight emitters affixed to body landmarks. Prior to the start of the driving simulation, the emitters were attached to the subject's skin and clothing (see Figure 21 for emitter location), and the location of the emitters was recorded with the subject in a relaxed, standing posture. After the subject was seated in the buck and the simulation begun, the emitter locations were sampled by an IBM PC every thirty seconds for the duration of the test.

The GP8-3D digitizer was also used to record the subject's chest and spine contours during the preliminary session. Four emitters were utilized to construct a digitizing probe, shown in Appendix C. An algorithm in software calculated the location of the tip of the probe from the reported locations of the four emitters. The probe was used to trace the subject's sternum and spine while the emitters were sampled by the computer. The same probe was also used to digitize seat surfaces (see Section 3.8). Appendix C details the algorithm used to calculate the location of the probe tip from the four emitter locations.

2.2.5 Electromyography. Sampling of electromyographic signals in the trunk muscles of the subject was performed using an instrument amplifier fabricated by The University of Michigan Center for Ergonomics. Single-use, infant ECG electrodes, manufactured by Baxter Health Care Corporation, were attached in pairs to the left and right lower back, and left and right abdomen of each subject. A ground electrode was attached over a lower left rib. The electrodes were sampled for differential voltage at approximately 2 Hz. Analog to digital (A-D) conversion and scaling were performed by a Metrabyte DAS-16 A-D board, interrogated by an IBM PC.

2.2.6 Pressure Sensors. Twelve pressure sensors were mounted on each seat to monitor seat-subject interface pressures in the lower-back and buttock areas. Manufactured by Interlink, these force sensing resistors (FSR) change resistance inversely with applied force. Prior to installation on the seats, the performance characteristics of each unit were established by static calibration. Values obtained from the calibration were used in software to interpret the resistance of each sensor. The FSRs were interfaced with an IBM PC through a Metrabyte DAS-16 A-D card and sampled at approximately 1 Hz.

2.2.7 Cross-Modality Matching Apparatus. Devices for the application, control and signal processing of CMM reference modalities were produced on-site or adapted from commercially available devices. The Pressure modality was administered by a small electrically-driven pneumatic pump, which filled a standard sphygmomanometer cuff. Pressure in the cuff was controlled by electrical switches and solenoid valves. The experimenter and subject each were provided with switches to increase or decrease the pressure at preset rates. A manual vent valve could also be activated by the experimenter to release the pressure in the cuff quickly. Air pressure in the cuff was monitored by a Hansen Scale Company digital blood pressure meter.

The reference stimulus for the Heat modality was produced by a thermo-electric heat pump manufactured by Melcor/Materials Electronic Products Corporation. An electronic controller supplied current to heat or cool the plate based on the setting of the subject's control dial. A Barnant 115 thermocouple reader was used with an E-type thermocouple to monitor the plate temperature.

The EV stimulus was produced by a Hanna Health Inc. electro-massager unit. The frequency of the low-power, AC signal was fixed at approximately 83 Hz. Two electrodes, of the type used for EMG (Section 2.2.5) were applied to the subject's left forearm. The signal amplitude was controlled by a potentiometer at the subject's right hand, and monitored through a peak-level processor and voltmeter. The levels reported are nominally peak voltage, but do not necessarily represent the actual voltage applied, because the brief duration of the signal pulse required adjustment of the peak level meter.

2.3 SUBJECT SELECTION

Eight male volunteers were recruited by newspaper advertisement to participate in the study. The ad specified that subjects should experience "moderate to severe" seating discomfort when driving long distances, but should be free of diagnosed leg and back problems. Interviews were conducted to evaluate the applicants' suitability. Subjects were selected with preference given to those who demonstrated an aptitude for the testing procedures. All were college students or graduates.

This small subject pool was designed to provide a range of subject anthropometry, and was not intended to be representative of any larger population. Weight was chosen as a primary selection parameter because of an interest in "build," or body shape. An attempt was made to distribute the subjects about median weight for adult males (Table 2). Five subjects were between 25th and 75th percentile weight for males 18–74 years of age, two were below 25th percentile, and one was above 75th percentile. These subjects provided a range of body shapes, from slight (subject 567) to bulky (subject 932).

TABLE 2

SUBJECT ANTHROPOMETRY
(All measurements in millimeters unless otherwise specified)

Subject Number	Age (yrs)	Weight kg (lb)	Stature mm (in.)	Sitting Height	Knee Height	Hip Breadth	Buttock-Knee Length	Shoulder Breadth
567	29	56 (123)	1702 (67.0)	892	498	332	581	408
658	42	65 (143)	1728 (68.0)	883	540	347	584	400
745	24	74 (163)	1683 (66.3)	859	493	382	610	413
746	25	74 (163)	1733 (68.2)	916	516	348	592	420
753	25	75 (165)	1780 (70.1)	905	620	359	618	450
764	46	76 (167)	1741 (68.5)	811	539	357	613	444
801	26	80 (176)	1815 (71.5)	896	536	357	628	449
932	32	93 (205)	1795 (70.7)	917	528	405	605	458

Each subject selected was assigned a three-digit subject number. The first two numbers represented the subject's weight to the nearest kilogram, while the last digit was the order in which the subjects were tested. Thus, subject 753 weighed 75 kilograms, and was the third subject to be tested.

During the preliminary sessions, certain anthropometric measures were taken by standard manual procedures. These are summarized in Table 2.

2.4 TEST PROCEDURES AND PROTOCOL

2.4.1 Physical Evaluation of Test Seats. Static deflection testing of each of the four test seats was carried out at Ikeda Engineering Corporation in Farmington Hills, Michigan, by representatives of Ikeda and UMTRI. Testing was performed using a Ueshima Static Load Deflection Tester with a deflection rate of 600 mm/min. for all tests. Each seat was first evaluated using a standard, contoured pan, designed to approximate the indentation pattern of a 50th percentile male. Three repetitions were performed on each cushion and each backrest. The backrests were supported by their frames for testing. Two other series of tests were conducted, using flat, circular indenters. The first employed a 200-mm-diameter plate, in two locations on the cushion and backrest. In the second series of tests, single indentation trials were performed at 50-mm intervals on the centerlines of the cushion and backrest using an 80-mm-diameter plate. Data from the static deflection tests are summarized in Appendix E.

Digital surface contours of the test seats were produced by software interfaced with the GP8-3D sonic digitizer, as part of the procedure for recording subjects' indentation contours. Appendix B details the procedures and algorithms used to record seat contours.

2.4.2 Preliminary Session. Prior to testing on the driving simulator, each subject participated in a preliminary session during which various measures of the subject and his initial interaction with the seat were taken. Standard anthropometric data were recorded as well as a digital tracing of the sternum and spine contours of the subject.

During the preliminary session, each subject completed a questionnaire evaluation of each of the test seats. The order of seat testing was varied systematically among the subjects; for each subject, the test order was the same as the order subsequently used in the driving-simulation sessions. After the seat to be evaluated was mounted in the buck, and the buck adjusted to correspond to the appropriate vehicle package configuration, the subject was instructed to be seated. The subject then adjusted the seat track and recline angle, being encouraged to consider his position relative to the features of the buck. The subjects typically gave particular attention to their proximity to the steering wheel and accelerator pedal, with the location of the left footrest as a lesser consideration. There was no apparent reference by the subjects to the dashboard height or headliner location.

After the seat was adjusted to his satisfaction, each subject completed a questionnaire on the features of the seat, his satisfaction with those features, and his overall evaluation of the seat. (Appendix F includes this questionnaire.) Two responses were required of the subject for each question. The first response was an assessment of a seat feature. For instance, the subject was asked to express his perception of the cushion width by making a mark on an open-scale line, anchored at the ends with the words "narrow" and "wide." The second section required the subject to report his satisfaction with the feature by circling a number from one to five, with five indicating highest satisfaction. To control the amount of time taken by the subject to consider each question, and in an attempt to standardize the interpretation of the question wording, each question was presented in an expanded form, along with illustrations, on a computer monitor immediately in front of the dashboard. Each question appeared on the screen for 15 seconds. The subject was encouraged to keep up with the video display, and to skip any question that he lacked sufficient time to answer. Any questions skipped were answered following the last question.

After completion of the questionnaire, the contour of the subject's indentation of the test seat was recorded. Thin, vinyl bags filled with small foam beads were placed on the cushion and backrest. The bags were pressed into place and the air evacuated. Drawing a vacuum in the bag pulled the vinyl against the beads and made the bags rigid. The subject was seated as before, and asked to assume a "normal driving position." Air was then allowed to return to the bags, rendering them flexible. After approximately 30 seconds, to allow the bags to conform to the shape of the indented seat, the air in the bags was once again evacuated, making the bags stiff and preserving the shape of the indentation. The subject then exited the buck, using a rope and handhold to raise himself vertically to avoid disturbing the bags. The surfaces of the bags were then digitized. The process of digitizing the indentation contours was complex. Details of the procedure are found in Appendix B. Briefly, the nodes of a grid marked on each bag were located using the sonic digitizing probe. These data were then aligned with a database containing the unindented seat contours. Finally, a constant vector transformation was used to compensate for the thickness of the vinyl bags (about 8 mm). The data were then examined relative to the unindented seat contours.

A recording of trunk muscle activity associated with a relaxed posture in each of the seats was also made during the preliminary session. The subject sat in each seat in test order with the recline angle as he had set it prior to completing the questionnaire. The subject was instructed to sit in a relaxed posture with his hands on his thighs. A two-minute recording of EMG activity was made. Immediately prior to the subject's first driving simulation session, this procedure was repeated with the two-minute EMG samples taken from the seats in reverse order.

Also during the preliminary session, the subject was given an hour of instruction and practice on the CMM equipment. The procedure was similar to the calibration procedure used before each driving simulation session, but included coaching and feedback from the experimenters.

2.4.3 Driving-Simulation Session. Following each subject's preliminary session, four driving-simulation sessions were conducted. The seats were tested in the same order used for the subject in the preliminary session. Driving-simulation sessions were scheduled on four consecutive days, with the first session on the day after the preliminary session.

The subjects were required to wear tight-fitting exercise tights and cut-away shirts provided by the experimenters. The exercise tights were selected to limit motion relative to the skin of the sonic emitters attached to the fabric. The shirt was cut away to allow attachment of emitters to the sternum and shoulder. Figure 4 shows a subject attired for testing in the driving simulator.

Prior to the start of the driving simulation, the subject underwent a calibration procedure to establish discomfort scales for each of the three CMM reference modalities. This procedure is detailed in Section 2.4.4 below. Two electrodes were attached to the subject's left forearm for application of the EV stimulus. When the calibration was complete, the subject was instrumented for the simulation. EMG electrodes were attached to the subject's lower back and abdomen. Emitters for the sonic digitization system were fastened to various landmarks on the subject's body, or on the clothing over those landmarks. Figure 21 shows the location of the emitters.

The seating buck was adjusted to conform to the appropriate vehicle package. The subject was seated and adjusted the seat track. The recline angle was set by the experimenters to the angle chosen by the subject in the preliminary session. The video display monitor for the driving simulator was placed just beyond the dashboard, directly in front of the subject. The subject was then re-fitted with the CMM pressure cuff and the electrodes on his left forearm were connected to the EV system.

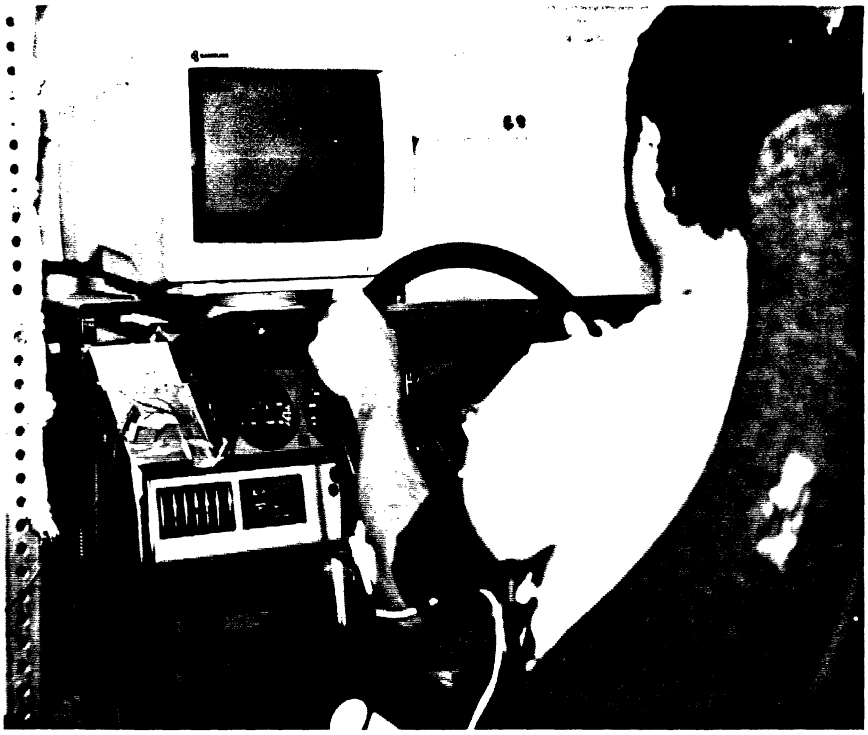


FIGURE 4. A subject operating the simulator.

Immediately prior to the start of the driving simulation, the subject was asked to sit in a relaxed posture for a two-minute, baseline EMG measurement. The sonic digitizer control software, the EMG recording system, the FSR monitor software, and the driving simulator were then activated synchronously. As the test was started, the subject began an evaluation of his discomfort.

The full discomfort-evaluation procedure was referred to as an evaluation interval. The subject first completed a questionnaire consisting of four open-scale questions. The subject was asked to indicate the level of discomfort in his middle-back, lower-back, buttock, and thigh areas by marking anywhere on a 100-mm line between "no discomfort" and "unbearable discomfort." (This questionnaire is included in Appendix F.) To diminish the potential for varying interpretations of the body areas, a symbolic diagram was used to indicate those areas relative to the seat and subject. The subject then repeated the evaluation of the four body areas, in the order middle back, lower back, buttock and thigh, with the Pressure, Heat and EV CMM modalities. Details of the CMM procedures are found in Section 2.4.4.

Following completion of the evaluation interval, the subject was asked to sit in a relaxed driving position for two minutes with his hands on the steering wheel while an

EMG measurement was taken. The subject then activated the display of the driving simulator by pressing a button on the steering wheel and proceeded with the simulation. When thirty minutes had elapsed from the start of the test, including the duration of the evaluation interval, the simulator display stopped, indicating the start of another evaluation interval. The subject then completed another questionnaire for body-area discomfort evaluation, and performed the three CMM modality evaluations and EMG measurement. These steps were repeated until three hours had elapsed, for a total of seven evaluation intervals.

2.4.4 CMM Procedures. Calibration procedures were developed for each of the CMM modalities to relate the objective level of the reference stimulus to the subject's own internal scale of discomfort. Calibrations of the three modalities preceded each driving-simulation session. The resulting data were used to interpret the CMM discomfort evaluations from that session as described below. Each of the three modalities in this study revealed individual characteristics during development of these procedures; consequently, a slightly different approach was used with each modality for calibration, data collection, and scaling of test data.

The calibration of each CMM modality was based on magnitude production techniques, whereby a subject would use the stimulus to produce a level of discomfort requested by the experimenter. Full-scale discomfort was identified as "maximum bearable discomfort," and fractional levels as percentages, *e.g.*, "fifty percent of maximum bearable discomfort." The suggested semantic interpretation of "maximum bearable discomfort" differed among the modalities because of the nature of the stimuli and their application apparatus.

Pressure Modality Calibration. The Pressure modality was calibrated first. The level of pressure supplied to the cuff on the subject's upper arm increased at approximately 5 mm Hg/sec with constant use of the "increase pressure" switch. This rate varied slightly depending on the pressure range and the size of the subject's upper arm (related to cuff volume). It was found that subjects could best attain a desired stimulus level by increasing the pressure steadily to that point. The subject's ability to judge the level of the stimulus was diminished if the increase was erratic or if the pressure was increased and subsequently decreased. In those situations, repeatability of the data was reduced. Consequently, the subjects were encouraged to find the appropriate level by continuous application of the "increase pressure" switch. The rate of increase was sufficiently slow that the subjects were generally able to perform the required match with a constantly increasing pressure. In the event that the subject overshot his intended level, he would use the "decrease pressure" switch to open a valve, releasing pressure slowly. If the first decrease was momentary, the data were considered valid. However, if the subject required a sustained decrease in pressure to perform the match (significant overshoot on the initial attempt) or activated the "decrease pressure" switch more than once, the cuff pressure was returned to zero gauge pressure by the experimenter and the trial repeated. All pressure readings were allowed three seconds to stabilize ± 2 mm Hg. If stabilization did not occur, the trial was voided and the pressure vented to zero. After each successful measurement, the cuff was vented and stabilized at zero mm Hg.

The Pressure modality was constrained by the air pump design to a maximum supplied pressure of approximately 300 mm Hg. Pressures approaching this level were found to be extremely uncomfortable, and were seldom produced. However, during preliminary trials, it was found that subjects differed considerably in their interpretation of "maximum bearable discomfort," when the level was requested without further explanation. The following explanation was found to stabilize maximum levels in a reasonable range. The subjects were asked to produce a level which would be equivalent to the maximum discomfort they could bear in a seating situation. The image of prolonged sitting on a flat wooden board was used to help the subjects anchor a mental scale. The resulting maximum pressure levels produced were high enough that they were almost certainly extremely uncomfortable, fulfilling the objective for anchoring the top end of the scale. Typically, subjects would indicate a maximum bearable discomfort in the range from 150 to 200 mm Hg (*cf.* normal systolic blood pressure from a sphygmomanometer of around 120 mm Hg).

The Pressure modality was found during preliminary trials to exhibit a pronounced sequential bias. That is, the mean of pressure levels produced to match a particular level of discomfort varied depending on the range of pressure experienced by the subject immediately previous. For instance, a "fifty percent of maximum discomfort" produced after a seventy-five percent stimulus would, on average, be higher than one produced after a twenty-five percent match. To produce calibration data relatively free from this bias, reference values were introduced into the calibration.

The subject first produced "maximum bearable discomfort." The experimenter recorded this pressure and vented the pressure in the cuff to zero. Approximately three seconds were allowed for the pressure to stabilize at the fractional levels of discomfort and at zero. The subject would then produce "fifty percent of maximum bearable discomfort." After recording this level and re-stabilizing the pressure at zero, the subject was asked to repeat the fifty-percent level. Typically, the second value would be lower than the first, although subjects varied in their demonstration of this sequential bias. These measurements were repeated three times, and means of the three maximum values and six fifty-percent values were calculated.

Using another set of modality control switches, the experimenter produced a pressure in the cuff equivalent to the mean of the subject's "maximum" trials, and identified the level to the subject as "maximum." The experimenter then requested that the subject produce a level equivalent to seventy-five percent of the reference level. After the level produced was recorded and the cuff vented, the mean of the previous fifty-percent trials was supplied by the experimenter, and identified as "fifty percent of maximum discomfort." The subject was then prompted with words to the effect of "If this [the reference] is fifty percent, produce seventy-five percent." As expected, the seventy-five-percent level readings were typically lower following the fifty-percent reference than after the maximum-level reference. Two repetitions of this sequence followed the first.

The same concept was applied to obtaining data at the twenty-five-percent level. The fifty-percent mean from the first section was used as the upper reference level, while zero was interposed for the lower, as in the first section. The sequence, then, was fifty-percent reference, twenty-five percent produced by the subject and twenty-five percent produced by the subject again. These steps were performed a total of three times.

Finally, a "maximum bearable discomfort" was requested of the subject. If the reading fell within the range of the three taken at the start of the test, the calibration was concluded. Otherwise, readings at maximum and fifty percent were taken, following the procedure of the first section.

During the driving-simulation session, discomfort in each of the four body areas was measured with the Pressure modality after the subject completed the open-scale questionnaire at each evaluation interval. The subject was first given a reference pressure supplied by the experimenter equivalent to the mean of the fifty-percent levels produced in the calibration prior to the test. After the stimulus was identified as "reference pressure at the fifty-percent level," the cuff was vented, and the subject asked to match the discomfort from the cuff to the discomfort in his middle back. The resulting pressure was recorded and the cuff vented. An identical reference pressure preceded the evaluation of the subject's discomfort in his lower-back, buttock, and thigh areas.

The Pressure modality calibration data were fit to a power function of the form

$R = aS^n$,

where,

R is the discomfort level in fraction of full scale;
S is the objective level of the modality stimulus in mm Hg;
a, n are constants determined by the curve fit.

The fit was performed by a linear, least-squares approximation of the data transformed to log-log coordinates, where n is the resulting slope of the line and a is the inverse log of the intercept. Pressure values recorded as discomfort matches during the driving simulation were transformed by the calibration function, yielding values indicated as "fraction of full scale discomfort."

Heat Modality Calibration. The Heat modality calibration followed that of the Pressure modality. The Heat stimulus was applied to the fleshy area at the base of the subject's left thumb. The thermo-electric heat pump, a plate approximately 24 x 30 mm, was mounted on small box easily accessible to the left hand of the subject. The subject rested his hand on top of the box, the base of his thumb in contact with the plate. A control knob at the subject's right hand provided adjustment of the plate temperature. A heat sink within the open-ended box helped to stabilize the performance of the heat plate.

Preliminary experiments showed that the Heat modality, while providing a sensation similar to that often described in connection with seating discomfort, posed problems in adjustment and interpretation of the temperature levels. The heat stimulus, unlike the other two modalities, had both "positive" and "negative" levels, corresponding to plate temperatures that felt hot and cold. It was determined that "zero discomfort" would be defined as the temperature at which the plate was neither hot nor cold. This temperature was seen to vary, both between subjects and with the condition of any single subject's hand. Typically, the level a subject would identify as "zero" heat sensation would rise several degrees after he had performed matches at some higher level. For this reason, the temperature of the plate was considered to be of lesser importance than the difference between the temperature identified as "zero" and the temperature indicated as the appropriate match. Additionally, the adjustment of the temperature modality was time consuming, because of delays caused by the mass of the subject's hand and the skin becoming accustomed to the temperature. Nevertheless, precise matches between modalities were demonstrated when sufficient time was available. The Heat modality also demonstrated a sequential bias similar to that experienced with the Pressure modality.

The time required to produce a stable level (stable for three seconds ± 0.2 degrees C) made a calibration similar to the one used with the Pressure prohibitive. Yet, without such duplication and reference procedures, only erratic results were obtained. Consequently, a much simpler calibration procedure was adopted. Preliminary testing of three subjects with extensive experience with the modality showed that the functions of the differential temperature versus fractional discomfort level were approximately linear. A simplified procedure was developed to produce a linear calibration.

The level of "zero" sensation, neither hot nor cold, was termed the "threshold" for consistency with the EV modality (below). Each measurement with the heat modality consisted of a threshold, and then an appropriate match. The temperature reading at the discomfort evaluation or calibration level could then be scaled with reference to the immediately preceding threshold level, a measure of the condition of the subject's sensitivity. The calibration consisted only of alternating threshold and "maximum bearable discomfort" productions by the subject. Three pairs were produced, followed by a break of about 15 minutes during which the EV calibration was performed. Three more threshold/maximum pairs were produced after the EV calibration.

During the driving-simulation session, a threshold measurement immediately preceded each body-area discomfort match. Scaling of the data was performed by subtracting each threshold from the following reading, producing a differential value. That value was divided by the difference between the threshold value that immediately preceded the reading and the mean maximum level from the calibration:

$$R = (S - Th)/(MAX - Th),$$

where,

R is the discomfort level as a fraction of full scale,
S is the objective stimulus level, in °C ,
Th is the immediately-preceding threshold level, in °C, and
MAX is the mean maximum value (°C) from the calibration.

Each discomfort evaluation, then, was reported as a fraction of the difference between the most recent threshold and the maximum reported in the calibration. This technique allowed, for instance, a 48°C reading which followed a 35°C threshold (differential of 13°C) to represent a higher level of discomfort than a 48°C reading which followed a 40°C reading (differential of 8°C), while preserving the implication that in the second instance, the 48°C reading represented a higher level of discomfort than the 13 to 8 differential ratio would suggest.

EV Modality Calibration. The EV modality, a cutaneous electro-vibratory stimulus, was applied by two electrodes placed on the medial, posterior portion of the subject's left forearm. The stimulus consisted of an 83 Hz, AC waveform with the amplitude adjusted to vary the level of the stimulus. The subject controlled the stimulus level with a potentiometer at his right hand. The stimulus level was monitored by a peak-level processor designed for this application. The instrument produced an output voltage proportional to the signal peak voltage and nominally 1/10 the magnitude. The instrument output was monitored with a voltmeter; a reading of 1.0 represented approximately 10 volts peak amplitude.

The control of the EV stimulus was the most responsive of the three CMM modalities. A ten-turn potentiometer served as the subject's control which gave excellent resolution. Another potentiometer, in series with the subject's control, was used to set the subject's maximum bearable discomfort level. At the start of the EV calibration, the subject's main control was set at its maximum level, while the subject used the second potentiometer to adjust the stimulus to his "maximum" level. Because of the nature of the stimulus, which feels much like a low-level electric shock, there were no semantic difficulties with the definition of "maximum bearable discomfort." When the value was determined, the level was reduced with the subject's control, leaving the setting on the second pot unchanged. The maximum value was thereby fixed, attainable by simply turning the subject's control to its maximum position. Without fixing the maximum, subjects were found to strive to increase the level, dulling the sensation in their arms, which prevented consistent readings.

A "threshold" was defined for the EV modality as the lowest point at which the stimulus could be detected. This value, like its analog in the heat modality, varied between subjects and also within the individuals, generally increasing as trials progressed. During calibration, the subject alternately produced threshold and fractional levels of his previously-selected maximum. The subject was first asked to turn his control to its highest setting, producing the maximum, followed by a threshold. He would then produce fifty, seventy-five, and twenty-five percent levels, each preceded by a threshold. This sequence was performed three times.

The calibration values were expressed as differences by subtracting each threshold from the reading which followed it. The three trials were then averaged for each fractional discomfort level. A power function fit was calculated by the same procedure described for the Pressure modality. The resulting calibration function related differential peak voltage to discomfort in fraction of full scale.

During the driving-simulation sessions, body-area discomfort was evaluated by the EV modality with a threshold preceding each discomfort match. The resulting differentials were scaled by the calibration function. After the first subject had been tested, an additional measurement was added prior to the middle-back reading. Because approximately thirty minutes had elapsed since the last application of the stimulus, the initial threshold was generally much lower than the ones which followed. In an effort to stabilize the subsequent threshold readings, the first threshold was followed by an "overall discomfort" match, which had the desired effect of bringing the next threshold to a level similar to the thresholds preceding the remaining measurements. Data from the "overall discomfort" match were not used for analyses.

3.0 DATA ANALYSES AND RESULTS

Following completion of subject testing, data analysis was conducted in accordance with the study objectives. The general analysis procedure was as follows:

1. examine each data type to determine the trends associated with each test seat,
2. compare the long-term and short-term subjective responses,
3. assess time-related trends in the driving-simulation data,
4. determine relationships between objective and subjective data,
5. assess long-term discomfort trends in relation to seat design parameters,
6. evaluate and compare the performance of the various testing methodologies employed.

The first five items are dealt with in this section of the report. The sixth is discussed in Section 4 below. The initial analysis for each data type was conducted separately and the findings from each compared. The remainder of this report section deals first with each data type separately, then with relationships between the various subjective and objective measures.

3.1 PRELIMINARY QUESTIONNAIRE

During the preliminary session, the subject completed a questionnaire for each test seat, evaluating various seat features and reporting his satisfaction with those features. The questionnaire and related test procedures are described in Section 2. The analyses of the questionnaire data were directed to:

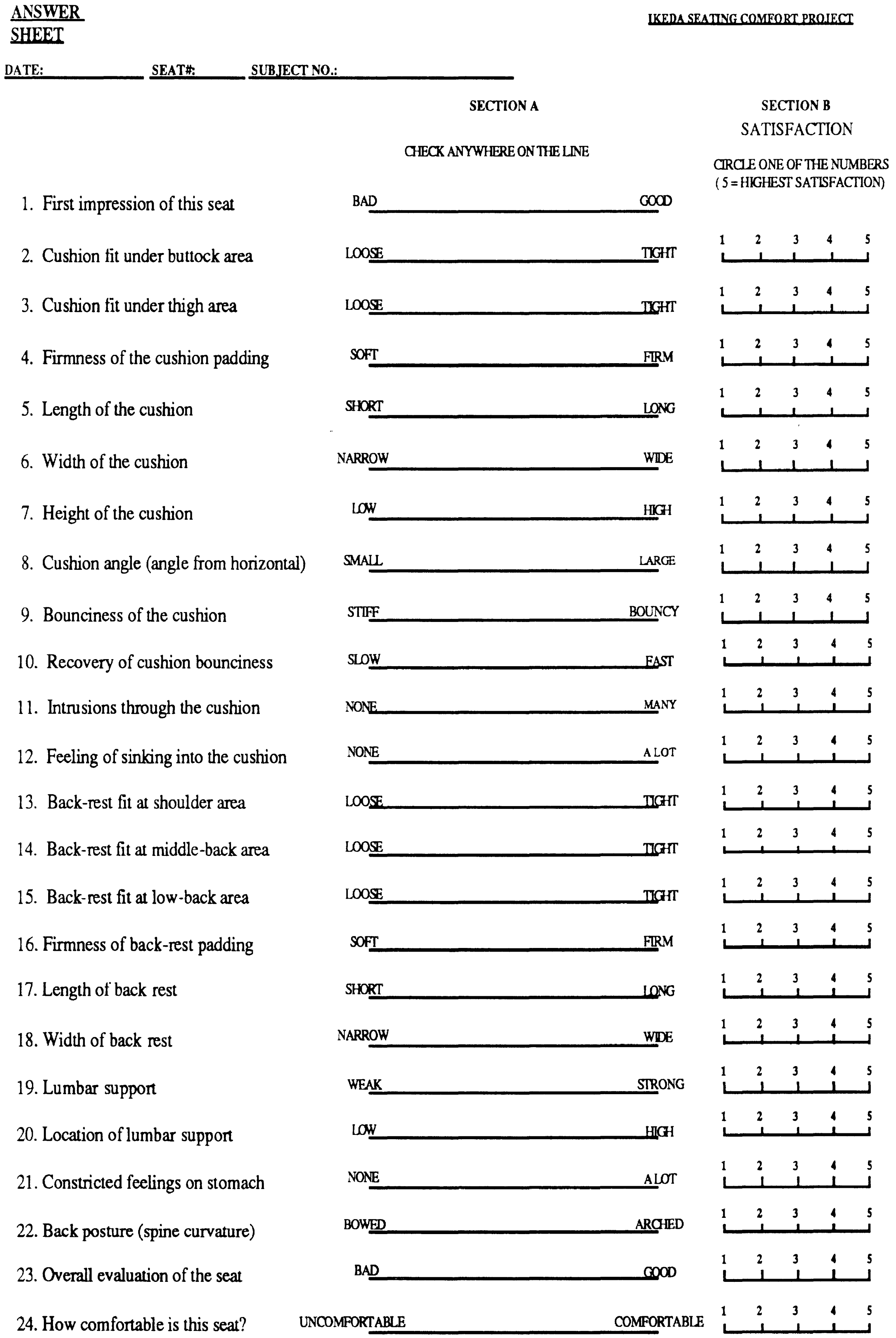
1. determine differences in the subject's perception of seat features,

2. evaluate the relationship between seat feature perception and satisfaction, and

3. investigate the relationships between feature perception, satisfaction, and overall ratings of the seat.

Preliminary analysis indicated that, because of varying response ranges employed by the subjects, standardization of the data would be beneficial. As the purpose of this analysis phase was to uncover differences between the seats, each question was standardized within subject to a mean of zero and unit standard deviation. For each subject, responses to a question from each of the four test seats were standardized together. Consequently, the standardized data expressed each subject's response relative to his response on the same question for the other seats.

For purposes of this analysis, the first section of the questionnaire, the evaluation of the feature, is referred to as Section A. The second section, satisfaction with the feature, is referred to as Section B. Thus, A14 refers to the response in Section A of question fourteen; B14 is refers to the same question, but to the satisfaction response. Question 14 as a whole is referred to as Q14. Also, because each question dealt with a specific feature or overall seat characteristic, the associated features will be indicated by the number of the question. For instance, feature 4 indicates seat cushion firmness, the subject of question 4. Feature 4 is abbreviated F4. Figure 5 is the questionnaire form, indicating Section A and Section B.



ANSWER SHEET

IKEDA SEATING COMFORT PROJECT

DATE: ______ SEAT#: ______ SUBJECT NO.: ______

	SECTION A CHECK ANYWHERE ON THE LINE		SECTION B SATISFACTION CIRCLE ONE OF THE NUMBERS (5 = HIGHEST SATISFACTION)
1. First impression of this seat	BAD	GOOD	
2. Cushion fit under buttock area	LOOSE	TIGHT	1 2 3 4 5
3. Cushion fit under thigh area	LOOSE	TIGHT	1 2 3 4 5
4. Firmness of the cushion padding	SOFT	FIRM	1 2 3 4 5
5. Length of the cushion	SHORT	LONG	1 2 3 4 5
6. Width of the cushion	NARROW	WIDE	1 2 3 4 5
7. Height of the cushion	LOW	HIGH	1 2 3 4 5
8. Cushion angle (angle from horizontal)	SMALL	LARGE	1 2 3 4 5
9. Bounciness of the cushion	STIFF	BOUNCY	1 2 3 4 5
10. Recovery of cushion bounciness	SLOW	FAST	1 2 3 4 5
11. Intrusions through the cushion	NONE	MANY	1 2 3 4 5
12. Feeling of sinking into the cushion	NONE	A LOT	1 2 3 4 5
13. Back-rest fit at shoulder area	LOOSE	TIGHT	1 2 3 4 5
14. Back-rest fit at middle-back area	LOOSE	TIGHT	1 2 3 4 5
15. Back-rest fit at low-back area	LOOSE	TIGHT	1 2 3 4 5
16. Firmness of back-rest padding	SOFT	FIRM	1 2 3 4 5
17. Length of back rest	SHORT	LONG	1 2 3 4 5
18. Width of back rest	NARROW	WIDE	1 2 3 4 5
19. Lumbar support	WEAK	STRONG	1 2 3 4 5
20. Location of lumbar support	LOW	HIGH	1 2 3 4 5
21. Constricted feelings on stomach	NONE	A LOT	1 2 3 4 5
22. Back posture (spine curvature)	BOWED	ARCHED	1 2 3 4 5
23. Overall evaluation of the seat	BAD	GOOD	1 2 3 4 5
24. How comfortable is this seat?	UNCOMFORTABLE	COMFORTABLE	1 2 3 4 5

FIGURE 5. Preliminary Questionnaire response form (smaller than actual size).

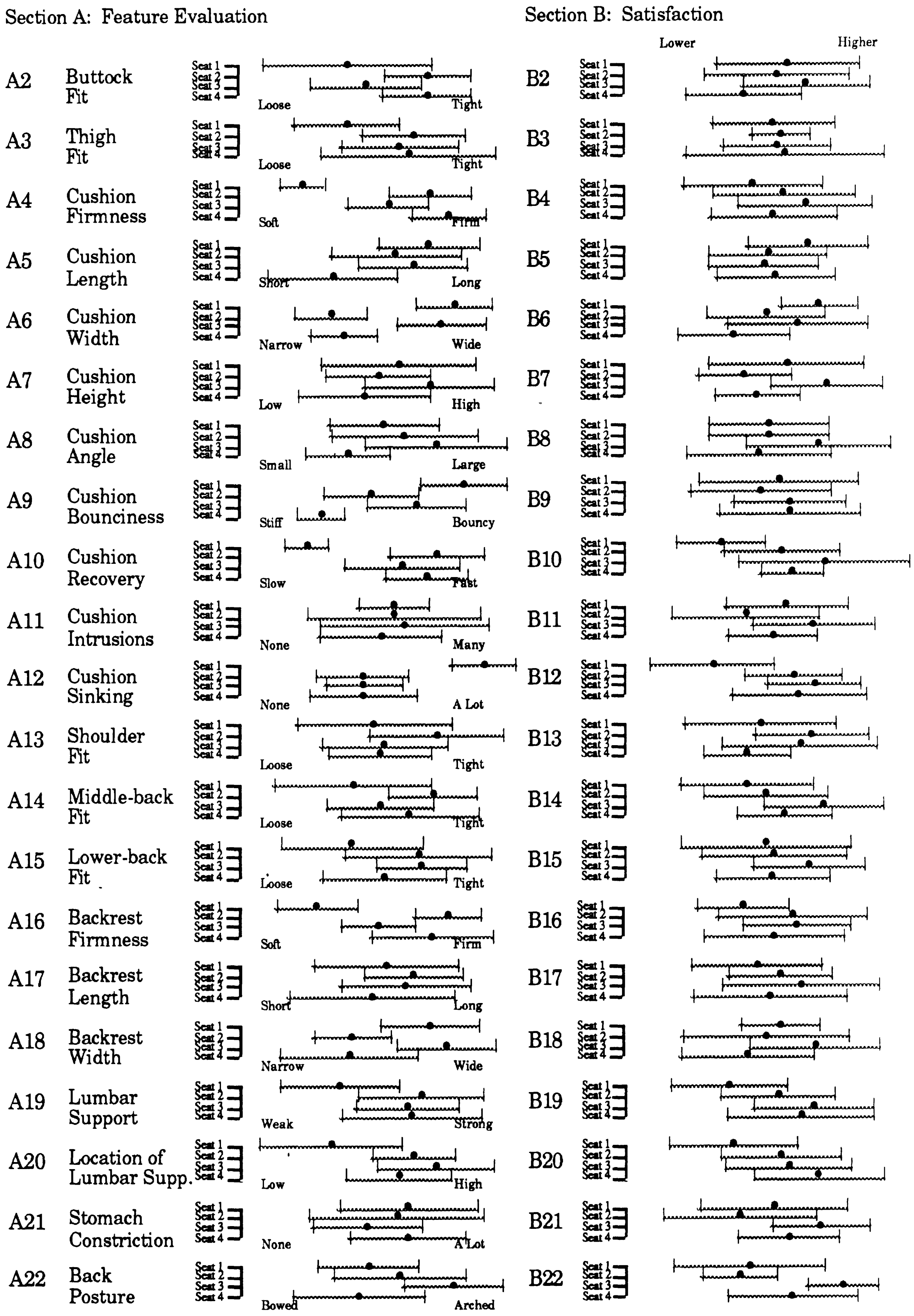


FIGURE 6. Means and standard deviations of standardized responses to Preliminary Questionnaire feature evaluation and satisfaction questions.

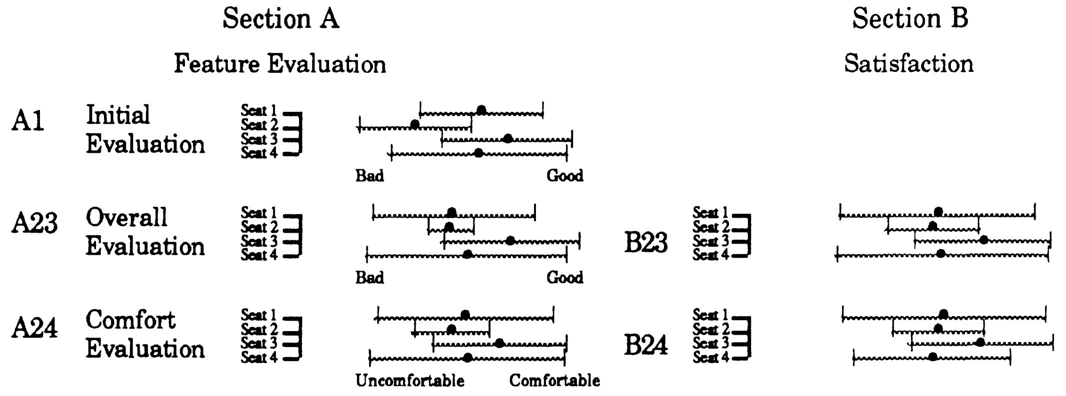


FIGURE 7. Means and standard deviations of standardized responses to Preliminary Questionnaire overall measures.

The standardized responses to the feature evaluation questions are shown in Figure 6 for both Section A and Section B, with the responses to each question broken down by seat. The plots depict the mean plus/minus one standard deviation. Similar plots for the overall evaluation questions (Q1, Q23, and Q24) are shown in Figure 7.

3.1.1 Selection of Complementary Subject Groups. Examination of scatter plots of the standardized data showed a pattern in A23 and A24 which proved to be useful in later analyses. Question 23 is the overall evaluation of the seat from "bad" to "good." Responses to A23 are highly correlated with those from A24, "How comfortable is this seat?" from "uncomfortable" to "comfortable" (r = 0.917). However, A23 was preferred as an overall evaluation because it exhibited a wider range of responses. It was hypothesized that the length of the anchor words ("uncomfortable" and "comfortable") on question 24 contracted the range of responses by reducing the apparent length of the response line.

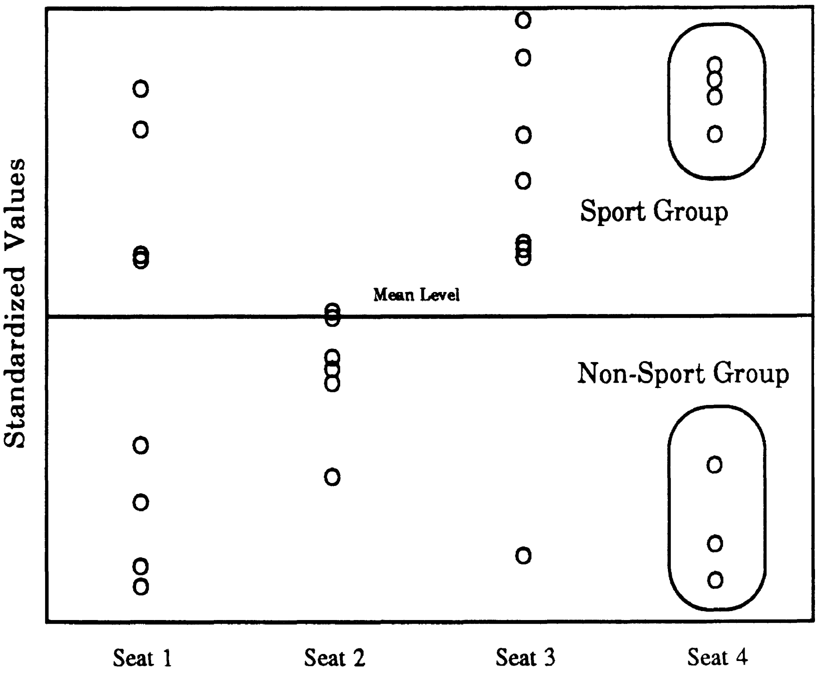


FIGURE 8. Standardized responses to question 23 by seat.

Figure 8 shows a scatter plot of the standardized data from A23 by seat. Groupings of subjects in their evaluations of Seats One and Four are indicated. Note that the responses for Seat Two are grouped slightly below the mean, while those for Seat Three are grouped above the mean, with one outlier. Seat Four, however, shows two distinct subject groups. Four subjects, 658, 745, 746, and 753, scored Seat Four high relative to the other seats, while subjects 567, 764, 801, and 932 reported low scores for Seat Four, relative to the other seats. These groupings reflect subject biases and preferences relative to the test seats, and proved to be useful in later analyses.

Recalling that Seat Four is a sport seat (240SX), those subjects who indicated higher evaluations of Seat Four were called the "Sport" group, and the other four subjects, the "Non-Sport" group. These names will be used subsequently to refer to these groups. When data from all eight subjects are used, the reference will be to "All Subjects." A similar division is evident for the Seat One data in Figure 8, but analysis with that division was not as informative as the Sport/Non-Sport subject groupings. Table 3 shows the complementary subject groups. Recalling that the first two digits of each subject number represent the subject's weight in kilograms, the Sport group is seen to comprise the subjects in the middle of the weight range, while the Non-Sport group includes the three heaviest subjects and the lightest.

TABLE 3

COMPLEMENTARY SUBJECT GROUPS

Subject Group	Subject Number
Sport Group	658 745 746 753
Non-Sport Group	567 764 801 932

3.1.2 Steps of Analysis. Inter-seat differences in response level for several questions are evident in Figure 6 and Figure 7. Analysis of variance, with seat as a factor and question responses as the independent variable, confirmed this observation. To further investigate inter-seat differences in the standardized data, two-tailed Student's t-tests for paired data were performed between seats for each of the questions. A significance level of $P \leq 0.05$ was established for the statistical tests; some consideration was also given to findings at $P \leq 0.10$.

Following the examination of inter-seat differences, the data from all four test seats were combined, and correlation/regression analyses were used to evaluate relationships between the questionnaire sections and between feature responses and the overall evaluation.

The report sections which follow present the results of the inter-seat comparisons and the correlation/regression analyses for All Subjects and for the Sport and Non-Sport complementary subject groups.

3.1.3 Results of Paired t-Tests - Section A. These results can be expressed as significant comparison pairs. For instance, "3>1" is used to express that on average, the response to Seat Three was significantly higher than the response to Seat One for the measure in question. For Section A, the meaning of the comparison differs, depending on the question, but for Section B, the higher response indicates a higher level of satisfaction. Table 4 shows the t-values calculated for the inter-seat comparison with the data from All Subjects. Identical analyses performed with the data from the Sport and Non-Sport subject groups produced the values in Table 5 and Table 6.

TABLE 4

INTER-SEAT COMPARISONS FOR PRELIMINARY QUESTIONNAIRE SECTION-A RESPONSES: ALL SUBJECTS

Response Variable	t-Values						Comparisons P ≤ 0.05
	1 v. 2	1 v. 3	1 v. 4	2 v. 3	2 v. 4	3 v. 4	
A1	2.647 *	-0.724	0.064	-2.559 *	-1.457	0.637	1,3>2
A2	-1.895 †	-0.423	-1.887	2.417 *	0.075	-2.166 †	2>3
A3	-2.751 *	-2.147 †	-1.322	0.399	0.111	-0.207	2>1
A4	-7.913 **	-4.047 **	-10.580 **	1.802	-0.690	-2.759 *	2,3,4>1 4>3
A5	0.979	0.659	2.639 *	-0.469	1.759	2.277 †	1>4
A6	6.531 **	0.468	6.525 **	-5.135 **	-0.549	4.715 **	1,3>2,4
A7	0.467	-0.773	0.846	-1.925 †	0.438	1.458	
A8	-0.543	-1.651	1.126	-0.650	2.021 †	2.803 *	3>4
A9	3.848 **	1.546	9.278 **	-1.626	2.059 †	5.253 **	1>2,4 3>4
A10	-8.202 **	-3.756 **	-6.840 **	1.033	0.376	-0.869	2,3,4>1
A11	-0.006	-0.334	0.535	-0.189	0.324	0.540	
A12	5.608 **	7.639 **	4.332 **	-0.042	-0.017	0.021	2,3,4>1
A13	-1.533	-0.217	-0.166	1.497	1.431	0.173	
A14	-2.104 †	-0.694	-1.303	2.679 *	0.720	-0.788	2>3
A15	-1.653	-2.074 †	-0.752	-0.083	0.837	1.701	
A16	-8.943 **	-2.614 *	-3.654 **	3.994 **	0.499	-1.906 †	2,3,4>1 2>3
A17	-0.690	-0.540	0.312	0.268	1.250	0.699	
A18	2.812 *	-0.685	2.285 †	-4.632 **	0.112	2.456 *	1,3>2 3>4
A19	-2.469 *	-1.951 †	-1.989 †	0.485	0.214	-0.141	2>1
A20	-2.505 *	-2.502 *	-1.858	-0.882	0.526	1.207	2,3>1
A21	0.266	1.045	-0.002	0.680	-0.236	-2.182 †	
A22	-1.320	-2.673 *	0.258	-1.404	0.934	4.084 **	3>1,4
A23	0.088	-1.456	-0.246	-2.373 *	-0.446	0.847	3>2
A24	0.435	-0.755	-0.035	-1.790	-0.380	0.688	

† P ≤ 0.10
* P ≤ 0.05
** P ≤ 0.01

In the data from Section A in Table 4, questions 7, 11, 13, 15, 17, 21, and 24 show no inter-seat comparisons significant with P ≤ 0.05 for All Subjects, though 7, 15, and 21 each show one pair at P ≤ 0.10. Most notably, A24, overall comfort, failed to produce a significant comparison, and A23 produced only 3>2. This clearly shows the limitations of the data set for overall seat comparisons. However, as indicated by the plot of A23 versus seat (Figure 8), dividing the subjects into complementary subject groups produces a greater number of significant differences on overall measures. The data for the Sport group indicate 4>1,2, meaning that those subjects rated Seat Four significantly higher on the overall measures than either Seat One or Seat Two. The Non-Sport group, on A23, rated Seat Three higher than Two or Four, but preferred Seat Two to Seat Four, establishing the ranking 3>2>4 for overall evaluation.

TABLE 5

INTER-SEAT COMPARISONS FOR PRELIMINARY QUESTIONNAIRE SECTION-A RESPONSES: SPORT GROUP

Response Variable	t-Values						Comparisons P ≤ 0.05
	1 v. 2	1 v. 3	1 v. 4	2 v. 3	2 v. 4	3 v. 4	
A1	1.278	-0.767	-1.953	-1.710	-11.846 **	-0.710	4>2
A2	-0.474	-0.084	-0.754	0.869	-1.139	-1.004	
A3	-2.254	-2.282	-31.187 **	0.346	-2.018	-2.709 †	4>1
A4	-7.063 **	-2.976 †	-71.128 **	1.720	-1.292	-1.772	4,2>1
A5	-0.487	0.817	1.156	1.007	2.949 †	1.102	
A6	4.105 *	-0.067	2.946 †	-2.560 †	-0.414	2.667 †	1>2
A7	1.121	0.108	0.966	-1.075	-0.291	0.562	
A8	1.307	-1.697	1.180	-5.553 *	0.702	6.716 **	3>2,4
A9	4.043 *	0.864	4.675 *	-2.199	2.794 †	2.592 †	1>2,4
A10	-18.893 **	-2.126	-4.934 *	1.269	0.717	-0.573	2,4>1
A11	0.312	0.018	-0.474	-0.225	-0.626	-0.282	
A12	9.116 **	3.789 *	36.315 **	-0.549	0.358	0.943	1>2,3,4
A13	-1.054	0.259	-0.322	2.125	1.107	-1.202	
A14	-2.242	-0.880	-0.890	1.437	0.112	-0.454	
A15	-10.738 **	-5.609 *	-3.650 *	0.297	1.039	2.036	2,3,4>1
A16	-16.486 **	-2.922 †	-10.898 **	2.517 †	1.480	-1.328	2,4>1
A17	0.022	0.400	-0.048	0.386	-0.115	-0.329	
A18	2.127	-0.514	0.646	-2.146	-0.599	0.749	
A19	-3.086 †	-2.962 †	-5.463 *	0.172	-0.139	-0.341	4>1
A20	-1.113	-0.703	-1.320	0.090	-1.024	-2.119	
A21	1.163	1.058	0.692	0.145	-0.384	-1.506	
A22	-2.326	-2.387 †	0.594	-0.479	2.051	6.279 **	3>4
A23	-1.128	-1.133	-5.398 *	-0.766	-10.548 **	-1.941	4>1,2
A24	-0.580	-0.842	-4.423 *	-0.759	-3.397 *	-1.654	4>1,2

† P ≤ 0.10
* P ≤ 0.05
** P ≤ 0.01

The analysis for the A24 responses shows only the 3>4 comparison to be significant with $P \leq 0.05$. Note that the Non-Sport group showed an overall comparison of Seats Two and Four opposite from that of the Sport group, with the Non-Sport group rating Seat Two higher.

For All Subjects, the responses to A4, A6, and A16 produced the largest number of significant inter-seat comparisons, as indicated in Table 4. Seat One was judged significantly softer than the others, while Seat Four was considered firmer than Seat Three. Both of the luxury seats were perceived as wider than both of the sport seats. The backrest padding was reported softer for Seat One than the others, while Seat Three was thought to be softer than Seat Two.

TABLE 6

INTER-SEAT COMPARISONS FOR PRELIMINARY QUESTIONNAIRE SECTION-A RESPONSES: NON-SPORT GROUP

Response Variable	t-Values						Comparisons P ≤ 0.05
	1 v. 2	1 v. 3	1 v. 4	2 v. 3	2 v. 4	3 v. 4	
A1	2.667 †	-0.190	1.290	-1.654	0.177	1.987	
A2	-3.303 *	-0.471	-2.324	2.720 †	1.654	-2.383 †	2>1
A3	-1.447	-0.891	0.487	0.212	1.825	1.102	
A4	-4.220 *	-2.433 †	-4.805 *	1.074	-0.177	-1.849	2,4>1
A5	2.018	0.362	5.229 *	-1.120	0.317	2.402 †	1>4
A6	4.929 *	1.810	10.866 **	-6.560 **	-0.316	3.792 *	1,3>2,4
A7	-0.315	-1.018	0.254	-2.135	0.991	1.675	
A8	-1.549	-0.625	0.170	0.651	2.121	0.745	
A9	1.805	1.412	9.975 **	-0.419	2.106	5.317 *	1,3>4
A10	-3.701 *	-2.926 †	-4.115 *	0.338	0.042	-0.651	2,4>1
A11	-0.288	-0.568	3.111	-0.051 †	1.213	1.585	
A12	2.472 †	9.765 **	1.674	0.603	-0.105	-0.589	1>3
A13	-0.975	-0.521	0.048	0.243	0.809	1.047	
A14	-1.101	-0.171	-0.895	2.227	1.016	-0.601	
A15	0.316	-0.015	0.795	-0.236	0.369	1.038	
A16	-5.798 *	-1.023	-1.533	2.881 †	-0.006	-1.260	2>1
A17	-0.957	-1.769	0.447	-0.175	1.909	2.087	
A18	1.679	-0.411	4.526 *	-7.687 **	1.474	6.551 **	1,3>4 3>2
A19	-0.900	-0.527	-0.385	0.591	0.313	0.111	
A20	-2.457	-14.436 **	-1.662	-1.222	2.458 †	6.763 **	2>1 3>4
A21	-0.679	0.220	-1.220	0.736	-0.015	-1.510	
A22	0.874	-1.298	0.024	-1.453	-0.161	1.667	
A23	1.328	-0.771	2.892 †	-3.540 *	7.286 **	12.084 **	3>2>4
A24	1.164	-0.122	2.353 †	-1.916	2.849 †	12.384 **	3>4

† $P \leq 0.10$
* $P \leq 0.05$
** $P \leq 0.01$

Several other questions produced noteworthy comparisons for All Subjects. On the first question, the initial evaluation, both Seat One and Seat Three were rated higher than Seat Two. Seat Two was considered to fit more tightly in the thigh area than Seat Three, and more tightly in the buttock area than Seat One. Seat Two was rated a tighter fit in the middle-back area than Seat Three. The backrest of Seat One was perceived to be wider than that of Seat Two, and Seat Three was judged to be wider than Seat Two and Seat Four. The lumbar support of Seat Two was rated stronger than that of Seat One. The location of the lumbar support in Seat One was indicated to be lower than the lumbar support of Seat Two or Seat Three. Seat Three was reported to provide a more arched back posture than Seat Four.

Differences in the statistical tests of Section-A data appeared between the complementary subject groups derived from the A23 responses. There was one instance in which complementary groups rated a pair in an opposite manner. In the Sport/Non-Sport comparison, the Sport group scored Seat Four higher than Seat Two on A23, while the Non-Sport group rated Seat Four lower than Seat Two. This was expected because of the manner in which the subject groups were defined. For most questions, the complementary groups indicated different perceptions of the seat features by producing different significant pairs. Some of those comparisons were not present in the analysis for All Subjects. These are detailed below.

COMPARISON OF SPORT AND NON-SPORT SECTION-A t-TEST RESULTS

- For the Sport group, the initial rating of Seat Four was higher than Seat Two. This parallels the overall rating by the group (A23). The Non-Sport group showed no significant comparisons for Q1.
- The Non-Sport group perceived Seat Two to fit more tightly in the thigh area, while the Sport group showed no significant comparisons on that feature.
- The Sport group rated Seat Four tighter in the buttock area than Seat One, with the Non-Sport group showing no differences.
- The Sport group found Seat Three to have a higher cushion angle than Seat Two. All Subjects indicated that the cushion angle was greater on Seat Three than on Seat Four.
- Backrest fit at low-back area, for which there were no significant comparisons with the data from All Subjects, was found to be looser in Seat One than in any other seat by the Sport group. The Non-Sport group showed no significant comparisons on the feature.
- The Non-Sport group results showed that the backrest of Seat One was rated wider than was the backrest of Seat Four, while the Sport group showed no significant comparisons.
- The Sport group rated the lumbar support of Seat Four stronger than that of Seat One. The Non-Sport group located the lumbar support in Seats Three and Four higher than in Seat One.
- The comparisons in A23 and A24 were mentioned above.

3.1.4 Results of Paired t-Tests - Section B. The data from Section B produced fewer significant differences than those from Section A, due in part to the difference in response type. Only seven questions produced comparisons significant at $P \leq 0.05$ for All Subjects. Table 7 summarizes the significant comparisons. The low level of discrimination was partially explained by later analyses which showed that among the complementary subject groups there were different criteria for satisfaction with individual features (see Section 3.1.5).

Table 7 indicates that, in the feature satisfaction responses from All Subjects, Seat Three was given higher satisfaction ratings than Seat Four for buttock fit, although there are no significant differences in Section A for Seat Three and Seat Four on that feature. Seat One received higher satisfaction than Seat Four on cushion width, and was reported to be significantly wider in Section A data. Seat Three was given higher satisfaction ratings than Seat Two or Four for cushion height, but the Section-A data analysis indicates no significant differences on that feature. The data for Seat One are lower than for the other seats in satisfaction with recovery of cushion bounciness; the Section-A data show the Seat One recovery rate to be slower than that of the other seats. On F12, sinking into the cushion, Seat Three received higher satisfaction ratings than Seat One; in the Section-A data, Seat One was rated significantly higher on that feature (more sinking). The backrest fit in the shoulder area of Seat Two was preferred to that of Seat Four, but that comparison is not reflected in the Section-A data for All Subjects. Similarly, the back posture of Seat Three was preferred to Seat One or Two; the significant comparisons in the Section-A data from All Subjects indicate that Seat Three provided a more arched posture than Seat One.

TABLE 7

SIGNIFICANT INTER-SEAT DIFFERENCES IN PRELIMINARY QUESTIONNAIRE SECTION-B DATA, WITH CORRESPONDING SECTION-A FEATURE EVALUATION WHERE SIGNIFICANT ($P \leq 0.05$): ALL SUBJECTS

Questionnaire Feature	Section B		Section A
	Satisfaction	t-Value	Feature Rating
Buttock Fit	3>4	2.415	- -
Cushion Width	1>4	3.555	1>4
Cushion Height	3>2	-3.180	- -
	3>4	2.499	- -
Cushion Recovery	2>1	-2.448	2>1
	3>1	-2.462	3>1
	4>1	-3.989	4>1
Cushion Sinking	3>1	-4.545	1>3
Shoulder Fit	2>4	2.969	- -
Back Posture	3>1	-2.951	3>1
	3>2	-5.946	- -

Table 8 shows the inter-seat comparisons which are significant for the Sport and Non-Sport Groups. No seat comparisons in the Section-B data are significant for both groups. Seven seat pairs also show significant differences in the Section-A data, as indicated. The Sport group gave Seat One lower satisfaction ratings on cushion sinking and cushion recovery, two features for which the group had indicated Seat One had slower recovery and produced more feelings of sinking. The Non-Sport group gave Seat Four lower satisfaction ratings on cushion width, shoulder fit and backrest width, after indicating in Section A that Seat Four was narrower and looser in those areas than the other seats. The Sport group also gave Seat One lower satisfaction ratings than Seats Three or Four for the height of the lumbar support, and the Non-Sport group found the back posture in Seat Three preferable to that of Seat Two. These feature comparisons are not significant in Section-A data.

TABLE 8

SIGNIFICANT INTER-SEAT DIFFERENCES IN PRELIMINARY QUESTIONNAIRE SECTION-B DATA, WITH CORRESPONDING SECTION-A FEATURE EVALUATION WHERE SIGNIFICANT ($P \leq 0.05$): SPORT AND NON-SPORT SUBJECT GROUPS

Questionnaire Feature	Section B		Section A	Subject Group
	Satisfaction	t-Value	Feature Rating	
Cushion Width	1>4	3.859	1>4	Non-Sport
Cushion Recovery	3>1	-21.617	- -	Sport
	4>1	-5.830	4>1	Sport
Cushion Sinking	2>1	-9.038	1>2	Sport
	3>1	-6.330	1>3	Sport
	4>1	-9.038	1>4	Sport
Shoulder Fit	2>4	4.584	- -	Non-Sport
Backrest Width	1>4	4.651	1>4	Non-Sport
	3>4	8.290	3>4	Non-Sport
Lumbar Height	3>1	-9.517	- -	Sport
	4>1	-13.748	- -	Sport
Back Posture	3>2	5.476	- -	Non-Sport

In the data from Section B, there are also two instances in which opposite comparisons were made between the Sport and Non-Sport groups at the $P \leq 0.10$ level. On back posture, F22, the Sport group preferred Seat Two to Seat Three, while the Non-Sport group gave Seat Three the higher satisfaction rating. This question produced no significant comparisons between Seats Two and Three in Section A for either subject group. On question 23, the overall evaluation of the seat, the Sport group preferred Seat Four to Seat One with $P \leq 0.10$, while the Non-Sport group rated Seat One higher. The Sport group comparison is significant in the Section-A data, but the Non-Sport comparison is not. These results are probably related to the manner in which the groups were selected.

3.1.5 Correlation/Regression Analyses. To better understand the trends in the preliminary questionnaire data, a series of correlation/regression analyses were performed, using pooled data from all subjects and seats. The feature evaluation responses for each question were regressed against the satisfaction responses for that question, and the Section-B responses were regressed against both the Section-A and the Section-B responses on the overall evaluation questions. The null hypothesis was taken that the slope of the least-squares regression line was equal to zero and $P \leq 0.05$ was set as the threshold of significance, with some consideration given to findings with $0.05 \leq P \leq 0.10$.

The first series of regressions, relating the Section-A responses to the Section-B responses for the same question, were used to discover relationships between the feature evaluations and satisfaction with the feature. The second series of regressions related the satisfaction with a feature to the overall evaluation of the seat. The analyses were performed between the Section-B responses for each question and the Section-B responses for questions 23 and 24, and between the Section-B responses and the Section-A responses for questions 23 and 24.

Of these, the highest correlations were found in the comparisons using the Section-A responses from question 23 as the overall measure; the results of those regressions were used for subsequent analyses. The Section-A responses for question 23 produced better correlations than the Section-B responses because of increased resolution and greater range in the response (open-scale line versus number from one to five). Also, the responses for question 23 were more useful than those from question 24, because of a greater distribution of responses (see Section 4.1). For question 23, the correlation between the Section-A and Section-B responses for All Subjects is 0.843, which is sufficiently high to consider the Section-A responses interchangeable with the satisfaction responses for the purposes of this analysis.

TABLE 9

CORRELATION COEFFICIENTS AND REGRESSION F-STATISTICS FOR PRELIMINARY QUESTIONNAIRE ANALYSES: ALL SUBJECTS

Question and Feature	BvA		A23vB	
	r	F	r	F
2. Buttock Fit	0.121	0.442	0.384	5.20 †
3. Thigh Fit	0.304	3.06	0.559	13.6 **
4. Cushion Firmness	0.316	3.34	0.756	40.0 **
5. Cushion Length	0.340	3.93	-0.010	0.003
6. Cushion Width	0.485	9.22 **	0.371	4.80 †
7. Cushion Height	0.668	24.2 **	0.287	2.69
8. Cushion Angle	0.135	0.556	0.386	5.26 †
9. Cushion Bounciness	-0.141	0.611	0.530	11.7 **
10. Cushion Recovery	0.581	15.3 **	0.323	3.49 †
11. Cushion Intrusions	-0.315	3.30	0.248	1.96
12. Cushion Sinking	-0.771	44.0 **	0.375	4.90 †
13. Shoulder Fit	0.211	1.40	0.421	6.49 *
14. Middle-back Fit	0.276	2.48	0.586	15.7 **
15. Low-back Fit	0.417	6.30 †	0.433	6.92 *
16. Backrest Firmness	0.443	7.31 *	0.333	3.74
17. Backrest Length	0.710	30.4 **	0.603	17.2 **
18. Backrest Width	0.457	7.90 *	0.557	15.3 **
19. Lumbar Support	0.876	98.8 **	0.535	12.1 **
20. Lumbar Location	0.148	0.675	0.249	1.99
21. Stomach Constriction	-0.751	38.9 **	0.373	4.85 †
22. Back Posture	0.426	6.65 *	0.516	10.9 **
23. Overall Evaluation	0.843	73.9 **	0.843	73.9 **
24. Overall Comfort	0.669	24.3 **	0.764	42.2 **

† $P \leq 0.10$
* $P \leq 0.05$
** $P \leq 0.01$

Tables 9, 10, and 11 show the compiled Pearson's r correlation coefficients and regression F-statistics for All Subjects and for the Sport and Non-Sport subject groups described above. The regressions of A23 on the Section-B responses are referred to as the A23vB regressions, and the regressions of the Section-B responses on the Section-A responses for the same question are labeled the BvA regressions.

TABLE 10

CORRELATION COEFFICIENTS AND REGRESSION F-STATISTICS FOR PRELIMINARY QUESTIONNAIRE ANALYSES: SPORT GROUP

Question and Feature	BvA		A23vB	
	r	F	r	F
2. Buttock Fit	0.225	0.746	0.292	1.30
3. Thigh Fit	0.608	8.20 *	0.707	14.0 **
4. Cushion Firmness	0.567	6.65 *	0.790	23.3 **
5. Cushion Length	0.384	2.42	-0.146	0.307
6. Cushion Width	0.224	0.743	-0.018	0.011
7. Cushion Height	0.373	2.26	-0.106	0.159
8. Cushion Angle	0.219	0.707	0.156	0.347
9. Cushion Bounciness	-0.377	2.32	0.496	4.58 †
10. Cushion Recovery	0.475	4.07	0.507	4.83
11. Cushion Intrusions	-0.115	0.186	0.274	1.14
12. Cushion Sinking	-0.963	178. **	0.597	7.76 *
13. Shoulder Fit	-0.016	0.003	0.519	5.16 †
14. Middle-back Fit	0.265	1.06	0.629	9.16 *
15. Low-back Fit	0.424	3.07	0.218	0.701
16. Backrest Firmness	0.550	6.08 †	0.535	5.63 †
17. Backrest Length	0.500	4.67 †	0.684	12.3 **
18. Backrest Width	0.114	0.186	0.522	3.03
19. Lumbar Support	0.859	39.3 **	0.708	14.0 **
20. Lumbar Location	0.480	4.19	0.565	6.57 *
21. Stomach Constriction	-0.707	14.0 **	0.397	2.62
22. Back Posture	0.345	1.89	0.556	6.26 †
23. Overall Evaluation	0.888	20.4 **	0.770	20.4 **
24. Overall Comfort	0.520	5.18 †	0.662	10.9 *

† $P \leq 0.10$
* $P \leq 0.05$
** $P \leq 0.01$

Interpretation of correlation/regression results must always proceed carefully, particularly when multiple causation is clearly involved, as is the case with the overall evaluation of the test seats. With those cautions in mind, the following interpretations of the statistically significant results from these analyses were applied.

BvA: The regression shows a relationship (positive or negative) between the evaluation of the feature and satisfaction with the feature. A significant, positive correlation on question 4, for example, would be interpreted to mean that the subjects were more satisfied with firmer cushions.

TABLE 11

CORRELATION COEFFICIENTS AND REGRESSION F-STATISTICS FOR PRELIMINARY QUESTIONNAIRE ANALYSES: NON-SPORT GROUP

Question and Feature	BvA		A23vB	
	r	F	r	F
2. Buttock Fit	0.016	0.004	0.477	4.12
3. Thigh Fit	0.043	0.026	0.433	3.23
4. Cushion Firmness	0.065	0.059	0.722	15.2 **
5. Cushion Length	0.318	1.58	0.086	0.104
6. Cushion Width	0.712	14.4 **	0.718	14.9 **
7. Cushion Height	0.926	84.6 **	0.628	9.10 *
8. Cushion Angle	0.050	0.036	0.616	8.57 *
9. Cushion Bounciness	0.095	0.126	0.564	6.54 *
10. Cushion Recovery	0.688	12.6 **	0.139	0.276
11. Cushion Intrusions	-0.491	4.45	0.226	0.752
12. Cushion Sinking	-0.580	7.09 *	0.153	0.334
13. Shoulder Fit	0.437	3.31	0.324	1.64
14. Middle-back Fit	0.291	1.29	0.541	5.78 †
15. Low-back Fit	0.409	2.81	0.647	10.1 *
16. Backrest Firmness	0.321	1.60	0.102	0.146
17. Backrest Length	0.919	76.6 **	0.523	5.27 †
18. Backrest Width	0.798	24.6 **	0.692	12.5 *
19. Lumbar Support	0.893	55.1 **	0.363	2.13
20. Lumbar Location	-0.183	0.483	-0.066	0.061
21. Stomach Constriction	-0.796	24.2 **	0.349	1.94
22. Back Posture	0.507	4.84 †	0.477	4.11
23. Overall Evaluation	0.911	68.2 **	0.911	68.2 **
24. Overall Comfort	0.791	23.4 **	0.855	38.2 **

† $P \leq 0.10$
* $P \leq 0.05$
** $P \leq 0.01$

A23vB: Satisfaction with the feature was correlated highly with overall satisfaction. The feature was said to be important to the overall evaluation.

Of initial interest in correlation coefficients from All Subjects is the high correlation (r = 0.731) between question 1, first impression of the seat, and question 23, overall evaluation at the end of the questionnaire. This indicates that subject initial preferences are substantially similar to those reported after approximately five minutes of feature evaluations. The correlation between A23 and A24 is 0.916, as mentioned above. In the regression results from All Subjects, satisfaction on the features addressed by the questions is correlated with the overall evaluation of the seat for ten features, shown in Table 12.

Of the features in Table 12, backrest length, backrest width, lumbar support, and back posture show relationships between the seat feature and satisfaction on that feature. The correlations in the BvA comparisons are positive, indicating that longer backrests, wider backrests, stronger lumbar support, and a more arched back posture received higher satisfaction ratings. These feature evaluations (longer backrests, wider backrests, etc.) are associated with higher overall seat evaluations, since they show significant relationships in both series of regressions. Six other questions listed in Table 13 show correlations between feature evaluation and satisfaction in the BvA regression results, but do not show correlations between satisfaction and the overall evaluation of the seat with $P \leq 0.05$. Of these, all but cushion height and backrest firmness also show relationships between satisfaction with the feature and the overall evaluation of the seat at the $P \leq 0.10$ level.

3.1.6 Correlation/Regression Analysis of Complementary Subject Data. Identical correlation/regression analyses performed on the smaller subject groups previously defined are informative because the influence of the groups on the All Subjects data can be observed. Of primary interest are relationships in the smaller groups that are not seen in the combined data, and differences between complementary groups on these analyses.

TABLE 12

FEATURES FOR WHICH SATISFACTION IS CORRELATED
WITH THE OVERALL EVALUATION OF THE SEAT:
ALL SUBJECTS

Number	Feature
3	Thigh Fit
4	Cushion Firmness
9	Cushion Bounciness
13	Shoulder Fit
14	Middle-back Fit
15	Low-back Fit
17	Backrest Length
18	Backrest Width
19	Lumbar Support
22	Back Posture

TABLE 13

OTHER FEATURES SHOWING FEATURE/SATISFACTION CORRELATIONS: ALL SUBJECTS

Number	Feature
6	Cushion Width
7	Cushion Height
10	Cushion Recovery
12	Cushion Sinking (negative)
16	Backrest Firmness
21	Stomach Constriction (negative)

The correlations between first-impression (question 1) responses and the overall evaluation (A23) are substantially the same for the Sport and Non-Sport groups as for All Subjects. The Sport group shows seven features for which the A23vB regressions are significant with $P \leq 0.05$; the Non-Sport group also has seven features significant at that level.

From the results of the A23vB regressions in Table 10 and Table 11, the features for which satisfaction is correlated with the overall evaluation with the seat are listed in Table 14. These features are considered important to the overall evaluation of the seats, for each group.

Comparison with the analysis for All Subjects shows that, of the features which show significant relationships in the A23vB regressions with the data from All Subjects, all but shoulder fit, backrest length, and back posture are represented in the Sport/Non-Sport analysis. However, only satisfaction with cushion firmness is significantly related to the overall evaluation for both the Sport and Non-Sport groups. Additionally, cushion sinking, cushion width, and cushion angle, which are significant with $P \leq 0.05$ for one or the other of the subject groups, show relationships in the data for All Subjects at the $P \leq 0.10$ level. Although the regressions for middle-back fit, backrest length, and cushion bounciness are significant with $P \leq 0.05$ for only one group in Table 14, the same features show relationships in the other group at the $P \leq 0.10$ level. Shoulder fit and back posture, two features for which the A23vB regressions were significant with $P \leq 0.05$ in the data from All Subjects, also show significant relationships in the data from the Sport group with $P \leq 0.10$.

From these findings, the contribution of each subject group as a whole to the results for All Subjects data can be assessed. Note that a non-significant regression implies that there is not a linear relationship which holds for the data from the group as a whole. However, individual members of a group may show a strong relationship, which is masked by the data from the other subjects in the group. The performance of the group as a whole is relevant in the context of the conditions for their selection, *i.e.*, the overall evaluation of the test seats, particularly Seat Four. Table 15 shows the significant features for each group which were significant with $P \leq 0.10$ in the data from All Subjects, but were not significant at that level for the other group.

The features listed in Table 15 can be regarded as those which are important to each group's overall evaluation of the seats, but which are less important for the other group, or the contribution of each group to the findings for All Subjects. Interpretation of these findings is aided by examination of the results of the BvA regressions for the two complementary subject groups.

TABLE 14

FEATURES FOR WHICH SATISFACTION IS CORRELATED WITH THE OVERALL EVALUATION OF THE SEAT: SPORT AND NON-SPORT SUBJECT GROUPS ($P \leq 0.05$)

Sport	Non-Sport
Thigh Fit	Cushion Firmness
Cushion Firmness	Cushion Width
Cushion Sinking	Cushion Height
Middle-back Fit	Cushion Angle
Backrest Length	Cushion Bounciness
Lumbar Support	Low-back Fit
Lumbar Support Location	Backrest Width

TABLE 15

FEATURES FOR WHICH SATISFACTION IS CORRELATED WITH THE OVERALL EVALUATION OF THE SEAT FOR ALL SUBJECTS ($P \leq 0.10$) AND WHICH SHOW SIGNIFICANT RELATIONSHIPS IN ONLY THE SPORT OR NON-SPORT SUBJECT GROUPS ($P \leq 0.10$)

Sport	Non-Sport
Thigh Fit	Cushion Width
Cushion Sinking	Cushion Angle
Shoulder Fit	Cushion Bounciness
Middle-back Fit	Low-back Fit
Backrest Length	Backrest Width
Lumbar Support	
Back Posture	

BvA Regressions for Complementary Subject Groups. Of those features listed in Table 15, thigh fit, cushion firmness, cushion sinking, and lumbar support show relationships in the BvA analysis for the Sport group at the $P \leq 0.05$ level, while cushion width, cushion height, and backrest width are significant on the BvA regressions for the Non-Sport group at that level. All but the cushion-sinking relationship are positive.

These results indicate the feature evaluations for which satisfaction is correlated with the overall evaluation of the seat, for the Sport and Non-Sport groups. For the Sport group, tighter thigh fit, firmer cushions, less sinking and stronger lumbar support are associated with higher overall evaluations. For the Non-Sport group, evaluations of wider cushions, higher cushions, and wider backrests correspond with higher overall evaluations. This difference in trends between the groups is also evident in Table 9, which indicates that, of the relationships significant for All Subjects, the Sport group associated more with those features having to do with support and tightness of fit, while the Non-Sport group data produced significant relationships for width measures and cushion bounciness. Although satisfaction with low-back fit was correlated with overall satisfaction for the Non-Sport group, the data do not show a relationship between the feature evaluation and satisfaction with the feature. Neither regression is significant for the Sport group on that feature. This suggests that satisfaction with low-back fit was important in the overall evaluation for the Non-sport group, but that no consensus arose regarding desirability of a tight or loose fit. A similar result is seen with middle-back fit in the Sport group data.

3.1.7 Summary of Results from Preliminary Questionnaire Analyses. Combining the results of the inter-seat comparisons with the regression analyses by the interpretation advanced above gives a picture of the subjects' preferences on feature parameters and also indicates which of those features were important in the subjects' overall preliminary evaluation of the test seats.

The preferred seat feature configurations are taken from the results of the BvA regressions. Not all of the features for which the feature evaluation and satisfaction are correlated also show relationships between satisfaction and the overall evaluation of the seat. For those features, the subjects indicated a preference on the feature, but satisfaction with the feature was not a primary factor in the overall evaluation of the seat. Table 16 shows the preferred feature configurations from the data for All Subjects and the Sport and Non-Sport groups, from regression results which were significant at the $P \leq 0.05$ level.

TABLE 16

SUBJECT FEATURE PREFERENCES
(Italics indicate features for which satisfaction
are correlated with the overall seat evaluation.)

All Subjects	Sport Group	Non-Sport Group
Wider Cushion Higher Cushion Faster Cushion Recovery Less Cushion Sinking Firmer Backrest *Longer Backrest* *Wider Backrest* *Stronger Lumbar Support* Less Stomach Constriction *More Arched Back*	*Tighter Thigh Fit* *Firmer Cushion* *Less Cushion Sinking* *Stronger Lumbar Support* Less Stomach Constriction	*Wider Cushion* *Higher Cushion* Faster Cushion Recovery Less Cushion Sinking Longer Backrest Wider Backrest Stronger Lumbar Support Less Stomach Constriction

Those preferences shown in italics in Table 16 are considered important to the overall evaluation of the seat, because of correlation between the satisfaction with the feature and the overall evaluation of the seat. Note that the important preferences for All Subjects involve backrest parameters, those for the Sport group are related to firmness and support, and those for the Non-Sport group are greater cushion height and width.

The results of the inter-seat comparisons with the Section-A and Section-B data are informative in relation to the feature preferences in Table 16. The data from All Subjects indicate that longer backrests, wider backrests, stronger lumbar supports, and more arched back postures were preferred by the subjects, and that those seat features influenced the subjects' overall evaluation of the seats. However, the t-test results with Section-A data in Table 4 indicate significant inter-seat differences for the feature evaluations of backrest width, lumbar support, and back posture, but not backrest length, even when the threshold of significance is extended to $P \leq 0.10$. These findings mean that the evaluation of backrest length was not consistent among subjects, although subjects indicated higher satisfaction when they indicated longer backrests, and they did so on seats which they then rated highly overall. This suggests that seats which were preferred for other reasons were considered to have longer backrests. Because all of the test seat backrests were long enough to contact even the largest subject's entire back, it seems likely that this parameter, because it could not be genuinely evaluated by a subject sitting in the seat, was instead rated based on the subject's overall perception of the seat.

A similar situation is implied by the results from the Non-Sport group data for cushion height. Table 6 shows no inter-seat comparisons on that feature at the $P \leq 0.10$ level, and yet higher evaluations on the feature were correlated with feature satisfaction and with overall satisfaction. As with backrest length, it appears that the cushion height parameter was not consistently evaluated by the subjects, and that they instead assigned higher cushion heights to seats which they preferred for other reasons.

Some feature satisfaction responses may have been influenced by a semantic bias in the question. Note that less cushion sinking, stronger lumbar support, and less stomach constriction appear for each subject group in Table 16, indicating subject preferences inferred from significant BvA regressions. The inter-seat comparisons show no significant differences in the feature evaluation for stomach constriction for All Subjects, the Sport group, or the Non-Sport group, while the significant comparisons for lumbar support and cushion sinking involve only Seat One. Additional regression analyses conducted after removing the Seat-One data show that the BvA regressions for the three features are reduced only slightly, and remain significant in all cases at the $P \leq 0.05$ level. Although less stomach constriction is associated with higher satisfaction responses, the satisfaction data are not correlated with the overall seat evaluation for any of the groups in Table 16. The implication is that when subjects marked a seat lower in stomach constriction, they tended to mark it higher in satisfaction, although they did not consistently judge the level of stomach constriction. Unlike backrest length, for which subjects tended to judge backrests longer on the seats they preferred, stomach constriction was not related to the overall evaluation. Therefore, it appears that the feature evaluation was influenced primarily by the wording of the question, particularly the word "constriction," which may have carried a negative connotation.

Responses for the cushion sinking feature, on which Seat One was singled out in the inter-seat comparisons, appear to be similarly influenced. Although satisfaction on that feature is correlated with the overall seat evaluation for the Sport group, the correlation is reduced to $r = 0.421$ when the data for Seat One are removed, a level which is not significant at the $P \leq 0.10$ level. Yet, the correlation between the feature evaluation and the satisfaction with the feature remains strong with $r = -0.807$. This situation is analogous to that of the stomach constriction question, with the responses influenced by the negative connotations of "sinking."

The evaluation of lumbar support and the satisfaction with the lumbar support are correlated for all three groups in Table 16. For All Subjects and the Sport group, the satisfaction responses for the feature are also correlated with the overall seat evaluations. However, only the Seat One lumbar support evaluations are significantly different from those of the other seats in the data from All Subjects and the Sport group, while for the Non-Sport group there are no significant inter-seat differences in lumbar support evaluation with $P \leq 0.10$. When the data for Seat One are removed, the correlations between feature satisfaction and overall seat evaluation fall to non-significant levels (All Subjects, $r = 0.261$; Sport Group, $r = 0.384$) while the correlations between the feature evaluation and satisfaction with the feature remain high (All Subjects, $r = 0.818$; Sport Group, $r = 0.750$). These findings indicate that subjects reported higher satisfaction when they reported stronger lumbar support for a seat, although they did not consistently evaluate the strength of the lumbar support, with the exception of Seat One, which was judged to have weaker support.

TABLE 17

INTER-SEAT COMPARISONS FOR PRELIMINARY QUESTIONNAIRE SECTION-A RESPONSES: OVERALL MEASURES

Response Variable	t-Values						Comparisons P ≤ 0.05
	1 v. 2	1 v. 3	1 v. 4	2 v. 3	2 v. 4	3 v. 4	
All Subjects							
A1	2.667 †	-0.190	1.290	-1.654	0.177	1.987	
A23	1.328	-0.771	2.892 †	-3.540 *	7.286 **	12.084 **	3>2>4
A24	1.164	-0.122	2.353 †	-1.916	2.849 †	12.384 **	3>4
B23	0.096	-1.076	-0.055	-1.447	-0.197	0.787	
B24	0.115	-0.754	0.194	-1.224	0.233	1.244	
Sport Group							
A1	1.278	-0.767	-1.953	-1.710	-11.846 **	-0.710	4>2
A23	-1.128	-1.133	-5.398 *	-0.766	-10.548 **	-1.941	4>1,2
A24	-0.580	-0.842	-4.423 *	-0.759	-3.397 *	-1.654	4>1,2
B23	-1.640	-1.640	-2.943 †	- -	-1.640	-1.640	
B24	-1.640	-1.640	-1.715	- -	-1.000	-1.000	
Non-Sport Group							
A1	2.667 †	-0.190	1.290	-1.654	0.177	1.987	
A23	1.328	-0.771	2.892 †	-3.540 *	7.286 **	12.084 **	3>2>4
A24	1.164	-0.122	2.353 †	-1.916	2.849 †	12.384 **	3>4
B23	2.480	-1.155	2.919 †	-1.601	1.670	5.476 *	3>4
B24	2.149	0.034	2.559 †	-1.278	1.000	2.714 †	

† P ≤ 0.10
* P ≤ 0.05
** P ≤ 0.01

When the data for Seat One are removed from the analysis, satisfaction with lumbar support strength is no longer correlated with the overall seat evaluation, and no significant differences among seats on the feature evaluation remain, although a strong correlation persists between the feature evaluation and satisfaction with the feature. It is possible that the words "strong" and "weak" led the subjects to indicate higher satisfaction when they marked stronger lumbar support because of the connotation of those anchor words. There is also the possibility that they considered "lumbar support" desirable, though for psychological rather than physical reasons, as it apparently was not a primary consideration in their evaluation of the seats.

Summary of Overall Measures. Questions 1, 23, and 24 dealt with overall evaluations of the seat. Question 1 asked for the subject's initial impression of the seat, question 23 required an overall evaluation, and question 24 asked the subject to rate the comfort of the seat. Table 17 shows the inter-seat comparisons significant in the overall measures for Section-A and Section-B data.

For All Subjects, Table 17 shows Seat Three to be rated most highly overall, followed by Seats Two and Four in sequence. This rating is the same for the Non-Sport group. The Sport group rated Seat Four higher than Seats One and Two in the overall evaluation. Table 18 shows the correlations among the overall measures, for All Subjects. The initial evaluation, A1, is correlated strongly with the overall measures A23 and A24.

TABLE 18

PEARSON'S r CORRELATION COEFFICIENTS AMONG
OVERALL MEASURES FROM PRELIMINARY QUESTIONNAIRE:
ALL SUBJECTS

Overall Measure	A1	A23	A24	B23	B24
A1	1.000				
A23	0.731	1.000			
A24	0.709	0.916	1.000		
B23	0.663	0.843	0.777	1.000	
B24	0.545	0.764	0.669	0.830	1.000

3.2 CROSS-MODALITY MATCHING

Cross-Modality Matching (CMM) was utilized during the driving simulation sessions as a technique for evaluating subject discomfort. The calibration of the modalities and the collection and scaling of data are described in Section 2.

The first part of the CMM analyses was directed toward determining differences in the long-term comfort performance of the four test seats. The remaining CMM analyses concerned the performance, validity, and effectiveness of the techniques. These issues are discussed in Section 4.2.

An open-scale questionnaire, such as that employed in conjunction with the CMM modalities, can also be described as a cross-modality match, with the length of a line, a visual stimulus, as a reference (Pepermans *et al.* 1983). The questionnaire responses from the driving-simulation session were analyzed as a fourth CMM modality, along with the Pressure, Heat, and EV modalities. The modality is referred to as the Open-Scale Graphic Response modality, or OSGR. As indicated in Section 2, each of the discomfort responses was scaled as a fraction of full-scale discomfort.

Additional discomfort measures were generated from a principal-component analysis of the data from the Pressure, Heat, and EV modalities. This analysis is described in Section 3.2.7 below. Although each of the modalities nominally measured discomfort on the same scale from "no discomfort" to "unbearable discomfort" or "maximum bearable discomfort," three characteristics of the data in particular made analysis difficult.

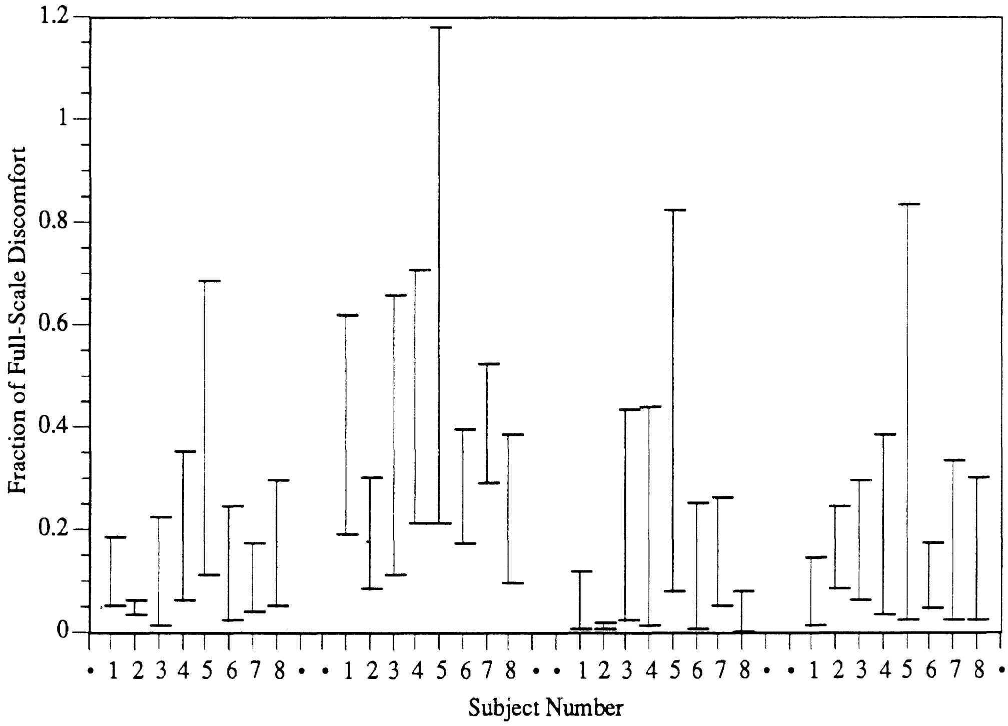


FIGURE 9. Range of subject responses by modality and subject: Seat One, middle-back area.

1. Each subject exercised a different range of responses. Some subjects were very uncomfortable in all seats, and used most of the range of responses on all modalities. Other subjects were less uncomfortable, and used a smaller range of responses. The scaled data in Figure 9 show the range of responses employed by the subjects for Seat One in the middle-back area. Note that there is a considerable difference in maximum discomfort level between the subjects. A standardization technique was desired, so that the data from such subjects could be effectively pooled for overall comparisons of the seats.

2. The modalities showed different levels of response. Although the modalities were calibrated and scaled to produce results on an equivalent scale, the data showed that some modalities had higher average response levels. Figure 10 shows the mean response levels for the modalities during testing of Seat One. A way of compensating for these varying levels was desired, so that the data from each modality could be compared.

3. The variability in the data for each seat made it difficult to make statements about the relative comfort performance of the seats for an individual subject's data, or for particular time intervals over a number of subjects. Means and standard deviations for data from the OSGR modality are plotted in Figure 11, showing the wide variance in the data from each seat. Because the modalities were calibrated to the subject's internal discomfort scaling, the wide variability in the discomfort reported by the subject was interpreted as evidence of inter-subject variability in sensitivity to seating discomfort. Discomfort responses for the EV modality are plotted in Figure 12, again showing a wide variance in reported discomfort level.

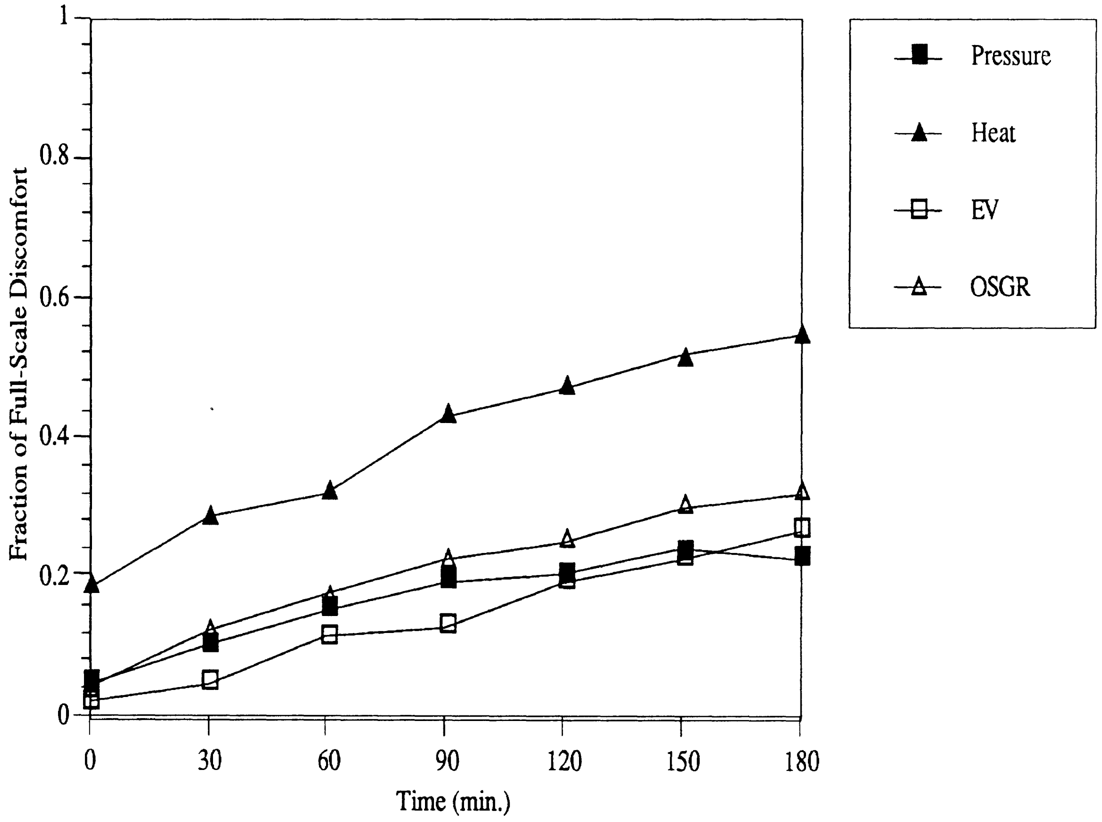


FIGURE 10. Mean response levels by modality;
Seat One, middle-back area.

To overcome the difficulties posed by these data characteristics, several techniques of indexing and standardizing the data were employed. Indexing reduced the discomfort for a body area experienced over the simulation to a single value to facilitate inter-seat comparison. Standardization helped to negate the effects of inter-subject variability.

3.2.1 Indices. Indices were devised which represent the discomfort in a body area over the course of the test as a single value. Each index was calculated for each of the four modalities. The following are the descriptions of the five indices which were used.

Average (AVG): the mean of the 120, 150, and 180 minute scaled responses; this index is a measure of the discomfort experienced during the third hour of the driving simulation.

Differential Average (DAV): AVG minus the mean of the 0 and 30 minute scaled responses; this index indicates the increase in discomfort level between first and last hours of the test.

Differential Zero Average (DZA): AVG minus the initial (first evaluation interval) scaled response; this index represents the increase in discomfort over the three hour simulation.

Total Integrated Discomfort (TID): an overall measure prepared by trapezoidal approximation:

$$TID = 30\,[(SR_0 + SR_{30})/2] + 30\,[(SR_{30} + SR_{60})/2] + \ldots + 30\,[(SR_{150} + SR_{180})/2],$$

where, SR_n is the scaled response n minutes into the test. TID is interpreted as fractional discomfort-minutes, and represents the cumulative discomfort experienced by the subject.

Differential Integrated Discomfort (DID): TID minus six times the fractional discomfort-minutes calculated using the 0 and 30 minute scaled responses; this index represents the discomfort attributable to increases in discomfort level reported after the first 30 minutes of the test.

Additionally, two overall measures based on the integrated indices (TID and DID) were calculated. Overall TID sums the TID for each body area; overall DID subtracts the total integrated discomfort over the four body areas for the first thirty minutes of the simulation from the overall TID figure.

The AVG index provides a good view of the CMM data, representing the average level of discomfort reported during the final three evaluation intervals as a fraction of full-scale discomfort. Figure 13 shows the AVG index values for each body area by modality and test seat. The mean discomfort level for All Subjects varies among modalities, but generally peaks at approximately 30% of full-scale discomfort during the final hour of the driving simulation.

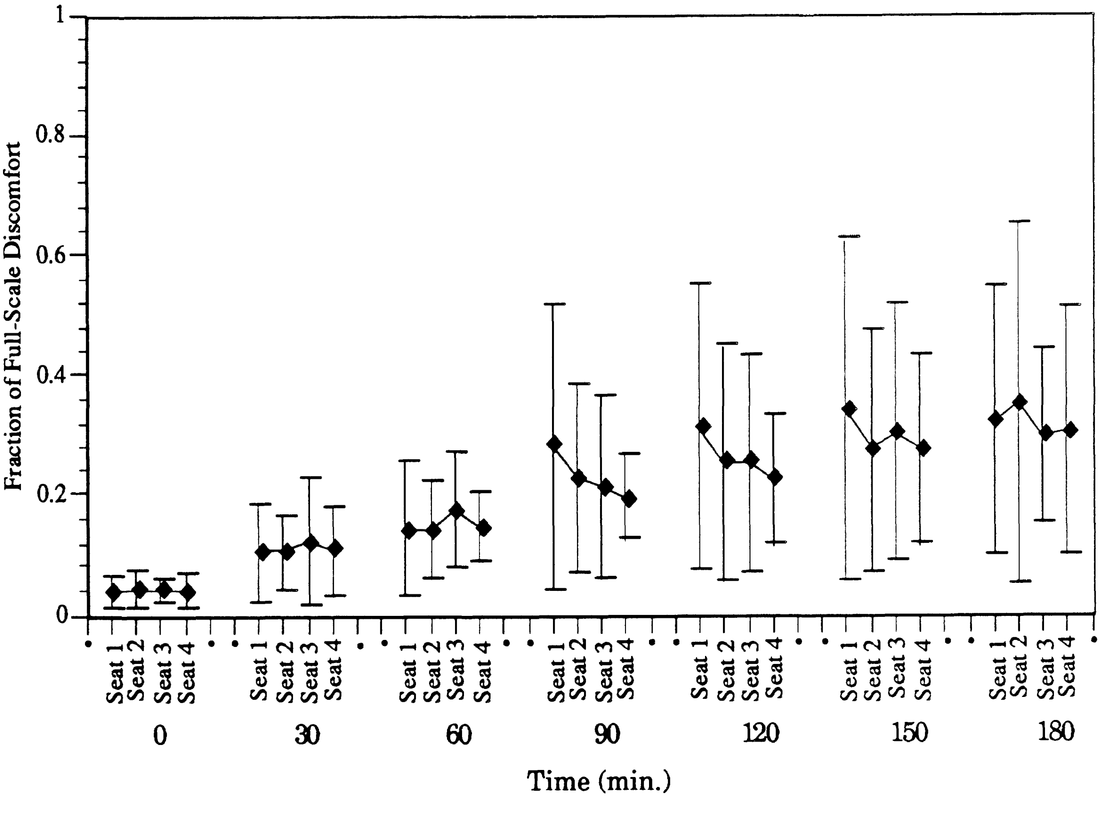


FIGURE 11. Mean and standard deviation of subject responses by seat: OSGR modality, middle-back area.

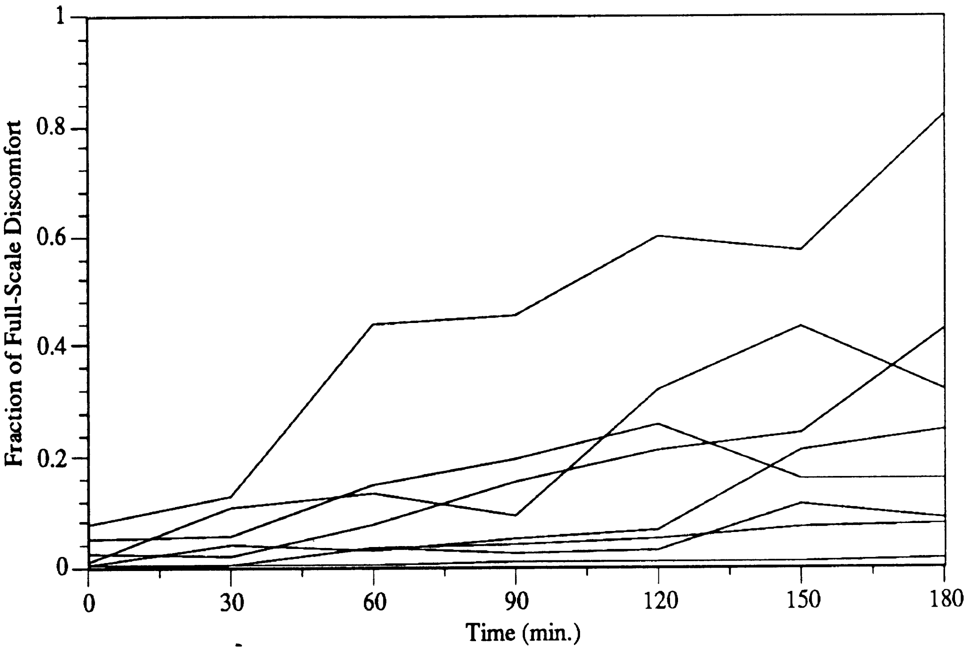


FIGURE 12. All subjects' responses on the EV modality:
Seat One, middle-back area

3.2.2 Standardization of the Indexed Data. Examination of the indexed data showed that the range of responses differed considerably among subjects, particularly on the EV modality. A standardization method was developed to facilitate comparison of the test-seat performance over groups of subjects. For each index, each subject's scores for the four test seats were standardized to have a range of three, with the highest score given a value of four and the lowest a value of one. The standardization preserved the distribution of index scores, so that the interval nature of the data was retained. Algebraically, the transformation was:

$$IS_n = 3[(I_n - MIN)/(MAX - MIN)] + 1$$

where,

IS_n is the scaled index for seat n;
I_n is the calculated index value;
MIN is the lowest of value of the four seats; and
MAX is the highest value of the four seats.

Comparisons among the seats were then made with each subject's maximum and minimum scores fixed. The choice of 1 and 4 as the end points was made to facilitate examination of the data. The seat for which the subject reported the lowest level of discomfort on the index was indicated by a 1, and the seat which had the highest discomfort level was assigned a 4. The values for the other two seats were distributed between 1 and 4; their relative levels of reported discomfort could be observed by simple inspection. This method of standardization was chosen over the more typical method of equalizing variances to standardize the amount of influence each subject's data could have on the inter-seat comparisons. With an equal variance for each subject, the range between a subject's highest and lowest possible index values could vary somewhat. In the paired t-tests that were subsequently performed, a subject's maximum possible influence on the test would likewise vary. The standardization technique adopted fixed the maximum difference between a subject's test seat scores. Analyses demonstrated that the fixed-range standardization resulted in a larger number of significant comparisons between the seats than the more typical unit-variance method.

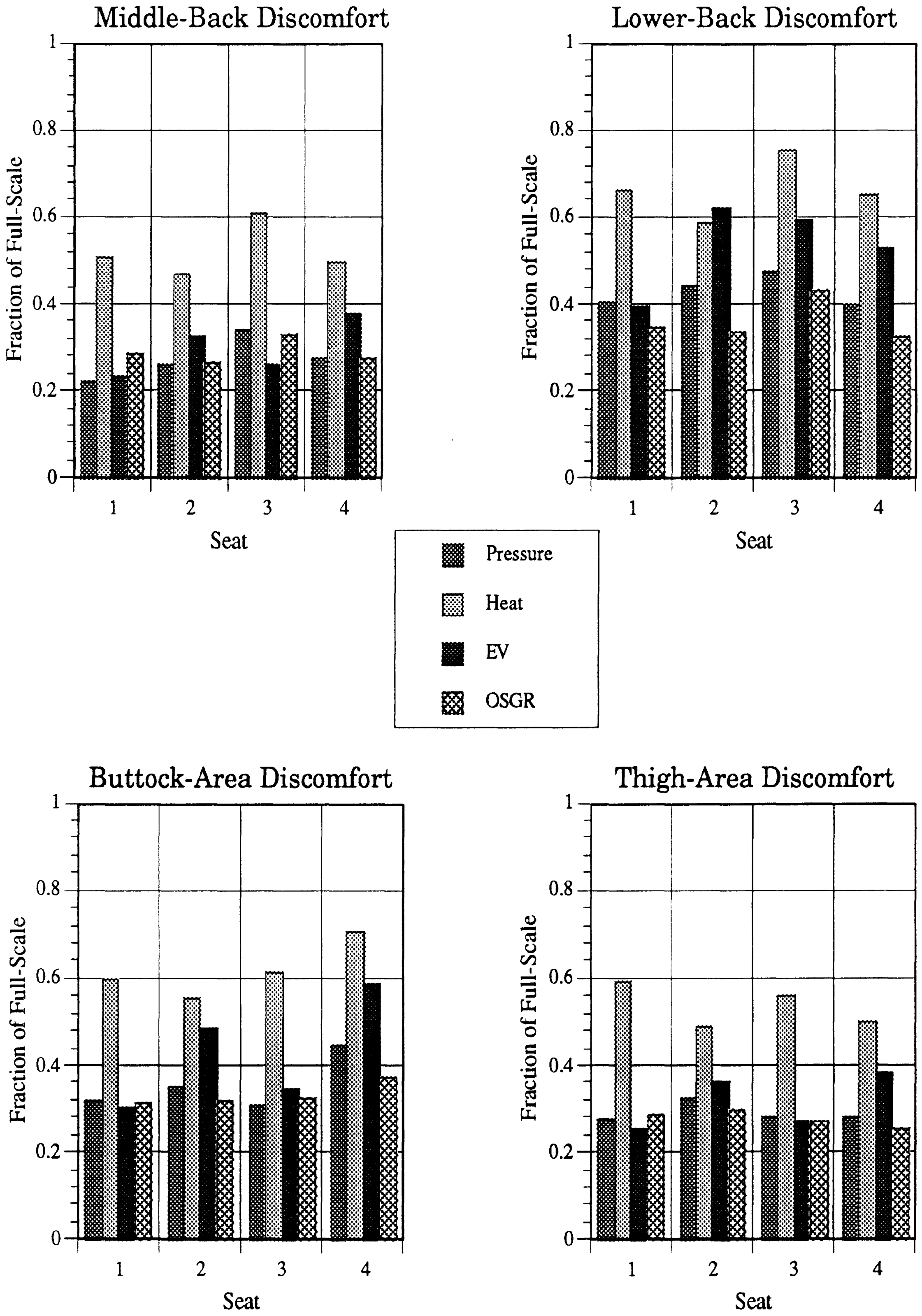


FIGURE 13. CMM Discomfort: All Subjects, AVG Index.

3.2.3 Index Assignment. Paired t-tests comparing index values between seats were performed for each index, body area, and modality. Data from All Subjects were pooled and also examined in the Sport and Non-Sport subject groups from question 23 of the Preliminary Questionnaire (see Section 3.1, above). The modalities performed differently on the various indices. Certain modalities produced many significant differences between the seats on one index, but fewer on another. (Comparisons of modality behavior are examined in Section 4.2.)

To simplify the determination of overall differences in discomfort between the seats, one index was chosen for each modality. Since differentiation between the seats' comfort performance was desired, for each modality the index which produced the greatest number of inter-seat comparisons significant at $P \leq 0.05$ was selected. Significant comparisons were totalled for the t-tests of All Subjects and the Sport and Non-Sport subject groups. The resulting index assignments were as follows:

Modality	Index
Pressure	DAV
Heat	TID
EV	DAV
OSGR	DID

These selected indices were used to determine overall differences in reported discomfort between the test seats. Results from the indices not selected were examined for comparisons which would be neglected by using only the selected indices. Several comparisons from the AVG and DZA indices were added to those from the selected indices in tabulating the overall results.

Figure 14 shows the means and standard deviations of the selected, standardized indices for the four modalities, plotted to show the relative index levels of discomfort on the test seats for All Subjects and the Sport and Non-Sport complementary subject groups.

The plots of standardized, indexed data indicate differences in seat discomfort performance in all four body areas. The plots for All Subjects show Seat Three higher on the discomfort indices in the back areas, while Seat Two is lower. The mean values for Seat Four are higher in the buttock area, indicating more discomfort. For Seat Three, the mean values are lower than those of the other seats on the EV and OSGR modalities. The discomfort ratings for Seat One are noticeably higher than the other seats in the thigh area on the Heat modality.

Figure 14 indicates that the Sport group and Non-sport group experienced different relative levels of discomfort in the test seats. On the EV modality, for instance, the mean level of thigh discomfort in Seat Two was much higher relative to the other seats for the Non-Sport group than was the case with the Sport group. There were two instances in which the standard deviation of the standardized, indexed data was zero for the Non-Sport group. In the buttock-area data from the EV modality, all four subjects in the Non-Sport group reported the lowest discomfort levels on Seat Three, as measured by the DAV index. On the OSGR modality, Seat Two was the most uncomfortable in the thigh area for all four subjects.

Paired t-tests were performed to test the significance of the inter-seat differences in mean levels apparent in Figure 14. Tables 19, 20, and 21 show the t-values calculated for All Subjects and the Sport and Non-Sport groups, and indicate the inter-seat comparisons which are significant with $P \leq 0.05$.

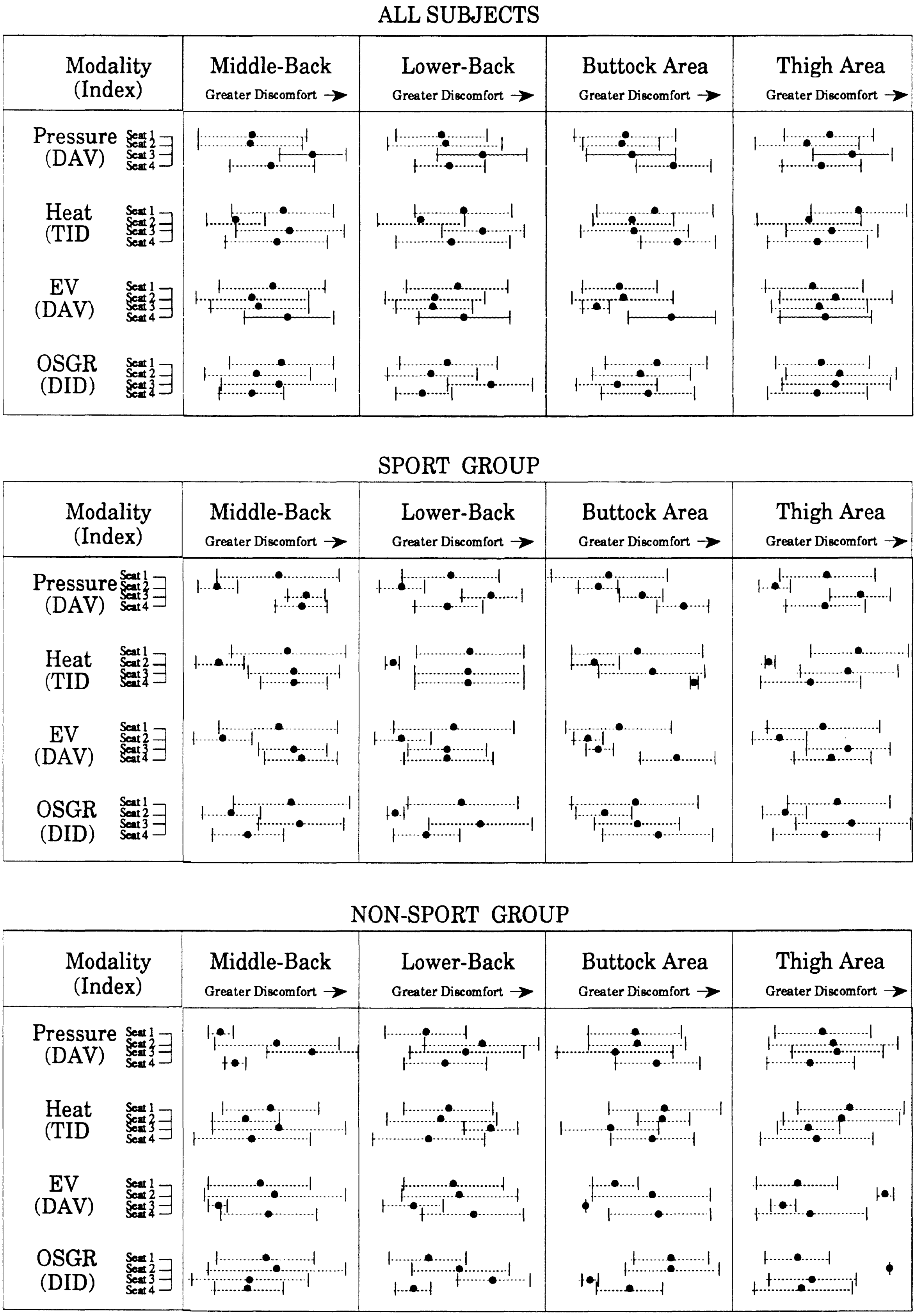


FIGURE 14. Means and standard deviations of standardized CMM index values.

TABLE 19

STANDARDIZED, INDEXED CMM DATA: PAIRED INTER-SEAT COMPARISONS, t-VALUES FOR ALL SUBJECTS

Modality (Index) Body Area	Inter-Seat Comparison						
	1 v. 2	1 v. 3	1 v. 4	2 v. 3	2 v. 4	3 v. 4	P ≤ 0.05
Pressure (DAV)							
Middle Back	0.058	-2.456 *	-1.277	-2.482 *	-0.680	2.211 †	3>1, 2
Lower Back	-0.097	-1.515	-0.376	-1.192	-0.201	2.831 *	3>4
Buttock Area	0.206	-0.231	-1.946 †	-0.410	-2.600 *	-1.863	4>2
Thigh Area	0.764	-0.988	0.389	-1.528	-0.451	1.794	
Heat (TID)							
Middle Back	2.033 †	-0.231	0.331	-2.534 *	-1.595	0.417	3>2
Lower Back	1.673	-0.751	0.528	-3.304 *	-1.004	1.019	3>2
Buttock Area	0.852	0.568	-0.750	-0.050	-1.868	-2.919 *	4>3
Thigh Area	1.630	1.112	1.805	-0.765	-0.284	0.624	
EV (DAV)							
Middle Back	0.594	0.571	-0.590	-0.230	-1.208	-1.835	
Lower Back	0.745	0.827	-0.331	0.037	-1.084	-1.076	
Buttock Area	-0.120	1.881	-2.303 †	1.339	-1.588	-4.793**	4>3
Thigh Area	-0.696	-0.275	-0.690	0.504	0.357	-0.225	
OSGR (DID)							
Middle Back	0.746	0.116	1.187	-0.584	0.257	1.415	
Lower Back	0.608	-1.493	1.401	-2.398 *	0.354	5.772**	3>4
Buttock Area	0.633	1.560	0.283	0.827	-0.215	-1.866	
Thigh Area	-0.609	-0.542	0.161	0.128	0.714	1.279	

† $P \leq 0.10$
* $P \leq 0.05$
** $P \leq 0.01$

TABLE 20

STANDARDIZED, INDEXED CMM DATA:
PAIRED INTER-SEAT COMPARISONS, t-VALUES FOR
SPORT GROUP

Modality (Index) Body Area	Inter-Seat Comparison						
	1 v. 2	1 v. 3	1 v. 4	2 v. 3	2 v. 4	3 v. 4	$P \leq 0.05$
Pressure (DAV)							
Middle Back	1.589	-0.681	-0.725	-15.431**	-4.094 *	0.252	3,4>2
Lower Back	1.453	-1.083	0.122	-5.807 *	-1.805	2.196	3>2
Buttock Area	0.314	-1.109	-1.762	-4.811 *	-8.048**	-2.277	3,4>2
Thigh Area	1.738	-0.947	0.104	-6.762**	-2.159	1.047	3>2
Heat (TID)							
Middle Back	1.699	-0.147	-0.250	-3.802 *	-2.704 †	0.009	3>2
Lower Back	2.553 †	0.051	0.206	-2.905 †	-2.479 †	-0.010	
Buttock Area	1.005	-0.308	-1.672	-1.819	-9.136**	-1.525	4>2
Thigh Area	3.286 *	0.252	2.164	-3.377 *	-1.515	0.901	3,1>2
EV (DAV)							
Middle Back	1.332	-0.358	-0.597	-5.881**	-3.153	-0.376 †	3>2
Lower Back	1.237	0.134	0.149	-6.307**	-1.365	-0.010	3>2
Buttock Area	1.009	0.774	-1.305	-1.484	-5.106 *	-3.398 *	4>2,3
Thigh Area	1.123	-0.684	-0.255	-4.001 *	-1.720	0.430	3>2
OSGR (DID)							
Middle Back	1.707	-0.208	1.090	-2.109	-0.577	5.016 *	3>4
Lower Back	2.313	-0.371	1.175	-2.943 †	-1.527	3.073 †	
Buttock Area	1.073	-0.079	-0.414	-0.999	-1.350	-0.760	
Thigh Area	1.862	-0.300	0.404	-1.855	-1.120	1.031	

† $P \leq 0.10$
* $P \leq 0.05$
** $P \leq 0.01$

TABLE 21

STANDARDIZED, INDEXED CMM DATA: PAIRED INTER-SEAT COMPARISONS, t-VALUES FOR NON-SPORT GROUP

Modality (Index) Body Area	Inter-Seat Comparison						
	1 v. 2	1 v. 3	1 v. 4	2 v. 3	2 v. 4	3 v. 4	$P \leq 0.05$
Pressure (DAV)							
Middle Back	-1.611	-4.264 *	-2.838 †	-0.722	1.156	3.801 *	3>4,1
Lower Back	-1.576	-0.923	-0.520	0.297	0.913	1.845	
Buttock Area	-0.074	0.431	-0.873	0.448	-0.610	-0.936	
Thigh Area	-0.234	-0.392	0.421	-0.078	0.415	1.676	
Heat (TID)							
Middle Back	1.082	-0.157	0.564	-0.884	-0.192	0.461	
Lower Back	0.192	-1.644	0.461	-1.667	0.262	1.543	
Buttock Area	0.043	1.070	0.264	1.787	0.523	-2.912 †	
Thigh Area	0.183	1.623	0.764	0.828	0.480	-0.446	
EV (DAV)							
Middle Back	-0.268	1.544	-0.201	1.484	0.132	-2.584 †	
Lower Back	-0.143	1.049	-0.769	1.857	-0.291	-1.537	
Buttock Area	-0.957	2.569 †	-2.578 †	2.257	-0.138	-2.916 †	
Thigh Area	-3.569 *	0.531	-1.327	19.238**	2.351	-0.835	2>1,3
OSGR (DID)							
Middle Back	-0.200	0.418	0.471	0.450	0.891	0.036	
Lower Back	-0.998	-2.018	0.650	-0.846	1.524	5.749 *	3>4
Buttock Area	-0.035	3.717 *	3.577 *	3.716 *	1.249	-1.937	1>3,4 2>3
Thigh Area	-5.703 *	-0.447	-0.156	3.481 *	3.501 *	0.646	2>1,3,4

† $P \leq 0.10$
* $P \leq 0.05$
** $P \leq 0.01$

3.2.4 Results of Statistical Tests. The following are notable features of these results.

- Every subject group indicated that Seat Three was significantly more uncomfortable than at least one other seat in one or both back areas.
- Seat Four was indicated to be more uncomfortable in the buttock area than at least one other seat for all subject groupings.
- The Sport and Non-Sport complementary subject groups reported opposite comparisons of thigh discomfort; the two groups also produced opposite results for the buttock-area comparison of Seats Two and Three.

The findings regarding the back areas of Seat Three are pervasive among the subject groups and modalities, yielding high confidence that the subjects on average were more uncomfortable in the back areas when tested in Seat Three than they were in the other seats. Similarly, the Seat Four buttock-area discomfort is frequently seen to be higher than that of other seats.

The results from the complementary Sport and Non-Sport groups show that the comparisons of Seat Two with the two luxury seats (One and Three) in the thigh area were opposite for the groups. The Sport group reported that Seat Two was more comfortable (less uncomfortable) in the thigh area than were Seats One and Three, the luxury seats.

In the buttock area, the two groups also differ in the comparisons of Seats Two and Three. Seat Two was found to be more uncomfortable than Seat Three by the Non-Sport group, while Seat Three was more uncomfortable than Seat Two for the Sport group. The Sport group results are from the Pressure modality, and the Non-Sport group results are from the OSGR modality. The existence of the same Sport group comparison in the OSGR modality at $P \leq 0.10$ increased confidence that this observed difference between the complementary groups was legitimate.

Another finding within the data from the complementary subject groups is also of interest. The Sport group reported Seat Four to be more uncomfortable than Seat Two in the middle-back area. This comparison, which was less frequently significant in the analyses than those mentioned above, was seen in the Pressure modality with $P \leq 0.05$, and in the selected indices for the Heat and EV modalities with $P \leq 0.10$. These results are interesting because they show negative comparisons for a seat that the group rated highly on the Preliminary Questionnaire. (The Sport group was comprised of those subjects who rated Seat Four highly overall on the Preliminary Questionnaire.)

3.2.5 Magnitude of Differences in Reported Discomfort Between the Test Seats. Because the t-test comparisons above were performed with standardized data, a direct estimate of the difference in mean index values could not be made. Instead, 95% confidence intervals were constructed using the non-standardized, indexed data. Some of the comparisons which were significant using standardized data produced confidence intervals which included zero, indicating that the average difference between seats was not significantly different from zero when the data were not standardized. Table 22 shows high and low limits for the differences between the index means for inter-seat comparisons on the selected indices. The Heat and OSGR figures should be interpreted as differences in fractional discomfort-minutes between the seats (integrated measures), while the Pressure and EV numbers represent the estimated difference between the seats in the fractional-discomfort increase over the course of the test. (For further clarification, see the definitions of the indices, Section 3.2.1, above.)

For purposes of comparison, approximate conversions can be made from the DAV index used for the Pressure and EV modalities to the TID and DID indices used for the

Heat and OSGR modalities, respectively. These figures are based on mean curve configurations for the modalities, as calculated for Section 4.2 below. For a change of 0.1 in the DAV Pressure or EV indices, the corresponding change in the TID Heat or DID OSGR indices is approximately 11. That is, an increase of 0.1 in the increase in discomfort over the course of the test (see the definition of DAV, Section 3.2.1) would be equivalent to an increase in fractional discomfort-minutes for the test of approximately 11. This would have the same mathematical contribution to TID as an eleven minute period of maximum discomfort. The conversions between the DAV indices and between the TID and DID indices are approximately one-to-one. (These estimates were calculated using mean standardized modality curves. See Section 4.2 for descriptions of those curves.)

Table 22 shows only three comparisons which indicate mean differences between seats of more than 0.1 on the DAV index at the 95% confidence level. All three were found in the Sport group in the middle- and lower-back areas. These were comparisons on the Pressure and EV modalities between Seats Two and Three. The Pressure comparison gives a confidence interval of (-0.273, -0.131), which indicates that on that

TABLE 22

SIGNIFICANT 95% CONFIDENCE INTERVALS
FOR NON-STANDARDIZED, INDEXED CMM DATA

Modality	Body Area	Index	Inter-seat Comparison	95% Confidence	
				Low	High
All Subjects					
Heat	Middle Back	TID	2 v. 3	-40.571	-3.891
Heat	Lower Back	TID	2 v. 3	-55.120	-0.029
Heat	Buttock Area	TID	3 v. 4	-14.502	-1.771
EV	Buttock Area	DAV	1 v. 4	-0.470	-0.004
EV	Buttock Area	DAV	3 v. 4	-0.497	-0.094
OSGR	Lower Back	DID	3 v. 4	3.975	23.813
Sport Group					
Pressure	Middle Back	DAV	2 v. 3	-0.322	-0.012
Pressure	Middle Back	DAV	2 v. 4	-0.161	-0.096
Pressure	Lower Back	DAV	2 v. 3	-0.273	-0.131
Pressure	Buttock Area	DAV	2 v. 3	-0.122	-0.022
Pressure	Thigh Area	DAV	2 v. 3	-0.156	-0.083
Heat	Thigh Area	TID	1 v. 4	4.408	17.621
EV	Middle Back	DAV	2 v. 3	-0.366	-0.119
EV	Lower Back	DAV	2 v. 3	-0.206	-0.101
EV	Buttock Area	DAV	2 v. 4	-0.677	-0.031
EV	Thigh Area	DAV	2 v. 3	-0.262	-0.018
Non-Sport Group					
EV	Middle Back	DAV	3 v. 4	-0.243	-0.016
EV	Thigh Area	DAV	2 v. 3	0.003	0.529
OSGR	Buttock Area	DID	1 v. 3	0.075	13.425

modality, Seat Three produced an increase in reported discomfort over the test greater than that of Seat Two by at least 13% of full-scale discomfort at the 95% confidence level. Similarly, on the EV modality, the Sport group reported a larger increase in discomfort over the course of the test on Seat Three than on Seat Two, by at least 10% of full-scale discomfort.

There are no inter-seat comparisons for the integrated indices which indicate differences of greater than 10 fractional discomfort-minutes. However, for the Sport group, the confidence intervals for the Heat modality indicate that Seat One produced at least 4.4 more fractional discomfort-minutes in the thigh area than did Seat Four, on average. This is particularly interesting because the comparison is not significant with $P \leq 0.10$ with the standardized data. It appears that the range-controlling effect of the standardization reduced the relative differences between the seats on this comparison. There are two other instances in which comparisons are significant with $P \leq 0.05$ in the non-standardized data, but are significant only at $P \leq 0.10$ when the data are standardized. These comparisons are in the EV modality of the All Subjects group, buttock area, and also in the EV modality, middle-back area, for the Non-Sport group. Neither confidence interval indicated a substantial difference in discomfort.

For All Subjects, two other comparisons show differences in index discomfort between seats of more than 3.5 fractional discomfort-minutes. Seat Three was more uncomfortable than Seat Two in the middle-back area on the Heat modality, and Seat Three was more uncomfortable than Seat Four in the lower-back area on the OSGR modality. These differences would be equivalent, for instance, to a difference between the seats of approximately 13% of full-scale discomfort in the reported discomfort for the last two evaluation intervals.

3.2.6 Data for Each Evaluation Interval Considered Separately. After the standardized, indexed data were examined for inter-seat differences, the CMM data for each evaluation interval were reconsidered to determine the time during the simulation at which the differences in discomfort performance became evident.

The scaled data for All Subjects were first combined. For each modality, the discomfort measures had been scaled so that each evaluation was reported as a fraction of full-scale discomfort (see Section 2). To prepare the data for time-series analysis, the data for each seat, body area, and modality were averaged over All Subjects. These values were plotted versus time and statistical comparisons were performed at each evaluation interval testing for inter-seat differences. Figure 15 shows one of these plots.

Because of the small number of subjects and the high variance of the data, results from the comparisons at individual confidence intervals can be regarded as only supporting information for the index results. For example, the mean level of reported discomfort could be higher for one seat than the others for the entire test, but with no statistical significance demonstrated at any evaluation interval. Yet, on an overall index measure, the seat could be shown to be significantly higher in reported discomfort. Such is the case, for instance, with the Pressure modality in the lower-back area. The t-tests of the time-series data show a difference with $P \leq 0.10$ only at the 150 minute evaluation interval. With the DAV index, however, which expresses the reported discomfort in that body area over the course of the simulation as a single value, Seat Three was judged more uncomfortable than Seat Four in the lower-back area at the $P \leq 0.05$ level.

The results of these statistical tests were examined for trends involving the modalities and body areas found to show significant inter-seat differences in the indexed data. Two significant findings with the indexed data for All Subjects guided the evaluation-interval investigation. These were: (1) Seat Three was found to be more uncomfortable than other seats in the back areas; and (2) Seat Four was more uncomfortable in the buttock area.

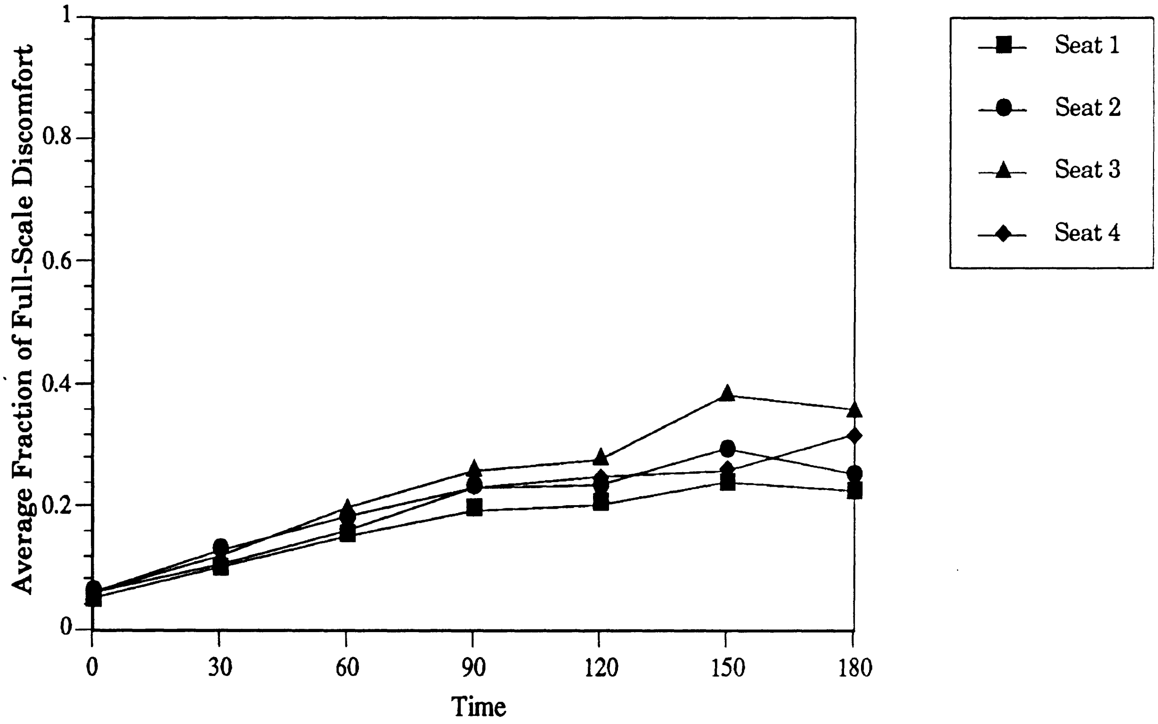


FIGURE 15. Average scaled CMM values by seat: Pressure modality, middle-back area.

The examination of the evaluation-interval data supported both of those findings from the indices. Using the indexed data for All Subjects, the significant middle-back area comparisons involving Seat Three were found in the Pressure and Heat modalities, while the lower-back area comparisons were found in the Pressure, Heat and OSGR modalities. Because of the limited number of subjects and the variance of the data, the threshold for significant was extended to $P \leq 0.10$ for these analyses.

For the middle-back area, the data from the Heat modality show Seat Three to have been more uncomfortable than Seat Two from 60 minutes until the end of the simulation. The Pressure modality data show no differences between Seats Two and Three at the evaluation intervals, but show that Seat Three was more uncomfortable than Seat One beginning at 120 minutes. Seat Three was also more uncomfortable than Seat Two on the OSGR modality at 120 minutes.

In the lower-back area, Seat Three is indicated to have been more uncomfortable than Seat Four at 150 minutes by the Pressure modality data. The Heat modality first shows that Seat Three was more uncomfortable than Seat Two at 60 minutes. The OSGR modality data indicate higher reported discomfort for Seat Three than Seat Two at 120 minutes. These results show Seat Three to have become more uncomfortable for All Subjects in the back areas than Seats Two or Four during the second hour of the driving simulation.

In the buttock area, index comparisons were significant on the Pressure, Heat, and EV modalities. The Pressure modality evaluation-interval analysis shows that Seat Four was more uncomfortable than Seat Two only at 120 minutes. However, statistical tests for the modality also indicate that Seat Four was higher in discomfort than Seats Three and One from 90 and 120 minutes, respectively, until the end of the simulation. The data from the Heat modality show that Seat Four was more uncomfortable than Seat Three in the buttock area at 120 and 150 minutes. The same comparison is significant in the EV modality data at 150 and 180 minutes. Also in the data from the EV modality, Seat Four was more uncomfortable than Seat One at 120 and 180 minutes. Seat Three was more uncomfortable than Seat Two at the 120 minute interval. Data from the OSGR modality, which failed to produce an inter-seat, buttock-area comparison on the selected index for All Subjects, show Seat Four to have been more uncomfortable at 150 minutes than Seat Three. These results indicate that Seat Four became significantly more uncomfortable in the buttock area than the other seats between 90 and 150 minutes into the driving simulation.

Several thigh-area comparisons are significant in the evaluation-interval analysis. Seat One was more uncomfortable than Seat Two at 30 and 150 minutes . Seat One was more uncomfortable than Seat Four at 150 and 180 minutes. Also, in the Pressure modality data, Seat Two and Seat Four were both more uncomfortable than Seat Three 30 minutes into the simulation. These results are not observed for later evaluation intervals, suggesting that thigh discomfort in those seats increased at a slower rate than that of other seats, after the first 30 minutes of the test.

3.2.7 Multivariate Analysis. The univariate analysis described above, which utilizes each modality as a separate measure of discomfort, suggests that the sensitivity of the three external modalities (Pressure, Heat, and EV) may differ depending on the type of discomfort experienced. That is, measurements with each modality may be more sensitive to a particular type of discomfort. Consequently, an analysis method which combines the three external modalities has the potential to be a broader measure of discomfort than each modality alone. The multivariate technique of principal component analysis was used to combine the scaled discomfort measurements from the Pressure, Heat, and EV modalities to produce a single discomfort measure.

The analysis algorithm computed the principal components using the matrix of correlations between modalities, for which the scaled responses for each modality were standardized to zero mean and unit variance. Table 23 shows the three principal components calculated from the scaled modality data. Note that over eighty percent of the data variance is explained by the first principal component. The eigenvectors for the components, which can be viewed as ordered coordinates on the original axes, show that

TABLE 23

PRINCIPAL COMPONENT ANALYSIS OF SCALED DATA
FROM PRESSURE, HEAT, AND EV MODALITIES

Principal Component Analysis				
		Eigenvalues	Variance Proportion (%)	
	e1	2.475	82.5	
	e2	0.303	10.1	
	e3	0.222	7.4	
Eigenvectors		V1	V2	V3
	Pressure	0.587	-0.140	-0.797
	Heat	0.569	0.772	0.283
	EV	0.576	-0.620	0.533
Unrotated Factor Matrix				
		F1	F2	F3
	Pressure	0.924	-0.077	-0.375
	Heat	0.895	0.425	0.133
	EV	0.906	-0.341	0.251

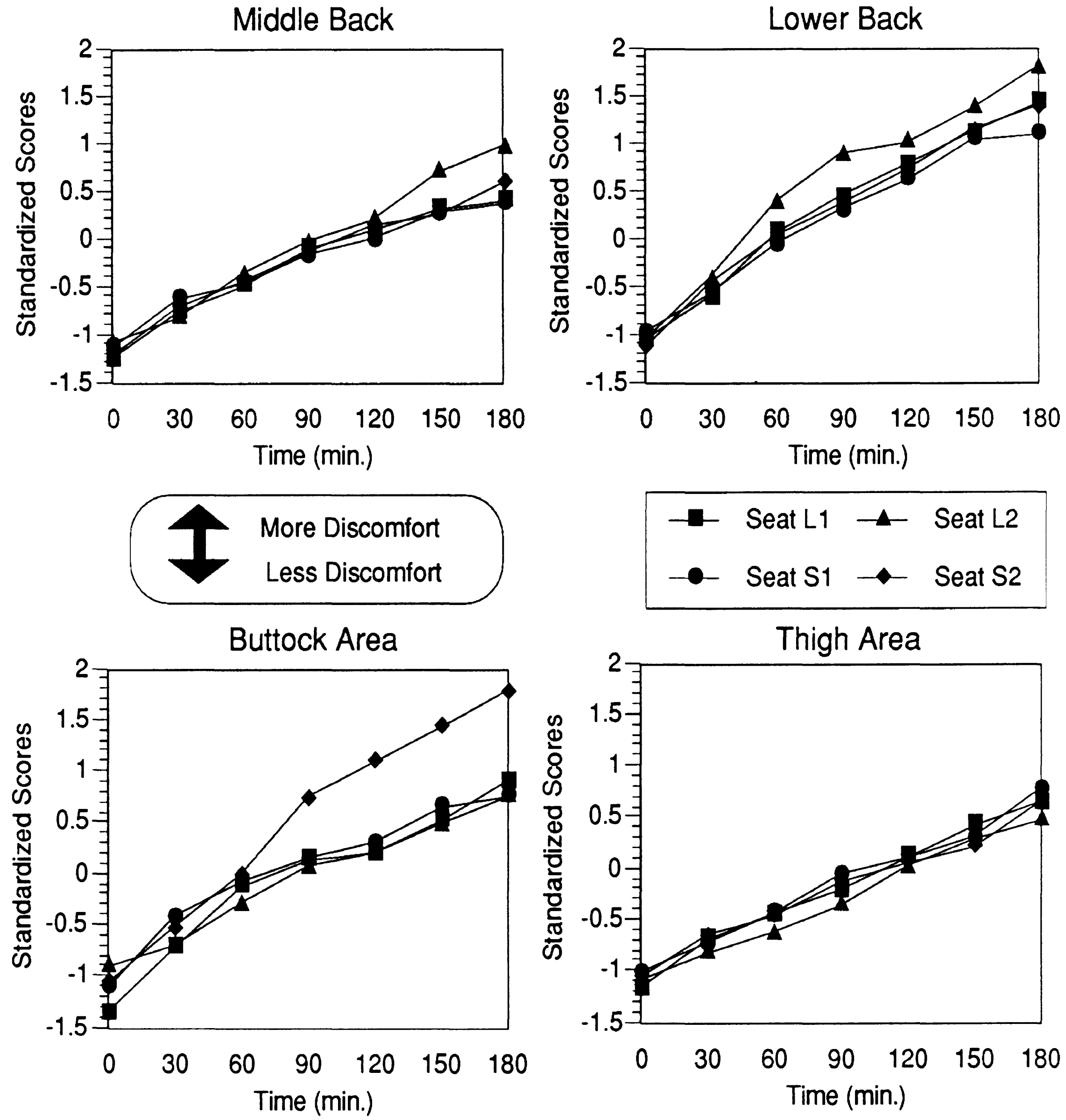


FIGURE 16. Scaled, standardized CMM responses on first principal component.

each modality contributes about equally to the first principal component. The correlations between the principal components and the scaled modality data are found in the unrotated factor matrix in Table 23. Each modality is highly, and nearly equally, correlated with the first principal component.

First Principal Component. The coordinates of each discomfort measurement on the first principal component axis were used as another measure of discomfort, one which combines the scaled measurements from the three modalities. The principal axis values were analyzed in a manner similar to that employed previously with each modality. The scaled data for each evaluation interval were transformed onto the first principal component axis, yielding one value for each body area at each evaluation interval.

Figure 16 shows the mean values on the first principal component, averaged over All Subjects, for each of the test seats. For the middle-back, lower-back, and buttock areas, some inter-seat differences in mean level are apparent. The mean value for Seat

Three is higher than those of the other seats in the middle-back area during the third hour of the simulation, and higher in the lower-back area from the beginning of the second hour. The mean value for Seat Four is higher in the buttock area during the second half of the simulation. Note that these observations closely parallel the aggregate findings from the univariate analyses.

Inter-seat comparisons were performed to quantify the observations from Figure 16. The values on the first principal component were standardized within each subject to zero mean and unit standard deviation to eliminate inter-subject differences in mean response level. For purposes of comparison to the findings obtained from each modality individually, the mean of the 120, 150, and 180 minute values for each driving simulation were calculated, a measure equivalent to the AVG index. These indexed values (one per driving simulation) were then standardized within each subject, using the same standardization procedure previously employed with indexed data. Paired t-tests were used as before to evaluate inter-seat differences.

Table 24 shows t-values and significant comparisons for the modality data transformed onto the first principal component axis. Based on the first principal component coordinate of each body-area evaluation, Seat Four was more uncomfortable in the buttock area than Seats One and Three for All Subjects and the Non-Sport group,

TABLE 24

CMM DATA TRANSFORMED ONTO THE FIRST PRINCIPAL COMPONENT: INTER-SEAT COMPARISONS, t-VALUES

Body Area	Inter-Seat Comparisons						
	1 v. 2	1 v. 3	1 v. 4	2 v. 3	2 v. 4	3 v. 4	$P \leq 0.05$
All Subjects							
Middle Back	0.373	-0.574	-0.475	-0.936	-0.805	0.187	
Lower Back	0.071	-0.803	-0.413	-0.781	-0.252	0.689	
Buttock Area	-0.555	0.796	-3.460 *	1.641	-2.170 †	-7.287**	4>1,3
Thigh Area	-0.671	-0.686	-0.263	-0.004	0.510	0.516	
Sport Group							
Middle Back	1.412	-0.455	-1.175	-3.910 *	-3.943 *	-0.408	3,4>2
Lower Back	1.710	-0.214	-0.581	-2.941 †	-2.317	-0.136	
Buttock Area	0.762	0.291	-1.695	-1.369	-9.006**	-6.173**	4>2,3
Thigh Area	2.030	-0.287	-0.037	-1.995	-2.001	0.237	
Non-Sport Group							
Middle Back	-0.610	-0.300	0.185	0.296	1.104	0.457	
Lower Back	-1.108	-0.971	0.145	0.394	1.301	1.987	
Buttock Area	-1.569	0.999	-23.753**	4.743 *	-0.214	-4.083 *	4>1,3 2>3
Thigh Area	-4.643 *	-0.665	-0.303	2.526 †	4.255 *	0.610	2>1,4

† $P \leq 0.10$
* $P \leq 0.05$
** $P \leq 0.01$

and more uncomfortable than Seats Two and Three for the Sport Group. Note that when the significance threshold is extended to $P \leq 0.10$, the index values for Seat Four in the buttock area are significantly higher than those of any other seat. In the back areas, both Seats Three and Four were more uncomfortable than Seat Two for the Sport group, but no significant differences between seats in the back areas are apparent for All Subjects and the Non-Sport group. The observations regarding the buttock area made with the mean values from All Subjects in Figure 16 are borne out by the statistical tests, but it is clear from the tests that variance in the data from the Non-Sport group prevented statistical inference regarding the back areas.

The lack of significant findings for the back areas is further explained by the univariate analysis for the individual modalities. Table 25 shows the findings from each which were significant with $P \leq 0.05$. While the buttock-area comparisons are similar for the principal component and univariate analyses, the back-area findings regarding Seat Three which are present in the univariate analysis are largely absent in the data transformed onto the first principal component. Note that for All Subjects, the EV modality failed to produce a significant inter-seat comparison in the back areas. Because the first principal component axis is influenced nearly equally by the three modalities, the lack of systematic inter-seat variability on the EV modality could have prevented such comparisons from being evident in the first principal axis coordinate data.

TABLE 25

SIGNIFICANT COMPARISONS FROM STANDARDIZED,
INDEXED CMM DATA
$P \leq 0.05$

Modality (Index)	Body Area			
	Middle Back	Lower Back	Buttock Area	Thigh Area
All Subjects				
Pressure (DAV)	3>1,2	3>4	4>2	--
Heat (TID)	3>2	3>2	4>3	--
EV (DAV)	--	--	4>3	--
OSGR (DID)	--	3>4	--	--
Sport Group				
Pressure (DAV)	3,4>2	3>2	3,4>2	3>2
Heat (TID)	3>2	--	4>2	1,3>2
EV (DAV)	3>2	3>2	4>2,3	3>2
OSGR (DID)	3>4	--	--	--
Non-Sport Group				
Pressure (DAV)	3>4,1	--	--	--
Heat (TID)	--	--	--	--
EV (DAV)	--	--	--	2>1,3
OSGR (DID)	--	3>4	1>3,4 2>3	2>1,3,4

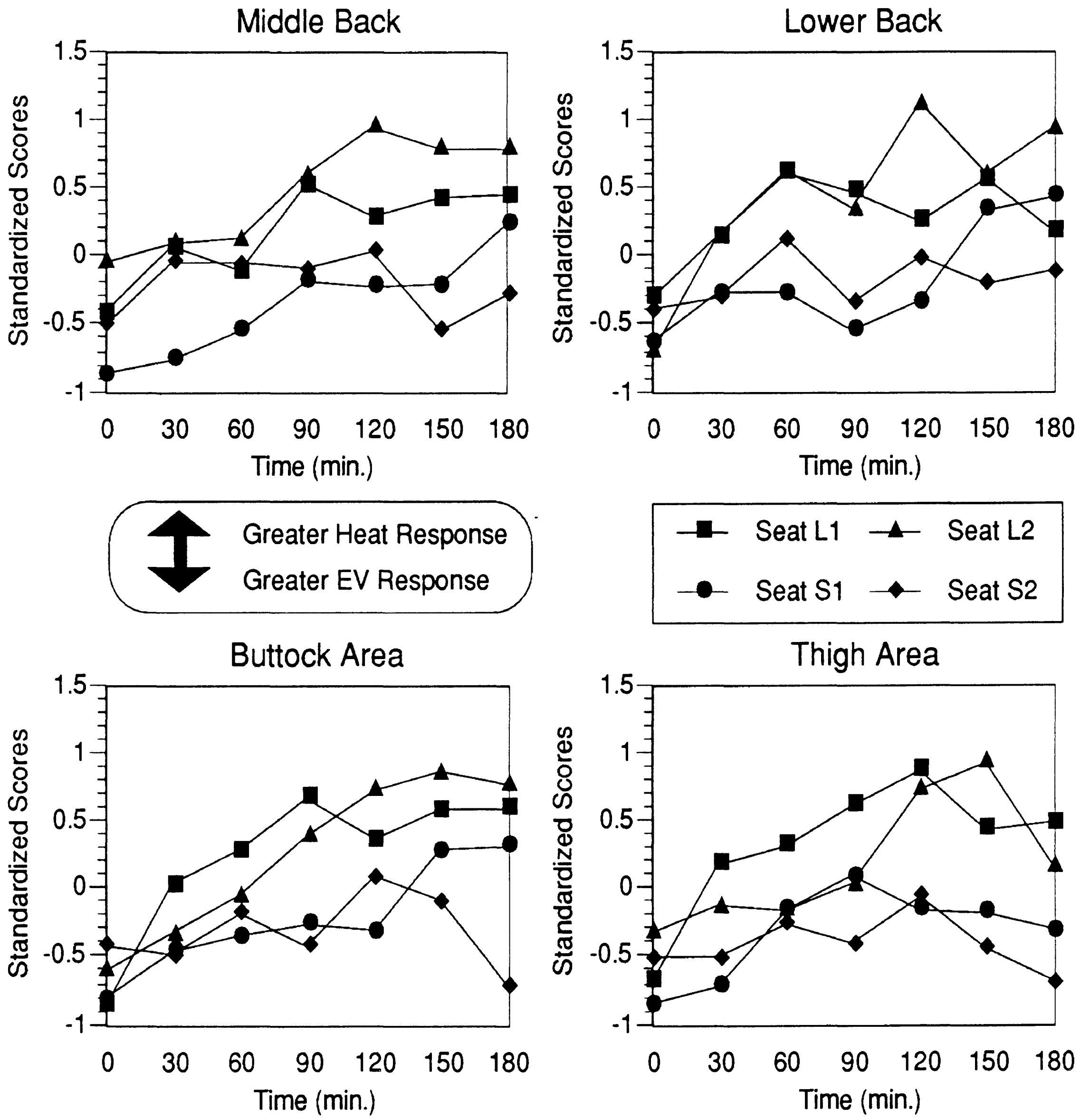


FIGURE 17. Scaled, standardized CMM responses on the second principal component.

Second and Third Principal Components. The second principal component in Table 23 indicates the axis perpendicular to the first component along which the data have the highest variance. This second component explains just over ten percent of the total data variance, and is affected primarily by the variance in the Heat and EV modalities. Data points (ordered sets of Pressure, Heat and EV observations) that have high values on the second principal axis have relatively high Heat modality contribution and low EV contribution to the aggregate discomfort measurement, while those which have low values on the second principal component have high EV modality contribution and low Heat contribution.

The third principal component in Table 23, which accounts for about seven percent of the total variance, expresses a difference between observations with high Pressure modality measurements and those which are relatively high on the Heat and EV modalities. High values on the third principal component indicate high scaled values from the Heat and EV modalities relative to the values from the Pressure modality.

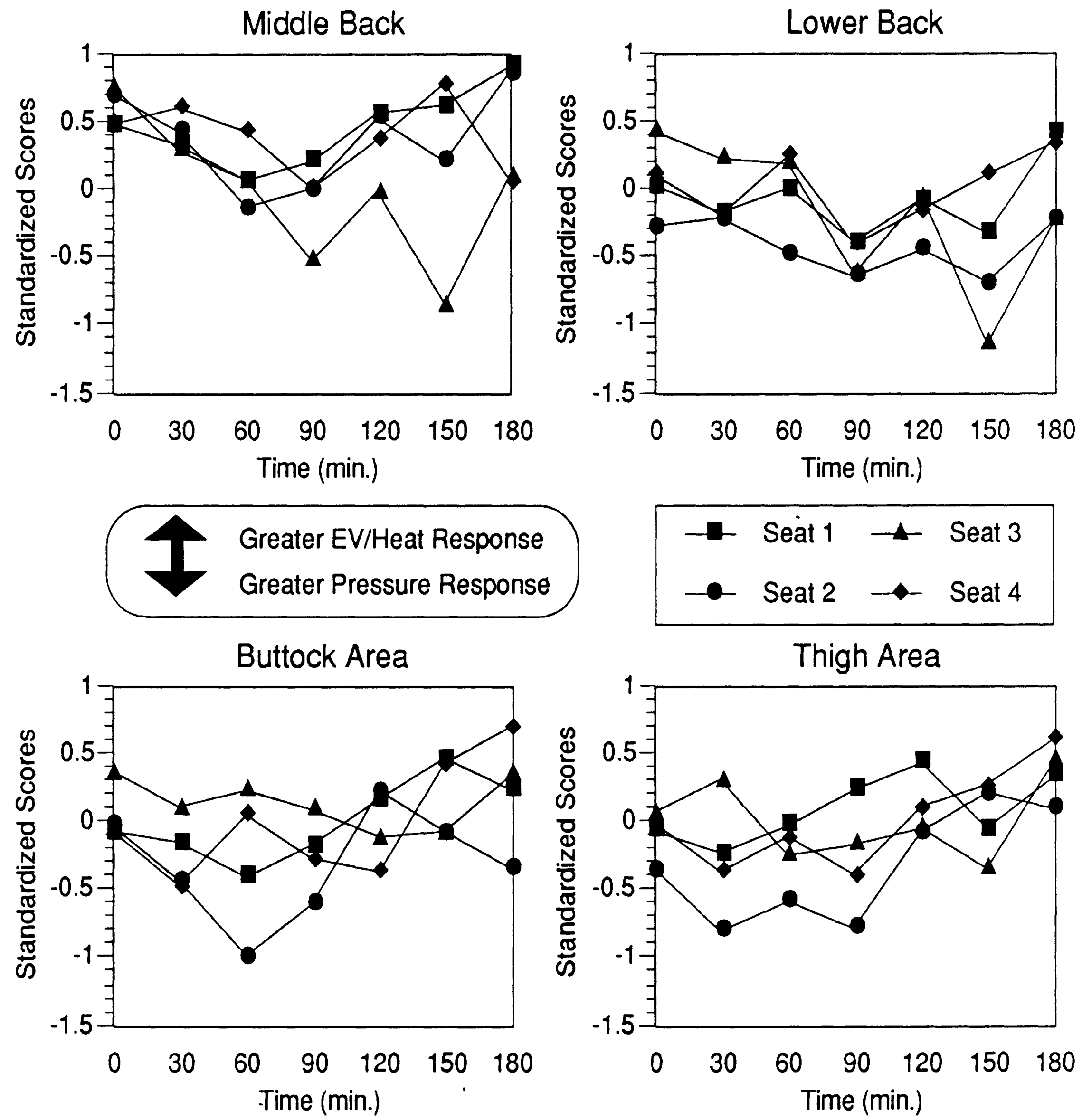


FIGURE 18. Scaled, standardized CMM responses on the third principal component.

Figure 17 and Figure 18 show the mean values on the second and third principal component axes for All Subjects. Each indicates some apparent inter-seat differences, and the plots for the second principal component show a time-related trend. Figure 17 shows generally positive trends for the second principal component over time, suggesting that Heat modality measurements increased faster than EV modality measurements. Analysis of characteristic modality behavior confirmed this observation (see Section 4.2). Note that there is some reversal of this trend at the later time periods for the buttock and thigh areas. This indicates that toward the end of the simulation the EV modality measurements increased at a rate equal to or greater than the Heat modality increase.

Because values on the second principal component axis indicate relative levels of modality response, the position of data from particular seats on the axis may be used to characterize the response for that seat. In the back areas, the discomfort evaluations for Seat Three are characterized by greater Heat response in relation to the EV response than other seats, although the proportion is about equal for Seat One in the lower back.

In the buttock and thigh areas, the data for Seat One indicate greater Heat response in relation to EV response than is the case for the other seats, although the data for Seat Three exhibit similar trends toward the end of the simulation.

The third principal component indicates trends between Pressure modality response and the combined responses of the Heat and EV modalities. High values on the third component indicate lower Pressure response in relation to the responses for the Heat and EV modalities. The mean values fluctuate more than did those of the first two components, reflecting the reduced data variance along the third axis. A few data characteristics are evident, however. The values for Seat Three show low mean values toward the end of the simulation, indicating that the Pressure response increased rapidly relative to the EV and Heat response. In the lower-back, buttock and thigh areas, the plots indicate that the Pressure response proportion for Seat Two was initially higher than for the seats, but the trend diminishes toward the end of the simulation.

Statistical tests were performed to evaluate the inter-seat comparisons on the second and third principal components. Values of the CMM data transformed onto the component axes were standardized for analysis and the AVG index prepared (average of 120, 150, and 180 minute values for each simulation). Tables 26 and 27 show the results of these tests. Fewer comparisons are significant than with the first component.

TABLE 26

CMM DATA TRANSFORMED ONTO THE SECOND PRINCIPAL COMPONENT: INTER-SEAT COMPARISONS, t-VALUES

Body Area	Inter-Seat Comparisons						
	1 v. 2	1 v. 3	1 v. 4	2 v. 3	2 v. 4	3 v. 4	$P \leq 0.05$
All Subjects							
Middle Back	1.392	-1.018	1.008	-3.075 *	-0.018	1.575	3>2
Lower Back	0.945	-1.243	1.053	-2.228 †	0.482	1.630	
Buttock Area	0.416	-0.185	0.365	-0.654	-0.008	0.659	
Thigh Area	2.279 †	0.906	2.140 †	-0.844	0.194	0.958	
Sport Group							
Middle Back	-0.075	-0.489	0.305	-0.773	0.472	0.638	
Lower Back	-0.785	-1.103	0.114	-0.622	0.686	0.834	
Buttock Area	-0.835	-1.840	-0.412	-0.137	0.358	0.590	
Thigh Area	0.523	0.295	1.920	0.011	1.173	0.737	
Non-Sport Group							
Middle Back	2.055	-0.930	1.724	-14.234**	-0.509	1.652	3>2
Lower Back	3.227 *	-0.507	1.821	-4.832 *	0.021	1.339	1,3>2
Buttock Area	4.020 *	0.992	1.076	-0.838	-0.351	0.265	1>2
Thigh Area	3.317 *	1.140	1.127	-1.606	-0.496	0.508	1>2

† $P \leq 0.10$
* $P \leq 0.05$
** $P \leq 0.01$

The values for Seat Three are lower than those for Seat Two in the middle-back area on the second component. A less significant trend in thigh area shows the values for Seat One are lower than those for Seats Two and Four, indicating a greater proportion of the total response is on the Heat modality. For the Non-Sport group, the EV response proportion for Seat Two is higher than are those for Seats One and Three, the luxury seats, particularly in the back areas.

Summary of Findings from Principal Component Analysis. The first principal component of the scaled CMM data provides a measure of discomfort which combines the data from the three external modalities. The trends evident along this axis are largely consistent with the findings of the univariate modality analyses, and the axis is highly and approximately equally correlated with each modality individually. In data from All Subjects, the values on the first component axis are higher for Seat Four in the buttock area, indicating increased discomfort. The Sport group data on the first component indicate that Seat Three was more uncomfortable in the middle-back area for the group, while the values for the Non-Sport group show increased discomfort associated with Seat Two in the thigh area.

The second and third principal components are of more interest, because they appear to indicate that the discomfort associated with different body areas was expressed

TABLE 27

CMM DATA TRANSFORMED ONTO THE THIRD PRINCIPAL COMPONENT: INTER-SEAT COMPARISONS, t-VALUES

Body Area	Inter-Seat Comparisons						
	1 v. 2	1 v. 3	1 v. 4	2 v. 3	2 v. 4	3 v. 4	$P \leq 0.05$
All Subjects							
Middle Back	0.849	3.631**	0.387	1.386	-0.612	-2.119 †	1>3
Lower Back	0.699	0.532	0.115	0.024	-0.507	-0.540	
Buttock Area	0.707	0.185	0.786	-0.668	-0.096	0.436	
Thigh Area	1.211	0.387	0.203	-0.834	-1.016	-0.233	
Sport Group							
Middle Back	0.306	1.379	0.015	0.401	-0.339	-0.946	
Lower Back	0.667	0.542	0.332	-0.295	-0.255	-0.038	
Buttock Area	0.596	0.072	2.179	-0.840	0.591	1.728	
Thigh Area	0.461	-0.292	0.527	-0.751	0.068	1.124	
Non-Sport Group							
Middle Back	0.952	5.880**	0.488	1.859	-0.678	-1.948	1>3
Lower Back	0.191	0.251	-0.192	0.238	-0.418	-0.899	
Buttock Area	0.324	0.158	-0.781	-0.141	-0.824	-0.749	
Thigh Area	1.272	0.733	-0.270	-0.324	-1.242	-3.120 †	

† $P \leq 0.10$
* $P \leq 0.05$
** $P \leq 0.01$

by different response relationships among the modalities. The second component shows that the responses for the middle-back area of Seat Three, which was shown to be an area of relatively high discomfort, included a higher response proportion from the Heat modality, relative to the other seats which did not show significantly higher middle-back discomfort. In the buttock and thigh areas, the CMM responses for Seat One also have a slightly greater proportion of Heat response than do those of the other seats. The values for Seat Two on the third component show increased pressure response, particularly in the buttock and thigh areas.

Because the discomfort in different body areas was expressed by different proportions of modality response, it is reasonable to conclude that the composition of the discomfort and its location affect the response sensitivity of the external modalities. The relative response levels of the modalities can then be considered as measures of the type of discomfort experienced.

On the third principal component, the values for Seat Three are higher than those of Seat One in the middle-back area, indicating greater Pressure modality response. The values for Seat Three are also higher than those for Seat Four in the middle-back and thigh areas, at a lower level of significance.

Correlation with OSGR Modality. The first principal component is moderately correlated with the OSGR modality scaled responses, as shown in Table 28. The other two components show virtually no relationship with the OSGR data. Note that the level of correlation between the OSGR modality and the first component is approximately the same level as the correlation between the OSGR modality and the three external modalities individually. This is to be expected, given the high correlations between each modality and the first component.

TABLE 28

CORRELATION COEFFICIENTS AMONG MODALITIES AND PRINCIPAL COMPONENTS (PC = PRINCIPAL COMPONENT)

Modalities	Pressure	Heat	EV	OSGR
Pressure	1.000			
Heat	0.744	1.000		
EV	0.769	0.699	1.000	
OSGR	0.692	0.785	0.661	1.000
PC1	0.924	0.895	0.906	0.784
PC2	-0.007	0.425	-0.341	0.179
PC3	-0.375	0.133	0.251	0.049

3.3 EXIT QUESTIONNAIRE

At the completion of each driving-simulation session, the subject completed a brief questionnaire with four parts. The subject first rated his overall discomfort on an open-scale response line with anchor phrases "No Discomfort" and "Unbearable Discomfort." Three open-ended questions followed, asking the subject to identify specific body areas in which he felt discomfort and to describe the discomfort. The subject was also asked to indicate seat features which might be linked to his discomfort, and suggest how they could be changed.

The responses to the open-scale overall discomfort evaluation were scaled just as were the responses to the OSGR modality during the simulation. For purposes of comparison with the Preliminary Questionnaire and CMM data, the responses were standardized using the unit-variance technique employed with the Preliminary Questionnaire data. Paired t-tests were used to determine significant inter-seat differences in the Exit Questionnaire overall discomfort data. Following a procedure similar to that used with the Preliminary Questionnaire Section-A data, t-statistics for each inter-seat comparison were calculated for All Subjects and the Sport and Non-Sport complementary subject groups.

3.3.1 Inter-Seat Differences in the Exit Questionnaire Overall Discomfort Evaluation. Only one significant difference between seats appeared in the analysis of the Exit Questionnaire overall discomfort evaluation. The Sport group found Seat Four to be more uncomfortable than Seat Two after the driving simulation, with $P \leq 0.01$. This contrasts with the data from question 23 of the Preliminary Questionnaire, which show Seat Four with a more favorable evaluation than Seat Two, also with $P \leq 0.01$. Figure 19 shows these relationships.

3.3.2 Open-ended Responses. The responses to the open-ended questions in the Exit Questionnaire are summarized in Table 29. Most body area identifications used the same terms employed in the evaluation intervals (middle back, lower back, etc.). Additional body areas identified as locations of discomfort are also listed (*e.g.*, neck). The second table column and Figure 20 indicate the number of subjects who mentioned discomfort in each area. The discomfort descriptions are comprehensive lists of adjectives used by the subjects in association with discomfort in the respective body area. The lower table section for each seat lists the features mentioned by the subjects in the Exit Questionnaire, along with the suggestions they made for improvement. Note that in one instance, the lower-back support on Seat Three, three subjects felt that more lumbar support would improve the seat, while two subjects preferred less support.

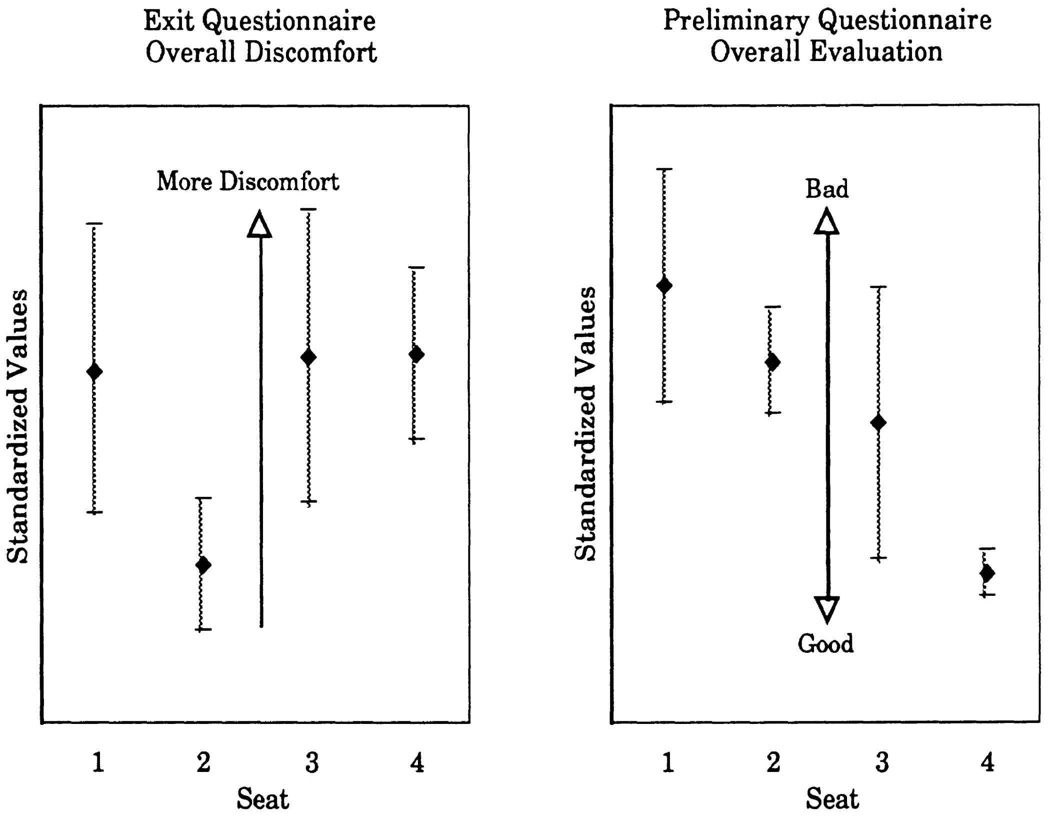


FIGURE 19. Standardized responses to Exit Questionnaire and Preliminary Questionnaire overall evaluations: Sport group.

For Seats One, Two, and Three, the lower back was mentioned most frequently as a site of discomfort. Seat Three had the most subjects reporting discomfort in that body area, with seven. Seat Four had six subjects identify discomfort in the buttock area, with five subjects describing discomfort in the lower-back area. The middle-back area was mentioned most for Seat Three, and the thigh area identified most often for Seats Three and One, with three subjects each.

The open-ended responses support the results of the CMM analyses. The CMM analysis for the data from All Subjects indicates that Seat Three was more uncomfortable than the other seats in at least one back area. On the Exit Questionnaire, the subjects made a total of twelve references to middle- and lower-back discomfort for

TABLE 29

SUMMARY OF RESPONSES TO EXIT QUESTIONNAIRE: AREAS OF DISCOMFORT

Area of Discomfort	No. of Subjects Reporting Discomfort	Descriptions of Discomfort
Seat One		
Middle Back	2	(Discomfort)
Lower Back	6	Dull pain, pressure, ache, heat, compacted
Buttock Area	4	Sore, compressed, tingling, numbness, pinched
Thigh Area	3	Stiff, tired
Right Calf	1	Twitching
Seat Two		
Middle Back	3	Tight, pressure
Lower Back	5	Numbing, sore, extreme fatigue, pressure, heat, aching
Buttock Area	5	Numb, compressed, pressure, burning
Thigh Area	2	Dull ache, burning, extreme fatigue, cramping
Right Calf	1	Pins and needles
Seat Three		
Middle Back	5	Stiff, aching
Lower Back	7	Aching, numbness, bruised, sore, spasm, heat, pressure
Buttock Area	3	Stiff, sore, compressed, pressure
Thigh Area	3	Stiff, numb, tired, pressure
Neck	1	(Discomfort)
Seat Four		
Middle Back	2	Stiff
Lower Back	5	Tired, aching, throbbing, bruised
Buttock Area	6	Sore aching, burning, numbing, compressed
Thigh Area	2	Aching, numb, tight, inflexible, tired
Neck	1	(Discomfort)

Seat Three, versus eight, eight, and seven back discomfort identifications for Seats One, Two, and Four, respectively. Similarly, Seat Four was identified by All Subjects in the CMM analysis to be more uncomfortable in the buttock area than the other test seats. On the Exit Questionnaire, buttock discomfort in Seat Four was mentioned by six subjects, versus four, five, and three for Seats One, Two, and Three, respectively. Of the five subjects who identified buttock discomfort in Seat Two, four comprised the Non-Sport group. The CMM data indicate that, on average, the Non-Sport group found Seat Two to be more uncomfortable than Seat Three in the buttock area.

The descriptions of discomfort included pain, pressure, and heat sensations, consistent with those reported by Schneider and Ricci (1989). The reported discomfort sensations are roughly analogous to the sensations employed as reference stimuli for the CMM, as was expected.

The recommendations for improved configuration of seat features were linked to the discomfort reported. These suggestions are shown in Table 30. Subjects who reported discomfort in a body area generally indicated a change which they felt would make the seat more comfortable in that area. For each seat, at least one subject indicated that they would like a lower cushion angle, with the surface of the cushion more nearly horizontal. This was associated with thigh discomfort reports.

For Seat One, three subjects indicated that more lower-back support was needed, while four felt the cushion should be firmer. Regarding Seat Two, one subject, who reported extreme discomfort in the buttock area, suggested that the cushion be made longer and wider. Other suggestions for Seat Two included additional padding in the

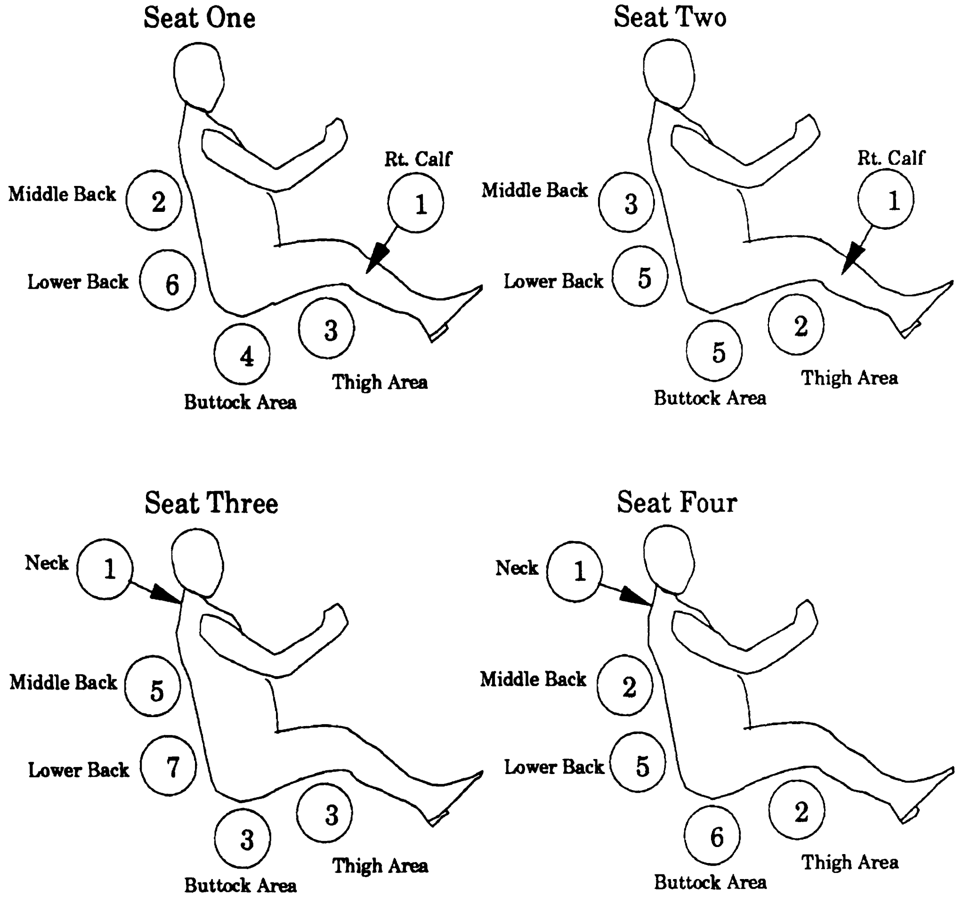


FIGURE 20. Number of subjects reporting discomfort by body area and seat.

cushion (two subjects), recliner adjustability allowing a more upright position (one subject), and less lower-back support (one subject). Seat Three received the most feature-improvement suggestions. Two subjects said that the seat needed to support the middle- and upper-back areas more. Of the seven subjects who mentioned lower-back discomfort in Seat Three, two suggested that less support in the area would make the seat more comfortable, while three indicated more support would be preferred. Other suggestions concerned the backrest shape, with one subject indicating it should be wider, another less rounded. The feature most often mentioned for improvement on Seat Four was the cushion padding. Four subjects suggested that the cushion be made softer. One subject indicated that the front lip of the cushion also should be softer. Other suggestions included more upper-middle-back support and a higher cushion.

TABLE 30

SUMMARY OF RESPONSES TO EXIT QUESTIONNAIRE: FEATURES ASSOCIATED WITH DISCOMFORT

Feature Mentioned	No. of Subjects	Recommendation
Seat One		
Cushion Angle	2	Lower (more level)
Cushion Padding	4	Firmer
Lumbar Support	3	More support
Seat Covering	3	Better heat dissipation
Seat Two		
Cushion Length	1	Longer
Cushion Width	1	Wider
Cushion Angle	2	Lower (more level)
Cushion Padding	2	Softer
Recliner	1	More upright
Lumbar Support	1	Less support
Seat Three		
Side-leg Support	1	More support
Upper-Middle-Back Support	2	More support
Cushion Length	1	Longer
Headrest	1	More adjustment
Lumbar Support	3	More support
Lumbar Support	2	Less support
Backrest Width	1	Wider
Buttock Area	1	Larger
Cushion Angle	2	Lower (more level)
Cushion Height	1	Higher
Backrest Lateral Contour	1	Less rounded, more flat
Seat Four		
Upper-Middle-Back Support	1	More support
Headrest	2	Further back
Cushion Angle	1	Lower (more level)
Cushion Height	2	Higher
Cushion Padding	4	Softer
Cushion Front Lip	1	Softer

3.4 RELATIONS AMONG PRELIMINARY-QUESTIONNAIRE, CMM AND EXIT-QUESTIONNAIRE DATA

Analyses were performed to examine the similarities and differences among the results from each of the three subjective data types, relative to the test seats. Comparison of the Preliminary Questionnaire findings with the CMM and Exit Questionnaire results provided an evaluation of the difference between short- and long-term comfort performance of the test seats.

3.4.1 Correlations Among Overall Discomfort Measures. As a first step, correlation coefficients were calculated for each of the overall integrated measures, the overall measure from the Preliminary Questionnaire (question 23), and the Exit Questionnaire "Overall Discomfort" data. Table 31 shows the correlation coefficients (r). Note that question 23 of the Preliminary Questionnaire has been inverted by subtracting each value from one to yield a "discomfort" measure from a "comfort" question (see Section 3.4.2).

In the "Overall Measures" columns of Table 31, TID refers to the Total Integrated Discomfort index, as calculated for Section 3.2 and summed over all four body areas. DID refers to the same index, minus the integrated levels for the first thirty minutes of the test..

As Table 31 shows, the overall seat evaluations from the Preliminary Questionnaire are not correlated with overall discomfort measures from the three-hour driving-simulation session. None show corresponding regression relationships significant with $P \leq 0.10$. The overall discomfort data from the Exit Questionnaire, however, are correlated with the CMM overall measures. Regression analyses showed that all of the relationships are significant with $P \leq 0.05$.

Two observations may be made. First, question 23 of the Preliminary Questionnaire is a poor predictor of overall discomfort experienced during the driving simulation, as measured by both CMM and the Exit Questionnaire. Second, the Exit Questionnaire overall discomfort measure, an open-scale question, is correlated with

TABLE 31

CORRELATION COEFFICIENTS FOR OVERALL MEASURES

Overall Measures		1 - Q23	Exit Q
Modality	Index	r	r
Pressure	TID	-0.115	0.551
Heat	TID	-0.082	0.711
EV	TID	0.024	0.515
OSGR	TID	-0.215	0.746
Pressure	DID	-0.058	0.689
Heat	DID	-0.095	0.667
EV	DID	0.029	0.582
OSGR	DID	-0.240	0.743
1 - Q23	- -		0.045

overall discomfort during the simulation as measured by the CMM modalities; the inferences made from the CMM data are supported by the Exit Questionnaire data.

3.4.2 Preliminary versus Exit Overall Evaluation. Interpretation of these statistics was potentially problematic because the wording of the questions was different. Question 23 of the Preliminary Questionnaire asked the subjects their overall evaluation of the test seat, from "Bad" to "Good." These responses were found to be highly correlated (r = 0.916) with the responses from question 24 dealing with comfort but were used rather than question 24 for an overall evaluation measure because of better differentiation between seats in the responses. For this analysis, the question-23 data were inverted by subtracting each scaled value from unity. The data were then standardized within each subject, so that the data for each seat effectively represented each subject's evaluation of the seat relative to his evaluation of the other seats. Because of the inversion, the data could be considered to represent a subject's relative measure of the "badness" of each seat in his initial evaluation. Those data were then compared with the Exit Questionnaire data, which consisted of responses to a question asking the subject to rate his overall discomfort from "No Discomfort" to "Unbearable Discomfort." These responses were also standardized within each subject, representing the level of overall discomfort at the end of the driving simulation, relative to the other test seats.

Table 32 shows the inter-seat comparisons for the overall evaluation data from both the Preliminary Questionnaire and Exit Questionnaire. The inter-seat comparison between Seat Two and Seat Four is reversed for the two measures in the data from the Sport group. The Preliminary Questionnaire data for the group indicate that Seat Two was rated more poorly overall than was Seat Four. However, the Exit Questionnaire overall evaluation data show that Seat Two was rated more comfortable than Seat Four after the driving simulation.

An additional comparison was made between the two data sets, matching the standardized values for each seat from the Preliminary Questionnaire against the

TABLE 32

INTER-SEAT COMPARISONS FROM PRELIMINARY QUESTIONNAIRE AND EXIT QUESTIONNAIRE OVERALL EVALUATIONS (t-VALUES, N = 8)

Overall Measure	Inter-Seat Comparisons						
	1 v. 2	1 v. 3	1 v. 4	2 v. 3	2 v. 4	3 v. 4	P ≤ 0.05
All Subjects							
1 - A23	-0.088	1.456	0.246	2.373 *	0.446	-0.847	2>3
Exit Q.	0.645	-0.221	-0.125	-0.787	-0.787	0.218	- -
Sport							
1 - A23	1.128	1.133	5.398 *	0.766	10.548 **	1.941	1,2>4
Exit Q.	1.461	-0.715	-0.476	-2.525 *	-3.802**	0.358	3,4>2
Non-Sport							
1 - A23	-1.328	0.771	-2.892 †	3.540 *	-7.286 **	-12.084 **	4>2>3
Exit Q.	-0.370	0.437	0.322	1.016	0.827	-0.463	- -

† P ≤ 0.10
* P ≤ 0.05
** P ≤ 0.01

values for that seat from the Exit Questionnaire. The data were standardized as for the previous analysis, so each value represented the evaluation of the seat relative to the other seats. Table 33 shows the comparisons by seat. There are two instances in the Sport group data for which the Exit Questionnaire overall evaluation of a seat is different from the Preliminary Questionnaire evaluation. The overall evaluation of Seat Two was poorer on the Preliminary Questionnaire than on the Exit Questionnaire. Also, Seat Four was rated more poorly after the driving simulation than during the Preliminary Questionnaire evaluation. For the Non-Sport group, Seat Three was rated more poorly after the driving simulation than in the earlier evaluation, while Seat Four was rated higher relative to the other seats on the Exit Questionnaire than was reported on the Preliminary Questionnaire.

TABLE 33

COMPARISON BETWEEN PRELIMINARY QUESTIONNAIRE AND EXIT QUESTIONNAIRE OVERALL EVALUATIONS BY SEAT: STANDARDIZED DATA (t-VALUES, N = 8)

Subject Group	Exit – Preliminary Comparison			
	Seat 1	Seat 2	Seat 3	Seat 4
All Subjects	-0.033	1.373	-1.682	-0.057
Sport Group	0.856	5.809 **	-0.705	-6.522 **
Non-Sport Group	-0.962	-0.482	-4.160 **	5.076 **

** $P \leq 0.01$

3.4.3 Comparison Between Preliminary Questionnaire and CMM Index Results. The data from the Preliminary Questionnaire were compared with the results from the CMM index data to determine the extent to which indications of the potential for discomfort could be seen in the initial evaluations of seat features. Table 19 in Section 3.2 shows the significant inter-seat comparisons from the CMM indices. These were compared with the Section-A data from the Preliminary Questionnaire to determine if perceived differences among the test seats were expressed in the initial evaluation for the same seat pairs which showed significant differences in discomfort on the CMM indices.

Because of the potential for body area discomfort to be affected by seat features not directly associated with the body area (*e.g.*, lower-back discomfort influenced by middle-back fit), the Preliminary Questionnaire data were divided into cushion and backrest sections (questions 1 through 12 and 13 through 22, respectively), and the CMM results for each body area were compared with the Preliminary Questionnaire data for the corresponding section. For example, middle-back differences in the CMM indices were compared with the responses for all questions in the Preliminary Questionnaire having to do with the seats' backrests (questions 13 through 23).

Features in the Preliminary Questionnaire which were perceived to be different within the seat pairs which showed significant differences in the CMM index data were then examined for feature-satisfaction relationships to determine if satisfaction with specific features in the preliminary session was associated with less discomfort during the driving simulation. (See Preliminary Questionnaire analyses, Section 3.1.)

Because the comparisons were inconclusive for the complementary subject groups, only the results for All Subjects are presented here.

Table 34 shows the seat pairs which were significant in the CMM analyses, along with the perceived differences between the seats expressed by All Subjects in the Preliminary Questionnaire with $P \leq 0.05$. The explanations indicate how the seat of the pair which was higher on the CMM index (more discomfort) was rated on the feature

TABLE 34

PRELIMINARY QUESTIONNAIRE SECTION-A COMPARISONS BETWEEN SEAT PAIRS THAT SHOWED DISCOMFORT DIFFERENCES IN THE CMM INDEX RESULTS

Significant Inter-Seat Comparisons from CMM Modalities	Preliminary Questionnaire Response	Feature Evaluation of Seat Which Was Rated Higher On CMM Discomfort Index
Middle-Back Area		
3 > 1	A15	*Tighter low-back fit*
	A16	Firmer backrest padding
	A19	*Stronger lumbar support*
	A20	Higher lumbar support
	A22	More arched spine posture
3 > 2	A14	Looser middle-back fit
	A16	Softer backrest padding
	A18	Wider backrest
Lower-Back Area		
3 > 4	A16	Softer backrest padding
	A18	Wider backrest
	A21	*Less constricted stomach*
	A22	More arched spine posture
3 > 2	A14	Looser middle-back fit
	A16	Softer backrest padding
	A18	Wider backrest
Buttock Area		
4 > 2	A8	Smaller cushion angle
	A9	Stiffer cushion
4 > 3	A2	*Tighter buttock fit*
	A4	Firmer cushion padding
	A5	*Shorter cushion*
	A6	Narrower cushion
	A8	Smaller cushion angle
	A9	Stiffer cushion
4 > 1	A4	Firmer cushion padding
	A5	Shorter cushion
	A6	Narrower cushion
	A9	Stiffer cushion
	A10	Faster bounce recovery
	A12	Less sinking into cushion

relative to the other seat. All feature differences were significant with $P \leq 0.05$ except those in italics, which were significant with $P \leq 0.10$. For instance, in the middle-back area, the CMM data indicate that Seat Three was more uncomfortable than Seat One (3>1); the Section-A responses for question 15 of the Preliminary Questionnaire show that subjects perceived Seat Three to be tighter than Seat One in the low-back area. Because there are no significant inter-seat comparisons from the indexed CMM data for the thigh area, that body area is not included in Table 34.

The findings in Table 34 were then combined with the results of the correlation/regression analyses of the Preliminary Questionnaire data (see Section 3.1.6) to determine the extent to which discomfort differences between the test seats indicated by the CMM results are associated with the satisfaction indicated by the test subjects on the relevant seat features during their initial evaluations of the seats. In general, the feature/satisfaction relationships found in the Preliminary Questionnaire data are poor predictors of the long-term discomfort results.

MIDDLE-BACK AREA

General: Seat Three was perceived to be tighter, firmer, etc. than Seat One, and looser, wider, etc. than Seat Two, but performed more poorly than either on CMM discomfort measures.

Correlations/Regressions:

- Of the features indicated in Table 34, feature satisfaction is correlated with the overall evaluation of the seat for middle-back fit, low-back fit, backrest width, and lumbar support. Of these, backrest width and lumbar support show feature/satisfaction relationships. The data for low-back fit also indicate a feature/satisfaction relationship with $P \leq 0.10$.

- The feature/satisfaction relationships for low-back fit, cushion width, and lumbar support show feature preferences opposite the CMM findings. For instance, Seat Three was perceived to have a wider backrest than Seat Two, and greater backrest width is correlated with greater satisfaction with backrest width; yet, the CMM findings show Seat Three to have been more uncomfortable than Seat Two during the driving simulation.

- The findings from question 16, for which firmer backrests were correlated with greater satisfaction, are consonant with the CMM finding 3>2, but not with the finding 3>1. Satisfaction with backrest firmness is not correlated with the overall evaluation of the seat.

Conclusions: The Preliminary Questionnaire results indicate subject preferences opposite to the CMM findings 3>2 and 3>1, except that backrest firmness is correlated with feature satisfaction, which is consistent with the CMM finding 3>2.

LOWER-BACK AREA

General: Seat Three was perceived to be softer, wider, and looser than Seat Two or Seat Four.

Correlations/Regressions:

- Satisfaction ratings for middle-back fit and backrest width are correlated with the overall seat evaluation.
- Greater width received higher satisfaction ratings, a finding opposite from the CMM findings of 3>4 and 3>2.
- On feature 22, for which satisfaction was correlated with overall satisfaction, more arched spine posture received higher satisfaction ratings, which favors Seat Three over Seat Four. This is also opposite of the CMM findings.
- The findings regarding feature 16, for which firmer backrests were correlated with greater satisfaction, are consonant with the CMM finding 3>2, but not with the finding 3>1. Satisfaction with feature 16 is not correlated with overall satisfaction.

Conclusions: The Preliminary Questionnaire results indicate subject preferences opposite to the CMM findings 3>4 and 3>2, except that backrest firmness is correlated with feature satisfaction, which is consistent with the CMM finding 3>2. Backrest firmness is not, however, correlated with the overall evaluation of the seat from the Preliminary Questionnaire.

BUTTOCK AREA

General: Seat Four was perceived as tighter, firmer, etc. than Seat One, Seat Two, and Seat Three.

Correlations/Regressions:

- Satisfaction with feature 9, cushion bounciness, is correlated with the overall evaluation, but there is no significant feature/satisfaction relationship.
- Satisfaction responses for cushion width and cushion sinking are correlated with overall satisfaction with $P \leq 0.10$, and each shows a feature/satisfaction relationship. Regression analyses show that wider cushions are associated with higher satisfaction, as is less sinking into the cushion. The first relationship supports the CMM findings of 4>3 and 4>2, while the second contradicts the CMM finding 4>1.

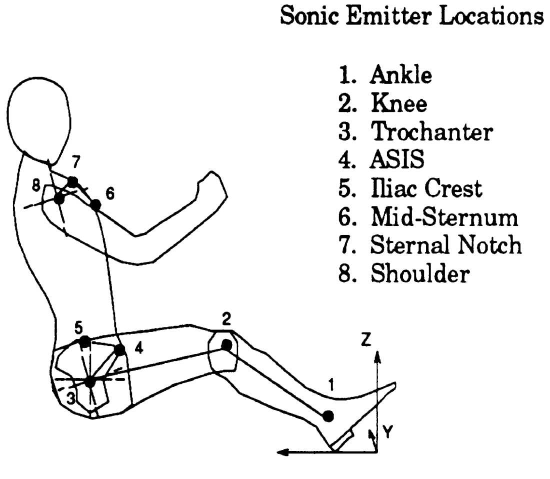
Conclusions: The Preliminary Questionnaire results indicate subject preferences consistent with the CMM findings 4>3 and 4>1, except that satisfaction with the feature "sinking into the cushion" favors Seat Four over Seat One.

3.5 SITTING POSTURE OF THE SUBJECTS DURING THE DRIVING SIMULATION

Subject posture was monitored throughout the driving simulation using the SAC GP8-3D sonic digitizing system. Eight sonic emitters were attached by various means to the subject over selected skeletal landmarks, and their locations were sampled at thirty-second intervals throughout the test. Prior to the start of the simulation, the locations of the emitters were recorded while the subject was in a standing position, so that postural variables could be assessed relative to the subject's standing posture.

Figure 21 shows the location of the emitters used for the driving-simulation sessions. Emitter eight was attached with medical tape to the skin on the subject's right shoulder, approximately adjacent to the gleno-humeral joint. Emitters six and seven were fastened to a plastic strip 95 mm apart. The strip was then attached to the skin of the subject's chest so that the emitters were approximately in the sagittal plane, with emitter seven located as close to the subject's sternal notch as possible. Emitters three, four, and five were attached to the subject's tight-fitting clothing using cloth adhesive tape. Emitter three was positioned over the most lateral point of the greater trochanter of the subject's right femur. Emitter four was located over the anterior-superior iliac spine of the pelvis, and emitter five was located over the most superior position on the subject's iliac crest, as determined by palpation. Because of difficulties posed by varying thickness of flesh over these body landmarks, the emitters were not considered to locate these landmarks with great accuracy; however, analysis of these data considered the change in the relative position of the emitters between the standing and sitting posture, and over the course of the test, which did not require that the emitters represent the exact skeletal location but only the relative movement of the skeletal landmarks. Emitters two and one were located at the subject's knee and ankle, respectively, by cloth straps which fastened around the leg.

The subjects wore close-fitting exercise tights during the driving-simulation session to minimize movement between the subject's skin and the emitters attached to the clothing. The distances between emitters three, four, and five in the data from the driving-simulations were not found to vary significantly during the course of the simulation, or between the standing measurement and the first driving-simulation samples. Stretching of the clothing material or "bunching up" during the simulation sufficient to cause distortion of the emitter locations would be evident as changes in the distances between emitters affixed to the clothing. Those data for which any of the three distances deviated by more than 5 mm from the distances calculated from the standing-position data (less than one percent of the total number of data points for those emitters) were deleted before further analyses were performed.



Sonic Emitter Locations

1. Ankle
2. Knee
3. Trochanter
4. ASIS
5. Iliac Crest
6. Mid-Sternum
7. Sternal Notch
8. Shoulder

FIGURE 21. Location of sonic emitters for driving simulation.

Postural variables were calculated from the data recorded during the driving simulation and previously in the standing posture. Although many possible measures were considered, twelve were chosen for subsequent analysis. Figure 22 and Table 35 summarize these variables.

Preliminary analysis of the data showed that the subject's posture could be affected by the activities during the evaluation intervals; consequently, the data from the emitters during those periods of the driving simulation when the subject was not operating the simulator were not used in calculating the postural variables.

Analyses were performed to investigate:

1. systematic differences in subject posture between seats,
2. changes in postural variables with time, and
3. systematic differences between seats in time-related posture changes.

The variables described in Table 35 were calculated for the emitter data taken between evaluation intervals. However, emitters were occasionally hidden from the digitizer microphone array by the subject's arms, which reduced the number of calculated values for some variables.

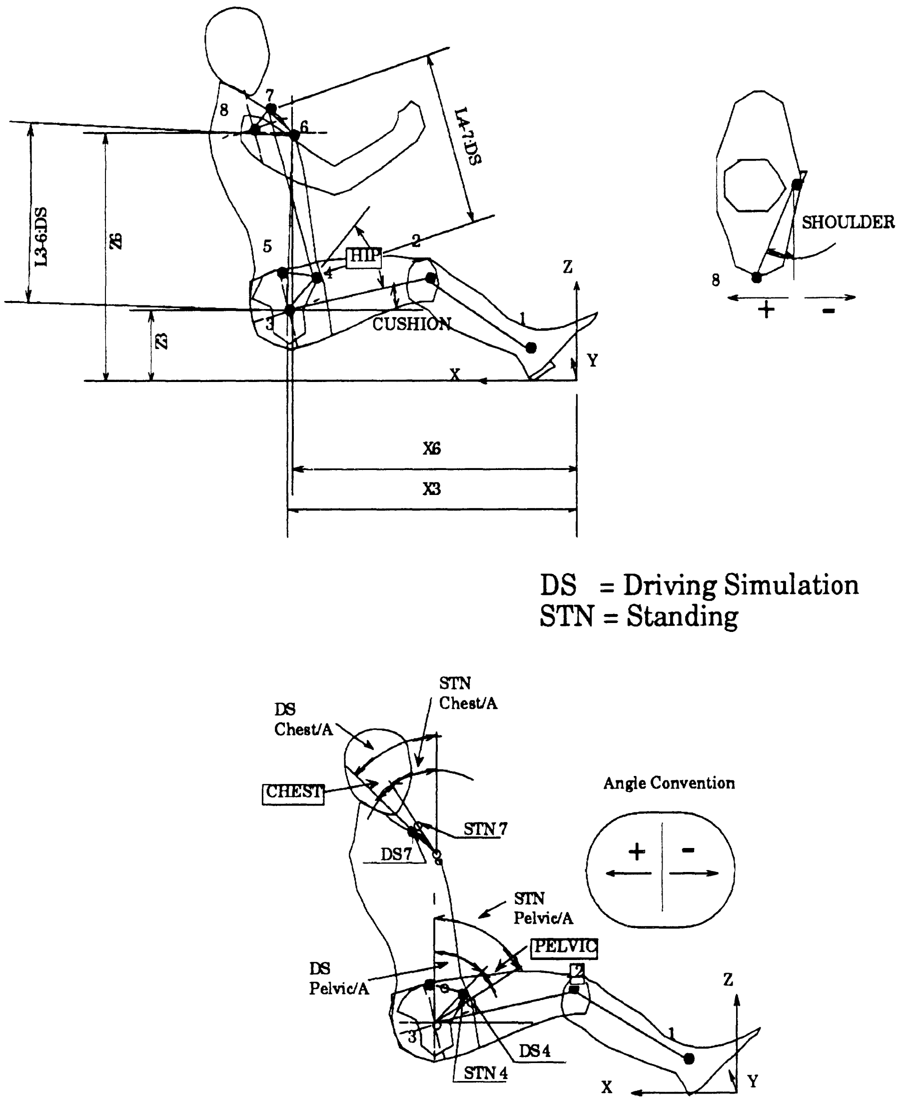


FIGURE 22. Definitions of postural variables.

TABLE 35

DEFINITIONS OF POSTURAL VARIABLES

Variable	Definition
1. CUSHION	Angle of right thigh above horizontal, projected onto a sagittal plane, determined by a line connecting emitters two and three and the horizontal.
2. HIP	Angle formed by emitters two, three and four; a measure of the angle between the pelvis and femur.
3. CHEST	The angle from the vertical of the line formed by emitters six and seven, minus the same measure taken from the standing-position data; a measure of the change in chest angle from standing to sitting.
4. SHOULDER	The angle between a line formed by emitters seven and eight, and another line through emitter seven perpendicular to a line through emitters six and seven; this variable measured the relative "hunching" of the shoulders.
5. PELVIC	The angle from the vertical of the projection onto a sagittal plane of a line formed by emitters three and four, minus the same measure taken from the standing-position data; a measure of the change in pelvic inclination from standing to sitting.
6. SLOUCH	PELVIC – CHEST; a measure of slouching.
7. L3-6	The three-dimensional length from emitter three to emitter six, divided by the same measure in the standing position, times 100%; another measure of slouch independent of the pelvic angle.
8. L4-7	The three-dimensional length from emitter four to emitter seven, divided by the same measure in the standing position, times 100%; another measure of slouch.
9. X3	The distance along the X axis from emitter three to the undepressed accelerator pedal center; a measure of the extension of the subject's right leg was.
10. Z3	The distance along the Z axis from emitter three to the floor of the buck; indicates how high the subject was relative to the heel location.
11. X6	The distance along the X axis from emitter six to the center of the undepressed accelerator pedal; a measure of how far the subject's chest was from accelerator pedal.
12. Z6	The distance along the Z axis from emitter six to the floor of the buck; a measure of how high the subject's chest was relative to the heel location.

3.5.1 Inter-Seat Comparisons of Postural Variables. As a first step, the values of the variables calculated for all sampled data were averaged over each simulation, resulting in eight average values for each seat (one for each subject). The mean values of the twelve postural variables are shown in Table 36. These variable values were then compared between seats, using a paired t-test. Table 37 shows the results of these tests, indicating seat comparison pairs which were significant at the $P \leq 0.05$ level. Inter-seat differences were found in five variables. (X>Y is used to indicate that, on average, Seat X is higher than Seat Y on the measure.)

These results show that the angle of the subject's right thigh from the horizontal was higher on average in Seat Two than in Seat One. The values for Seat Three show a smaller change in pelvic inclination from the standing to sitting positions than do those

TABLE 36

MEANS OF POSTURAL VARIABLES BY SEAT

Variable	Seat 1	Seat 2	Seat 3	Seat 4	Units
CUSHION	15.1	17.8	14.3	17.2	degrees
CHEST	8.9	13.0	7.4	15.1	degrees
PELVIC	49.9	47.8	38.4	50.7	degrees
L3-6	82.0	82.1	80.0	86.7	percent
L4-7	78.3	79.4	79.2	82.9	percent
HIP	71.8	69.7	70.1	73.9	degrees
SHOULDER	3.1	3.2	2.6	2.6	degrees
SLOUCH	41.1	34.9	30.0	32.4	degrees
X3	87.1	84.1	85.5	83.5	cm
Z3	25.8	23.0	28.1	23.9	cm
X6	93.4	92.0	89.5	91.0	cm
Z6	57.9	55.2	60.0	58.4	cm

TABLE 37

SIGNIFICANT RESULTS FOR INTER-SEAT COMPARISONS OF POSTURAL VARIABLES, USING PAIRED t-TESTS WITH MEAN VALUES FROM EACH DRIVING SIMULATION

Variable	Significant Inter-Seat Comparisons *
CUSHION	2>1
PELVIC	1>3 4>3
SLOUCH	3>1
L3-6	4>2 4>3
L4-7	4>3

* $P \leq 0.05$

from Seats One or Four. For the three measures of slouching, Seat Three produced less difference in inclination between the chest and the pelvis than Seat One, but the subject's chest was typically closer to the pelvis in Seat Three than in Seat Four. Seat Two also tended to produce a smaller chest-to-pelvis distance in L3-6 than did Seat Four.

The fact that more variables failed to produce significant differences among seats was due, in part, to large variability in the data among subjects, despite an attempt to standardize some variables for subject anthropometry (*e.g.*, L3-6). Additionally, however, analysis of variance indicated that several variables were also significantly time-dependent, meaning that the variables showed systematic changes over the course of the driving simulation. An analysis of the time trends is presented in Section 3.5.2.

In view of these trends, the data were reconfigured for further inter-seat comparison. The calculated variables were divided into six partitions, corresponding to the six half-hour periods in the driving-simulation session between evaluation intervals. The variable values were then averaged within each of these partitions for each of the driving-simulation sessions.

The paired t-test comparisons were repeated, with nominally 48 values for each seat (8 subjects times 6 partitions). Because of hidden emitters, insufficient variable values were available to calculate a meaningful average for some partitions. Those data were neglected in the subsequent analysis. The degrees of freedom for the statistical tests were adjusted appropriately and varied from 27 to 45 out of a possible 47 (N-1). Table 38 summarizes the inter-seat comparisons which were significant with $P \leq 0.05$. Table 39 contains the calculated t-statistics, 95% confidence intervals and number of observations for each comparison. Of the inter-seat comparisons which are significant with $P \leq 0.05$, 39 out of 46 are also significant with $P \leq 0.01$.

These results are more informative than were those from the previous statistical tests. CUSHION and CHEST show significant differences in posture between the luxury and sport seats. The two luxury seats (Seat One and Seat Three) produced lower thigh angles and smaller changes in chest angle from the standing posture than did the sport

TABLE 38

SIGNIFICANT RESULTS OF INTER-SEAT COMPARISONS OF POSTURAL VARIABLES USING PAIRED t-TESTS WITH SIX TIME PARTITIONS FROM EACH DRIVING SIMULATION

Variable	Significant Inter-Seat Comparisons *
CUSHION	2>1 4>1 2>3 4>3
CHEST	2>1 4>1 2>3 4>3
PELVIC	1>3 2>3 4>3
SLOUCH	1>2>3 1>4>3
L3-6	4>1>3 4>2>3
L4-7	4>2>1 4>2>3
X3	1>2 1>3>4
Z3	3>1>4>2
X6	1>2>3 1>4>3
Z6	3>1>2 3>4>2

* $P \leq 0.05$

TABLE 39

95% CONFIDENCE INTERVALS FOR INTER-SEAT POSTURE VARIABLE COMPARISONS

Variable	Inter-Seat Comparison					
	1 v. 2	1 v. 3	1 v. 4	2 v. 3	2 v. 4	3 v. 4
CUSHION						
High	-1.66	1.81	-0.02	4.80	2.70	-1.48
Low	-3.21	-0.01	-3.17	1.85	-0.12	-4.78
N	37	45	28	38	28	30
CHEST						
High	-0.75	3.40	-1.76	5.43	0.06	-5.06
Low	-3.87	-0.34	-7.52	1.72	-5.34	-8.49
N	41	45	37	40	38	37
PELVIC						
High	3.90	13.06	2.19	12.89	1.79	-8.65
Low	-0.66	9.14	-2.96	5.75	-4.83	-13.74
N	40	46	36	40	37	37
L3-6						
High	2.28	3.52	-1.55	3.59	-3.08	-6.09
Low	-0.69	0.83	-4.95	1.01	-6.50	-8.54
N	36	42	29	37	31	31
L4-7						
High	-1.26	0.35	-2.99	3.07	-0.51	-2.74
Low	-3.36	-1.81	-5.47	0.04	-6.27	-5.28
N	36	42	32	37	35	34
HIP						
High	4.13	4.22	2.75	3.14	2.04	2.06
Low	-2.04	-0.65	-7.06	-4.34	-7.11	-4.84
N	37	45	28	38	28	30

seats. The lower thigh angle (CUSHION) is related to the height of the seats. The values for Z3, which is the height of the trochanter emitter above the buck floor, indicate that subjects sat higher in the luxury seats than in the two sport seats. Additionally, the X3 values show that the trochanter emitter was closer to the accelerator pedal for the sport seats, which also would tend to produce higher thigh angles. This angle may be important, particularly with Seat Four, because high values of CUSHION might result in a greater concentration of body weight in the buttock area.

Virtually all of the average values for CHEST calculated for the time partitions are positive, indicating that subjects' chests were inclined more rearward in sitting than in standing, as would be expected. The finding that the CHEST values were lower for the luxury seats than the sport seats indicates that in those seats the subjects' chests were typically in a position closer to the standing posture than was the case with the sport seats. The subjects' chests were more reclined in the sport seats.

Values for PELVIC, the measure of pelvis rotation from the standing to sitting positions, indicate that Seat Three restricted pelvis rotation significantly more than the other seats. The values of PELVIC for Seat Three are at least 5.7 degrees lower than Seat Two, 9.1 degrees lower than Seat One, and 8.7 degrees lower than Seat Four with

TABLE 39 (*cont.*)

95% CONFIDENCE INTERVALS FOR INTER-SEAT POSTURE VARIABLE COMPARISONS

Variable	Inter-Seat Comparison					
	1 v. 2	1 v. 3	1 v. 4	2 v. 3	2 v. 4	3 v. 4
SHOULDER						
High	1.51	1.45	2.21	1.36	1.62	1.61
Low	-0.38	-0.33	-0.10	-0.98	-0.39	-0.59
N	41	45	37	40	38	37
SLOUCH						
High	6.53	12.09	8.68	9.31	5.51	-0.59
Low	1.51	6.82	0.95	1.29	-3.85	-5.75
N	40	44	34	38	35	34
X3						
High	4.36	2.38	4.94	0.50	1.17	2.86
Low	1.59	0.78	2.97	-2.29	-0.40	0.91
N	40	46	35	40	36	36
Z3						
High	3.19	-1.82	2.20	-4.69	-0.09	5.12
Low	1.43	-2.79	0.79	-5.95	-1.54	3.60
N	40	46	35	40	36	36
X6						
High	3.28	4.52	3.37	3.56	1.30	-1.12
Low	0.51	3.03	1.29	1.12	-0.37	-2.67
N	41	45	37	40	38	37
Z6						
High	3.08	-1.50	0.12	-4.54	-2.33	2.46
Low	1.86	-2.73	-0.74	-5.56	-3.58	1.35
N	40	46	35	40	36	36

$P \leq 0.05$. There are no significant differences in PELVIC values for the other seats with $P \leq 0.10$.

The three measures of slouching, SLOUCH, L3-6, and L4-7, each show five significant comparisons between the seats. L3-6 and L4-7 show four of the same comparisons; combining the results from the two variables, all four seats are ranked 3<1<2<4 on the percentage-distance measures. Again, a difference is indicated between the sport and luxury seats, with the luxury seats typically producing a posture in which the distance from the chest to the pelvis was a lower percentage of the same distance in the standing position than was the case with the sport seats.

On the SLOUCH variable, one luxury seat is higher than the two sport seats, while the other is lower. While there is no significant difference between the two seats on the CHEST variable, Seat Three is significantly lower in pelvic rotation, resulting in the lower SLOUCH values for Seat Three. The values of PELVIC for Seat Three are sufficiently low to keep the seat below the sport seats for the SLOUCH variable, even though values of CHEST for Seat Three are lower than those of the sport seats. So, for Seat Three, while the subjects' chest and pelvic angles were closer to the standing values than they were for the sport seats, the chest-to-pelvis distances as a percentage of standing-position distances were typically lower than for the other three seats.

The confidence intervals for SLOUCH (Table 39) indicate that the difference between Seat One and Seat Three is the largest of the significant findings regarding the SLOUCH variable. SLOUCH represents the difference between the pelvic rotation and the chest rotation. A SLOUCH value of zero would indicate that the chest and pelvis rotated an equivalent amount from the standing position. For Seat Three, the SLOUCH average of 30 degrees means that the pelvic inclination was 30 degrees greater than the chest inclination on average. The SLOUCH measure for Seat One, by contrast, is at least 6.8 degrees greater than the average measure for Seat Three. For Seat Two, the mean SLOUCH value is at least 1.2 degrees higher than the value for Seat Three, while for Seat Four the difference at the 95% confidence bound is less than one degree.

Also of potential importance is the absence of the HIP and SHOULDER variables from Table 38. The lack of significant inter-seat differences for these variables suggests that they are fairly independent of the seat configuration, at least within the range of parameters represented by the geometries of the seats in these tests. Subject posture, with respect to those variables, may be determined more by personal preference than by seat design. Because SLOUCH, a measure of the angle between the pelvis and the thorax, varied systematically between seats, while HIP did not, subjects appear to have adjusted their pelvic inclination with more emphasis on the angle between the thighs and pelvis, rather than with primary reference to the backrest configuration. The values for Seat Three, which show pelvic angles closest to those measured in the standing posture, also indicate lower values for CUSHION, the angle of the subject's right thigh relative to the horizontal. The trochanter location, as measured by Z3, was also the highest for Seat Three, which would tend to reduce CUSHION and also reduce PELVIC, if HIP remained constant.

3.5.2 Time Effects. The postural variable means for the six time partitions changed markedly over time for most subjects. Investigations were conducted to determine the magnitude and direction of these changes, and also whether they were significant and consistent for all subjects.

To assess the magnitude and direction of these changes, Pearson product-moment correlations between the variables and time were calculated for the data from All Subjects. This analysis failed to show significant correlations. Examination of the data revealed two possible confounding factors. First, the range of values differed among subjects, depending on anthropometry and posture selection. Second, correlations within individual subjects revealed that the time-related changes often differed between subjects. For instance, CUSHION on Seat One was positively correlated with time for five subjects, and negatively correlated for three.

In an attempt to discover time-related trends in the data for all subjects, the six time-partition means for each driving simulation were standardized to zero mean and unit variance. Correlation coefficients between the postural variables and time were then generated for each seat. Table 40 shows these results.

These coefficients show trends in postural changes, but do not indicate the magnitude of the changes over time. In order to investigate the implications of the stronger correlations in Table 40, estimates were made of the average change in the corresponding variables over time.

Because of the low number of time partitions (six) and relatively high variability of the partition means, comparing the means of subsequent partitions was not meaningful. Rather, to evaluate the data trends from each subject, a least-squares linear curve fit of the means of each of the six time partitions was performed for each variable with the data from each driving simulation. Using the slopes of the resulting lines, values estimating the change in the variables over the course of the driving simulation were calculated. These values are summarized for seats and variables whose correlations with time were of interest in Table 40. Table 41 shows the mean estimated change in selected variables over the course of the driving simulation, calculated by this method.

TABLE 40

CORRELATION COEFFICIENTS FOR STANDARDIZED POSTURE VARIABLES VERSUS TIME BY SEAT

Variable	Seat 1	Seat 2	Seat 3	Seat 4
CUSHION	0.222	0.043	0.303	0.112
CHEST	0.212	0.524	0.002	0.349
PELVIC	0.444	0.222	0.068	0.515
L3-6	0.009	0.614	-0.096	0.514
L4-7	-0.092	0.432	-0.100	0.519
HIP	0.411	0.130	0.230	0.060
SHOULDER	-0.361	0.491	0.116	0.016
SLOUCH	0.316	0.151	0.076	0.217
X3	-0.551	-0.318	-0.159	-0.619
Z3	0.034	-0.157	-0.337	-0.417
X6	0.416	0.326	0.011	0.248
Z6	-0.153	0.097	-0.521	-0.028

For Seat One, Table 41 shows a slight increase in HIP of approximately two degrees over the course of the test. The positive correlation of PELVIC with time is not significant in the estimated changes because two subjects have negative estimated changes in the value of PELVIC of about four degrees. The mean change in the value of PELVIC for the other six subjects is nearly four degrees positive.

For Seat Two, the value of CHEST is estimated to have increased about two degrees over the course of the driving simulation, and the chest-to-pelvis distance increased between two and three percent. This indicates that the subjects' chests on average became more reclined as the simulation progressed. However, the distance from a subject's chest to the accelerator pedal, measured along the X axis, tended to decrease a little more than a centimeter over the course of the simulation. This indicates that as the subjects' chests reclined (as measured by the angle formed by the two emitters on the sternum), the lower sternal emitter (number 6) moved slightly forward.

For Seat Three, emitter six dropped an average of one centimeter during the simulation. The value of PELVIC for Seat Four is estimated to have increased over six degrees on average during the course of the simulation. The estimates for the five heaviest subjects average +10.4 degrees, while those for the other three average -0.4 degrees. Also for Seat Four, the trochanter distance from the accelerator pedal decreased slightly during the simulations. Three subjects are estimated to have slid forward more than two centimeters, while five others moved forward less than one centimeter.

TABLE 41

MEAN VALUES OF ESTIMATED CHANGES OVER TIME FOR POSTURAL VARIABLES BY SEAT

Variable	Mean	Std. Dev.	Units
Seat 1			
PELVIC	1.98	3.979	degrees
HIP	1.60 *	1.548	degrees
X3	-0.62	1.625	cm
X6	0.17	0.958	cm
Seat 2			
CHEST	1.88 *	1.952	degrees
L3-6	3.17 *	3.708	percent
L4-7	2.35 *	2.955	percent
Seat 3			
Z6	-1.27 *	1.376	cm
Seat 4			
PELVIC	6.32 *	6.373	degrees
L3-6	2.22	3.297	percent
L4-7	2.35	3.524	percent
X3	-1.32 *	1.806	cm

* $P \leq 0.05$

3.6 ANALYSIS OF ELECTROMYOGRAPHY DATA

Two types of EMG data were taken from each subject. Two-minute samples were taken during the preliminary session with the subject in each test seat and were collected again immediately prior to the subject's first driving-simulation session. This second set of two-minute samples was taken with the seats tested in reverse order from the preliminary session.

The second type of EMG data was taken during each driving-simulation session. These data included continuous sampling throughout the simulation, as well as two-minute sample periods at the conclusion of each evaluation interval, during which the subject was asked to sit relaxed with his hands on the steering wheel. Analysis of the data taken while the subject was operating the simulator was uninformative, because voluntary muscle activity associated with the steering motions and posture changes confounded the data. However, measurement of the frequency of these periods of relatively high-level muscle activity indicated significant inter-seat differences.

EMG signals were collected with four pairs of electrodes placed on the subject's lower back and abdomen. The differential voltage between each electrode pair was sampled at approximately 2 Hz using a 12-bit A-D converter. Software routines rectified the signals about the mean voltage of each electrode pair. For the driving-simulation sessions, data were collected and stored in segments of 120 samples (approximately one minute of data). Because of the relatively slow sampling rate, spectral analysis of the data was not appropriate. Rather, the analysis focused on the amplitude of the EMG signal as a measure of muscle activity.

Salient data trends in the samples from the driving simulation were primarily indicative of voluntary muscle activity. That is, the magnitude of the EMG trends associated with subject motions such as "steering" the simulator or changing the position of a leg, during which the subject would be expected to contract both abdominal and lumbar muscles for stability, masked any lower-level muscle activity which might be more directly related to fatigue. "Postural" muscle activity, a low level of exertion associated with maintaining the sitting position and which was expected to occur in the lumbar area with greater magnitude than in the abdominal area, was not detectable in the overall driving-simulation data. However, the two-minute samples taken on each test seat during the preliminary session and those taken at the conclusion of each evaluation interval were considered to represent "rest" muscle activity because the subject was asked to remain still during the sample period. As such, these data were used as a measure of the muscle activity necessary to maintain the chosen posture in the seat. Movement artifacts present in those data were considered to be involuntary and were treated as evidence of postural stress or fatigue. The data from the preliminary sessions and the sampling periods at the evaluation intervals showed some differences between the lumbar and abdominal muscle activity.

3.6.1 Short-Term EMG Samples. During the preliminary session, each subject sat in each test seat in turn while a two-minute EMG sample was taken. The subject was asked to remain relaxed and still during this period, so that all data were associated with maintaining the sitting posture, rather than with extraneous voluntary muscle activity. These samples were taken again immediately prior to the subject's first driving simulation, with subject sitting in the seats in reverse order. Thirty seconds of a typical rectified EMG signal is shown in Figure 23.

As a first step in the analysis, the data from the first and last thirty seconds of each two-minute sampling period were deleted, leaving a one-minute set of approximately 120 samples. This was to eliminate data related to subject movements which might have occurred at the beginning or toward the end of the sampling period.

Analysis concentrated on statistical measures of EMG voltage distributions. Because the signals were rectified, the mean levels of the resulting data measure the amplitude of the original signals. Preliminary investigations showed that signal amplitude was directly related to muscle activity. The standard deviation of the data from a sample period provides an indication of the magnitude of the changes in muscle activity. For instance, a high standard deviation indicates the presence of both high and low levels of the rectified signal, corresponding to both high and low levels of muscle activity.

The one-minute data sets extracted from the short-term samples were compared to determine if there was a significant difference between those data taken during the preliminary session and those taken prior to the start of the first driving simulation session (one day later and with the seats in reverse order). No significant differences were found in mean rectified signal levels between different days for individual seats. Two subjects, however, showed slight differences in variance between the days. Confidence intervals showed these differences to be minor, however, and the data sets for the two days were pooled for each seat and subject. The mean rectified EMG levels were compared between seats, and 95% confidence intervals were estimated for the magnitudes of the differences between means. Seat Four was found to have a slightly higher mean rectified EMG level in the lumbar area than other the other seats, while Seat One was slightly higher for the abdominal muscles. Table 42 shows these results.

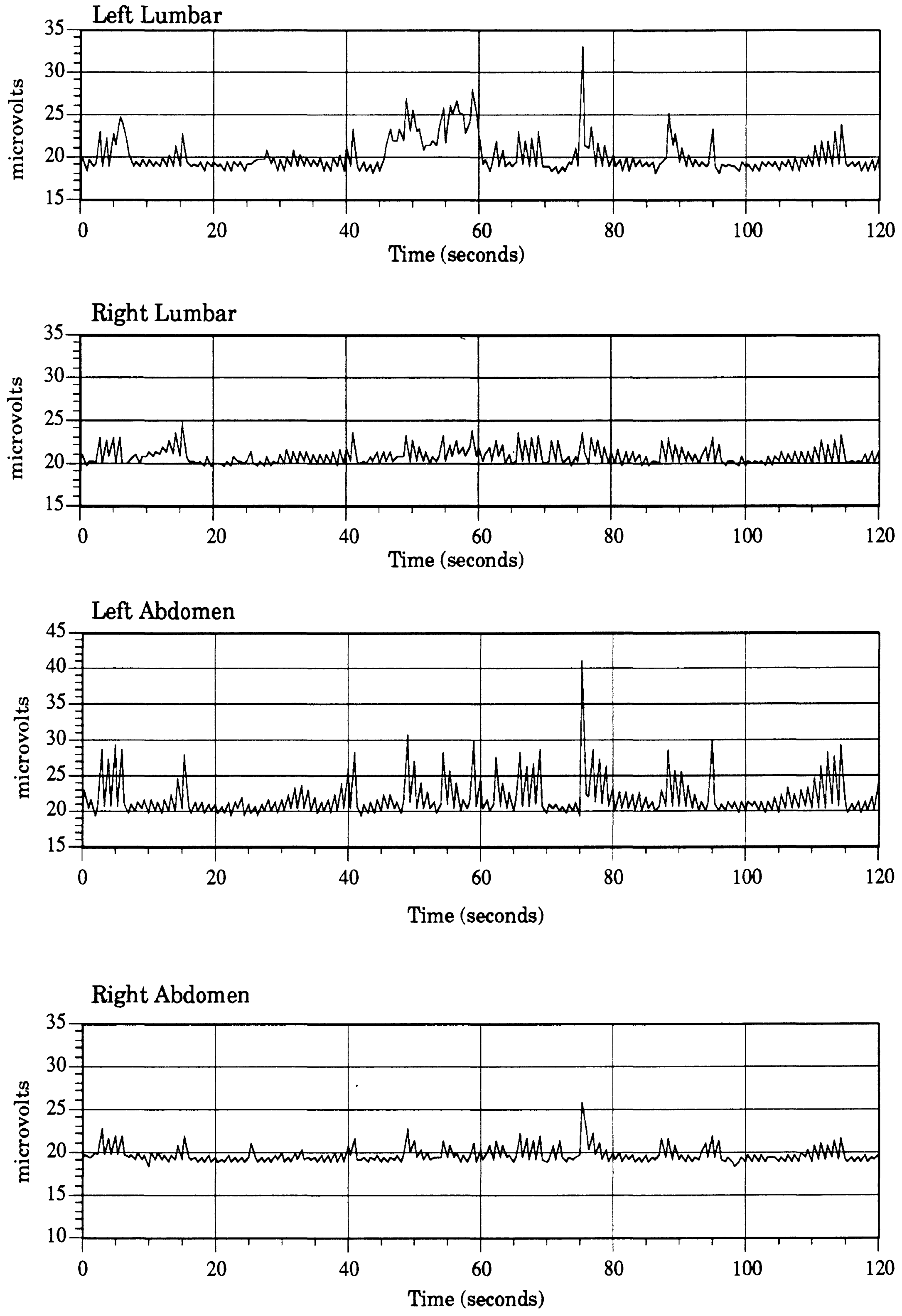


FIGURE 23. Typical rectified EMG signals.

TABLE 42

INTER-SEAT DIFFERENCES IN MEAN, SHORT-TERM, RECTIFIED EMG LEVELS: 95% CONFIDENCE INTERVALS

Inter-seat Comparison	Rectified EMG Levels, μV	
	High	Low
LUMBAR		
Seat 4 - Seat 1	1.52	0.86
Seat 4 - Seat 2	1.28	0.65
Seat 4 - Seat 3	1.21	0.55
ABDOMEN		
Seat 1 - Seat 2	0.59	0.14
Seat 1 - Seat 3	0.67	0.23
Seat 1 - Seat 4	0.67	0.23

Further investigations were conducted using data standardized to remove confounding factors such as inter-subject differences. No other analyses produced results which confirmed the findings in Table 42, nor were any other findings meaningful. The differences observed in Table 42 were significant in part because of a large sample size (n=1200) and relatively small sample variances. The mean level for all seats together was approximately 20 μV, so the lower confidence bounds above represent approximately four percent of the mean or less.

3.6.2 Evaluation-Interval EMG Samples. EMG data from the two-minute samples taken at the end of each evaluation interval were analyzed to determine inter-seat differences in muscle activity during the simulations. The first and last thirty seconds of each sample period were deleted, as with the short-term data. The data were then standardized to facilitate comparison among seats. For each driving simulation, the data for each evaluation interval sample (middle sixty seconds) were standardized by dividing by the mean of the data from all six evaluation intervals combined. The mean of the standardized data from each evaluation-interval data set was then calculated. These means were compared between seats for each evaluation interval.

In the data from the lumbar area, significant inter-seat differences in mean rectified EMG level were detected for several evaluation intervals. The average standardized EMG level is higher for Seat Two than for Seats One and Four during the last hour of the simulation, and the values for Seat Three are higher than those of Seat One and Seat Four at the 90-minute evaluation interval. Figure 24 shows the mean standardized EMG levels for the lumbar muscles.

The data from the abdominal muscles for Seat Two exhibit a time-related trend, increasing in mean level over time relative to Seats Three and Four. Figure 25 shows the trend. The apparent difference in overall level between Seat Three and Four is not significant in the data, nor is the apparent difference in the data for Seats Three and One because of high variability among subjects. However, the values for Seat Two are significantly higher than those for Seat Three over the last hour of the simulation.

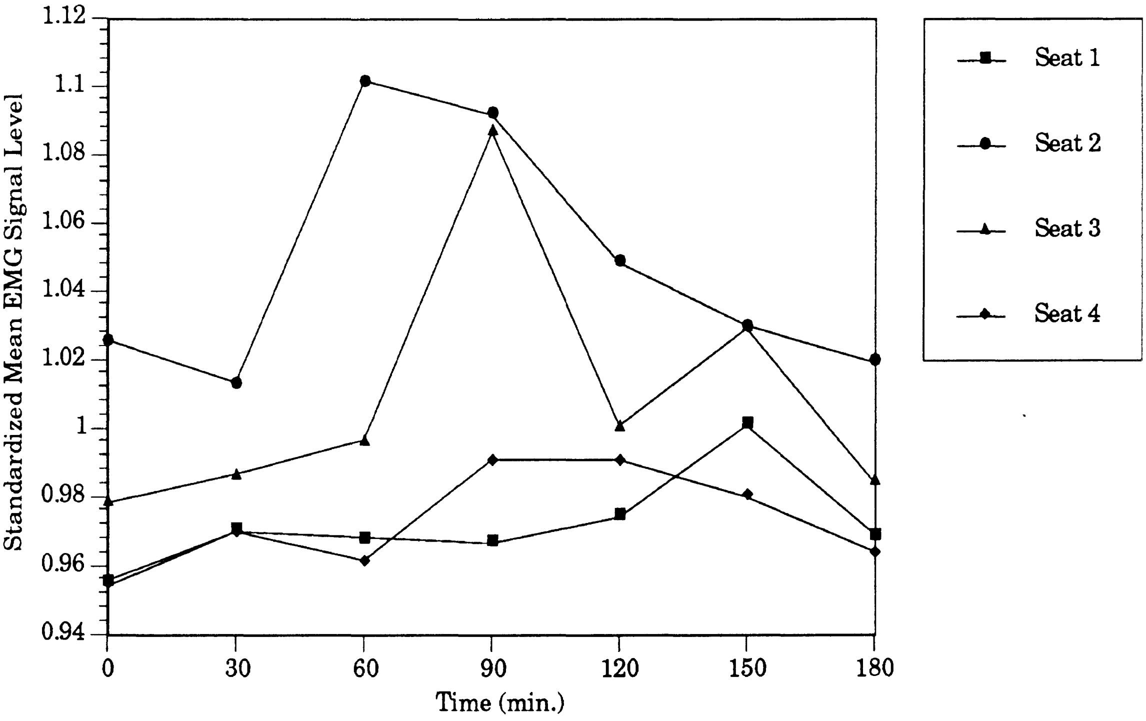


FIGURE 24. Standardized mean rectified EMG level in LUMBAR muscles, evaluation interval data.

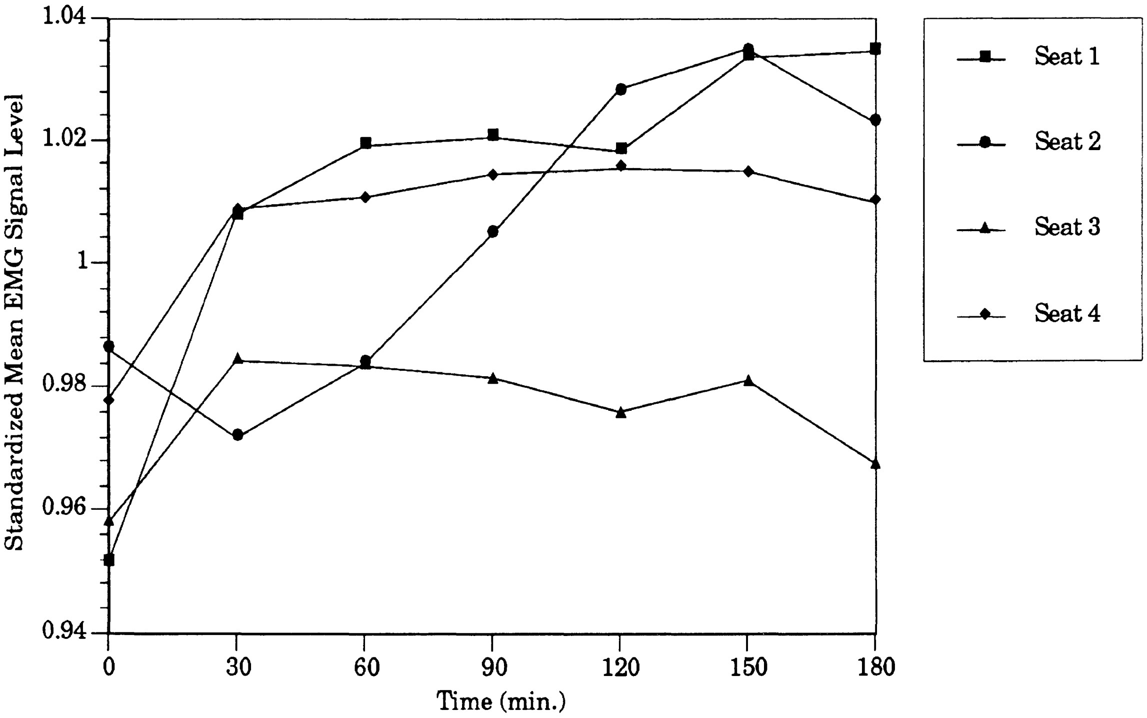


FIGURE 25. Standardized mean rectified EMG level in ABDOMINAL muscles, evaluation interval data.

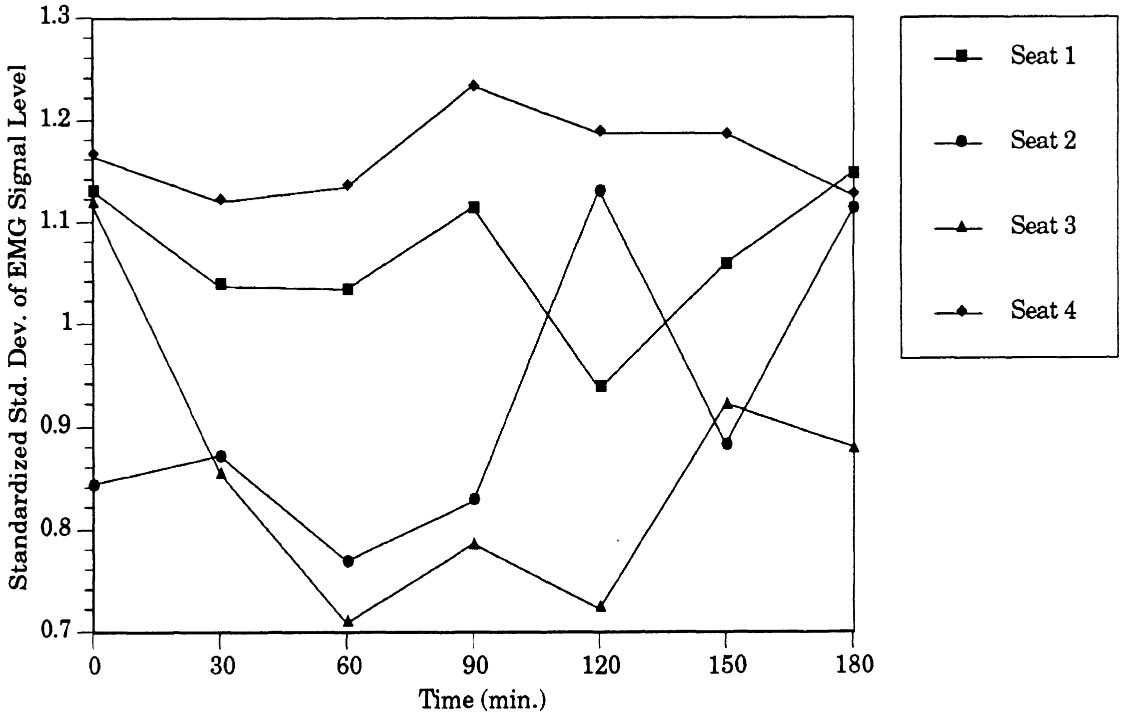


FIGURE 26. Standardized standard deviations of EMG signals from ABDOMINAL muscles, evaluation interval data.

Because the mean level of the rectified signal is directly related to muscle activity, the data indicate that subjects on average experienced increasing abdominal muscle activity over the course of the simulation on Seat Two. Also, the level of lumbar muscle activity was higher on Seat Two than on Seats One and Four during the last hour of the simulation.

Similar comparisons using the standard deviation of each evaluation interval sample produced no significant inter-seat comparisons in the data from the lumbar area. However, in the data from the abdominal area, the values for Seat Four show higher standard deviations throughout the driving-simulation than do those for Seats Two and Three, indicating greater variability in muscle activity. Figure 26 shows the mean standard deviations for each evaluation interval.

The standard deviation of the rectified EMG signal is a measure of the magnitude of changes in EMG level. A sample period which contains high amplitude signals along with low amplitude signals produces a high standard deviation from the rectified data. This is indicative of non-constant muscle activity levels. Figure 26 shows Seat Four to have produced more irregular patterns of muscle activity than Seats Two or Three for most of the evaluation intervals.

3.6.3 Count of High EMG Amplitudes. Another method of analysis applied to the EMG data attempted to compare seats on the basis of the frequency of voluntary muscle activity. The data from the driving-simulation sessions were divided into five minute stages. For each stage, the number of data points which exceeded a criterion value were counted. These count values were compared pairwise between seats. Several different criteria were tried, but a two standard-deviation level produced the most meaningful results. Figure 27 shows the mean number of data points which were more than two standard deviations from the mean for each simulation. Paired t-tests showed that the counts were higher for the two sport seats than for the two luxury seats. The t-values are listed in Table 43. Asterisks indicate significance with $P \leq 0.05$.

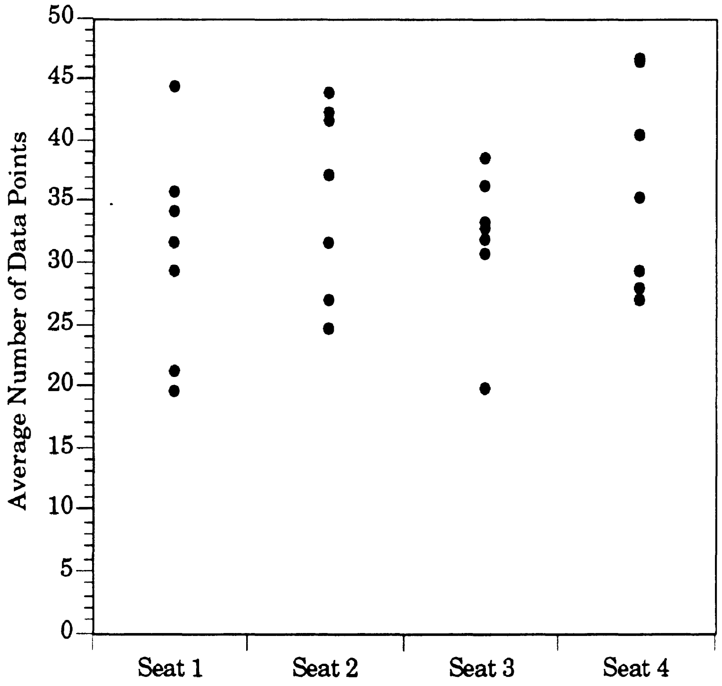


FIGURE 27. Mean number of data points in excess of two standard deviations from the mean per five-minute interval.

The values in Table 43 indicate that subjects produced EMG levels which were more frequently in excess of two standard deviations from the mean in Seats Two and Four than in Seats One and Three. Because high values were associated with muscle activity, these results suggest that the sport seats induced more voluntary muscle activity than did the luxury seats.

TABLE 43

EMG INTER-SEAT COMPARISONS WITH COUNT DATA
(> 2 Std. Dev., t-Values)
N = 239

Seat Comparison	t-Value
1 v. 2	2.281 *
1 v. 3	-0.010
1 v. 4	2.365 *
2 v. 3	-1.989 *
2 v. 4	0.106
3 v. 4	2.229 *

* $P \leq 0.05$

3.7 ANALYSIS OF DATA FROM SEAT PRESSURE SENSORS

Pressure levels at certain areas of the seat/subject interface were monitored using thin, flat, polymer-film devices known as Force Sensing Resistors (FSRs). These sensors exhibit decreasing resistance with increasing force. The computer software which sampled the FSRs mounted to the test seats converted each resistance measure to a pressure reading using a calibration curve generated previously for each sensor. Each sensor was sampled at approximately 1 Hz.

These pressure data were analyzed to examine:

1. inter-seat pressure level differences at the sensor areas,

2. changes in subject-seat interface pressures with time, and

3. the frequency and magnitude of pressure changes as a measure of posture shifts.

3.7.1 Sensor Groups and Average Values. To obtain a general overview of the pressure present in the sensor areas during the driving simulations, sensors were paired into six groups and all data for each simulation were averaged within the groups. Figure 28 shows the sensor locations and group designations.

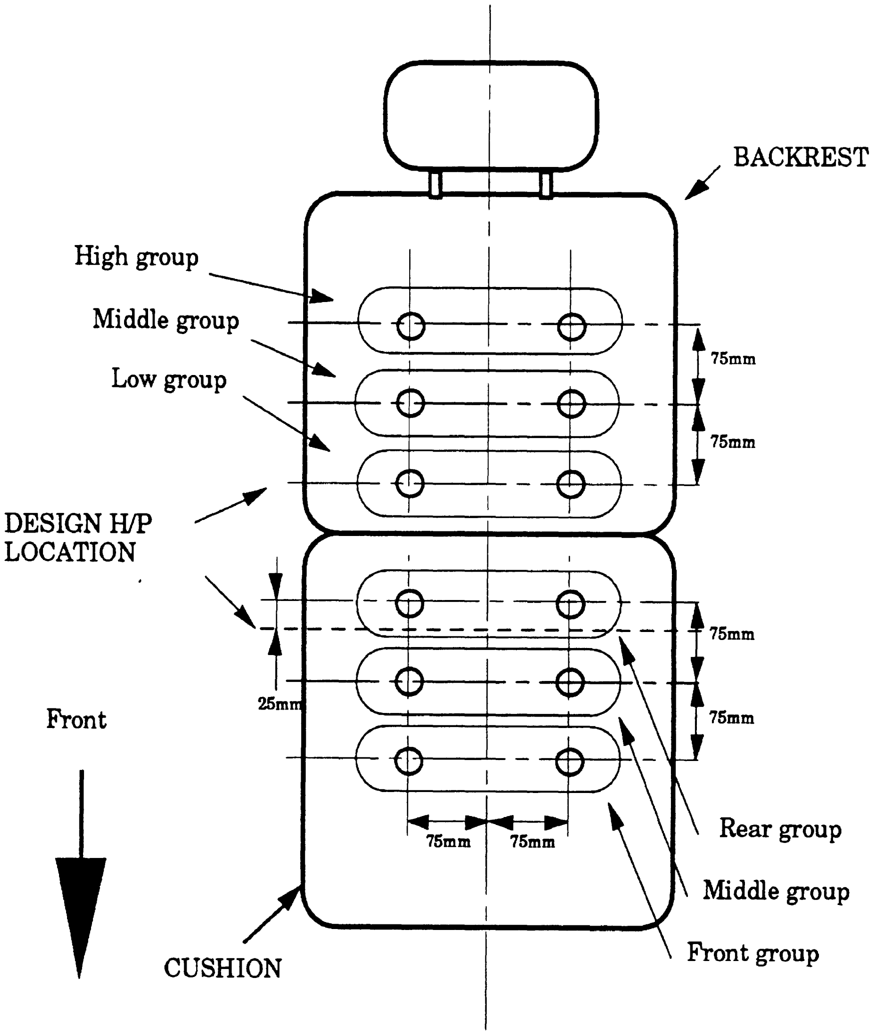


FIGURE 28. FSR pressure sensor locations and groups.

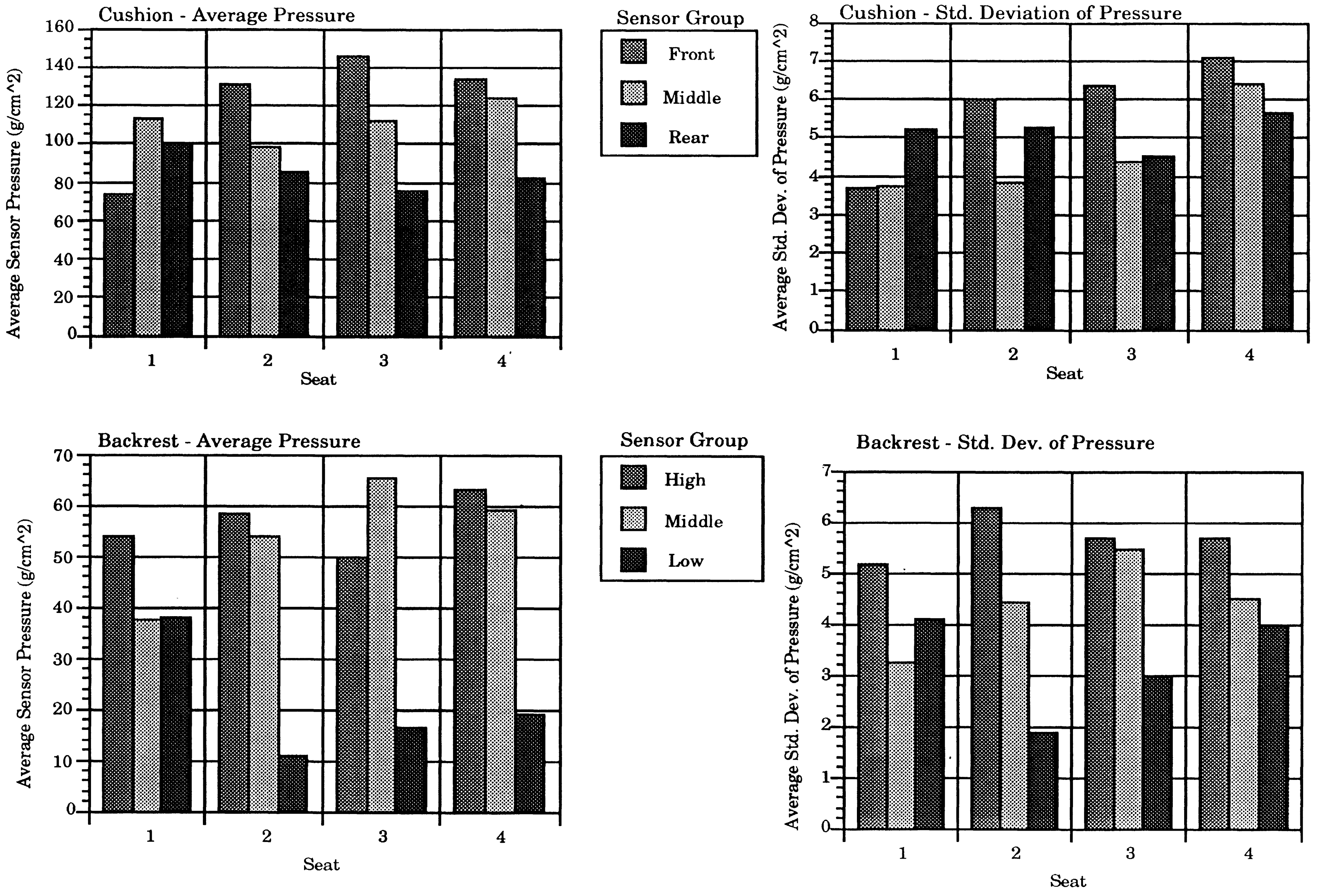


FIGURE 29. Means and standard deviations of sensor pressures by group.

TABLE 44

MEAN AND STANDARD DEVIATION OF FSR SENSOR PRESSURE READINGS, BY SENSOR GROUP ALL SUBJECTS (g/cm^2)

Sensor Group	Seat 1		Seat 2		Seat 3		Seat 4	
	Avg.	S.D.	Avg.	S.D.	Avg.	S.D.	Avg.	S.D.
Cushion								
Front	74.0	3.7	130.6	6.0	145.8	6.3	133.9	7.1
Middle	112.8	3.7	98.3	3.8	111.8	4.4	124.2	6.4
Rear	100.0	5.2	85.2	5.3	75.2	4.5	82.4	5.7
Backrest								
High	53.8	5.2	58.5	6.3	49.7	5.7	63.4	5.7
Middle	37.7	3.2	53.8	4.4	65.3	5.5	59.1	4.5
Low	38.2	4.1	10.8	1.9	16.6	3.0	19.1	4.0

The mean pressures and standard deviations for each group were averaged over all eight subjects for each seat. Table 44 and Figure 29 show these mean values. Statistical comparisons between seats for these measures were made using a paired t-test. The comparisons which were significant with $P \leq 0.05$ are shown in Table 45.

TABLE 45

SIGNIFICANT INTER-SEAT COMPARISONS IN PRESSURE SENSOR DATA

Sensor Group	Seat Comparisons ($P \leq 0.05$)	
	Average Pressure	Std. Deviation
Cushion		
Front	1 < 2, 3, 4	1 < 2, 3, 4
Middle	2 < 1, 3	2 < 4
Rear	3 < 1	- -
Backrest		
High	2, 3 < 4	- -
Middle	1 < 2, 3, 4 2 < 3	1 < 3,4
Low	2, 3, 4 < 1	2 < 1

In Figure 29 and Table 44, the smaller average pressure in the low backrest sensor group of Seats Two, Three, and Four was due to the fact that most subjects rarely made contact with those sensors. Similarly, in the cushion area, some subjects made only occasional contact with the rear group of sensors for those three seats. The average pressure data for the cushion show Seat One higher for the rear group, because of nearly constant contact with that group by all subjects. Seat One had the lowest pressure readings of the test seats for the front sensor group, apparently because of areas of greater pressure toward the rear of the seat.

For the backrest sensor groups, the average pressure data for Seat Four show greater pressures for the highest group than for Seats Two and Three, while for the middle group, Seat Three showed higher pressures than Seats One and Two. For the low sensor group, Seat One had higher average pressure readings than the other seats, largely because the sensors were often not contacted in the other seats.

The standard deviation data, a measure of subject movement, are higher for Seat Four than for the same groups on Seat One and Seat Two for the front and middle cushion groups, respectively. This indicates that the changes in pressure magnitude during the simulation on Seat Four were typically larger than for Seats One and Two. On the backrest, results for Seats Three and Four show greater activity in the middle group than do the results for Seat One. The data for the low group were affected by the lack of contact with the group's sensors by most subjects in seats other than Seat One.

3.7.2 Pressure Variances. The standard deviation of the pressure readings from each sensor is a measure of the magnitude and frequency of pressure changes at that location. The data from each driving simulation were partitioned into one-minute ranges and a standard-deviation value calculated for each range. Using the data from all sensors and subjects, the standard-deviation levels were compared between seats for the cushion and backrest.

For the data from the cushion sensors, Seat One shows lower standard deviations than do the other seats, while standard deviations for Seat Four are higher than for the other seats. For the backrest data, Seats Three and Four show higher standard deviations than do Seats One and Two. Figure 30 shows these relationships which were significant with $P \leq 0.05$.

From these results it was inferred that subjects' posture changes produced larger-magnitude changes in pressure in the area of the sensors for Seats Three and Four. This is probably indicative of larger posture changes during the simulation for those seats.

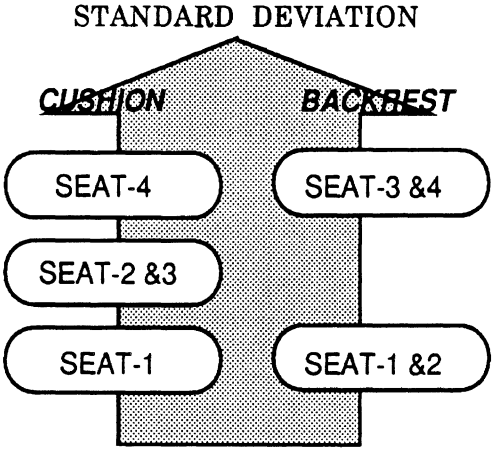


FIGURE 30. Sensor standard deviation inter-seat relationships.

Another measure of subject movement was found by calculating the standard deviation of groups of ten consecutive range standard deviations. These values assess the variance of standard deviations between one-minute ranges. If the measure is low, it indicates that the activity measured by the range standard deviation is similar for most ranges. However, if the measure is high, some one-minute ranges during the test show high activity, while others show lower activity.

For each simulation, fifteen averaged values were calculated, representing the first 150 minutes of the test. A paired t-test was used to compare the values calculated for all subjects between seats. Seat One produced a lower variance in range standard deviations, indicating that the variance in activity between subsequent one-minute periods was lower for that seat. Seat Four was higher than Seats One and Two in the cushion area, suggesting that activity in Seat Four was more variable than in the other two seats.

3.7.3 Sensor Center of Pressure. The sensor pressure data were also used to calculate a measure of subject position on the cushion called the sensor center of pressure, or SCP. The sensor center of pressure was defined to be the point of application of a hypothetical resultant force which summarized moments of the forces applied to the sensors about the point on the cushion directly below the design H-point on the seat centerline. The magnitude of the resultant force was equivalent to the sum of the forces on the sensors. Because each of the sensors had equivalent surface area, the pressure levels recorded for each sensor were used directly in these calculations. Figure 31 shows a theoretical diagram of how the SCP location was calculated. The sum of the moments about the pivot point beneath the H-point is balanced by the force at the SCP location, which has a magnitude equal to the sum of the sensor pressures.

Initial investigations utilized each of the six cushion sensors separately. Figure 31 shows the SCPs calculated for each seat based on the average pressure value over time for each sensor, over all subjects. The positions indicated in the figure express the relative loading of the cushion pressure sensors during the driving simulation. While these SCP locations are related to the subjects' positions on the seats, they do not express

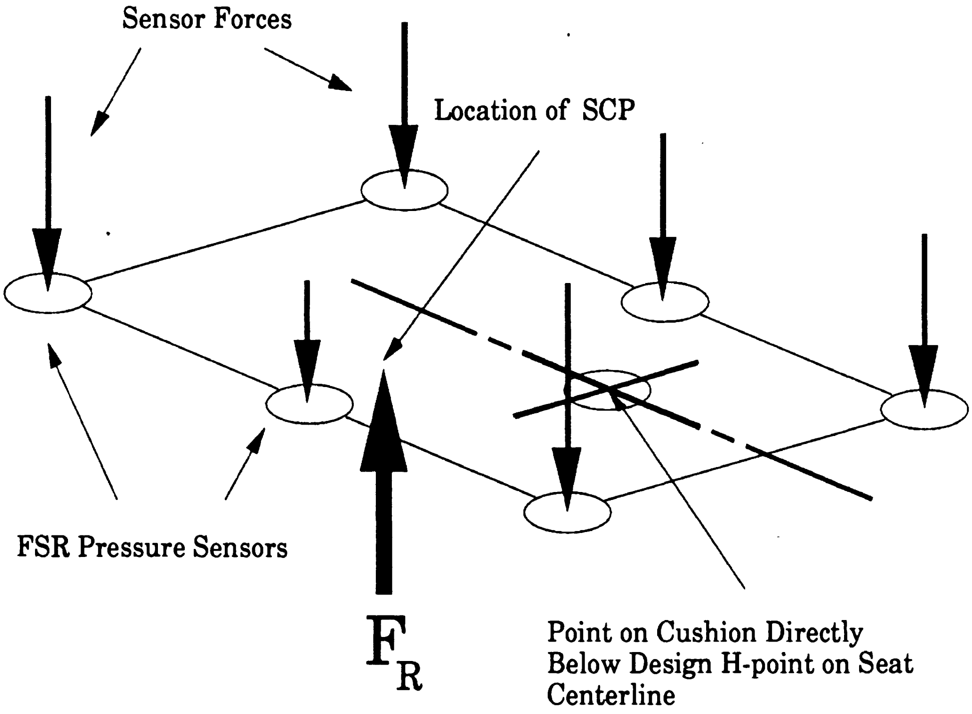


FIGURE 31. Sensor Center of Pressure Diagram.

information about the true center of pressure for the seat/subject interface, which would require information about the distribution of pressure on the whole of the seat.

The circles at each mean SCP location in Figure 32 represent the standard deviation of of the SCP, which were calculated by expressing each SCP data point for the seat in terms of its distance from the mean location and computing the standard deviation of these distances.

The figure shows the SCP of Seat One to the rear of the other SCPs, and with a smaller standard deviation. This is consistent with the results of earlier analyses, which showed the sensor data from Seat One to have lower variances. It is also consistent with the hypothesis that subjects were more frequently in contact with the rear cushion sensors on Seat One than on the other seats, which would tend to locate the SCP more rearward.

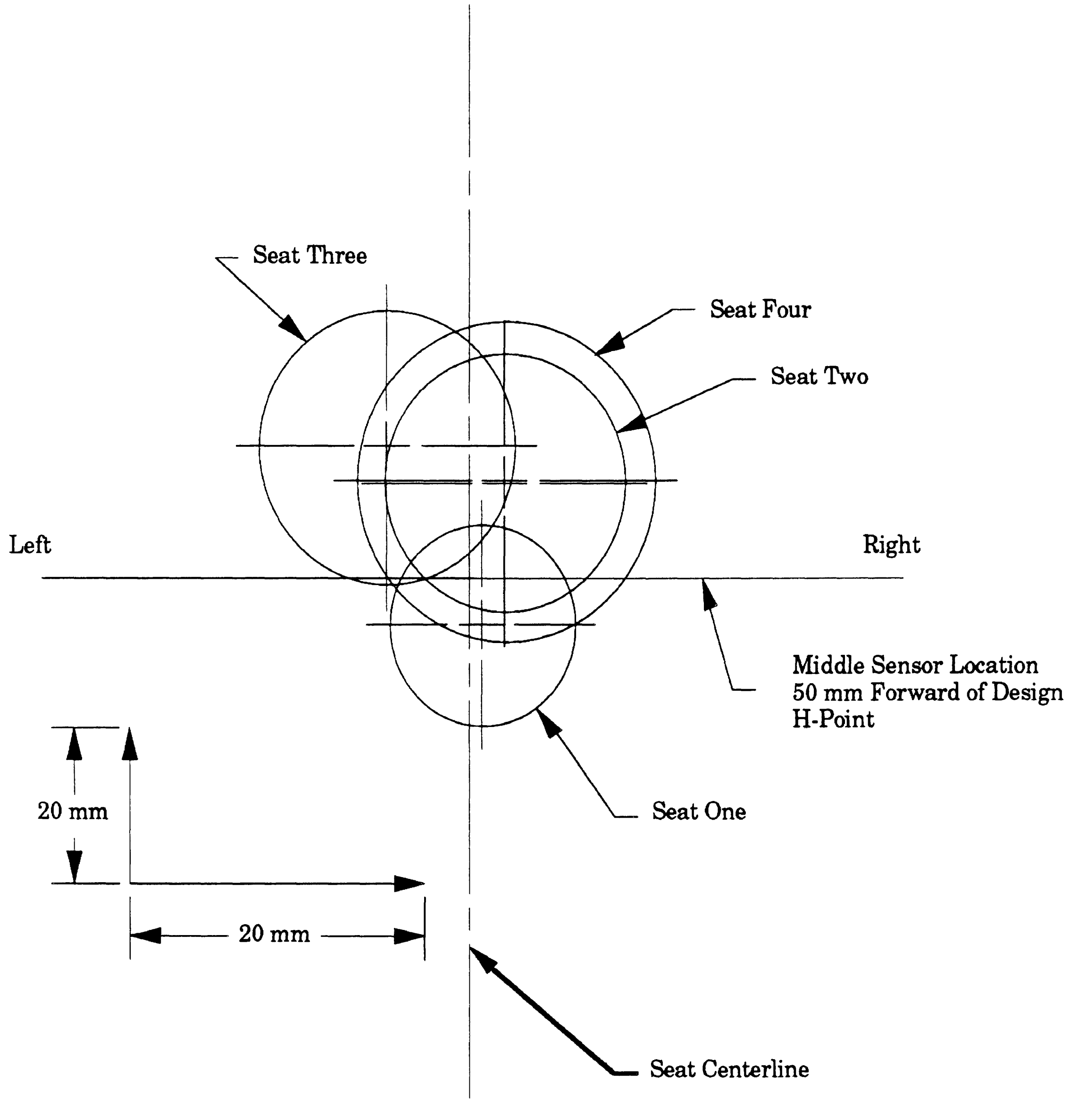
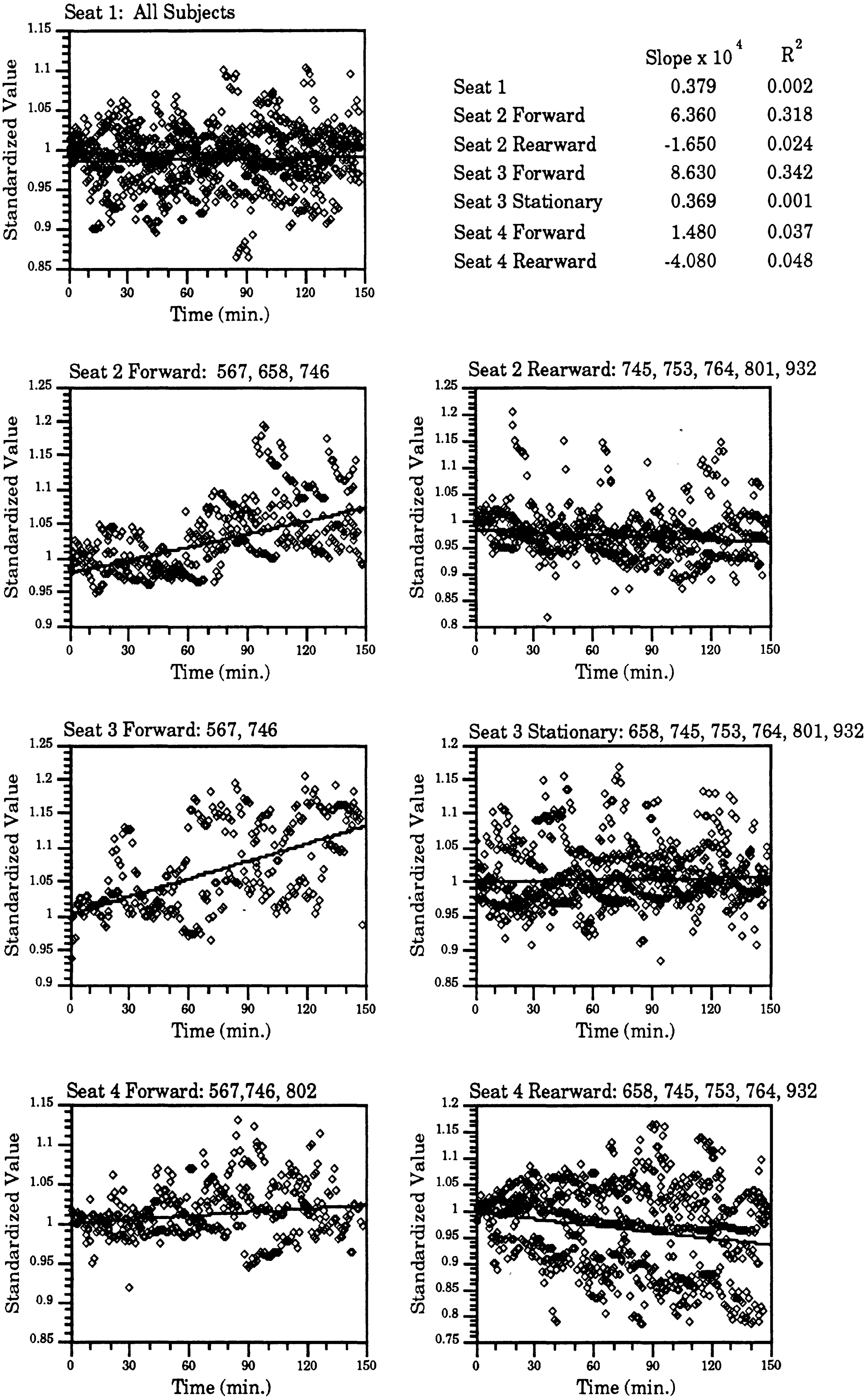


FIGURE 32. Sensor center of pressure locations and standard deviations.



	Slope x 10^4	R^2
Seat 1	0.379	0.002
Seat 2 Forward	6.360	0.318
Seat 2 Rearward	-1.650	0.024
Seat 3 Forward	8.630	0.342
Seat 3 Stationary	0.369	0.001
Seat 4 Forward	1.480	0.037
Seat 4 Rearward	-4.080	0.048

FIGURE 33. Scatter plots of standardized longitudinal SCP locations.

The data for Seat Four exhibit a higher standard deviation than the other seats, which is again consistent with previous results. Also noteworthy is the lateral location of Seat Three mean SCP, to the left of the other seats and the centerline. This indicates that higher pressure levels were recorded by the sensors on the left side of the cushion than the right. The mean indentation contour data (Section 3.8) support this view of subject positioning on Seat Three.

The SCP was also employed to examine time-related trends in subject movement. Because of the erratic nature of the data from the rearmost group of sensors, these SCP calculations were performed again using only the middle and front sensor groups. Since no lateral time-related trends were observed, the data from the two sensors in each group were averaged and only a longitudinal SCP was calculated. The SCP values were divided into one-half hour periods for time analysis. Statistical comparisons were made of the longitudinal SCP locations from successive time periods for each seat. Only one seat showed significant differences between periods of the driving simulation. On Seat Four, the SCP locations were significantly further forward during the second hour than during the first half hour. More meaningful results were obtained from scatter plots of the SCP values as described below.

For each driving simulation, a longitudinal SCP value was calculated for each one-minute interval of data. Because of an intermittent hardware failure during testing, only the first 150 minutes of pressure sensor data were available for some subjects. Consequently, only 150 minutes of data were used to calculate SCPs for all subjects. These data were standardized by dividing each one-minute-interval SCP value by the mean of the SCP location for the first ten minutes. Scatter plots of the data from each simulation were then examined for time-related trends. A least-squares line was fit to the data in each plot to determine the direction of trends.

Figure 33 shows the SCP time-interval data segregated by seat and SCP movement direction. For Seat One, no time-related trends are evident. For Seats Two, Three and Four, some subjects' SCP values moved forward over the course of the simulation. The subject numbers are indicated above each plot. For Seats Two and Four, the group of subjects whose plots did not indicate forward movement indicated rearward movement instead.

The slopes and R^2 values for the least-squares linear fits are tabulated in the upper-right-hand corner of the figure. Only the "Seat 2 Forward" and "Seat 3 Forward" plots show noteworthy trends. Subjects 567 and 746 were selected for both plots, suggesting that the trends may be primarily influenced by subject propensity rather than seat factors.

3.8 SEAT INDENTATION AND SUBJECT SPINE/STERNUM CONTOURS

To better assess the interaction between the subject and the seat, a procedure was developed to record each subject's indentation contour. During the preliminary session, a pair of flat, vinyl bags filled with small foam beads was placed on the seat cushion and backrest. While the subject sat on the seat, the air was evacuated from the bags, causing them to stiffen. The subject then exited the seat while the bags retained the shape of the indented seat surface. The bag surfaces were digitized using the GP8-3D sonic digitizer. The digitization procedures are detailed in Appendix B.

Because of anthropometric differences among the subjects and variations in selected posture, each subject's contours were slightly different. However, the largest variability was related to characteristics of the seat, including the surface contour and firmness. To compare the contours associated with each seat, the data were averaged systematically to produce plots of the mean deflected shape for each seat cushion and backrest.

Appendix B details the transformation of each subject's indentation data onto a 25 mm grid in buck coordinates. These data were used to produce comparable plots of mean seat deflection. For each subject and seat, the indented surface contours were compared with the unindented contours, and a linear deflection measurement was calculated for each grid node. Cushion deflections were measured along the buck Z-axis, while backrest deflections were measured parallel to the longitudinal or X-axis. Because subjects had chosen different recline angles, the backrest contour data for each subject were transformed for a backrest angle of 25 degrees before computing the X-axis deflection for each grid node.

For each seat, the average deflection value for each grid node was then calculated. These values were plotted in two dimensions for each seat. The plots in Figures 34 through 41 show that each seat has characteristic indentation patterns for the cushion and backrest. Examination of these plots may be aided by reference to the photos of the test seats (Figure 1) and the seat geometric data (Appendix A).

3.8.1 Cushion Indentation Contours. Comparing the plots in Figures 34 through 37, each seat is seen to have produced a distinct pattern. For Seat One, the depth of the indentation was large and the area of indentation was distributed over most of the cushion. An approximately oval-shaped area, about 5 cm by 20 cm, was deflected more than 6 cm, on average. The constant-deflection curves are seen to follow a concentric pattern, becoming slightly kidney-shaped at the lower deflection levels and closer to the front of the seat due to pressure under the thighs. In general, the average cushion indentation contour for Seat One is broad and deep.

Seat Two, in contrast, exhibited a more varied deflection pattern. Directly beneath the subject, large deflections occurred about 5 cm in front of the design hip point of the seat (H-point) and also about 17 cm in front of the H-point.* (Note that the greatest average indentation on Seat Two is less than 5 cm while, on Seat One, a larger area showed deflections greater than 6 cm.) The rear area of maximal deflection occurred under the ischia, while the more forward areas of similar deflection were beneath the subjects' thighs, at the most rearward portion of the prominent under-thigh support. The average indentation values also show deflection of the cushion side supports for Seat Two, with peak deflections for those areas occurring between 15 and 20 cm forward of the H-point. The side supports are rounded toward the seat centerline in that area, allowing for vertical deflection. The indentation contour indicates that the subjects' thighs were in contact with both the side-supports and the under-thigh support between 15 and 20 cm forward of the design H-point. The greater deflection on the right side of the seat than the left is probably due to the requirement that the subjects place their right foot on the accelerator pedal. Thus, the subject's right leg was typically in a more extended position than the left.

The average indentation data for Seat Three show a large, symmetric area of deflection under the ischia. The lines of constant deflection follow markedly kidney-shaped paths, indicating greater deflection under the thighs. The area of greatest indentation is located under the ischia, centered about 12 cm forward of the H-point. The evenness and broadness of the pattern suggests that the subjects were in contact with the cushion over a large area and that the cushion deflected in a fairly uniform manner.

The indentation contour for Seat Four shows a pattern more localized than those of the other seats. Compared with Seat Three, Seat Four has a smaller area at the higher deflection levels and the area of indentation greater than 1 cm is much smaller. The contour lines for Seat Four are also less kidney-shaped, indicating less deflection under the thighs.

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* This H-point represents the vehicle package design H-point translated to the subject-selected seat position.

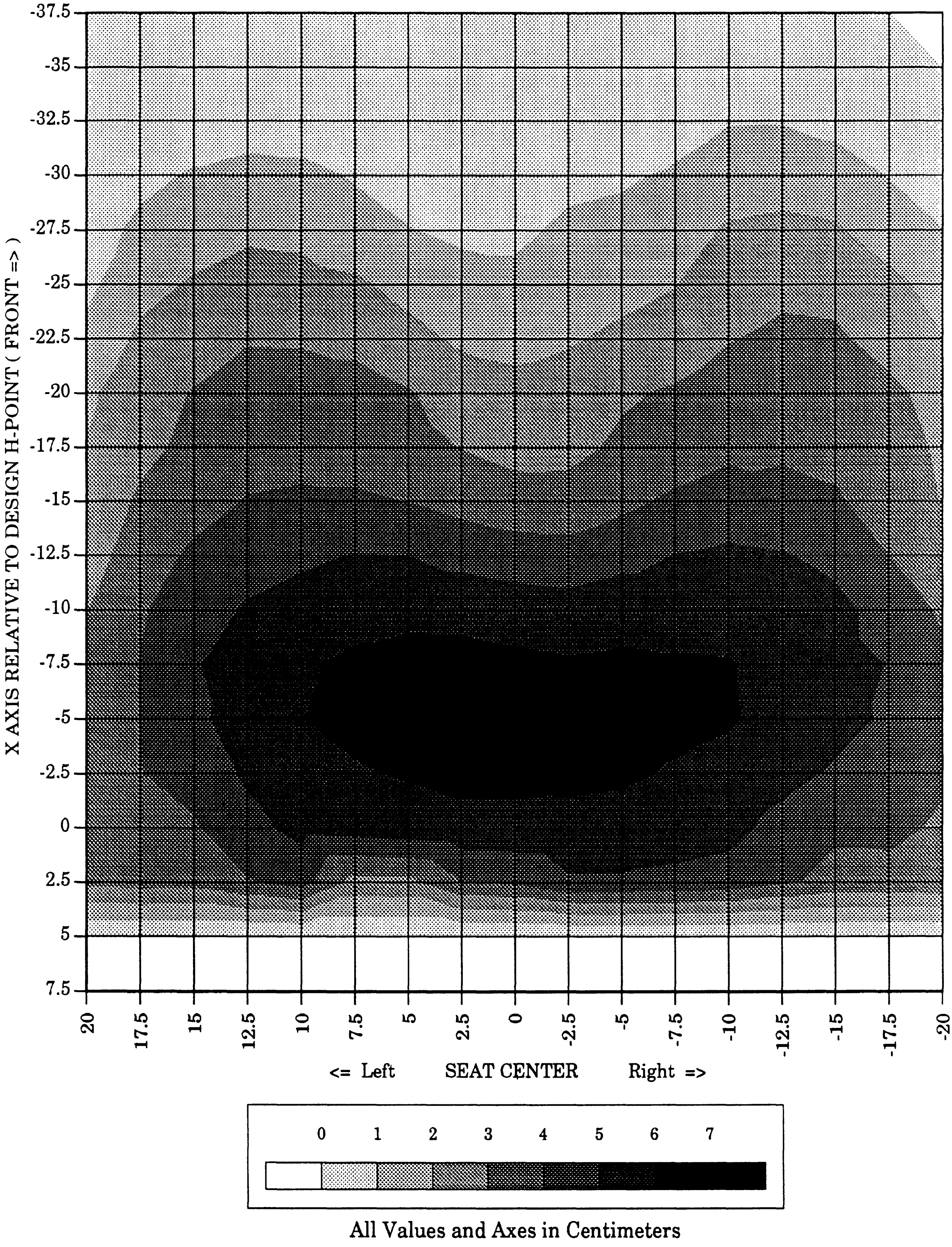
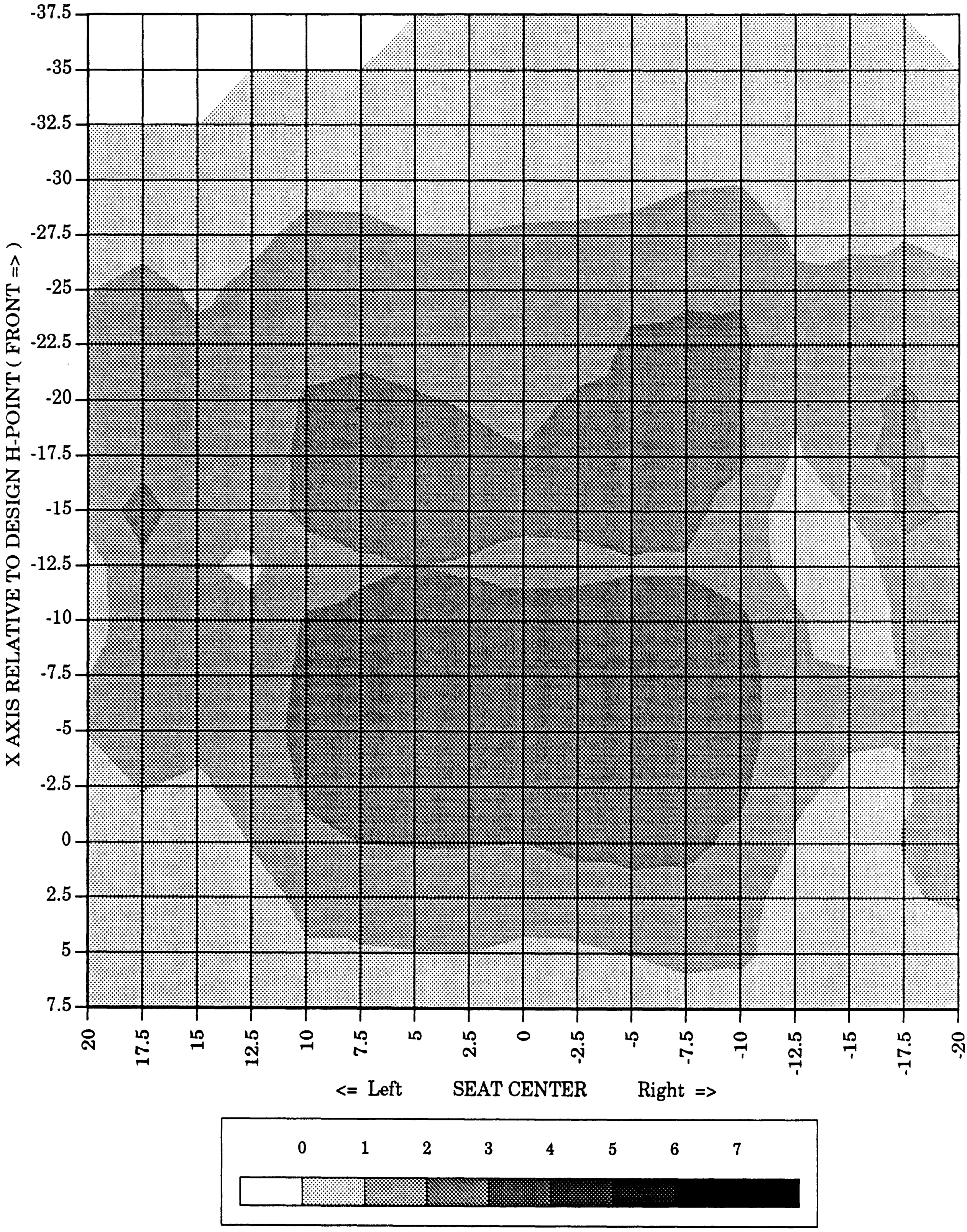
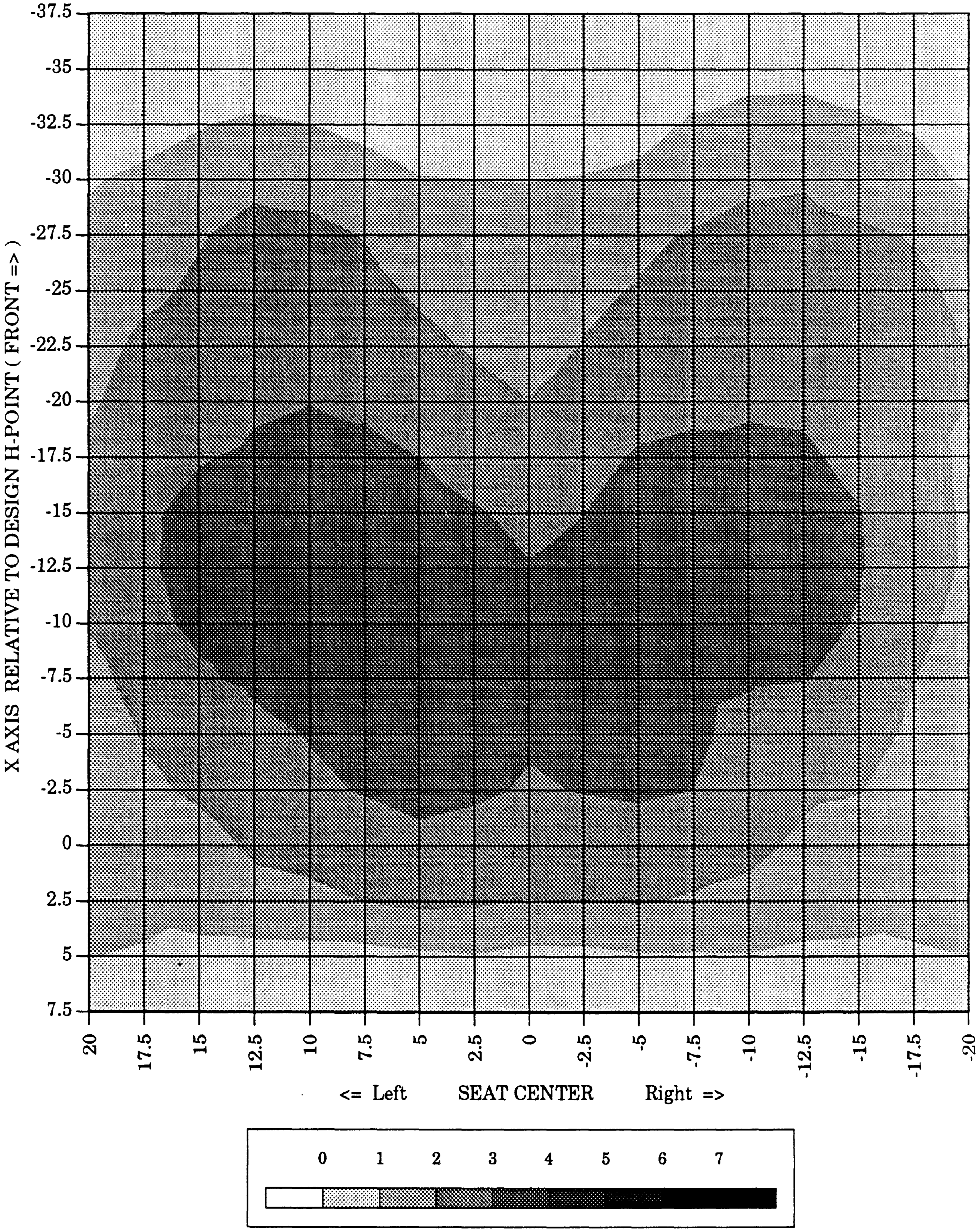


FIGURE 34. Average cushion indentation contour, Seat One.



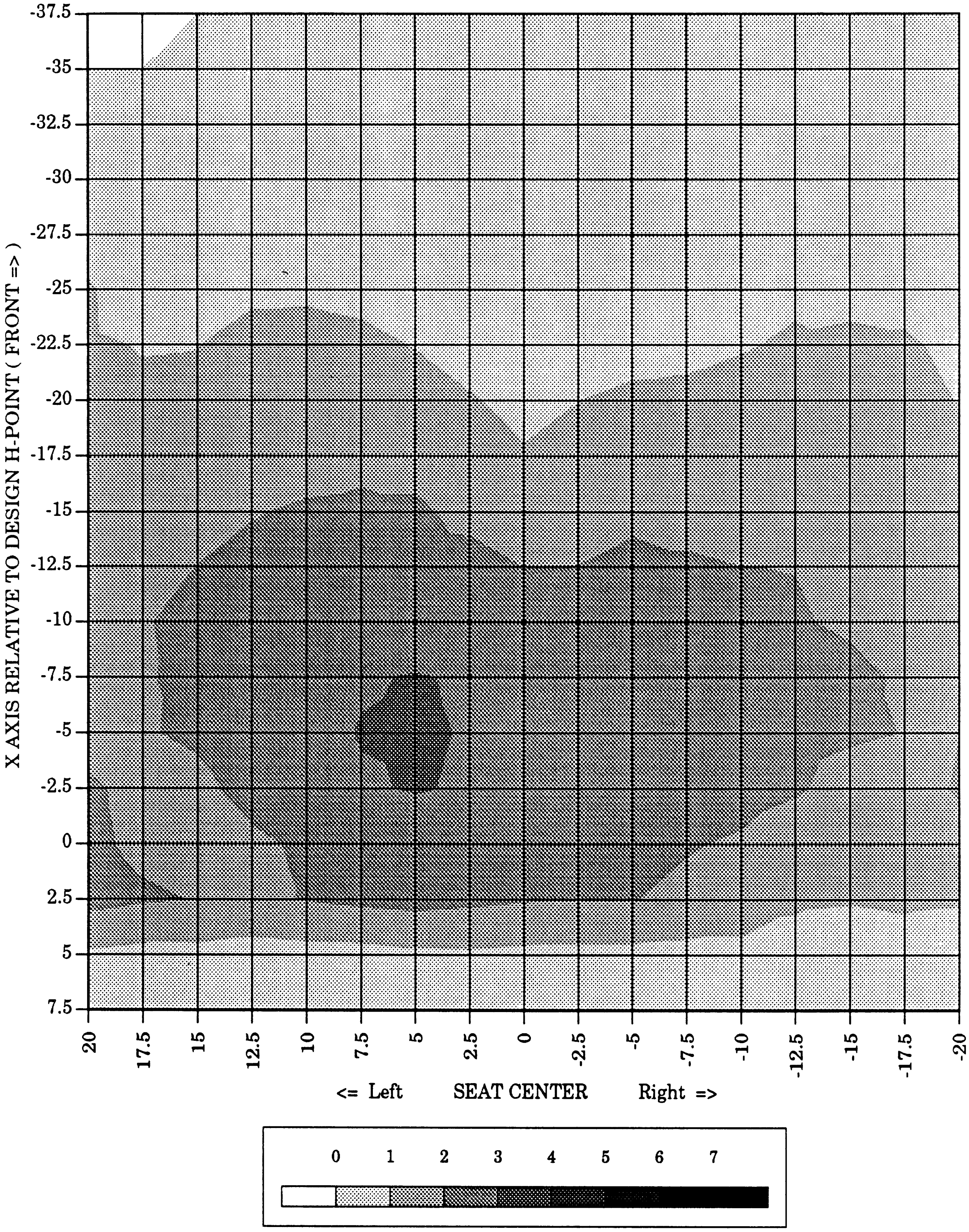
All Values and Axes in Centimeters

FIGURE 35. Average cushion indentation contour, Seat Two.



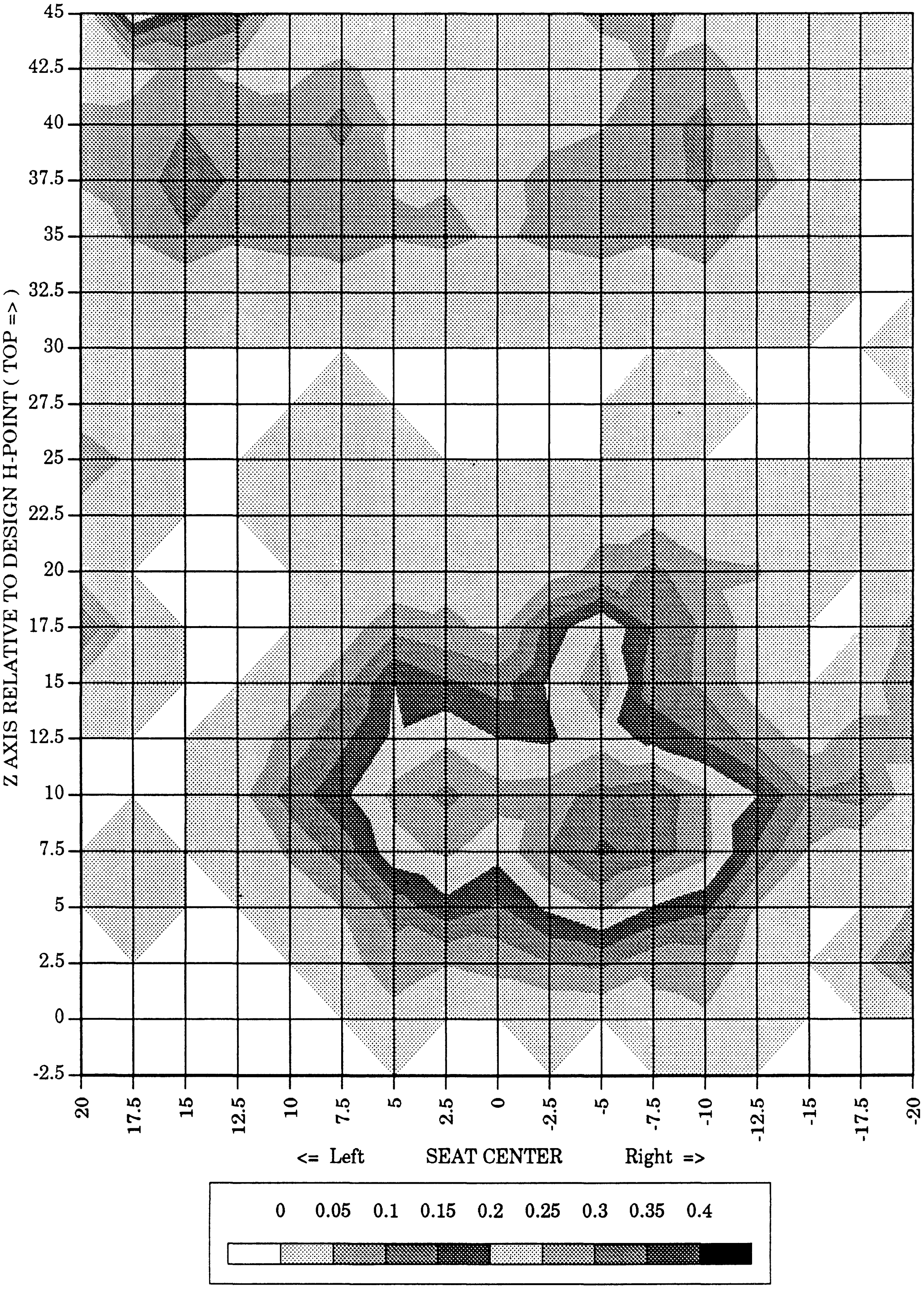
All Values and Axes in Centimeters

FIGURE 36. Average cushion indentation contour, Seat Three.



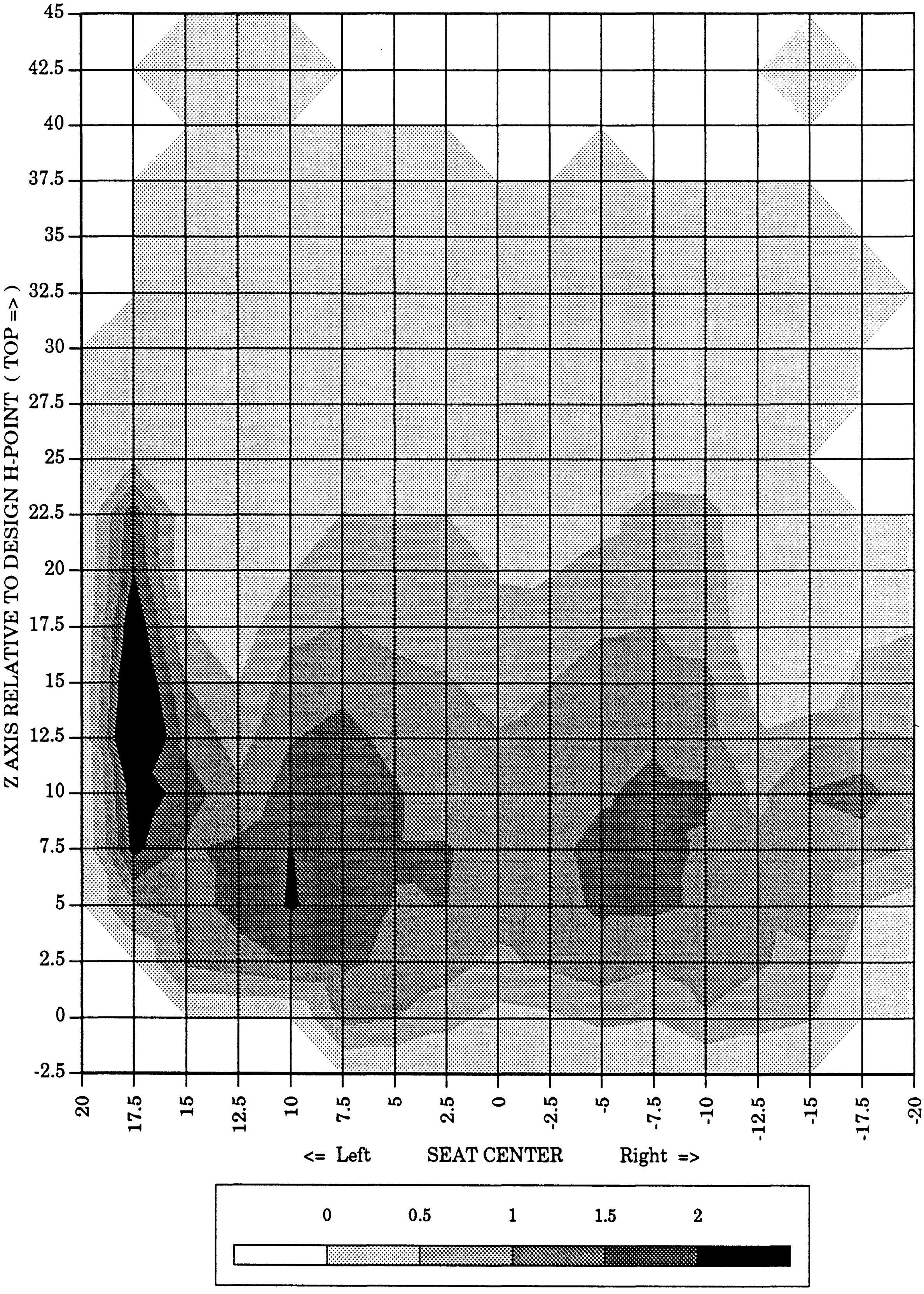
All Values and Axes in Centimeters

FIGURE 37. Average cushion indentation contour, Seat Four.



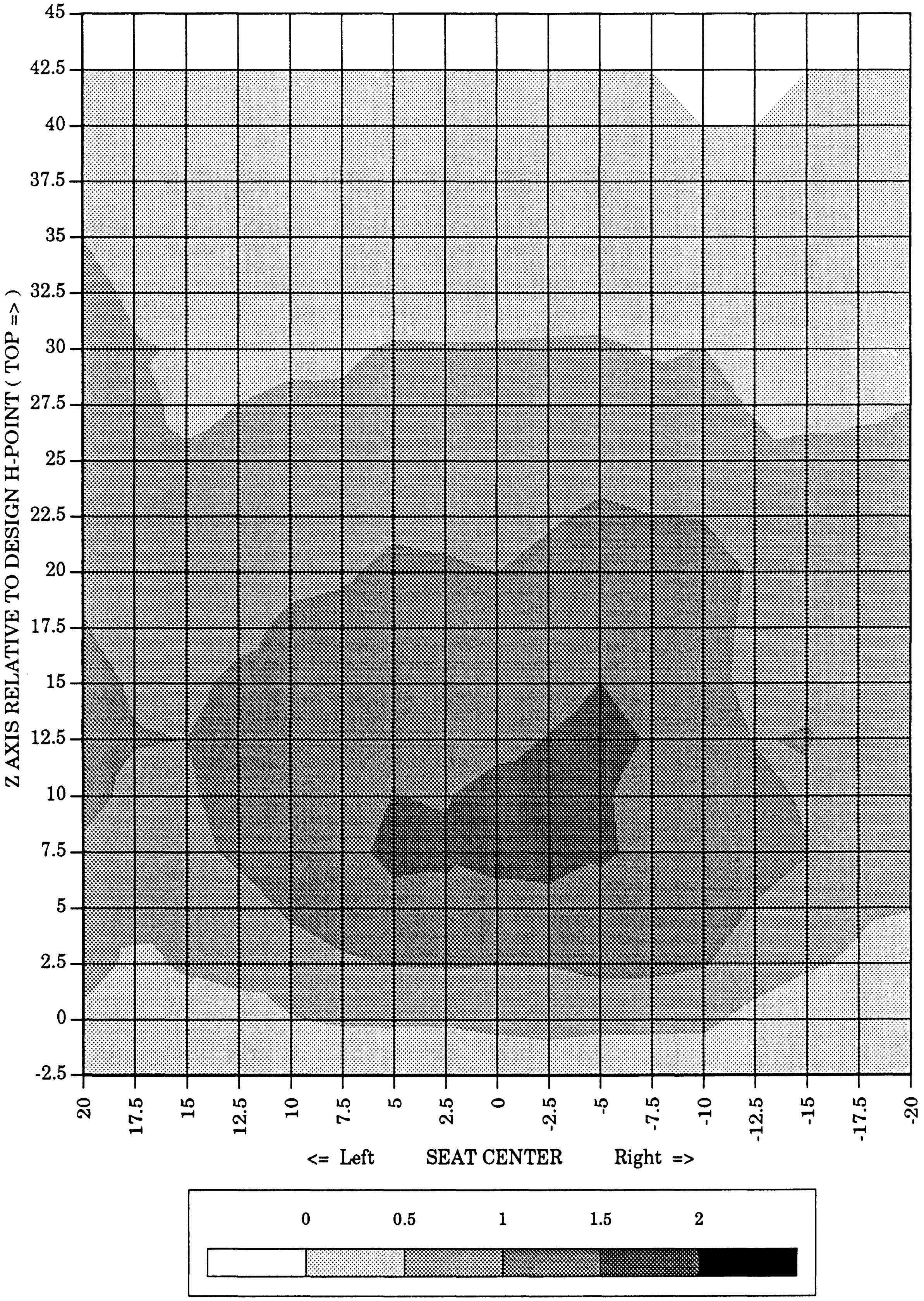
All Values and Axes in Centimeters

FIGURE 38. Average backrest indentation contour, Seat One.



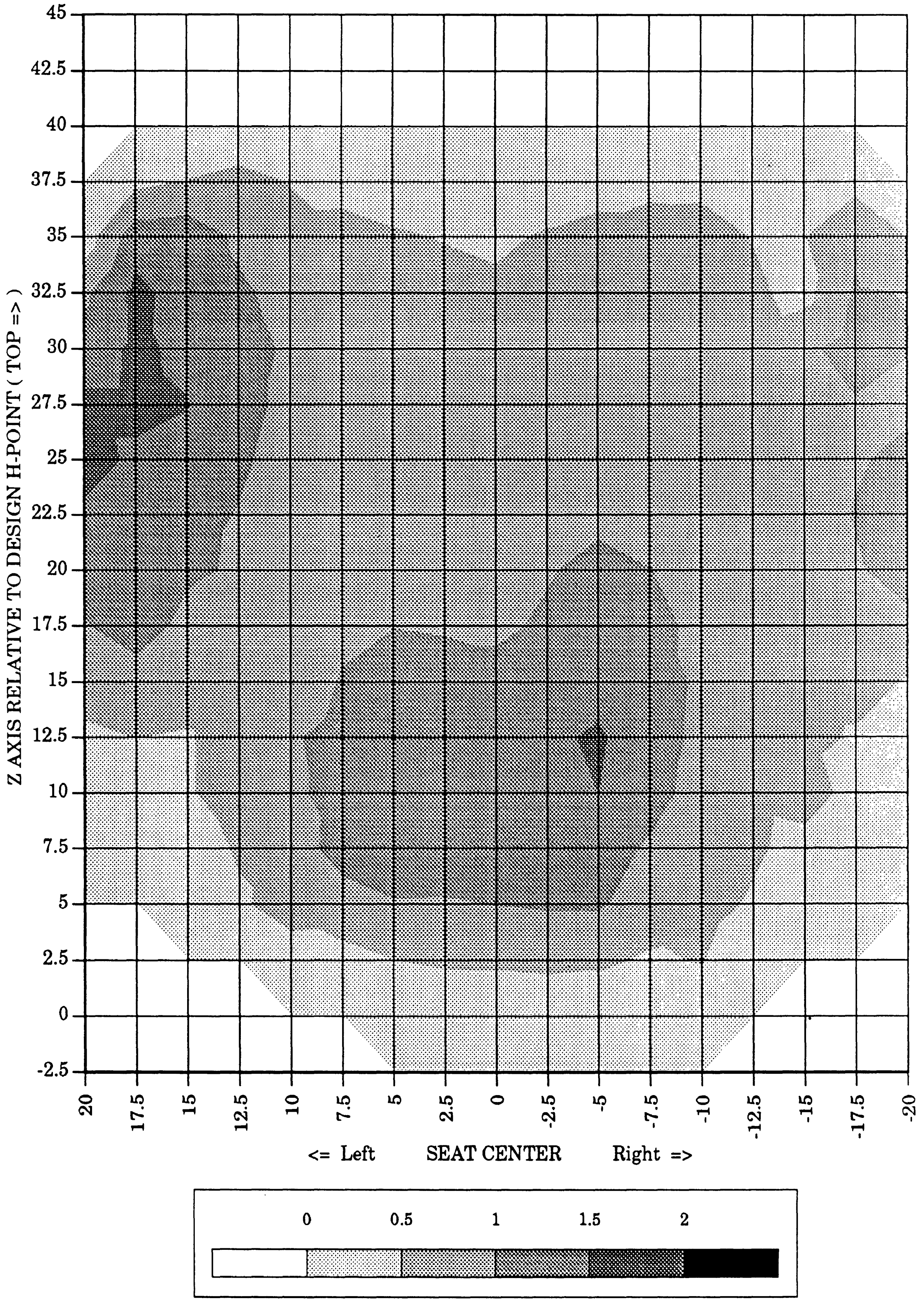
All Values and Axes in Centimeters

FIGURE 39. Average backrest indentation contour, Seat Two.



All Values and Axes in Centimeters

FIGURE 40. Average backrest indentation contour, Seat Three.



All Values and Axes in Centimeters

FIGURE 41. Average backrest indentation contour, Seat Four.

3.8.2 Backrest Indentation Contours. Figures 38 through 41 demonstrate marked differences between the seats in mean backrest indentation patterns. Seat One (note that the scale is different from the other seats) shows areas of higher deflection at the center of the low-back area and two areas further up the backrest corresponding to the shoulder blades (*i.e.*, scapulae) of the subjects. The indentations are low relative to the other seats although the data show contact as much as 40 cm above the design H-point. The low values of average deflection at most points, particularly in the upper-middle-back area, reflect the fact that some subjects produced no deflection at those points, contributing a deflection of zero to the average. The important characteristics of the average indentation pattern for Seat One are (a) the area of greatest deflection was fairly symmetric, approximately oval, and centered about 10 cm above the H-point, and (b) the seat contact area was broad, including deflection at the shoulder blades for at least some subjects.

Seat Two shows two distinct areas of higher deflection in the lower back and another on the left lateral support ("wing"). The greater deflection of the left side than the right was seen in the data for most of the subjects. This difference could be due to a systematic error in the data collection process, or to a postural or leg positioning phenomenon. Subjects typically sat with their left foot closer to the seat than their right foot, which was on the accelerator pedal. This might tend to incline the torso slightly to the left, which would explain the higher deflections on that side. In the lower-back area, higher average deflections are seen to each side of the centerline. This is due to the contour of the unindented seat surface in those areas.

The averaged data for Seat Three show an area of maximum indentation approximately 10 cm above the H-point and roughly symmetric about the centerline. The area of deflection greater than 1.5 cm extends approximately 15 cm to either side of the centerline. Seat Four also has its area of highest deflection in the lower back, centered about 12 cm above the H-point. There is also deflection of the backrest side-supports in Seat Four, about 27 cm above the H-point. These are deflections along the X-axis (horizontal, parallel to plane of seat centerline) and so do not directly measure lateral deflection of the side support. The same caveat applies to the deflections at the sides of the cushion for Seat Two.

3.8.3 Sternum/Spine Profiles. At each preliminary session, the sonic digitizing probe was used to record the profile of the subject's spine and sternum. Fixed emitters attached to the subject's clothing allowed the data to be corrected for movement during the measurement. Appendix D details the procedures and data processing.

Figure 42 shows one subject's data. The origin for the plot is the subject's trochanter, as palpated during the measurement, projected onto a sagittal plane.

These data were used to evaluate changes in spinal shape between the standing and sitting positions. The mean locations of all targeted body landmarks were determined from the posture data for each driving-simulation session (see Section 3.5). The data from the spine and sternum tracing in the standing posture were then aligned with the driving-simulation data. To facilitate the comparison between standing and sitting postures, several assumptions were made. First, the subject's rib cage was assumed to be rigid (*i.e.*, the thoracic vertebrae above T10 do not change position relative to the sternum when the subject is seated). Second, rotation of the pelvis was assumed to be accurately gauged by the PELVIC postural variable (see Section 3.5). The PELVIC variable represents the change in pelvic inclination between the standing and sitting positions, as measured by the angle of the line from the trochanter emitter to the ASIS emitter. Third, the subject's spine was assumed to be in contact with the indented seat contour measured during the preliminary session. For some of the larger subjects, with more flesh to either side of the spine, this assumption may have been in error by one or two centimeters.

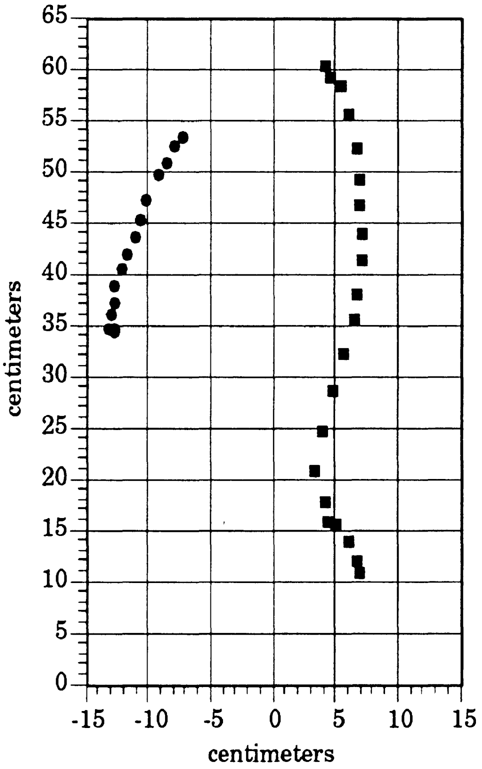


FIGURE 42. Spine and sternum profile, subject 753.

The subject's spine and sternum profiles were aligned to the data from the driving-simulation sessions in two ways. In one, the profiles were matched to the location of the sternum, based on the mean positions of emitters six and seven. In the other, the profiles were rotated from the vertical by the amount of the mean value of PELVIC for the test and aligned by translation relative to the ASIS locations sampled from emitter four in the standing (when the profile was recorded) and sitting positions. The position of two vertebrae were estimated in the resulting plots. The estimated position of L4 was located at the same height on the spine profile as that recorded for emitter 5 in the standing position, the most superior point on the iliac crest. The location of T10, which was assumed to be the lower edge of the rigid spine and chest, was estimated by considering each vertebra between C7 and T4 to contribute equally to the height of the spinal column. T10 was located nine-sixteenths of the measured distance from C7 to the estimated position of L4.

These data were combined with indentation contour measurement data at the seat centerlines. Figure 43 shows the data configuration for a particular subject and seat.

Two general observations can be made regarding these data.

1. Lumbar-spine curvature for all subjects in all seats was apparently kyphotic, often markedly so.

2. H-point location estimates based on trochanter data from the indentation measurement were generally about 5 cm higher than the design H-points, while the estimated H-points for the driving simulation data were about 6 cm higher than the design H-point and 4 cm forward.

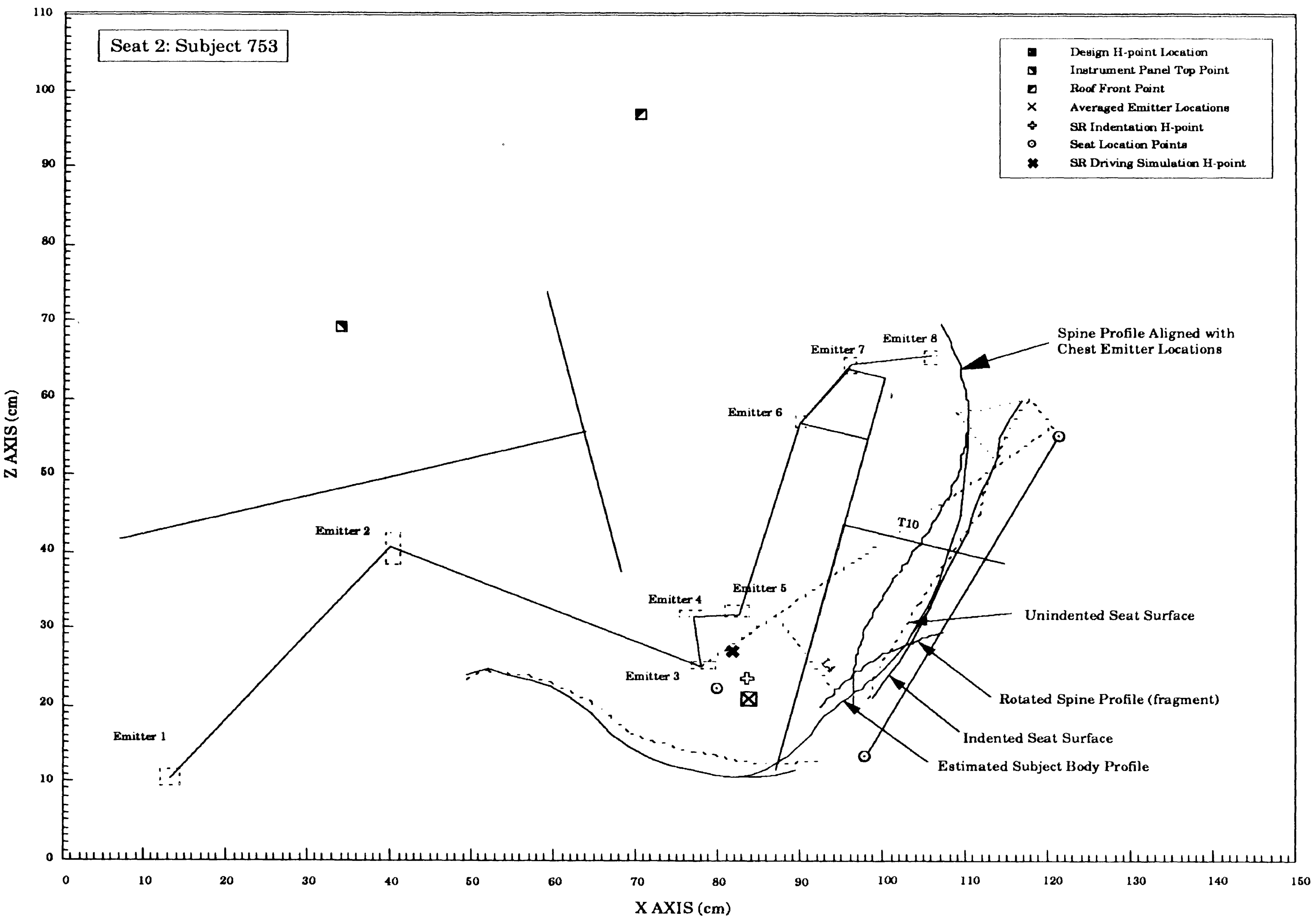


FIGURE 43. Combined indentation, posture, and spine profile data.

It is evident from Figure 43 that significant kyphosis in the lumbar spine would be necessary to meet the third assumption, that the spine contacted the seat surface. A curve has been drawn on the figure as an estimate of the mean location of the subject's body profile during the driving simulation. The curve location was determined by the indentation patterns of the cushion and backrest, and the location of the lowest point in the rotated spinal trace, which was assumed to be fixed to the pelvis. A small flesh margin was assumed in that area to account for the upper portion of the buttocks. The general shape of the curve in the lower-back area during sitting was verified by examination of subjects and reference to data from a previous UMTRI study (Schneider *et al.* 1983). The curve location does not exactly correspond with the indented seat surface, due to the difference between the subject's estimated hip-point locations during the indentation measurement and the driving simulation.

The body profile curve indicates considerable spinal kyphosis, particularly in the upper-lumbar spine. It may be that the first assumption noted above, that the chest functions as a rigid body, is in error, since the location of the chest emitters relative to the seat backrest for the driving-simulation session indicate that increased curvature of the thoracic spine from the standing posture would be necessary for the subject's middle-back to contact the seat. That middle-back contact occurred during the simulation is supported by photographs taken of the subject operating the simulator, and by data from the upper set of FSR sensors, which showed almost continual contact. Additionally, the indentation contour data for the seat centerline (also shown in Figure 43) shows deflection of the seat in the middle-back area.

The second observation above regarding the locations of estimated and design H-point is also demonstrated in Figure 43. According to skeletal reconstruction previously performed by UMTRI the H-point should be located approximately 35 mm rearward and 12 mm above the trochanter landmark on an average size male (Robbins *et al.* 1983). Two corresponding skeletal reconstruction (SR) H-point locations are indicated in Figure 43, one calculated from the mean emitter-three location from the driving simulation data (trochanter location), and one calculated from the trochanter location recorded during the indentation contour measurement. The difference between the two trochanter points is possibly due to (a) differences in location of the emitter relative to the subject for the two sessions (data were collected on separate days), (b) movement of the emitter relative to the subject during the first few minutes of the driving simulation, or (c) the subject sitting more forward for the driving simulation than for the short-term indentation measurement. Of these possible explanations, the third is the most likely. Data for other subjects show a similar relationship between indentation-measurement trochanter location and that recorded during the driving simulation. The H-point locations for the driving simulation were estimated to be, on average, four centimeters forward of the design H-points of the seats.

These findings imply that all of the test seats, even those which were designed specifically to preserve the standing lordosis of the lumbar spine to a certain extent (Seat Three, for instance) failed to accomplish that goal over the course of the three-hour simulation. The extent of pelvic rotation which occurred when the subjects were seated, coupled with the positioning of the chest, resulted in apparent kyphotic curvature for the thoracic and lumbar spines of All Subjects.

The position of the estimated H-point locations relative to the design H-points helps to explain this phenomenon. Subjects sat forward of the design H-point location, which may have allowed greater pelvic rotation than if they had been seated further to the rear. The data from the indentation contour measurement, which were taken when the subjects had been seated for only a few minutes, show a trochanter position further to the rear than was the case with the averaged data from the driving simulation. During this short-term measurement, it is possible that the lordosis evident for the subjects in the standing position was preserved to a greater extent than was the case during the long-term simulation.

3.8.4 Mean Seat Indentations Considered with Static Force-Deflection Data. The mean indentation pattern for each seat was examined relative to the data collected during static force-deflection testing of the seats, described in Appendix E. One series of tests employed a flat, circular 80-mm diameter indenter. Force-deflection curves were generated along the cushion and backrest centerlines at 50-mm intervals. To compare the relative levels of pressure required to produce the average deflections calculated for each seat, the static force-deflection curves were used to produce relative estimates of average local loading along seat centerlines.

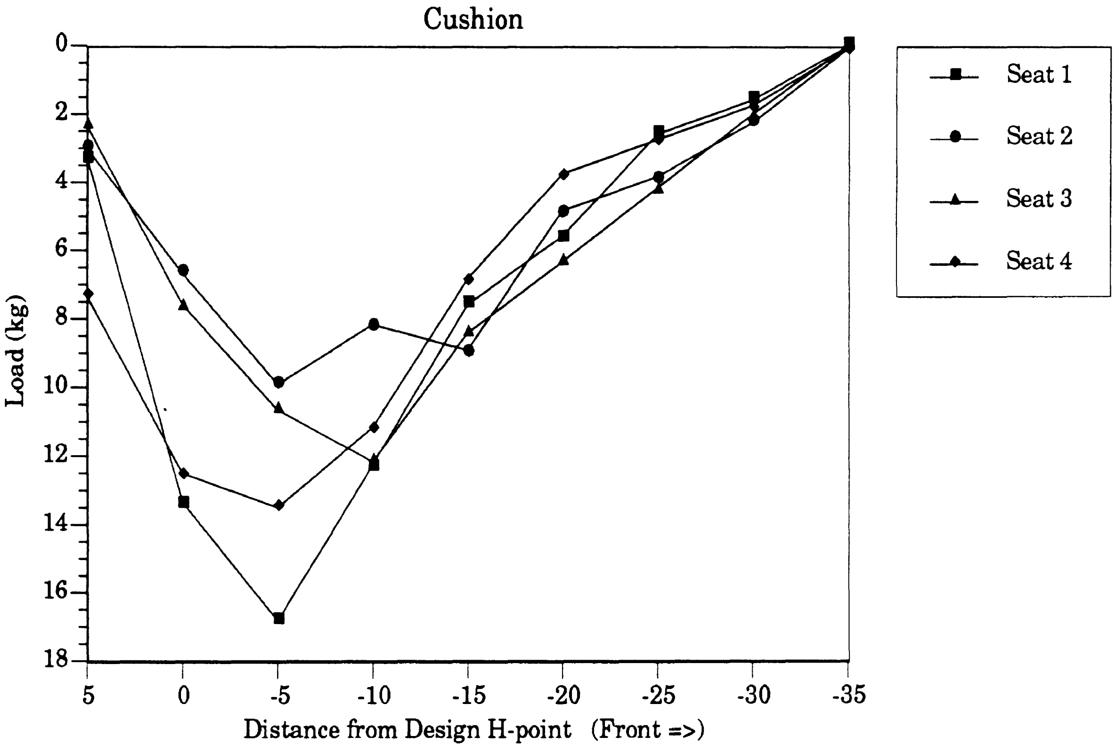
For each seat, the average deflection at 50-mm intervals along the centerline of the cushion and backrest were matched to the force-deflection curve from the 80 mm indenter for the same location. The load required to produce the deflection was expressed in kilograms. The resulting values are plotted in Figure 44. Note that load values are positive downward.

The load curves in Figure 44 are useful to estimate the relative levels of pressure along the centerline of each seat when a subject was seated. Although the load values are not representative of the actual loads on the seat due to a subject, the relative load levels shown in Figure 44 are consistent with the actual relationships between seat loads to the degree that the 80-mm indenter produced the same pressures as did the subject. In other words, if the ratio of the loads required for the 80-mm indenter to deflect two seats the same amount is equivalent to the ratio of the pressures exerted by a subject deflecting the seats that same amount, the comparison between seat loads shown in Figure 44 is accurate.

For at least one seat, this condition appears not to be met. The values for Seat One may not be comparable to those obtained for the other seats. For the cushion data, the average deflections produced by the subjects along the centerline of Seat One were quite large, as much as six or seven centimeters. The 80-mm indenter required considerable load to deflect the seat to that extent. However, that deflection was produced with considerably higher average pressure under the indenter than would have been required to produce the same deflection with a larger indenter. The seat surface contributed inordinately to the resistance encountered by the small indenter by forcing the indenter to "pull down" a large portion of the surrounding cushion. This effect was less pronounced with the other seats, which had firmer cushions and smaller deflections.

The load values calculated for Seats Two, Three, and Four, and for Seat One in the backrest can be compared. Each seat shows a characteristic load profile on the cushion and backrest. On the cushion, the load values for Seat Four are peak about five centimeters to the rear of the peak for Seat Three and are at a higher level than for Seats Two or Three. The load values also decrease more quickly toward the front of the seat for Seat Four than for the others. This is consistent with the indentation patterns observed for Seat Four, in which the contact with the cushion was more localized than in the other seats and seat deflection under the thigh areas was minimal. The load values for Seat Two are more evenly distributed than those for Seats Three and Four. The values under the thigh area are higher than those for Seat Four, suggesting that more under-thigh support was provided by Seat Two. Seat Three shows a load peak more forward than the other seats, with slightly higher load values to the front of the seat as well. The load profile suggests a relatively small region of higher pressure under the buttocks, with support continuing under the thighs to near the front of the cushion.

Each seat shows a characteristic curve in the plot of load values for the backrests as well. Seat Three has slightly higher values than other seats, although in the middle-back area the values are virtually identical to those of Seat Four. Load values for Seat Two are higher in the lower-back area than for Seat Four, but decrease from about 15 cm above the H-point to minimal values in the middle-back region. The load profiles for all seats peaked about 10 cm above the design H-point, in the lower-back area.



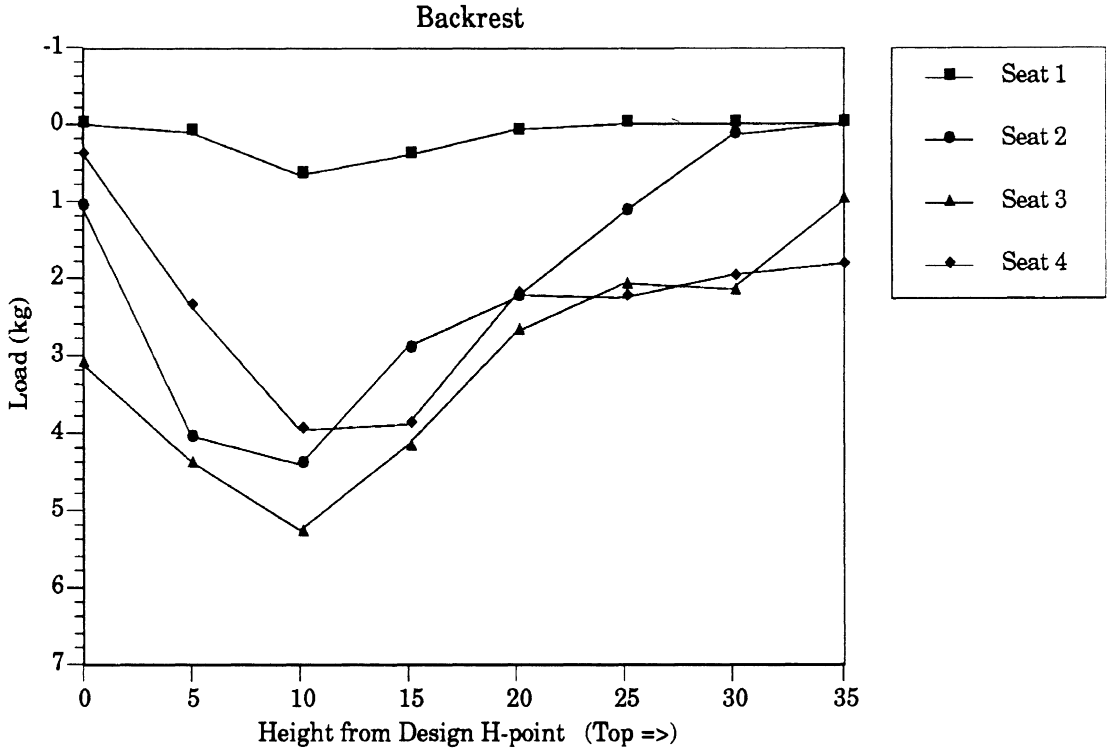


FIGURE 44. Load values from force-deflection curves with 80-mm indenter corresponding to average seat indentation on seat centerlines.

3.9 SUMMARY OF FINDINGS FROM OBJECTIVE MEASURES

Comparison of the findings from the objective data types is less revealing than are the relationships between the subjective measures because there are fewer findings of significance within the objective data types. Statistical analyses were not performed between objective data types. Rather, the significant findings with respect to each test seat are summarized below, for purposes of comparison between the results of the objective methods. Details of the analyses and results are found in the associated report sections. Tables 46 through 49 summarize these findings.

TABLE 46

SIGNIFICANT FINDINGS IN OBJECTIVE DATA:
SEAT ONE

Data Type	Significant Findings
EMG	• Higher rectified EMG values in preliminary-session data, indicating higher abdominal activity than other seats. • Fewer samples greater than two standard deviations from the mean in abdomen data, indicating less voluntary muscle activity than in Seats Two and Four or fewer posture shifts.
Pressure	• Front cushion group had lower average pressure than other seats, caused by larger contact area on cushion. • Lower standard deviations for several sensor groups; results caused by intermittent contact with those sensor groups on other seats. • Lower standard deviations for individual sensors on backrest and cushion; partially caused by "soft" load/deflection behavior.
Indentation	• Much larger contact area and deflection magnitude on seat cushion than other seats; large area of contact on backrest.
Posture	• Larger SLOUCH values than other seats, indicating greater difference between pelvic and chest angles. • Lower than Seats Two and Four on the CUSHION and CHEST measures, meaning a lower angle between the subjects' right femurs and the horizontal and more reclined chests. • Higher than Seats Two and Four, and lower than Seat Three on the Z3 measure, indicating the relative height of the right trochanter emitter. • Slight increase estimated during simulation in the HIP measure (the angle between the pelvis and the right femur).

TABLE 47

SIGNIFICANT FINDINGS IN OBJECTIVE DATA: SEAT TWO

Data Type	Significant Findings
EMG	• Higher than Seats 1 and 3 on the count measure, indicating higher voluntary muscle activity in the lumbar area. Increasing abdominal muscle activity throughout simulation, to a level higher than that of Seat Three.
Pressure	• Mean pressure levels for the middle cushion sensor group lower than for Seats One and Three. • Lower standard deviation of sensor pressure on backrest than Seats Three and Four.
Indentation	• Cushion contour indicates four areas of higher deflection: two under ischia and two forward under thighs. • Backrest shows two areas of higher deflection in lower-back region, one to either side of the seat centerline.
Posture	• Greater CUSHION, CHEST and X6 values than Seats One and Three, indicating higher angle of the right femur to the horizontal, a more reclined chest, and a greater distance from the accelerator pedal to the chest. • Increase in estimated CHEST, L3-6, and L4-7 over simulation, meaning the subjects' chests reclined further during the test, and their sternum moved farther from their pelvises. • Lowest X3 and X6 values of test seats, meaning the subject's chest and trochanters were closest to the accelerator pedal in this seat.

TABLE 48

SIGNIFICANT FINDINGS IN OBJECTIVE DATA: SEAT THREE

Data Type	Significant Findings
EMG	• Lower standard deviation of signal level in the abdominal muscles than Seat Four; lower mean rectified signal levels than Seat Two. • Fewer samples greater than two standard deviations from the mean than Seats Two or Four, suggesting less voluntary muscle activity or fewer posture shifts.
Pressure	• Higher average pressure in the middle backrest sensor group than Seats One and Two. • Higher standard deviation of backrest sensor pressure than Seats One and Two. • Forward movement of sensor center of pressure (SCP) by two subjects.
Indentation	• More localized backrest indentation than other seats. • Broad, even cushion indentation. • Load estimates indicate higher pressures in low back regions than for other seats.
Posture	• Lower PELVIC , SLOUCH, and L3-6 values than the other test seats, indicating less pelvic inclination, less of a difference between pelvic and chest angles, and a smaller fraction of standing distance from pelvis to chest. • The highest X3 value of the test seats, meaning that the position of the trochanter was the furthest from the accelerator pedal in Seat Three. • Slight decrease in chest height over the simulation.

TABLE 49

SIGNIFICANT FINDINGS IN OBJECTIVE DATA: SEAT FOUR

Data Type	Significant Findings
EMG	• Slightly greater activity in short-term lumbar samples than other seats. • Higher standard deviations in evaluation interval abdomen samples than Seats Two or Three, implying greater muscle activity. • More samples greater than two standard deviations from the mean than Seats One or Three, indicating more frequent voluntary muscle activity.
Pressure	• Higher standard deviations on cushion sensors than other seats; higher standard deviations on backrest sensors than for Seats One and Two.
Indentation	• Smaller contact area and indentation on seat cushion than other seats. • Higher estimated pressures in the cushion area than other seats.
Posture	• Greater values of L3-6, L4-7 than other seats, indicating a greater distance from the chest to the pelvis. • Greater CUSHION and CHEST values than Seats One and Three, meaning subjects had more reclined chests and greater angles between their right femur and the horizontal. • Lower trochanter location than Seats One or Three. • PELVIC estimated to increase during simulation, meaning that the pelvis rotated backward. • X3 estimated to decrease during simulation, meaning subjects slid forward on seat cushion.

4.0 EVALUATION OF TEST METHODOLOGY

The test techniques used in this study can be divided into subjective and objective types. The subjective tools gauged subject responses and were the Preliminary Questionnaire, the Exit Questionnaire, and the CMM modalities, including the open-scale discomfort evaluation questions (OSGR modality). The objective methods measured muscle activity (EMG), pressure at the seat-subject interface (FSR), and subject posture (sonic digitizer).

The purposes of this evaluation are:

- to examine the validity of the results, as far as that is possible,
- to compare results among techniques which measure the same or similar parameters, and
- to consider the efficiency and potential of each technique for producing meaningful data regarding specific seat configurations.

The subjective techniques will be dealt with first, followed by the objective techniques.

4.1 EVALUATION OF PRELIMINARY QUESTIONNAIRE

The Preliminary Questionnaire collected subject evaluations of seat features, as well as the satisfaction with those features and the overall evaluation of the seat. The feature evaluations in Section A of the Questionnaire were validated to some extent by comparison with physical measurements of the seats. For instance, cushion firmness was measured using a static-deflection apparatus, and the relative firmness of the test of each test seat were compared with the responses to the corresponding question. However, when the objective and subjective measures differ, information may be gained about how the subjects perceived the seat feature, but the subjective measure cannot be considered to be in error; the subject may have in fact felt that a seat, which was objectively firmer than another, was softer.

An additional test of the Questionnaire performance is made possible by the several near-redundancies in the questions. For instance, cushion firmness and cushion bounciness are related features, as well as cushion sinking. It would be expected that these measures would be highly correlated, if in fact the subjects had made consistent evaluations. If these measures are assumed to evaluate the same feature, then the correlation between the responses can be used as an estimate of the Questionnaire's Section-A precision.

In both Section A and Section B, the distribution of responses can be analyzed as a measure of the discriminatory power of the Questionnaire. If a subject's responses tend to be tightly grouped, then the power of the question to discriminate between seats is diminished. These analyses can provide information regarding the choice of anchor words or question syntax.

4.1.1 Correspondence with Objective Measures. One way of evaluating the performance of the Preliminary Questionnaire is to compare the data on feature evaluations (Section A of the Questionnaire) with objective measures of the feature. For instance, cushion firmness was evaluated by static-deflection testing; the resulting data were then compared to rankings of the seats on that feature which were prepared from the Preliminary Questionnaire data.

The objective reference data for these comparisons were obtained from the static-deflection testing of the seats (Appendix E), the seat geometry (Appendix A), and the indentation contour measurements (Section 3.8). In most instances for which objective measures related to the seat features are available, the Preliminary Questionnaire data properly indicate inter-seat differences. On buttock fit, cushion firmness, cushion width, backrest width, and backrest firmness, among others, the data from the static deflection tests, the seat geometry, and the indentation contour measurements correspond with the inter-seat comparisons which are significant in the Preliminary Questionnaire data. On several features, however, there are indications that subject perceptions may have produced different seat rankings on feature parameters than the objective measures.

The Preliminary Questionnaire data indicate that the subjects reported the cushion of Seat One to be longer than that of Seat Four. Measurements taken on the seats indicated that the distance from the front of the cushion to the most-forward part of the backrest (on the centerline) with the backrest in design position was farther on Seat Four than on Seat One. In fact, that measurement was shorter for Seat One than for the other three test seats. Another measure of the cushion length, the distance from the design H-point to the front of the cushion along the centerline produced about equal values for the two seats. An explanation for the subjects' perception may be found in the indentation contours. The data indicate that the indentation area on Seat One was localized under the subjects' ischia, and that little deflection of the seat occurred under the thighs. On Seat One, by contrast, subjects produced much larger areas of deflection, extending much further forward on the cushion than was the case with Seat Four. This suggests that the length of the contact area, rather than the actual length of the seat, was the quantity reported by the subjects on that question.

Subjects reported on average that the cushion angle on Seat Three was higher than that of Seat Four. Measurements taken on the seat indicated that there was barely one degree of difference in the general angle of the cushion surface. Again, this reported difference appears to be due to the lack of contact under the subjects' thighs on Seat Four. The posture that the subjects assumed in Seat Four placed their thighs at a higher angle than in Seat Three, despite the actual cushion angles being approximately equal. The posture data in Section 3.5, in particular the CUSHION variable, demonstrate this phenomenon for the driving-simulation data.

4.1.2 Quasi-Redundant Questions. Several features mentioned in the Preliminary Questionnaire were related. Cushion firmness, cushion bounciness, cushion sinking, and speed of cushion recovery all have to do with the deflection characteristics of the seat cushion. The correlations among the Section-A responses for these questions can indicate if subjects responded consistently. Low correlations would indicate that either the questions were not substantially redundant, or that the subjects' responses were largely random for those questions.

Table 50 tabulates the correlation coefficients for four questions, all of which are related to the performance of the cushion and might be expected to be related. The coefficients show a reasonable level of correspondence between responses on the questions, an indication which supports the validity of the data. Note that several of the coefficients are negative, reflecting the arrangement of the anchor words on the questionnaire.

TABLE 50

CORRELATION COEFFICIENTS FOR SELECTED PRELIMINARY QUESTIONNAIRE RESPONSES

Questions	Q4-A	Q9-A	Q10-A
Q9-A	-0.683	- -	- -
Q10-A	0.867	-0.670	- -
Q12-A	-0.619	0.508	-0.667

4.1.3 Distribution of Responses. Statistics generated from the pooled responses for each question illustrate the distribution of responses for each question. Tables 51 and 52 show selected statistics for the Section-A and Section-B data, respectively. Data are scaled as indicated in Section 3.1.

TABLE 51

SELECTED STATISTICS:
POOLED PRELIMINARY QUESTIONNAIRE DATA
SECTION A
(N=32)

Question	Mean	Median	Std. Dev.	InterQ Range*	Range
1	0.64	0.68	0.18	0.23	0.70
2	0.56	0.61	0.19	0.32	0.66
3	0.55	0.63	0.22	0.45	0.70
4	0.52	0.62	0.25	0.47	0.76
5	0.54	0.56	0.18	0.31	0.64
6	0.55	0.58	0.20	0.35	0.63
7	0.45	0.48	0.19	0.37	0.60
8	0.50	0.49	0.18	0.33	0.61
9	0.41	0.33	0.22	0.41	0.69
10	0.57	0.60	0.24	0.46	0.70
11	0.14	0.10	0.11	0.09	0.57
12	0.37	0.30	0.24	0.44	0.80
13	0.49	0.51	0.24	0.45	0.71
14	0.61	0.66	0.16	0.23	0.55
15	0.57	0.67	0.23	0.41	0.80
16	0.62	0.70	0.19	0.30	0.65
17	0.54	0.57	0.21	0.37	0.66
18	0.49	0.49	0.22	0.41	0.72
19	0.57	0.63	0.22	0.40	0.74
20	0.47	0.48	0.16	0.20	0.60
21	0.24	0.18	0.18	0.24	0.61
22	0.42	0.38	0.18	0.23	0.56
23	0.64	0.68	0.18	0.25	0.72
24	0.60	0.63	0.14	0.19	0.55

* 25th to 75th percentile range

The values in Table 51 for the Section-A data show the responses to most questions are well distributed, indicating that subjects exercised a usable response range. Question 11, however, showed a more restricted range of responses at the low end of the scale, with one outlier (658, Seat 2) boosting the range to 0.57. Also note that the responses to question 24 had a small spread compared to other questions. Question 23, the other overall evaluation measure, received a larger range of responses, although the standard deviation and interquartile range were only slightly larger than those for question 24. In the paired t-test comparisons conducted between seats, the data from question 23 had shown a larger number of significant differences between seat responses. It was hypothesized that the range contraction evident in Table 51 for question 24 was caused by the length of the anchor phrases intruding on the response line (see Section 3.1).

In Table 52, the Section-B responses are seen to center slightly above response "3." Only question 11 shows a markedly higher mean, indicating that subjects gave high satisfaction ratings for the number of intrusions through the cushion, which Table 51 indicates on average were judged to be few. The spread measures for the two overall evaluation questions (23 and 24) are approximately equal, although question 24 showed a higher range.

TABLE 52

SELECTED STATISTICS:
POOLED PRELIMINARY QUESTIONNAIRE DATA
SECTION B
(N = 32)

Question	Mean	Median	Std. Dev.	InterQ Range*	Range
2	3.38	3	0.79	1	3
3	3.31	3	0.74	1	3
4	3.63	4	0.91	1	3
5	3.41	3	0.84	1	3
6	3.41	3	0.95	1	3
7	3.13	3	0.83	2	3
8	3.25	3	0.84	1	3
9	3.19	3	0.82	1	3
10	3.28	3	0.89	1	3
11	4.34	5	0.94	1	4
12	3.25	3	1.08	2	4
13	3.19	3	1.03	2	4
14	3.56	4	0.67	1	3
15	3.50	4	0.80	1	4
16	3.59	3	0.80	1	3
17	3.47	4	1.02	1	3
18	3.38	3	1.18	1	4
19	3.53	4	1.14	1	4
20	3.59	4	0.95	1	3
21	3.88	4	0.91	2	3
22	3.38	3	0.91	1	3
23	3.59	4	0.91	1	3
24	3.44	4	0.91	1	4

* 25th to 75th percentile range

The Preliminary Questionnaire design provided accurate, reliable data for most questions, which allowed meaningful inferences to be made from the data analyses, despite the small number of subjects. Some changes to the questionnaire format would result in more usable data.

The response type for Section B should be made equivalent to that of Section A. The range and spread measures in Tables 51 and 52 indicate that the Section-A responses are more suited to inter-seat comparisons, and present a better data set for correlation and regression analyses. Because of the unipolar nature of the satisfaction response, a single open-scale line with only the direction of greater satisfaction indicated would allow a graphic response.

Additional emphasis should be placed on the selection of seat features and anchor phrases. Analyses suggested that subjects responded to certain feature evaluations with reference to their overall evaluation of the seat, rather than rating the feature (*e.g.*, backrest length). Those features are misleadingly correlated with overall evaluation. Experiments with the connotation of anchor phrases on near-redundant questions would provide insight into the responses for certain questions, for which relationships were established between the feature evaluation and satisfaction with the feature, but no consistent pattern of feature evaluation was apparent.

In particular, additional emphasis should be placed on the definition of the lumbar support feature, and a proper semantic axis on which it may be evaluated. Analyses of this data set suggested that subjects responded with higher satisfaction ratings when they evaluated a seat as having strong lumbar support but, for at least some of the subjects, no consistent evaluation pattern for the feature was evident. In one other minor note, the anchor words should be made to impinge evenly or not at all on the response lines, to avoid a shrinking of the effective response range, as was the case with question 24.

4.2 EVALUATION OF CMM DISCOMFORT MEASUREMENT TECHNIQUES

The four CMM modalities (Heat, Pressure, EV, and OSGR) nominally measure the same quantity: discomfort. However, the four techniques differ both in the mode of subject response and the methods used to interpret the responses, and the data produced by each modality show readily discernable individual characteristics.

The OSGR modality is a variation on a traditional subjective assessment instrument. Studies (*e.g.*, Grigg 1978) have indicated that the particular formulation used here (open-scale, anchor words only at the ends) is a preferred question configuration for measuring levels on a single continuum, in this case, discomfort. Responses were pencil marks on an open-scale line which were interpreted directly by measuring the location of the response mark. Each measurement was expressed as a fraction of the full-scale length.

For the other three modalities, responses were in the form of an objective measurement of the applied stimulus magnitude: degrees C for the Heat modality, mm Hg for the Pressure modality, and volts peak amplitude for the EV modality. The subjective equivalent of these objective responses was determined by reference to a calibration curve produced by each subject prior to the test (see Section 2). In the case of the Pressure and EV modalities, the response magnitude was related to subject discomfort by a power function determined from the calibration. For the Heat modality, responses were expressed as a fraction of the temperature differential between the most recent threshold measurement and the average maximum value obtained during calibration. The subjective responses from these three modalities were expressed as fractions of "maximum bearable discomfort," as determined in the calibration procedure.

TABLE 53

COMPARISON OF MODALITY RESPONSE ON AVG INDEX

Modality Comparison	t - Statistic (N = 128)	95% Confidence Bounds	
		High	Low
P v. H	-16.248	-0.217	-0.277
P v. EV	-1.954	0.001	-0.114
P v. OSGR	1.702	0.051	-0.004
H v. EV	5.707	0.257	0.124
H v. OSGR	18.750	0.300	0.242
EV v. OSGR	2.462	0.145	0.016

Although each modality was scaled to an equivalent semantic discomfort scale during calibration and data processing, the modalities produced different levels of responses for similar measures during the same evaluation interval. To compare these levels, values of the AVG index were tabulated for each driving-simulation session. Using a pair-wise comparison, which matched each value with values from the other modalities obtained during the same test and over the same body areas, t-statistics and 95% confidence intervals were calculated. Table 53 shows these results.

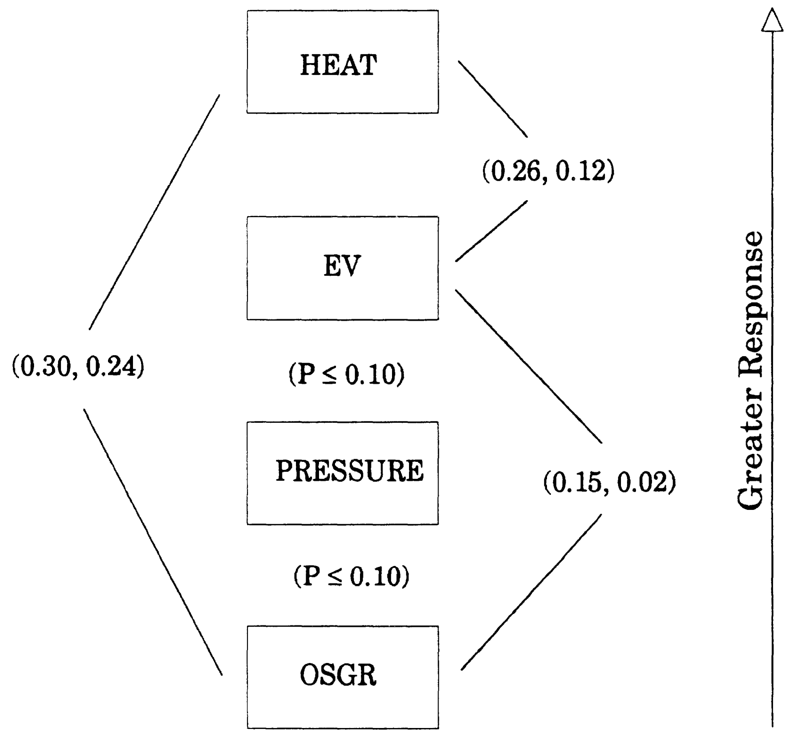


FIGURE 45. 95% confidence intervals, indicating relative response of CMM modalities on AVG index.

The Heat modality, on average, produced higher response levels than the other modalities. The Pressure modality was only slightly lower, on average, than the EV modality, and slightly higher than the OSGR modality. Including differences significant with $P \leq 0.10$ (P v. EV and P v. OSGR), the relative ranking of modality levels is shown in Figure 45. Modality differences with $P \leq 0.05$ are indicated with 95% confidence intervals.

In addition to the greater response levels for the Heat modality, other differences in modality performance are evident. The inter-seat comparisons significant in the CMM analysis (Section 3.2) indicate that while the modalities produced similar results in some instances, differences are easily discernable between the individual modalities for other comparisons. Analyses were conducted to explore the extent and causes of the variations in results between the modalities. Four areas were identified on which the modalities could be contrasted and appropriate analyses performed.

1. Each modality exhibited a characteristic response curve versus time. Over the course of the simulation, the subject's discomfort, as measured by each modality, was seen to increase at a rate dependent on the modality used for the observation. By standardizing the data for differences in maximum discomfort level, an indication of these modality behaviors was evident.

2. The modalities behaved differently on the indices which were used as measures of overall test discomfort. In particular, for certain modalities, the indices which represented the change in discomfort evaluation during the simulation provided increased inter-seat discrimination over those indices which represented the maximum discomfort level attained; for other modalities, the discrimination was decreased by compensation for initial evaluations.

3. The modalities were compared based on the body-part discomfort distributions that each produced. At every evaluation interval, the subject used each modality in turn to rate the discomfort in his middle-back, lower-back, buttock, and thigh areas. The relative levels reported for each body area are indicative of the distribution of discomfort. The distributions produced by the four modalities are compared below.

4. An important characteristic of the modalities is their susceptibility to test-order influence. Because the extended duration of the driving simulation made testing of the seats on subsequent days necessary, a test-order effect would interfere with the potential for inter-seat discomfort comparisons. This effect was examined for implications pertinent to the results of these and similar tests.

4.2.1 Modality Performance on Inter-Seat Discomfort Comparisons. Table 54 shows the seat-comparison pairs which show a significant difference in discomfort magnitude during the driving simulation ($P \leq 0.05$), by body area and modality. These results are from the selected indices; for each modality, the index which produced the largest number of significant inter-seat comparisons in All Subjects and the two sets of complementary subject groups was selected (see Section 3.2).

The difference in modality performance for these tests is evident in Table 54. On the selected indices, the Pressure modality indicated four significant inter-seat comparisons, while the Heat modality indicated three and the EV and OSGR modalities showed one each. Of the three comparisons included from the non-selected indices, two were found in the results of the Heat modality, and one was indicated in both the Pressure and EV modalities.

TABLE 54

SIGNIFICANT COMPARIONS FROM STANDARDIZED, INDEXED CMM DATA FOR ALL SUBJECTS

$P \leq 0.05$

Modality (Index)	Body Area			
	Middle Back	Lower Back	Buttock Area	Thigh Area
Pressure (DAV)	3>1,2	3>4	4>2	
Heat (TID)	3>2	3>2	4>3	
EV (DAV)			4>3	
OSGR (DID)		3>4		

The seat discomfort stimuli that are apparent in these results are focused on the back areas of Seat Three and the buttock area of Seat Four. These two areas of discomfort are confirmed by the results of the Exit Questionnaire (see Section 3.3). Considering this evidence to indicate the "objective" presence of greater discomfort, the modality results may be examined for identification of these two areas.

For purposes of this analysis, the index assignment for each modality was reconsidered based on the number of significant ($P \leq 0.05$) seat comparisons made in the t-tests of standardized data from All Subjects, concerning Seat Three in the back areas and Seat Four in the buttock area. Table 55 shows the number of significant comparisons for each index and modality, taken from the results of the t-tests with standardized data.

Because of the small number of possible comparisons (six for the Seat Three data and three for Seat Four), it was not practical to assign an individual index to each modality. However, Table 55 provides a view of the relative discrimination provided by the modalities for the two discomfort areas identified.

TABLE 55

NUMBER OF SIGNIFICANT INTER-SEAT COMPARISONS ($P \leq 0.05$) IN t-TESTS OF STANDARDIZED CMM DATA, ALL SUBJECTS

CMM Index	Seat Three: Back Areas				Seat Four: Buttock Area			
	Press	Heat	EV	OSGR	Press	Heat	EV	OSGR
AVG	0	1	0	0	2	2	2	0
DZA	0	0	0	1	1	0	2	0
DAV	3	0	0	1	1	0	1	0
TID	0	2	0	0	2	1	2	0
DID	1	1	0	2	1	0	1	0

Two observations may be made. First, the modality performance was sensitive to the index chosen. For instance, in the back areas of Seat Three, three significant comparisons were indicated for the Pressure modality by the DAV index, but none by the DZA, AVG, and TID indices. Second, the area of discomfort may have been a factor in modality performance. The EV modality showed no significant comparisons in the backrest areas of Seat Three, while it showed comparisons on every index in the buttock areas of Seat Four. A similar phenomenon occurred with the OSGR modality. This body-area difference is thought to be due to variations in the type of discomfort experienced.

In general, if the index with the highest count for each modality (summed over the body areas tabulated for Seat Three and Seat Four) is taken as representative of the discriminatory ability of the modality, the Pressure modality would be highest ranked at four, the Heat modality next with three, followed by the EV and OSGR modalities with two each. Because of the small number of significant comparisons, this contrast between modalities can only be made with caution.

4.2.2 Comparison of Modality Performance on the Indices. Table 55 shows that each modality performed better on some indices than on others. This is indicative of differences in the characteristic response of the modalities. The Heat modality produced the most significant comparisons for the absolute indices AVG and TID. These two indices represent the absolute level of discomfort during the third hour of the test, and the number of absolute fractional-discomfort-minutes over the course of the test, respectively (see Section 3.2 for the index calculations). When the responses were corrected for the initial discomfort on the seat, as was the case with the differential indices, only one comparison was significant. An absolute index was apparently superior to a differential index for the Heat modality data.

The Pressure modality showed fairly consistent behavior over the five indices for the Seat Four buttock comparisons, but performed considerably better on the DAV index than the others for the Seat Three back area comparisons. It is most interesting that the DAV index produced three significant comparisons, yet the DZA index produced none. The DAV index subtracts the average of the first two evaluation intervals (0 and 30 minutes) from the average of the last three (120, 150, and 180 minutes). The DZA subtracts only the first evaluation interval discomfort level. This difference suggests that for the first evaluation interval, the Pressure modality responses were inconsistent, relative to those from the remainder of the driving simulation.

The OSGR modality data, which show no significant comparisons for Seat Four in the buttock area, indicate one Seat Three back area comparison in the DZA and DAV indices and two in the DID index. Note that all three of these indices are differential, that is, they represent the change in reported discomfort level over the course of the test. This suggests that the absolute response levels for the OSGR modality were not consistent indicators of discomfort, but that the change in reported level over the course of the simulation was more meaningful. The discovery of a substantial test-order effect for the modality helps to explain this characteristic. This behavior is opposite of that observed for the Heat modality, for which absolute indices provided better results than did differential indices.

The EV modality performed best on absolute indices or when only the first evaluation interval was used to obtain a differential. Both the DID and DAV indices also use the 30-minute evaluation interval data, and resulted in fewer significant comparison pairs for the modality.

4.2.3 Characteristic Shapes of the Modality Response Curves. Preliminary observation of test data indicated that the subject responses over the course of the test tended to follow different paths for the several modalities. The Heat and OSGR modalities were generally seen to increase gradually, with the rate of discomfort

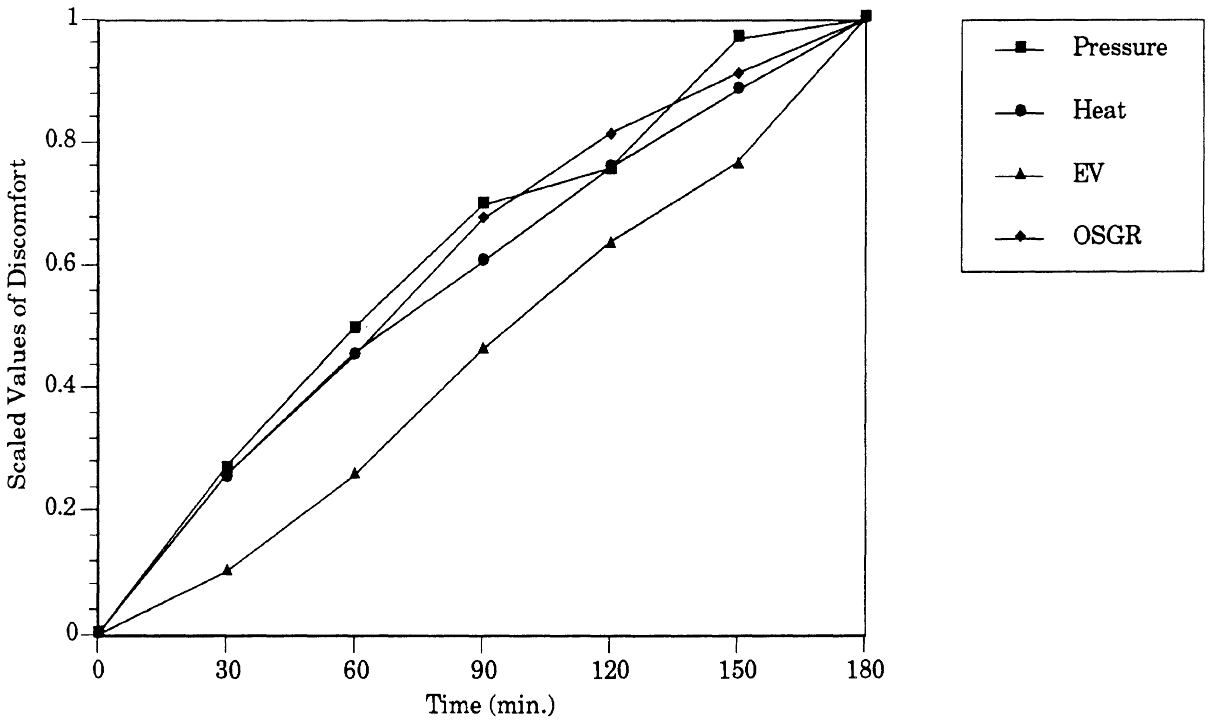


FIGURE 46. Adjusted average modality curve shapes.

increase declining as the test progressed. The EV modality responses would typically increase slowly until the last half of the test, when the responses would increase dramatically.

To investigate this effect, the scaled data from each test were standardized by expressing each value as a fraction of the maximum scaled response reported during the simulation. The data from all body areas and subjects were combined and the mean values of each modality at each evaluation interval were calculated and plotted. As the means for every modality were monotonically increasing, the data were adjusted to bring the means for the first and final evaluation intervals together. Paired t-tests between the modalities were then performed at each evaluation interval to ascertain the statistical significance of the observed difference in curve shape. Figure 46 shows the adjusted standardized modality curves.

The EV modality curve shape was most markedly different from the rest, with approximately constant slope over the course of the simulation. The discomfort responses for other three modalities increased more rapidly in the first hour of the simulation, with the rate of increase diminishing toward the end of the test. The t-tests showed that the EV modality was significantly lower ($P \leq 0.01$) for all evaluation intervals but the first and last (which were fixed to zero and one). The Pressure modality was higher than the Heat modality at 90 and 150 minutes, also with $P \leq 0.01$, and higher than the OSGR modality at 150 minutes with $P \leq 0.05$. The value approaching one for the Pressure modality curve at 150 minutes indicates that the responses for that modality tended to level off during the last hour of the simulation. The decline in the rate of increase in the Pressure modality at the 120-minute mark was not caused by outliers, but rather was a consistent observation, although the cause is unknown. The OSGR modality curve in Figure 46 follows a smooth path just above that of the Heat modality. The OSGR modality differed significantly from the Heat modality in this analysis only at the 90-minute evaluation interval.

Each of the modalities was calibrated to produce a linear scale of discomfort from the generally nonlinear subject sensitivity to the stimulus. Consequently, the difference in average response characteristics shown in Figure 46 suggests that the CMM responses do not represent an accurate measure of a single discomfort stimulus. The following were among possible explanations.

1. The modality calibration did not accurately represent the relationship between the discomfort and the reference stimuli, or became invalid over the course of the simulation.

2. The sensitivity of the modalities differs when they are matched to various types of discomfort (sharp pain, numbing, burning, etc.) and the nature of the complex discomfort stimuli changed over time. For example, the Heat modality might be more responsive in matches with "burning" discomfort sensations, and those sensations were more prevalent later in the simulation.

Because the calibrations performed at the beginning of each driving-simulation session were generally consistent over subsequent days, the second explanation above seems the more promising. The count data in Table 55 showed two modalities which indicated significant differences in one body area, but not in another. The descriptions of the discomfort experienced in those two areas suggests that the back discomfort in Seat Three was of a different type from the buttock discomfort in Seat Four (see Section 3.3 re open-ended questions in the Exit Questionnaire). These findings support the possibility that the modalities may be measuring different discomfort types, or that their sensitivity in matches with a discomfort stimulus is dependent to some extent on the composition of that stimulus.

4.2.4 Body-Area Distributions by Modality. Another technique used to examine differences in modality performance involved the body-area discomfort distribution information produced by each modality. At every evaluation interval, the subject reported the discomfort in his middle-back, lower-back, buttock, and thigh areas (in that order) using each of the modalities in turn. Consequently, for each evaluation interval and modality, an assessment can be made of the distribution of the subjects' discomfort.

A simple correlation procedure was developed to compare distributions between modalities. Data from the selected CMM indices were used. For each modality and body part, a single value was available for each test. The value for each body part was expressed as a fraction of the total for that test over all four body parts. For each modality, the four body-part percentage scores summed to one-hundred percent. The data from each modality were then plotted pair-wise with the data from each other modality. For instance, the DAV index value of the Pressure modality response (as a fraction of the sum of all body areas for that test) for the middle-back area of a subject was plotted against the TID index value of the Heat modality response for the middle-back area (as a fraction of the body-area sum). If the distributions were identical, the points would lie

TABLE 56

CORRELATION COEFFICIENTS FOR BODY-AREA DISCOMFORT DISTRIBUTIONS

Modalities	Pressure	Heat	EV
Heat	0.674	- -	- -
EV	0.743	0.700	- -
OSGR	0.716	0.690	0.703

TABLE 57

BODY AREA DISCOMFORT DISTRIBUTIONS:
RESULTS OF REGRESSIONS
(N = 128)

Regression	Slope	Std. Error	t-Value
P v. H	1.470	0.144	3.26
P v. EV	0.670	0.054	-6.23
P v. OSGR	0.908	0.079	-1.16
H v. EV	0.289	0.026	-27.10
H v. OSGR	0.400	0.037	-16.04
EV v. OSGR	0.988	0.089	-0.14

Note: t-values are for testing a null hypothesis of unit slope.

on a straight 45 degree line (y = x). Correlation/regression analyses were used to compare the modalities. Tables 56 and 57 show the correlation coefficients (Pearson's r) and regression results from the analyses.

The correlation/regression results for this analysis show significant differences between modalities in discomfort distribution. In Table 56, the correlation coefficients are a measure of the consistency of the distribution trend between the modalities compared, while the regression slopes are a measure of how close the modality distributions are to being alike.

By this analysis, the regression results show the Pressure and EV modalities to produce distributions not significantly different from that of the OSGR modality with $P \leq 0.05$. However, the Pressure and EV modalities are seen to differ somewhat. The Heat modality distributions are considerably different from those of the other modalities. The slope of the regression curves show that the body-area fractions for the Heat modality indicate little difference in situations where the EV modality fractions show some body areas much higher in discomfort than others. In other words, the Heat modality tends to show the discomfort with a more level distribution across body areas, whereas the other modalities show larger differences between high-discomfort and low-discomfort body areas.

A second, similar technique used the scaled data from each evaluation interval to calculate distributions. For each evaluation interval and modality (all tests) the scaled values were expressed as fractions of the total discomfort over all body areas indicated by that modality at that interval. These were then compared pair-wise, as they were with the index data. This analysis was more complicated, because of outliers from the early evaluation intervals of some tests. For example, if the discomfort in one body area was indicated to be 25% of full-scale discomfort, while the discomfort in the other body areas was reported to be nearly nonexistent, the fraction data for the high body area would become nearly 100%.

After the data from each modality were trimmed for outliers (greater than three standard deviations from the mean), the correlation/regression analyses were performed as they were above. The results are not presented here because they were substantially the same as those from the first set of distribution analyses.

4.2.5 Susceptibility to Test-Order Influence. The lengthy test periods needed for the evaluation of long-term seating comfort necessitate that the initiation of each testing session be sufficiently delayed from the end of the previous session that the subject may reasonably be expected to be in a "baseline" state at the start of each test. For this study, each subject was tested on each of the four test seats on subsequent days, starting at approximately noon each day. The potential for a test-order effect existed, in which the discomfort data could be influenced by the order in which the subjects were exposed to the seats. This potential could be alleviated by testing each subject on one seat only; however, that would necessitate the testing of larger numbers of subjects, because trends in the data would be confounded with inter-subject differences.

Testing each subject on the several seats to be compared is desirable. However, comparison among the seats using the resulting data is difficult if the subjects' response characteristics change from day to day, particularly if the change is systematic. The experimental design in this study included the potential for error from training effects associated with the CMM modalities. Analyses were therefore performed to evaluate the test-order bias present in the subjective discomfort evaluation data. Evidence of a test-order effect came from correlation analyses performed with overall CMM data (TID and DID indices summed over all four body areas) and test order. Table 58 shows the correlation coefficients for the overall measures and test order (scored 1 through 4, indicating that the seat was the subject's first, second, etc.). Calculations were performed using standardized index data. The results from non-standardized data were similar, although more susceptible to outlier effects.

TABLE 58

CORRELATION COEFFICIENTS OF OVERALL CMM MEASURES WITH TEST ORDER

Overall Measure	Correlation with Test Order
TID P	-0.048
TID H	-0.310
TID EV	-0.412
TID OSGR	-0.758
DID P	0.064
DID H	0.083
DID EV	-0.375
DID OSGR	-0.246

A negative correlation in Table 58 indicates that the overall measures declined on average for later tests. The TID index shows the OSGR modality in particular to exhibit a pronounced test-order effect. However, in the differential DID index, for which the discomfort levels reported in the first 30 minutes of the test were extrapolated for the duration of the test and subtracted from the total integrated discomfort, the OSGR modality exhibits less of an effect. This was taken to indicate that the absolute response levels for the modality were dependent on test order, while the increase in response level over the course of the test was largely not. These analyses assume that the test-order effect was a linear function, proportional to test order. Further investigation of the effect, using analysis of variance techniques, was not fruitful because of the small sample size and interaction between the test-order effect and other factors.

5.0 DISCUSSION AND CONCLUSIONS

This study was exploratory, but yielded valuable results, both with regard to measurement of discomfort and insight into seat design for comfort in extended-duration driving. The subjective evaluation techniques and the sonic posture tracking in particular produced important findings. Data from the other objective measures were more difficult to interpret, in part because of the small sample size.

5.1 PRELIMINARY QUESTIONNAIRE

The Preliminary Questionnaire was effective for discriminating among the test seats on feature evaluations and indicated relationships between feature evaluations and satisfaction with those features. The findings indicate that in most instances, subjects evaluated the seat features in a manner compatible with objective measurements of those features. For instance, the evaluations of cushion firmness were consistent with the data obtained in static force-deflection testing of the seats. For several features, however, the data show that the subjects' evaluations were not consistent for the feature. For certain features, subjects apparently evaluated the feature in relation to their overall perception of the seat, rather than with reference to the specific feature. The evaluation of backrest length, for instance, was related to the overall evaluation of the seat, with seats which were preferred overall rated as having longer backrests. However, no consistent evaluation of backrest lengths is evident among the subjects. This is reasonable, because the backrests of all of the test seats were sufficiently long to contact even the largest subject's entire back, leaving little on which a seated subject could base his evaluation. Consequently, it appears that when a feature was not easily evaluated by the subject, the responses were chosen based on the subject's overall perception of the seat instead of the feature.

A similar mechanism appeared to have been operating in the responses to the question on lumbar support. When a subject indicated that a seat had strong lumbar support, he tended to indicate high satisfaction with lumbar support. Yet, there was not consistent evaluation of the lumbar support feature, with the exception of Seat One, which was considered to have weaker support than the other seats. Even when the responses for Seat One are removed, a strong relationship persists between the feature evaluation and the satisfaction with the feature. This suggests that, like backrest length, lumbar support is a feature not easily evaluated by the subjects, and that their evaluations are based on considerations other than the feature.

The Preliminary Questionnaire also provided the opportunity for comparison of short-term and long-term evaluations of the seat by comparing the Preliminary Questionnaire responses with those from the discomfort evaluations during and after the three-hour driving simulation. These data indicate that the Preliminary Questionnaire was a poor predictor of long-term discomfort.

Section 3.4 details the comparisons between the findings from the CMM discomfort evaluations during the driving simulation to the findings from the Preliminary Questionnaire. The findings regarding the two areas of significantly greater discomfort during the simulation, the buttock area of Seat Four and the back areas of Seat Three, show that the evaluation of those areas which results from the Preliminary Questionnaire data is considerably different from the conclusions drawn from the CMM data. In the back areas, subjects preferred tighter back fit, stronger lumbar support, and more arched spine posture, and rated Seat Three higher on those features than the other seats. However, the CMM data show that Seat Three was significantly more uncomfortable than at least one other seat in the back areas by the second hour of the simulation, and more uncomfortable than all other seats in the third hour of the simulation. Clearly, the short-term evaluation of Seat Three was inconsistent with its long-term comfort performance.

Also, for Seat Four, the Preliminary Questionnaire failed to predict the discomfort experienced in the buttock area during the driving simulations. The short-term data showed preferences for firmer cushion padding, stiffer cushions and smaller cushions, parameters for which the evaluations of Seat Four were significantly higher than the evaluations of the other seats. Yet, Seat Four became significantly more uncomfortable than the other seats in the buttock area about halfway through the simulation. Again, the short-term evaluation did not demonstrate the inter-seat differences in comfort performance which appeared during the course of the driving simulation.

5.2 CROSS-MODALITY MATCHING

Three external stimuli (heat, pressure, and cutaneous electro-vibration) were used as references for discomfort evaluation. The findings from those CMM techniques were compared to the findings obtained from a traditional open-scale questionnaire. Although the external modalities demonstrate high correlations with the data from the open-scale graphic response (OSGR) modality, additional resolution among the test seats is provided by the external modalities. Findings regarding one of the areas of discomfort which are significant in the external modality data are not significant in the data from the OSGR modality, and the relationship between the external-modality response levels may be indicative of the type of discomfort evaluated.

The external CMM modalities (hereafter referred to as CMM) were calibrated prior to each driving simulation by a magnitude-production technique which allowed later discomfort measurements to be scaled according to the subject's internal reference scale of discomfort. The discomfort measurements from the driving simulations were scaled using these calibration data to a nominally uniform scale of discomfort. This allowed direct comparison between the discomfort levels reported on each modality. In spite of this calibration procedure, the response levels for the Heat modality, as measured in fraction of full-scale discomfort, were consistently higher than the levels of the Pressure and EV modalities. This may indicate that the calibration procedure for the Heat modality did not produce a discomfort scale equivalent to those generated for the other modalities. However, the results of the principal component analysis suggest that another explanation is found in the relative levels of the various sensations which make up the discomfort sensation.

The principal component analysis of the CMM data shows that the two areas on the test seats identified as producing greater discomfort were characterized by different relative levels of response on the external modalities. The discomfort responses in the back areas of Seat Three were high in the data from the Heat modality, relative to the data from the Pressure and EV modalities. In contrast, the discomfort responses for the buttock area of Seat Four show more even levels of Heat and EV response. These findings suggest that the relative levels of modality response are related to the type of discomfort evaluated.

Inter-seat comparisons of overall discomfort performance for the driving simulations were made using indexed values for the modalities which expressed the discomfort experienced during the simulation as a single value. The index which produced the best inter-seat differentiation for each modality was selected for that modality. This process revealed characteristics of the data from each modality.

The Total Integrated Discomfort (TID) index was selected for the Heat modality. This index represents the area under a curve of fractional discomfort level versus time. During data analysis, it was found that the inter-seat differentiation that was significant with the TID index was no longer present when the data were transformed by a differential index, which expresses the change in discomfort level over the course of the simulation, rather than the absolute reported level. For instance, the Differential Integrated Discomfort (DID) index, which is useful with the OSGR modality data, produces virtually no significant inter-seat comparisons when used with the Heat modality data.

However, for the Pressure and EV modalities, inter-seat differentiation is improved by subtracting the average of the scaled responses for the first two evaluation intervals from the AVG index. The AVG index represents the average scaled responses for the last three evaluation intervals (at 120, 150, and 180 minutes into the simulation). The resulting index, DAV (differential average), produces better inter-seat differentiation than does the AVG index for the Pressure and EV modalities.

For the OSGR modality, the open-scale discomfort-evaluation questions, a differential index also aided inter-seat discrimination. The Differential Integrated Discomfort (DID) index subtracts the integrated discomfort due to discomfort reported during the first thirty minutes of the simulation from the total integrated discomfort for the simulation. With the data for All Subjects, the OSGR modality produced two inter-seat comparisons significant with $P \leq 0.05$ using the DID index (Seat Three was more uncomfortable than Seats Two and Four in the lower-back area), while with the TID index no comparisons were significant with $P \leq 0.05$ for any body area.

The results of this study indicate that these CMM techniques, utilizing external reference stimuli under the control of the subject, offer increased resolution over a conventional questionnaire, and, when used in combination, offer the potential for evaluating the composition of a complex discomfort stimulus. However, this increased performance is not without costs. Most notable are the need to train the subjects on the equipment and the calibration which is necessary prior to each driving simulation session. The calibration protocol for this testing required approximately forty minutes for three modalities. Additionally, each subject was given about an hour of instruction and practice with the CMM equipment during the preliminary session prior to the first driving simulation. The questionnaire which comprised the OSGR modality required virtually no instruction, because the subjects were familiar with the response format, and no calibration was required.

Additionally, the external modalities required a considerable amount of concentration and mental effort on the part of the subjects. The subjects in this study were paid for their participation and, consequently, their attention was easily commanded. However, in larger-scale testing where substantial compensation would be impractical, or in situations in which the subject's attention would be less easily focused, the techniques might be more difficult to apply. The amount of time required for each subject to master the CMM procedures varied considerably, suggesting that the technique might be more easily applied with some subjects than others. Presumably, this increases the opportunity for errors due to improper implementation of the techniques.

5.3 SITTING POSTURE OF THE SUBJECTS DURING THE DRIVING SIMULATION

The GP8-3D sonic digitizing system was used to track the location of eight body landmarks during the driving simulation. Analysis of these data provided a means to quantify the differences in subject posture between the seats.

In general, subjects sat higher and more upright in the luxury seats (One and Three) and lower in the sport seats (Two and Four), with their chests more reclined and higher angles between the right thigh and the horizontal in the sport seats. Pelvic rotation was the least in Seat Three, while Seat One produced the highest values on the variables measuring slouching.

Estimation of mean changes in variable values over time shows that the pelvic rotation for Seat One and Seat Four increased during the simulation, as did the chest angle for Seat Two. On Seats Two and Four (the sport seats), the distance between the thorax and pelvis as a percentage of the distance in the standing position increased over the course of the simulation. Also, subjects are estimated to have slid forward an average of slightly over one centimeter.

An important finding was that, on average, chest angles indicated rearward rotation of the pelvis from the standing posture considerably greater than the rearward rotation of the chest. If the thorax and pelvis are viewed as two rigid masses connected by a flexible linkage (the lumbar spine), the relative positioning of the thorax and pelvis are primary determinants of lumbar spine curvature.

The body-landmark data for the chest and pelvis of each subject were used to estimate the subject's lumbar curvature in the seated posture. Based on the relative positions of the thorax and pelvis, the lumbar curvature was in all instances estimated to be neutral or kyphotic. This observation was useful in regard to the lower-back discomfort experienced by the subjects on Seat Three.

Seat Three has a firm, prominent lumbar support, designed for a lumbar spine curvature similar to the lordotic curvature typical of a standing posture. The postures assumed by the subjects in this study included a neutral or kyphotic lumbar curvature. In these postures, the firm lumbar support in Seat Three protrudes against the upper portion of the lower back, creating an area of higher pressure. These elevated pressures were recorded using the surface-mounted FSR sensors. The observed lumbar-spine curvatures also resulted in a gap between the lower back and the backrest at the bottom of the backrest. Several of the lowest lumbar spine vertebrae were not directly supported in this posture, possibly contributing to the lower-back discomfort experienced on Seat Three.

5.4 ELECTROMYOGRAPHY

The results of the EMG analysis were not sufficiently conclusive to allow the exploration of relationships between the EMG findings and the subjective discomfort evaluations. However, several findings were of interest, although their connection to the discomfort reported was not directly apparent.

The mean level of the rectified signal increased significantly over time in the data for Seat Two from the abdominal muscles. This indicates an increase in the mean level of muscle activity. Because of the more reclined chest angles measured in Seat Two (see Section 3.5), it was hypothesized that voluntary subject motions such as posture shifts required a greater level of abdominal muscle involvement in Seat Two than was the case in other seats for which the subjects' postures were more upright. The increase in activity over the course of the test could be due to the increasing chest inclination on Seat Two during the simulation or to an increase in the frequency or magnitude of voluntary movements.

The CMM discomfort evaluations indicate that the subjects found Seat Two to be more comfortable than at least one other seat, except in the thigh area. For the Non-Sport subject group, Seat Two was more uncomfortable in the thigh area than were other seats. A possible connection is suggested between these findings and the EMG results in that greater thigh discomfort might be associated with more frequent lifting of the legs to relieve pressure or to shift position, which would cause contraction of the abdominal muscles. Other data do not specifically support or contradict this possibility.

The analysis of data from the lumbar area shows a greater number of data points at relatively high signal levels for Seats Two and Four than for Seats One and Three. These findings imply that the sport seats (Two and Four) induced more frequent large-scale posture changes than did the two luxury seats (One and Three). This evidence is not clearly related to the findings from the discomfort evaluations.

A primary difficulty encountered with the EMG methodology was the confounding effect of voluntary muscle activity. Initially, interest centered on the low-level activity necessary to maintain the chosen posture. Changes in the characteristics of the EMG signal generated by that postural muscle activity could be interpreted as evidence of fatigue. However, the salient trends in the data from the driving simulations are largely due to posture changes and motions made in the operation of the simulator, such as steering.

Because of the low sample rate used in this study, frequency analysis of the data was not appropriate. Some studies have indicated that changes in the frequency of EMG signals may be related to fatigue. Frequency analysis might be conducted without interference from changes in the amplitude of the signal caused by voluntary subject motions.

5.5 SEAT SURFACE PRESSURE SENSOR DATA

Analysis of the data from the FSR pressure sensors mounted on the seat surfaces produced three types of results. The mean pressure levels at the sensor locations differed between seats. Also, the variances of the sensor pressures indicated differences in subject movement between the seats. Finally, changes in the distribution of pressure over the course of the test indicated trends in subject movement during the simulation for some seats.

The mean pressure levels reflect the fact that only on Seat One were the lowest sensors on the backrest and the rearmost sensors on the cushion contacted consistently. These data are supported by observations made of the subjects during the simulation. Because of the postures frequently chosen by the subjects, there was often little contact between the seat and the subject's body at the back of the cushion and bottom of the backrest. This is reflected in the estimated body position in Section 3.5.

In the data from the cushion sensors, the variances of the pressures at the sensor locations show greater movement for Seat Four than for the other seats. In the data from the backrest sensors, the variances are higher for both Seats Three and Four than for Seats One and Two. In conjunction with the findings from the CMM data, these results indicate that the sensor standard deviations are highest for the two seats in which the subjects reported significantly greater discomfort. This could be interpreted to indicate that the subjects moved more frequently when they were uncomfortable, which is consistent with a pre-test hypothesis. However, the data are insufficiently broad to estimate the strength of the relationship.

A sensor center of pressure was calculated as a measure of subject positioning on the seat (see Section 3.7). This analysis indicated that some subjects moved forward or rearward on the seat cushion during the course of the simulation. The data showed no overall longitudinal movement in Seat One, but in Seat Two and Seat Three, some subjects slid significantly forward. Because the SCP does not correspond to a physical location, these data were not used to estimate the magnitude of the movement. However, the posture tracking data suggest that those subjects who slid forward moved up to five centimeters. The SCP analysis indicated that two subjects accounted for three-quarters of the instances in which the data indicate that subjects moved forward, and so it was concluded that the phenomenon was related to subject propensity as well as possibly to seat design.

5.6 SEAT INDENTATION AND SUBJECT SPINE/STERNUM CONTOURS

The indentation contours provide useful visualization of the seat-subject interface. In particular, they demonstrate the manner in which the supportive loads were distributed on the cushion and backrest and allow valuable inference regarding the discomfort findings.

The average indentation contour from the cushion of Seat Four shows a more localized area of indentation than was measured for the cushions of the other seats. Estimates of loading derived from static force-deflection testing indicate that the resulting pressures were higher than for the other seats. It is reasonable to assume that this increased pressure could account in whole, or in part, for the increased discomfort reported in the buttock area on Seat Four.

For Seat Three, the average indentation contour for the backrest shows a smaller area of deflection than for the other seats. As was the case with the buttock area of Seat Four, the data indicate that this smaller area of deflection is associated with higher pressures in that area than is the case with the other seats. This could help to account for the increased discomfort in the back areas of Seat Three.

Some additional characteristics of the indentation contours are of note. The mean deflection contour for the cushion of Seat Two shows some areas of high deflection to the sides of the cushion. This pattern is due to deflection in those areas from the larger subjects. The discomfort data for those subjects, who largely comprise the Non-Sport group, show greater discomfort in the thigh area for Seat Two than for the other seats. The indentation contour shows deflection, and consequently pressure, caused by constriction by the lateral supports at the side of the cushion.

The spine and sternum contours, when oriented to correspond to the locations of key emitter targets during the driving simulation, provided insight as to the probable positioning of the subject's spine. One spine profile was aligned to the mean location of the chest emitters during the simulation, while the other was oriented relative to the pelvis location. The resulting arrangement confirms an observation that had been made during the testing, that the subjects' lumbar spines almost always exhibited kyphotic curvature during the simulations. Also, the reoriented spine profiles show that some curvature of the thoracic spine above T10 is indicated by the positioning of the subjects' chests and the indentation contours.

5.7 DIRECTIONS FOR FURTHER RESEARCH

Several of these findings point directly to further efforts which would be valuable to advance the research already performed. In particular, the subjective evaluation techniques, including CMM, and the influence of backrest configuration on preferred posture are promising areas for future research.

CMM has demonstrated the capability to produce subjective evaluations compatible with those produced by conventional means with resolution superior to that obtained with standard questionnaires. Further research might be directed to:

1. reduce the time required for calibration and training through additional study to characterize the modalities,

2. explore other modality response stimuli which might produce additional information in seating discomfort evaluation,

3. cross-modality matching to combinations of known stimuli (*i.e.*, heat, pressure, shear) to quantify the relationship between the nature of the stimulus and the relative responses of the modalities,

4. verify the effectiveness of the technique for assessing seating comfort with a larger number of subjects, and

5. implement the technique for the evaluation of specific design features in extended-duration driving situations.

The posture data generated from these long-term driving simulations indicate that the posture assumed by the subject after as little as thirty minutes in the seat is significantly different from that adopted in a short-term, "showroom" situation. Most notably, a subject tends to slide his hips forward, easing tension on his hamstrings and allowing his pelvis to rotate backward. A prominent lumbar support creates a large gap behind the subject's lower spine where there is no contact with the seat, and hence no support. A firm, prominent lumbar support also can act to localize the backrest support forces, creating an area of unacceptably high pressures.

The data from this study also indicate that subjects position their chests more upright than the postures for which the seats are designed. This poses an additional problem for the design of low-back supports, because in a more upright position, the weight of the thorax against the backrest is insufficient to adapt the spine curvature to the contour of the seat. Rather, as was the case with Seat Three in this study, the spine assumes a kyphotic curvature, producing higher, localized contact pressures and higher lumbar muscle strain.

A research protocol investigating the influence of pelvic restriction on thigh angles and preferred recline angles could be informative regarding the optimal configuration of a backrest, including the contour, firmness, and angle.

REFERENCES

Akerblom, B. (1948) Standing and sitting posture. Unpublished thesis. Stockholm, Nordiska Bokhandeln.

Andersson, G.B.J. (1980) The load on the lumbar spine in sitting postures. In *Human Factors in Transport Research. Volume 2—User Factors: Comfort, the Environment and Behavior*, pp. 231-239. Edited by D.J. Oborne and J.A. Levis. New York, Academic Press.

Andersson, G.B.J; Ortengren, R.; Nachemson, A.; and Elfstrom, G. (1974) Lumbar disc pressure and myoelectric back muscle activity IV. Studies on a car driver's seat. *Scandinavian Journal of Rehabilitation Medicine*, 6:3, pp. 128-133.

Andersson, G.B.J.; Murphy, R.W.; Ortengren, R.; and Nachemson, A.L. (1979) The influence of backrest inclination and lumbar support on lumbar lordosis. *Spine*, 4:1, pp. 52-58.

Arrowsmith, M.J. (1986) The design and development of the XJ40 seating system. *Proc. Institute Mechanical Engineers*, 200:D5, pp. S79-S85.

Babbs, F.W. (1979) A design layout method for relating seating to the occupant and vehicle. *Ergonomics*, 22:2, pp. 227-234.

Bader, D.L.; Barnhill, R.L.; and Ryan, T.J. (1986) Effect of externally applied skin surface forces on tissue vasculature. *Archives of Physical Medicine and Rehabilitation*, 67:11, pp. 807-811.

Bennett, E.M. (1963) Study 3: The feeling of comfort. In *Human Factors in Technology*, pp. 543-552. McGraw-Hill.

Bohlin, N.; Hallen, A.; Runberger, S.; and Asberg, A. (1978) *Safety and comfort: Factors in Volvo occupant compartment packaging.* SAE paper no. 780135.

Branton, P. (1969) Behavior, body mechanics, and discomfort. *Ergonomics*, 12:316-327.

Branton, P. (1984) Backshapes of seated persons: How close can the interface be designed? *Applied Ergonomics*, 15:2, pp. 105-107.

Bridger, R.; Winkinson, D.; and van Houweninge, T. (1989) Hip joint mobility and spinal angles in standing and in different sitting postures. *Human Factors*, 31:2, pp. 229-241.

Brigham, F.R. (1975) Some quantitative considerations in questionnaire design and analysis. *Applied Ergonomics*, 6:2, pp. 90-96.

Chaffin, D.B.; and Andersson, G. (1984) Chapter 9: Guidelines for seated work. In *Occupational Biomechanics*, pp. 289-323. John Wiley and Sons, New York.

Chow, W.W.; and Odell, E.I. (1978) Deformation and stresses in soft body tissues of a sitting person. *Journal of Biomechanical Engineering*, 100:79-87.

Corlett, E.N. (1989) Aspect of the evaluation of industrial seating: The ergonomics society lecture. *Ergonomics*, 32:257-269.

Corlett, E.N.; and Bishop, R.P. (1976) A technique for assessing postural discomfort. *Ergonomics*, 19:175-182.

Corlett, E.N.; and Eklund, J.A.E. (1984) How does a backrest work? *Applied Ergonomics*, 15:2, pp. 111-114.

Dempster, W.T. (1955) *Space requirements of the seated operator. Geometrical, kinematic, and mechanical aspects of the body with special reference to the limbs.* WADC technical report 55-159. Wright Air Development Center, Ohio.

Diebschlag, W.; and Mueller-Limmroth, W. (1980) Physiological requirements on car seats: Some results of experimental studies. In *Human Factors in Transport Research. Volume 2–User Factors: Comfort, the Environment and Behaviour*, pp. 223-230. Edited by D.J. Oborne and J.A. Levis. New York, Academic Press.

Diebschlag, W.; Heidinger, F.; Kuurz, B.; and Heiberger, R. (1988) *Recommendation for ergonomic and climatic physiological vehicle seat design.* SAE paper no. 880055. (Also in German, Der autositz aus physiologischer und biomechanischer sicht. Automobiltechnische Zeitschrift, 90:545-548.)

Drummond, D.S.; Narechania, R.G.; Rosenthal, A.N.; Breed, A.L.; Lange, T.A.; and Drummond, D.K. (1982) A study of pressure distributions measured during balanced and unbalanced sitting. *Journal of Bone and Joint Surgery*, 64:7, pp. 1034-1039.

Drury, C.G.; and Coury, B.G. (1982) A methodology for chair evaluation. *Applied Ergonomics,* 13:3, pp. 195-202.

Drury, C.G.; and Searle, J.A. (1965) *A study of the seating and control positions in commercial vehicle cabs.* Report no. 1965-17. Motor Industry Research Association, Warwickshire, England.

Ferguson-Pell, M.; Barbenel, J.C.; and Evans, J.H. (1980) The pressure distributing properties of hospital mattresses and their cover. *Proc. of International Conference on Rehabilitation Engineering*, pp. 178-182.

Foley, D.E.; and Allemang, R.J. (1988) Vibration considerations concerning vehicular seating systems. *Experimental Techniques*, 12:7, pp. 19-21.

Garber, S.L.; Krouskop, T.A.; and Carter, R.E. (1978) A system for clinically evaluating wheelchair pressure-relief cushions. *American Journal of Occupational Therapy*, 32:9, pp. 565-570.

Geoffrey, S.P. (1961) *A 2-D manikin: The inside story.* SAE paper no. 267A.

Glassford, E.J. (1977) *The relationship of hemodynamics to seating comfort.* SAE paper no. 77024.

Gleser, G.; and Trotter, M. (1958) A re-evaluation of estimation of stature based on measurements of stature taken during life and of long bones after death. *American Journal of Physical Anthropometry*, 16:1, pp. 79-124.

Grandjean, E.; Boni, A.; and Kretzschmar, H. (1969) The development of a rest chair profile for healthy and notalgic people. In *Sitting Posture*, pp. 193-201. Edited by E. Grandjean. London, Taylor and Francis.

Grandjean, E. (1980) *Fitting the task to the man.* International Publications Service, 1980.

Grandjean, E. (1980) Sitting posture of car drivers from the point of view of ergonomics. In *Human Factors in Transportation Research, Vol. 2,* pp. 205-213. Edited by D.J. Oborne and J.A. Levis. New York, Academic Press.

Grandjean, E.; Hunting, W.; Wotzka, G.; and Scharer, R. (1973) An ergonomic investigation of multipurpose chairs. *Human Factors,* 15:3, 247-255.

Griffin, M.J. (1978) The evaluation of vehicle vibration and seats. *Applied Ergonomics,* 9:1, pp. 15-21.

Grigg, A.O. (1978) *A review of techniques for scaling subjective judgments.* Transport and Road Research Laboratory Supplemental Report 379. Crowthorne, Berkshire, England.

Habsburg, S.; and Middendorf, L. (1977) *What really connects in seating comfort? Studies of correlates of static seat comfort.* SAE paper no. 770247.

Harder, A. (1972) *Airdraulic seat system.* SAE paper no. 720915.

Hawkins, F. (1974) Ergonomic aspects of crew seats in transport aircraft. *Aerospace Medicine,* 45:2, pp. 196-203.

Hertzberg, H.T.E. (1958) *Annotated bibliography of applied physical anthropology in human engineering.* WDAC Technical Report 56-30. Aeromedical Laboratory, Wright-Patterson Air Force Base, Ohio.

Hertzberg, H.T.E. (1972) *The human buttocks in sitting: Pressures, patterns, and palliatives.* SAE paper no. 720005.

Hosea, T.M.; Simon, S.R.; Delatizky, J.; Wong, M.A.; Hsieh, C.-C. (1986) Myoelectric analysis of the paraspinal musculature in relation to automobile driving. *Spine,* 11:9, pp. 928-936.

Hubbard, R.P.; and Reynolds, H.M. (1984) *Anatomical geometry and seating.* SAE paper no. 840506.

International Organization for Standardization (1974) *Guide for the evaluation of human exposure to whole-body vibration, 1st ed.* Report no. ISO 2631-1974(3). Geneva, Switzerland.

Iwasaki, S.; Matsuoka, Y.; and Yamanoi, T. (1988) Objective evaluation of seating comfort. *Automotive Technology,* 42:11, pp. 1403-1408.

Kadaba, M.P.; Ferguson-Pell, M.W.; Palmieri, V.R.; and Cochran, G.V.B. (1984) Ultrasound mapping of the buttock-cushion interface contour. *Archives of Physical Medicine and Rehabilitation,* 65:476-469.

Kamijo, K.; Tsujimura, H.; Obara, H.; and Katsumata, M. (1982) *Evaluation of seating comfort.* SAE paper no. 820761.

Keegan, J.J. (1964) *The medical problem of lumbar spine flattening in automobile seats.* SAE paper no. 838A.

Kelsey, J.L.; and Hardy, R.J. (1975) Driving of motor vehicles as a risk factor for acute herniated lumbar intervertebral disc. *American J. Epidemiology*, 102:63-73.

Kohara, J.; and Sugi, T. (1972) *Development of biomechanical manikins for measuring seat comfort.* SAE paper no. 720006.

Kozawa, Y.; Sugimoto, G.; and Suzuki, Y. (1986) *A new ride comfort meter.* SAE paper no. 860430.

Kozlowski, E. (1988) Comfort and convenience in automotive seating. *Body Engineering Journal*, 16:2, pp. 62-64.

Le, Khanh M.; Madsen, B.L.; Barth, P.W.; Ksander, G.A.; Angell, J.B.; and Vistnes, L.M. (1984) An in-depth look at pressure sores using monolithic silicon pressure sensors. *Plastic and Reconstructive Surgery*, 79:6, pp. 745-756.

Lloyd, N.M. (1960) Comfort criteria for seat design. *Automotive Industries*, pp. 44-48.

Lueder, R.K. (1983) Seat comfort: A review of the construct in the office environment. *Human Factors,* 32:701-711.

Maertens, D.E. (1985) *Automotive seating comfort criteria, 2nd ed.* G.M. Technical Center.

Matsuoka, Y.; and Hanai, T. (1988) *Study of comfortable sitting posture.* SAE paper no. 880054.

Montgomery, L.D.; and Glassford, E.J. (1978) *A pulsating cushion that improves lower body hemodynamics of seated individuals.* SAE paper no. 780421.

Nachemson, A.; and Morris, J.M. (1964) In vivo measurements of intradiscal pressure. *Journal of Bone and Joint Surgery,* 45A:5:1077.

Newstead, S.E.; Pollard, P.; and Riezebos, D. (1987) The effect of set size on the interpretation of quantifiers used in rating scales. *Applied Ergonomics,* 18:3, pp. 178-182.

Nyquist, G.W.; and Murton, C.J. (1975) *Static bending response of. the human lower torso.* SAE paper no. 751158.

Nyquist, G.W.; and Patrick, L.W. (1976) *Lumbar and pelvic orientations of vehicle seated volunteer.* SAE paper no. 760821.

Oborne, D.J. (1978) Vibration and passenger comfort: Can data from subjects be used to predict passenger comfort? *Applied Ergonomics*, 9:3, pp. 155-162.

Oborne, D.J.; and Clarke, M.J. (1975) Questionnaire surveys of passenger comfort. *Applied Ergonomics*, 6:2, pp. 97-103.

Oliver, R.J. (1970) *A study of the comfort characteristics of production car seats.* MIRA Report No. 1970/12.

Parsons, K.C.; and Griffin, M.J. (1980) Predicting the vibration discomfort of seated passengers. In *Human Human Factors in Transport Research. Volume 2–*

Factors: Comfort, the Environment and Behaviour, pp. 114-122. Edited by D.J. Oborne and J.A. Levis. New York, Academic Press.

Parsons, K.C.; and Griffin, M.J. (1983) *Methods for predicting passenger vibration discomfort*. SAE paper no. 831029.

Patterson, R.P.; and Fisher, S.V. (1980) Pressure and temperature patterns under the ischial tuberosities. *Bulletin of Prosthetics Research*, 17:2, pp. 5-11.

Pepermans, R.G.; and Corlett, E.N. (1983) Cross-modality matching as a subjective assessment technique. *Applied Ergonomics*, 14:3, pp. 169-176.

Pheasant, S. (1986) *Bodyspace: Anthropometry, ergonomics and design*. Taylor and Francis, Ltd., London, England.

Porter, J.M.; and Sharp, J.C. (1984) The influence of age, sex, and musculo-skeletal health upon the subjective evaluation of vehicle seating. *Contemporary Ergonomics*, pp. 148-154.

Pottier, M.; Dubreuil, A.; and Monod, H. (1969) The effects of sitting posture on the volume of the foot. *Ergonomics*, 12:5, pp. 753-758.

Poulton, E.C. (1982) Biases in quantitative judgements. *Applied Ergonomics*, 13:1, pp. 31-42.

Preuschen, G.; and Dupuis, H. (1969) Korperhaltung und sitzgestaltung des kraftfahrzeugfuhrers [The carriage and posture of motor vehicle drivers]. In *Sitting Posture*, pp. 120-131. Edited by E. Grandjean. London, Taylor and Francis Ltd.

Rebiffe, R. (1966) *An ergonomic study of the arrangement of the driving position in motor cars.*

Rebiffe, R. (1980) General reflections on the postural comfort of the driver and passengers: Consequences on seat design. In *Human Factors in Transport Research. Volume 2–User Factors: Comfort, the Environment and Behaviour*, pp. 240-248. Edited by D.J. Oborne and J.A. Levis. New York, Academic Press.

Reddy, N.P.; Patel, H.; and Cochran, G. Van B. (1982) Model experiments to study the stress distribution in a seated buttock. *Journal of Biomechanics*, 15:7, pp. 493-504.

Reswick, J.B. (1961) *Devices for measuring contact pressures exerted on the human body*. Progress Report RD-768. Case Institute of Technology.

Robbins, D.H.; Schneider, L.W.; Snyder, R.G.; Pflug, M.; Haffner, M. (1983) Seated posture of vehicle occupants. In *Proc. 27th Stapp Car Crash Conference*, pp. 199-244. Society of Automotive Engineers, Warrendale, Pa.

Rosegger, R.; and Rosegger, S. (1960) Health effects of tractor driving. *Journal of Agricultural Engineering Research*, 5:241-274.

Schneider, L.W.; and Ricci, L. (1989) *Survey of driver seating discomfort and related factors*. Report no. UMTRI-89-23. University of Michigan Transportation Research Institute, Ann Arbor.

Schneider, L.W.; Anderson, C.K.; and Olson, P.L. (1979) *Driver anthropometry and vehicle design characteristics related to seat positions selected under driving and non-driving conditions.* SAE paper no. 790384.

Schneider, L.W.; Robbins, D.H.; Pflug, M.A.; and Snyder, R.G. (1983) *Development of anthropometrically based design specifications for an advanced adult anthropomorphic dummy family: Volume 1.* Final report no. UMTRI-83-53-1. University of Michigan Transportation Research Institute, Ann Arbor.

Shackel, B.; Chidsey, K.D.; and Shipley, P. (1969) The assessment of chair comfort. *Ergonomics*, 12:2, pp. 269-306.

Stokes, I.A.F.; and Abery, J.M. (1980) Influence of the hamstring muscles on lumbar spine curvature in sitting. *Spine*, 5:6, pp. 525–528.

Thier, R.H. (1963) Measurement of seat comfort. *Automobile Engineer*, 53:2, pp. 64-66.

Treaster, D.; and Marras, W.S. (1987) Measurement of seat pressure distributions. *Human Factors* 29:5, pp. 563-575.

Treaster, D.E.; and Marras, W.S. (1989) *Seat pressure: Measurement and analysis.* SAE paper no. 890849.

Troup, J.D.G. (1978) Driver's back pain and its presentation: A review of the postural, vibratory and muscular factors, together with the problem of transmitted road-shock. *Applied Ergonomics*, 9:4, pp. 207-214.

Varterasian, J.H.; and Thompson, R.R. (1977) *The dynamic characteristics of automobile seats with human occupants.* SAE paper no. 770249.

Verriest, J.P. (1986) Driving posture and comfort drivers of road vehicles, (passenger cars, commercial vehicles, and heavy lorries). *Recherche Transports Securite, Special Issue*, pp. 38-44. Institut National de Recherche sur les Transports et leur Securite, France.

Wachsler, R.A.; and Learner, D.B. (1960) An analysis of some factors influencing seat comfort. *Ergonomics*, 3:315-320.

Weichenrieder, A.; and Haldenwagner, H. (1985) *The best function for the seat of a passenger car.* SAE paper no. 850484.

Winkel, J. (1981) Swelling of the lower leg in sedentary work–A pilot study. *Journal of Human Ergology*, 10:139-149.

Winkel, J. (1986) Evaluation of foot swelling and lower-limb temperatures in relation to leg activity during long-term seated office work. *Ergonomics*, 29:2, 313-328.

APPENDICES

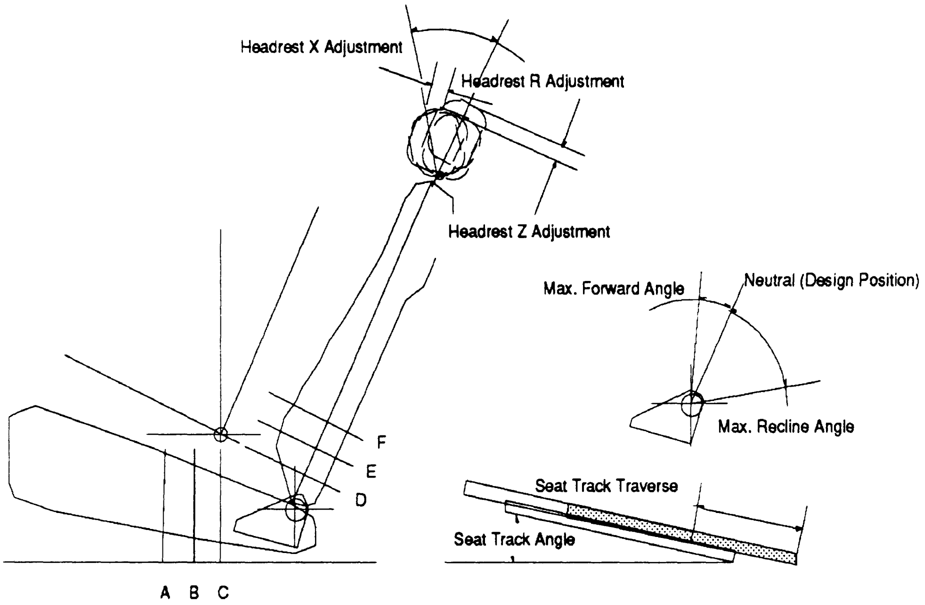
APPENDIX A

TEST SEAT DESIGN PARAMETERS

TEST SEAT DESIGN PARAMETERS

Seat Adjustments

(All dimensions in milllimeters unless otherwise noted.)



Parameter	Seat One	Seat Two	Seat Three	Seat Four
Headrest				
X Adjust	--	43	†	--
Y Adjust	55	50	80	--
R Adjust	--	26	55	--
Seat Track				
Traverse	168	165	264	228
Angle (deg.)	7	9	8	10
Recliner				
Max. Recline (deg.)	51	55	55	56
Max. Forward (deg.)	--	--	16	4
Recline Pitch (deg.)	Infinite	2	2	2

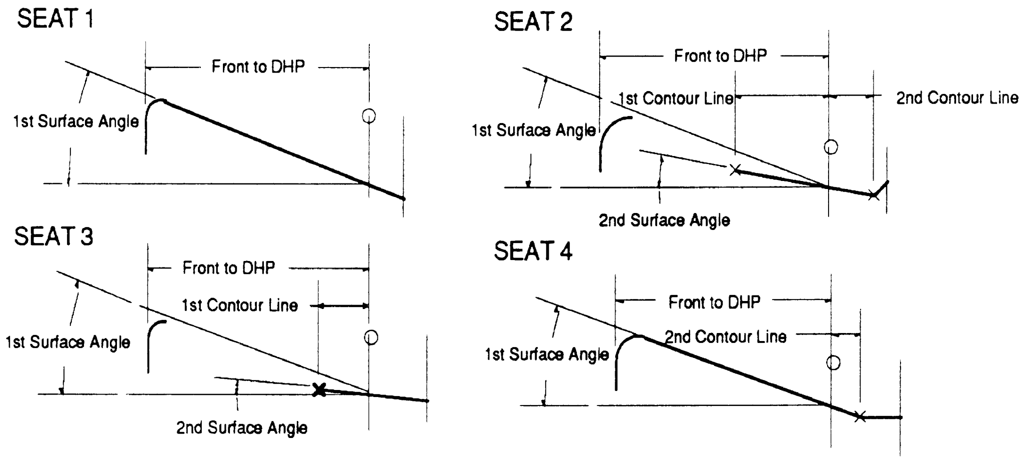
-- N/A

† Rotational headrest adjustment results in a net X Adjust of 64 mm for Seat Three.

TEST SEAT DESIGN PARAMETERS - *(continued)*

Cushion Centerline Dimensions

(All dimensions in milllimeters unless otherwise noted.)

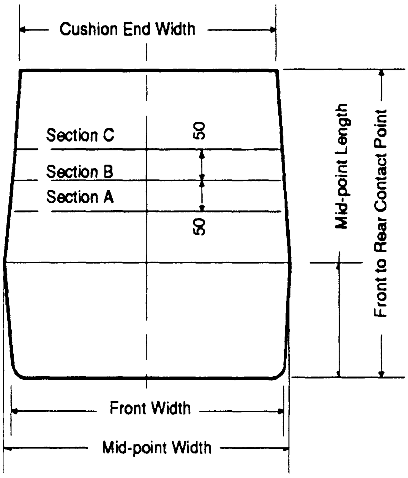


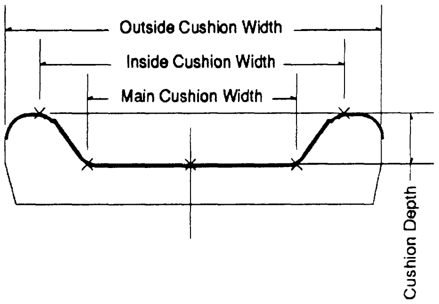
Parameter	Seat One	Seat Two	Seat Three	Seat Four
Cushion Centerline				
1st Surface Angle (deg.)	21	20	20	19
2nd Surface Angle (deg.)	- -	10	6	- -
Front to DHP	387	394	397	385
1st Contour Line	- -	170	100	- -
2nd Contour Line	- -	71	- -	50

TEST SEAT DESIGN PARAMETERS - *(continued)*

Cushion Dimensions

(All dimensions in milllimeters unless otherwise noted.)



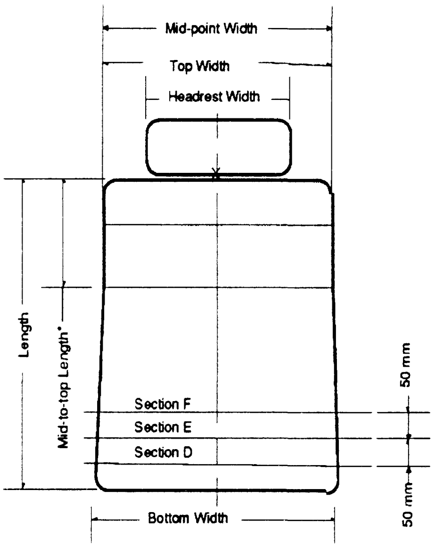


Parameter	Seat One	Seat Two	Seat Three	Seat Four
Cushion				
Front Width	495	486	546	406
Mid-point Width	552	445	508	505
End Width	552	432	457	413
Front to Rear Contact	457	508	502	495
Mid-point Length	191	254	305	305
Outside Width				
Section A	546	451	508	495
Section B	546	451	483	445
Section C	546	445	470	419
Inside Width				
Section A	483	406	432	457
Section B	483	394	419	432
Section C	483	394	381	419
Main Width				
Section A	356	292	279	279
Section B	356	292	279	279
Section C	356	292	279	279
Depth				
Section A	15	53	56	58
Section B	20	46	53	53
Section C	23	43	43	38

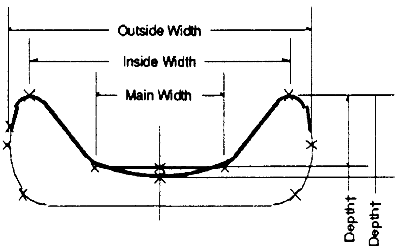
TEST SEAT DESIGN PARAMETERS - (*continued*)

Backrest Dimensions

(All dimensions in milllimeters unless otherwise noted.)



* Distance from middle horizontal contour line to top of backrest.



† Differs by section.

Parameter	Seat One	Seat Two	Seat Three	Seat Four
Headrest Width	300	300	300	300
Backrest				
Top Width	419	406	343	483
Middle Width	521	470	508	457
Bottom Width	533	508	521	495
Length	584	584	559	533
Mid-to-top Length	216	203	178	178
Outside Width				
Section D	546	495	514	419
Section E	546	508	521	508
Section F	546	521	521	508
Inside Width				
Section D	457	406	432	330
Section E	457	419	457	457
Section F	457	419	457	457
Main Width				
Section D	356	292	292	- -
Section E	356	292	292	216
Section F	356	292	292	216
Depth				
Section D	25	38	41	10
Section E	38	73	64	51
Section F	41	102	74	83

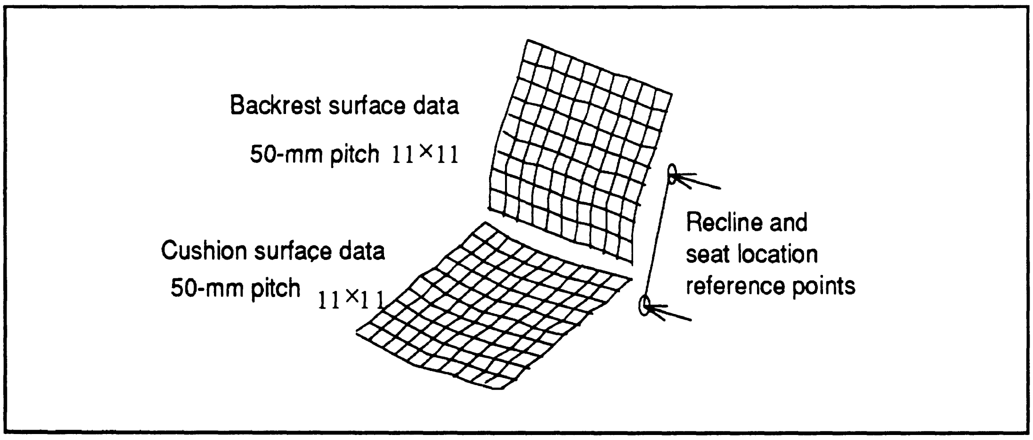
APPENDIX B

SEAT SURFACE CONTOUR MEASUREMENT

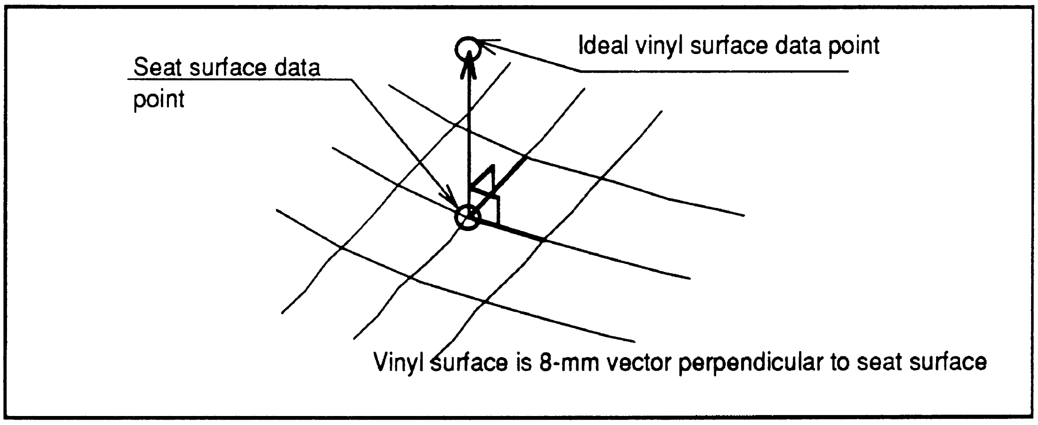
SEAT SURFACE CONTOUR MEASUREMENT

PURPOSE:	To generate a three-dimensional database representing the contour of the seat surface.
EQUIPMENT:	Science Accessories Corp. GP8-3D Digitizer and Multiplexer IBM PC for control and data acquisition Digitizing Probe (Appendix C) Thin, flat, vinyl bags filled with foam beads, imprinted with a 50-mm grid
PROCEDURE:	A three-dimensional contour of the seat/subject interface was generated for each test seat. The indentation pattern made by each subject on each test seat was determined and compared with the unindented contour.

First, the unloaded seat surface contour for each seat was measured. An 11 by 11 grid of points with 50-mm pitch was drawn on the cushion and backrest of each seat and each grid node location recorded using the digitizing probe. Two additional points on each seat, one at the backrest recline pivot and one about midway up the backrest at a fixed target were also digitized as reference points for the recline angle and seat track position. The unloaded seat contour data could then be oriented for comparison or display by reference to the two seat pivot/recline points.

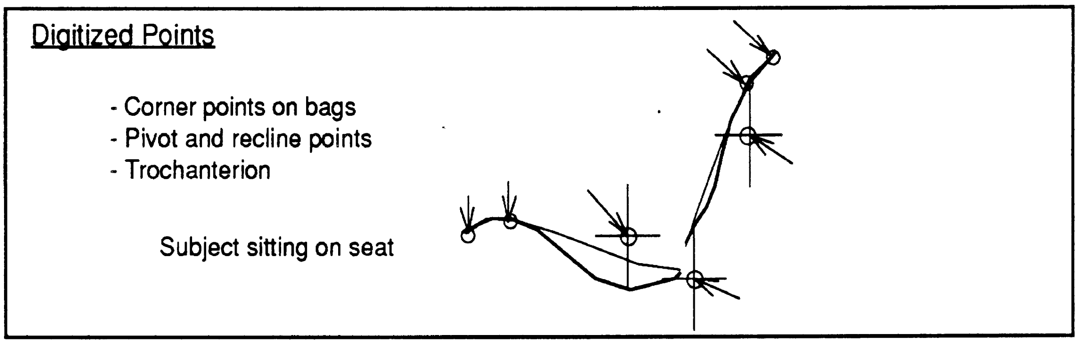


The next step in the preparation of the database for indentation contour measurements was the construction of an ideal vinyl bag surface. Preliminary experiments indicated that the foam-filled vinyl bags, when placed on the seat, were approximately 8-mm thick, with a small standard deviation. Rather than redigitize the vinyl surface contour each time the bags were placed on a seat, an ideal vinyl surface was prepared by adding a constant 8-mm vector perpendicular to the seat surface to the unloaded seat surface contour. This new contour represented the theoretical contour of the seat with the vinyl bags in place.

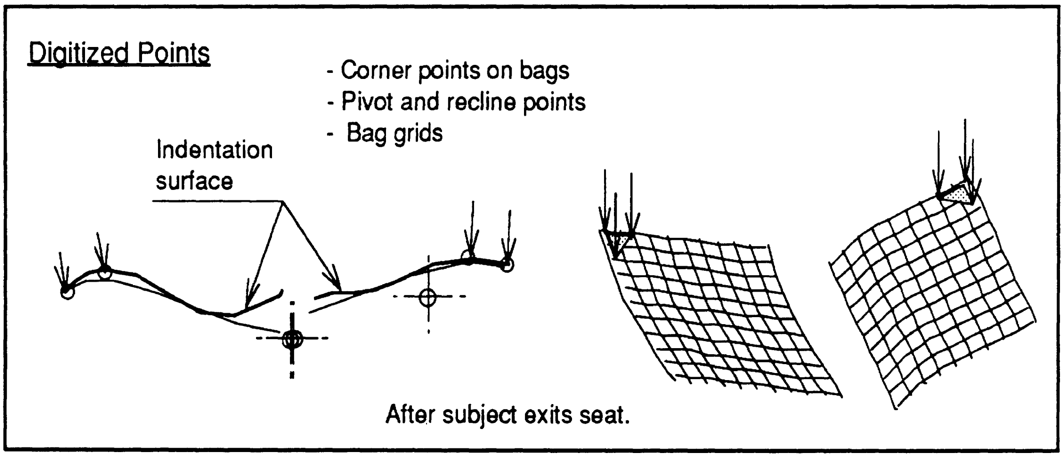


During the preliminary test session, the subject's indentation contour was measured in each of the four test seats. First, the vinyl bags were placed on the seat and smoothed into place so that they followed the contour of the seat. The centerline of the bag grid was aligned as closely as possible with the centerline of the seat. The air was then evacuated from the bags with a vacuum pump, making them rigid. The subject sat in his preferred position on the seat, with care taken to avoid disturbing the bags. Air was then allowed to flow back into the bags making them flexible so they would adjust to the indentation of the seat. After approximately thirty seconds had elapsed, the air was once again evacuated, rendering the bags rigid.

While the subject remained in the seat, three points attached to rigid triangular frames at the corner of the cushion bag and the backrest bag were digitized as reference data for the location of the bags with the subject in the seat. The seat pivot point and recline target, and the subject's trochanter target, as palpated in the standing position prior to the indentation measurement, were also digitized at this time.

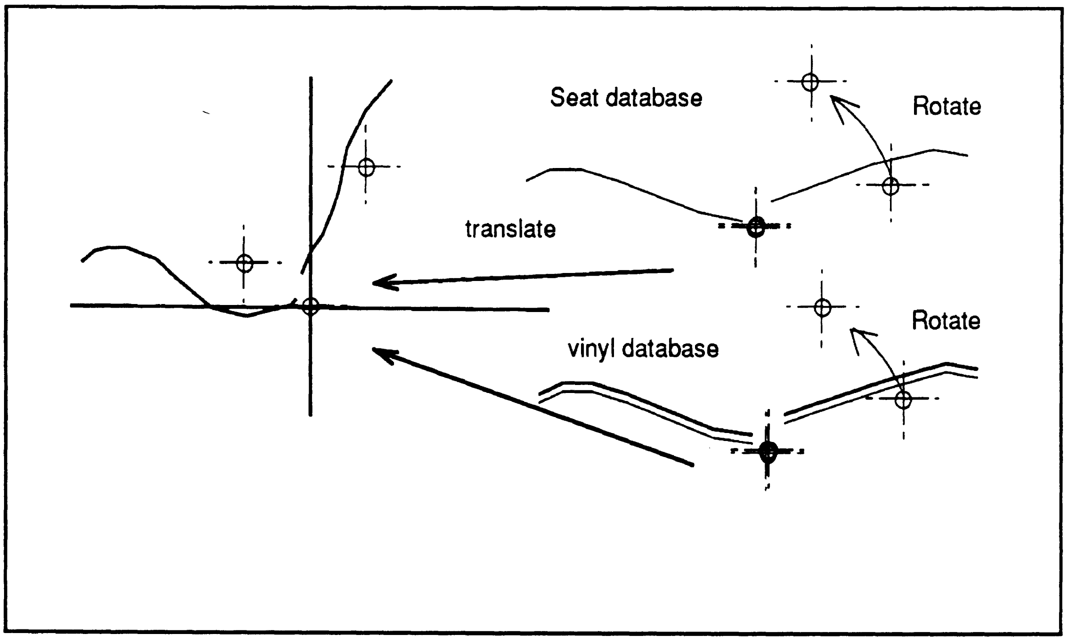


The subject then exited the seat, using a rope and handhold to avoid disturbing the shape of the bags. The bags translated as the subject left the seat, but retained the shape of the indented contour. The experimenters reclined the seat to its rearmost point, to facilitate digitization of the bag surfaces. The three corner targets of each bag were digitized again, as were the pivot and recline targets. Each point of the 11 by 11 grids on the cushion and backrest bags was then digitized.



Next, the indented bag contour data were aligned with the ideal vinyl contour for the appropriate seat using coordinate translation and rotation techniques, as follows.

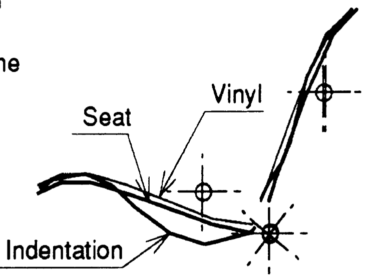
First, the database was adjusted to correspond to the subject's selected seat track position and recline angle, by aligning the pivot point and recline target data from the database with those from the indentation measurement. The figure shows the ideal vinyl database transformations. The digitized backrest contour data were rotated about the pivot point to the appropriate angle, then both the backrest and cushion data were translated to correspond to the seat track position selected by the subject.



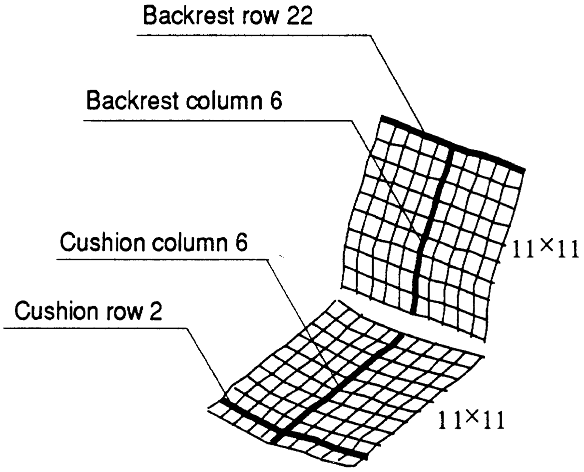
The aligned databases for each test were then converted to buck coordinates. An interpolation procedure was used to convert the databases in seat coordinates to buck coordinates, so that the data from each test would be comparable despite slightly different locations for the bag grid data relative to the seat between tests.

The interpolation procedure assigned a perpendicular axis value to each point on a buck coordinate grid with 25-mm pitch. For the cushion data, the buck coordinate grid was in the X-Y plane. The backrest data were interpolated to an X-Z grid. The calculation used interpolation from the three closest data points.

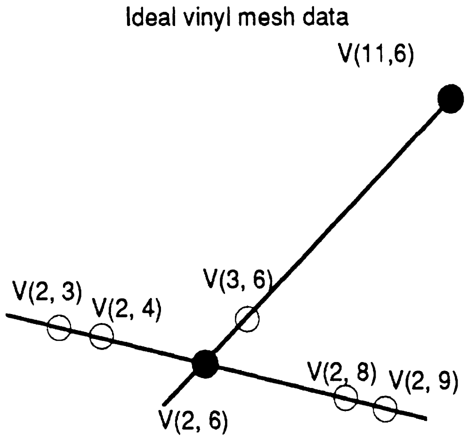
The unindented seat surface, the ideal vinyl surface (unindented) and the indented vinyl surface contour were all aligned to the recline angle chosen by the subject.

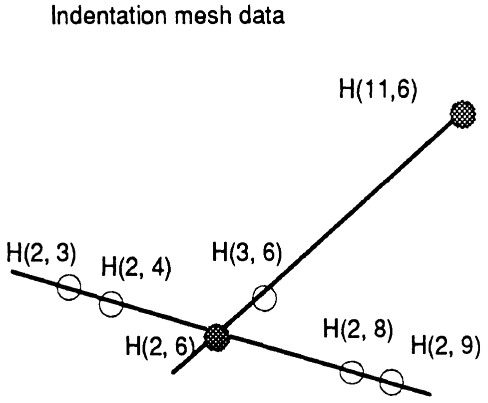


After the databases were transformed into buck coordinates, some further transformation of the indentation data was necessary to correct for movement of the bags caused by the subject exiting the seat. Several reference points on the centerline and edges of each grid (cushion and backrest) were used to define axes of rotation, as follows.



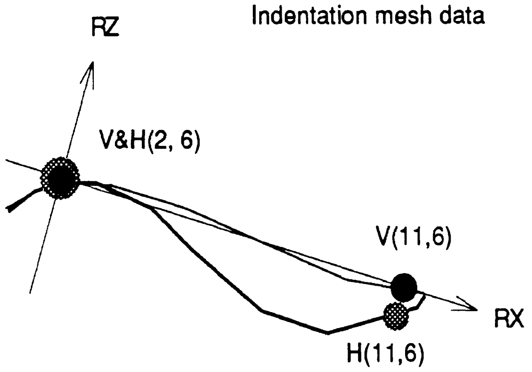
Reference points from the ideal vinyl surface and indentation cushion databases were used to define axes for rotations. (V denotes ideal vinyl surface points, H denotes indentation data. Numbers refer to grid nodes.)





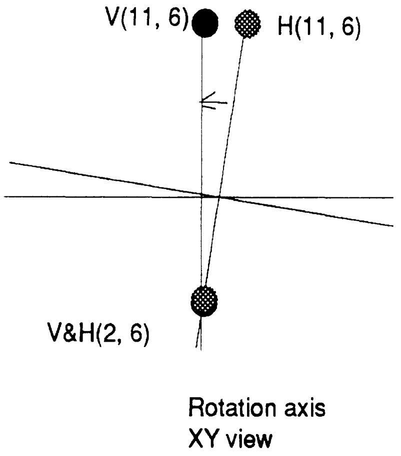
The indentation cushion database was then rotated on three axes as follows.

①

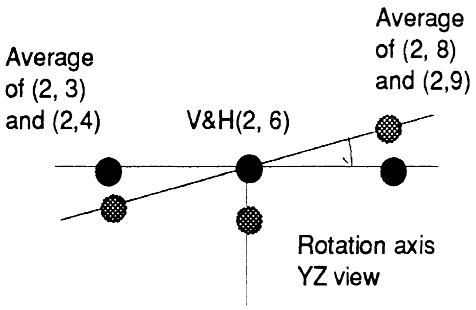


Rotation using vinyl V(2, 6) - V(11, 6) axis

②

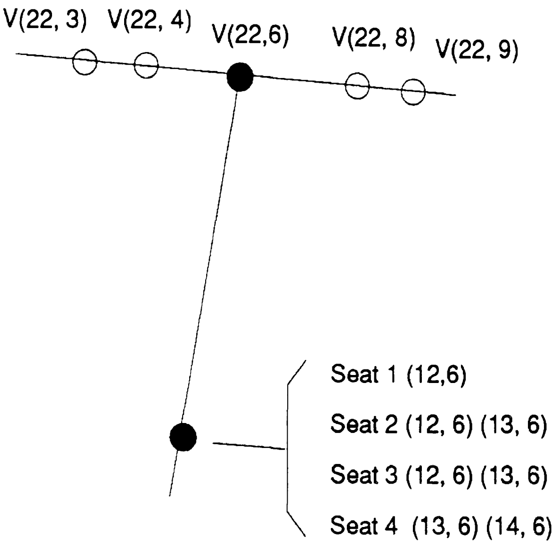


③

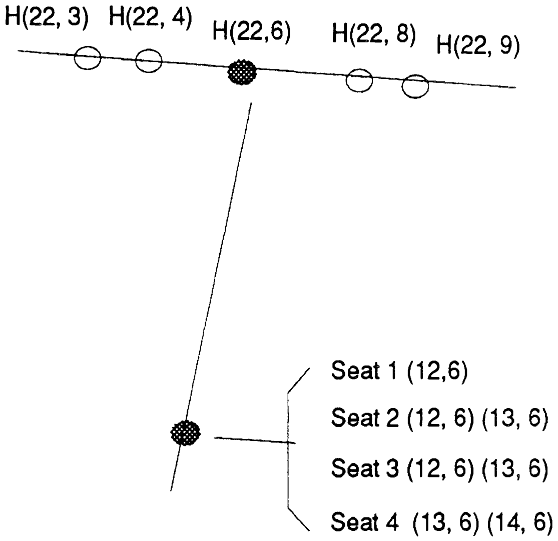


Next, transformation of the backrest indentation database was performed. The following reference points were selected from the vinyl and indentation databases.

Ideal vinyl mesh data

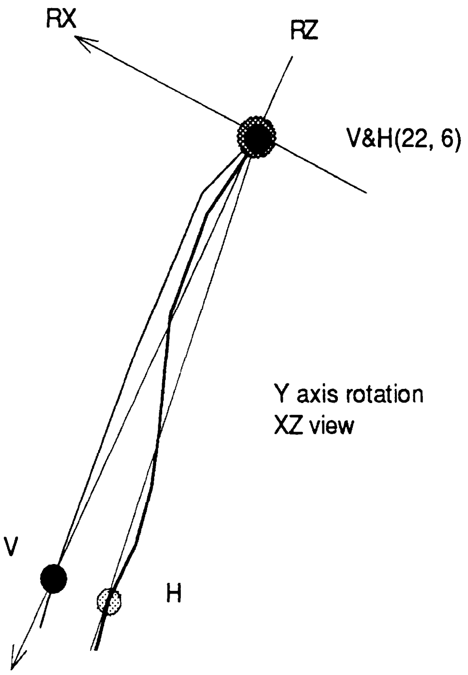


Indentation mesh data

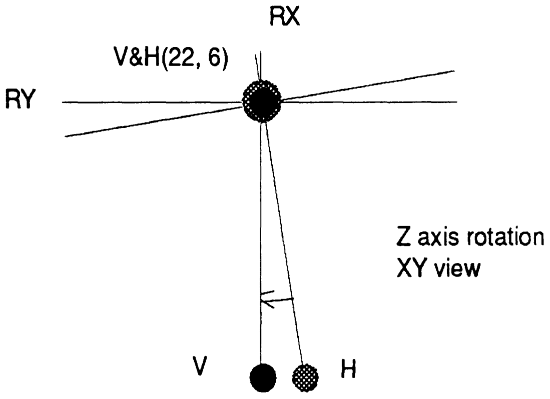


Three rotations were performed, as follows.

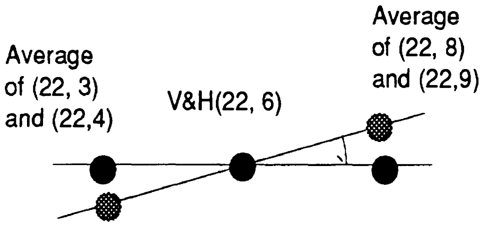
①



②

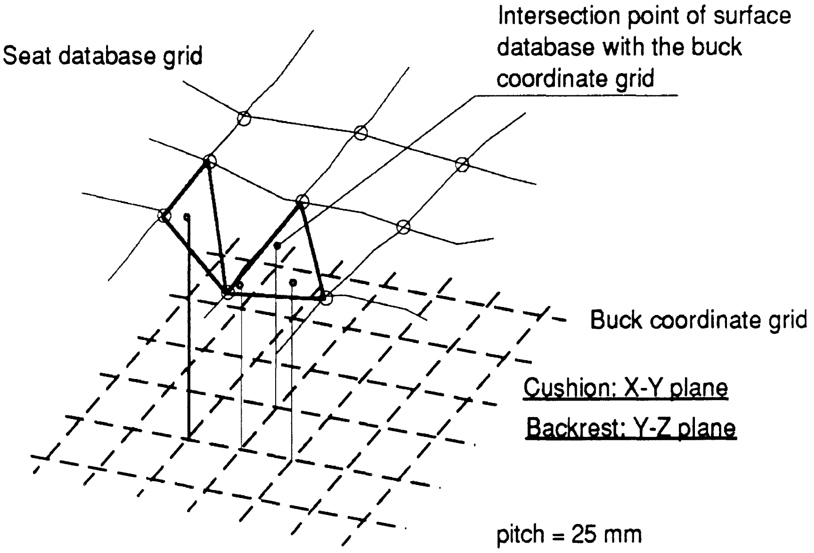


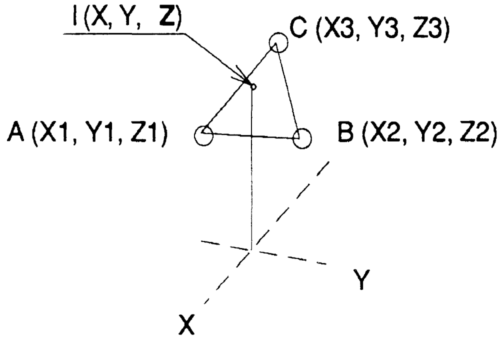
③



The indentation database in buck coordinates was then ready for display or analysis.

INTERPOLATION PROCEDURE: SEAT TO BUCK COORDINATES





$$\begin{vmatrix} X_1-X_3 & Y_1-Y_3 & Z_1-Z_3 \\ X_2-X_3 & Y_2-Y_3 & Z_2-Z_3 \\ X-X_3 & Y-Y_3 & \mathbf{Z}-Z_3 \end{vmatrix} = 0$$

$$\begin{vmatrix} A_1 & B_1 & C_1 \\ A_2 & B_2 & C_2 \\ A_3 & B_3 & \mathbf{C_3} \end{vmatrix} = 0 \qquad \mathbf{C_3} = \frac{A_3\cdot B_2\cdot C_1 + A_1\cdot B_3\cdot C_2 - A_2\cdot B_3\cdot C_1 - A_3\cdot B_1\cdot C_2}{A_1\cdot B_2 - A_2\cdot B_1}$$

X= known Y= known (fixed node on grid)

$$\boxed{Z = C_3 + {}^{-}Z_3}$$

For backrest data, the grid was in the Y-Z plane and the interpolation solved for an X value.

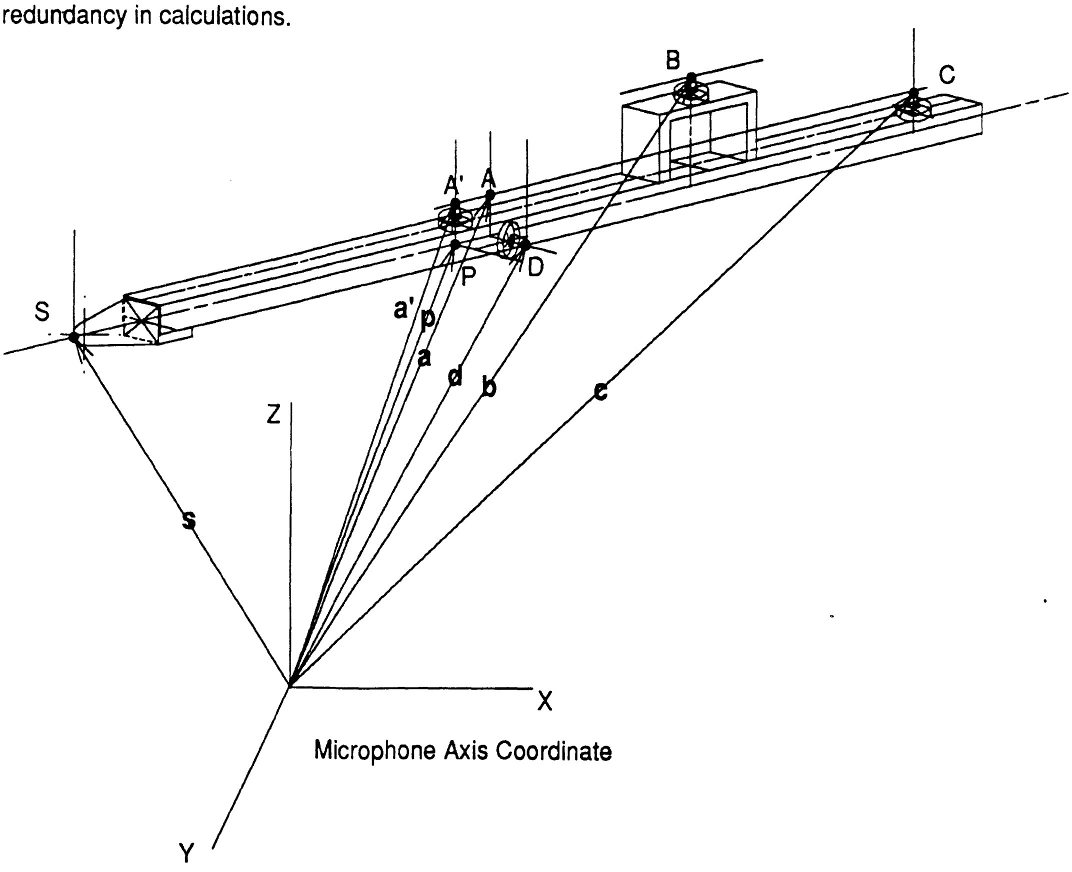
APPENDIX C

DIGITIZING PROBE ALGORITHM

DIGITIZING PROBE ALGORITHM

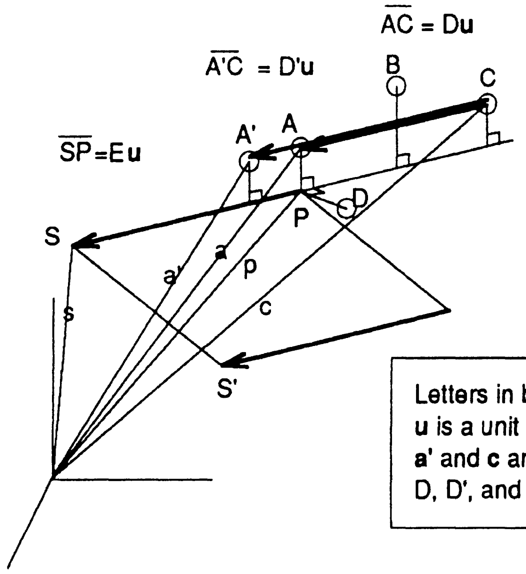
The digitizing probe was fabricated of aluminum and equipped with four emitters. The locations of these emitters were sampled and calculations performed to locate the point at the tip of the probe. The following algorithm details the calculation process. Outputs from the digitization equipment are in the form of three-dimensional vectors, represented here in bold-faced type.

Using a third emitter, in addition to the two which are required to locate the tip of the probe, allows the calculation of the rotational angle of the probe about the S-P axis. This means that the location of any point at a known distance and angle from the probe can be located. The fourth emitter provides redundancy in calculations.



In the figure above, **a'**, **d**, **b**, and **c** are output from the digitization equipment and are the inputs to the algorithm.

The first step is to find the unit vector **u**, representing the direction the probe is pointing.



Letters in bold are 3-D vectors.
u is a unit vector in the direction of the ray $\overrightarrow{CA}$ or $\overrightarrow{PS}$
a' and **c** are data from GP8-3D.
D, D', and E are physical dimensions of probe.

The following vector formulas apply:

Section 1

$\mathbf{a} = \mathbf{c} + D\mathbf{u}$

$\mathbf{a}' = \mathbf{c} + D'\mathbf{u}$

$\mathbf{u} = (\mathbf{a}' - \mathbf{c})/D'$

$\mathbf{a} = (\mathbf{a}' - \mathbf{c})D/D' + \mathbf{c}$

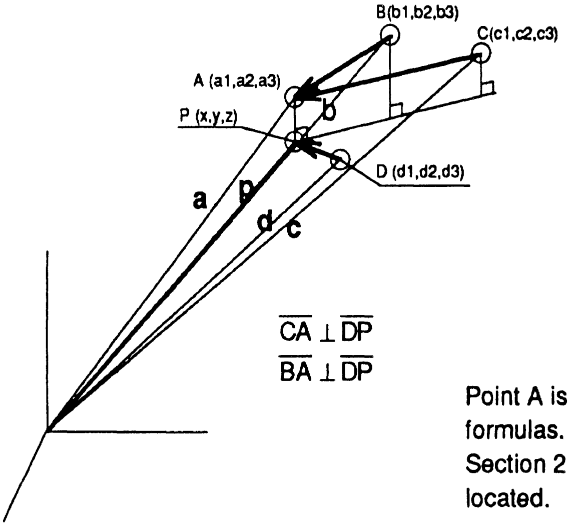
$\mathbf{u} = (\mathbf{a} - \mathbf{c})/D$

$\mathbf{s} = \mathbf{p} + E\mathbf{u}$

$\mathbf{s} = (\mathbf{a} - \mathbf{c})E/D + \mathbf{p}$

If the vector **p** is known, **s** (the location of the probe tip) may be calculated.

The vector **p** is determined as follows:



Section 2

$(\mathbf{c} - \mathbf{a}) \cdot (\mathbf{d} - \mathbf{p}) = 0$

$(\mathbf{b} - \mathbf{a}) \cdot (\mathbf{d} - \mathbf{p}) = 0$

$|\mathbf{a} - \mathbf{p}| = L1$

$|\mathbf{d} - \mathbf{p}| = L2$

Point A is located by the Section 1 formulas. From the Section 1 and Section 2 formulas, Point P is located.

The following calculations perform the algebraic manipulations of the formulas in Section 1 and Section 2.

$$(c1-a1,\ c2-a2,\ c3-a3) \bullet (d1-x,\ d2-y,\ d3-z) = 0 \tag{1}$$

$$(b1-a1,\ b2-a2,\ b3-a3) \bullet (d1-x,\ d2-y,\ d3-z) = 0 \tag{2}$$

$$(a1-x)^2+(a2-y)^2+(a3-z)^2=L_1^2 \tag{3}$$

$$(d1-x)^2+(d2-y)^2+(d3-z)^2=L_2^2 \tag{4}$$

where x, y, and z are coordinates of point P.

Manipulating (1) and (2):

$$(c1-a1)d1-(c1-a1)x+(c2-a2)d2-(c2-a2)y+(c3-a3)d3-(c3-a3)z=0 \tag{5}$$

$$(b1-a1)d1-(b1-a1)x+(b2-a2)d2-(b2-a2)y+(b3-a3)d3-(b3-a3)z=0 \tag{6}$$

Manipulating (3) and (4):

$$a1^2-2a1x+x^2+a2^2-2a2y+y^2+a3^2-2a3z+z^2=L_1^2 \tag{7}$$

$$d1^2-2d1x+x^2+d2^2-2d2y+y^2+d3^2-2d3z+z^2=L_2^2 \tag{8}$$

Combining (5) and (6):

$$(a1-c1)x+(a2-c2)y+(a3-c3)z=(a1-c1)d1+(a2-c2)d2+(a3-c3)d3 \tag{9}$$

$$(a1-b1)x+(a2-b2)y+(a3-b3)z=(a1-b1)d1+(a2-b2)d2+(a3-b3)d3 \tag{10}$$

Subtracting (7) from (8):

$$(a1-d1)x+(a2-d2)y+(a3-d3)z=\frac{1}{2}\left[L_2^2-L_1^2+(a1^2-d1^2)+(a2^2-d2^2)+(a3^2-d3^2)\right] \tag{11}$$

Matrix solution of (9), (10) and (11) for point P(X, Y, Z):

$A1=a1-c1$	$B1=a2-c2$	$C1=a3-c3$	$D1=(a1-c1)d1+(a2-c2)d2+(a3-c3)d3$
$A2=a1-b1$	$B2=a2-b2$	$C2=a3-b3$	$D2=(a1-b1)d1+(a2-b2)d2+(a3-b3)d3$
$A3=a1-d1$	$B3=a2-d2$	$C3=a3-d3$	

$$D3=\frac{1}{2}\left[L_2^2-L_1^2+(a1^2-d1^2)+(a2^2-d2^2)+(a3^2-d3^2)\right]$$

$$D_a=\begin{vmatrix} A1 & B1 & C1 \\ A2 & B2 & C2 \\ A3 & B3 & C3 \end{vmatrix} \qquad D_X=\begin{vmatrix} D1 & B1 & C1 \\ D2 & B2 & C2 \\ D3 & B3 & C3 \end{vmatrix} \qquad D_Y=\begin{vmatrix} A1 & D1 & C1 \\ A2 & D2 & C2 \\ A3 & D3 & C3 \end{vmatrix} \qquad D_Z=\begin{vmatrix} A1 & B1 & D1 \\ A2 & B2 & D2 \\ A3 & B3 & D3 \end{vmatrix}$$

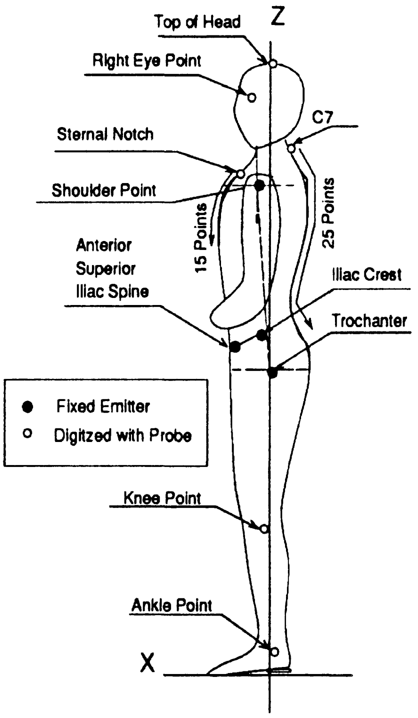
$$X=\frac{D_X}{D_a} \qquad Y=\frac{D_Y}{D_a} \qquad Z=\frac{D_Z}{D_a}$$

APPENDIX D

SPINE AND STERNUM CONTOURS

SPINE AND STERNUM CONTOURS

PURPOSE:	To produce digitized representations of the subject's spine and sternum contours.
EQUIPMENT:	Science Accessories Corp. GP8-3D Sonic Digitizer and Multiplexer Four Emitters for Digitizer Digitizer Probe IBM PC for control and data acquisition
PROCEDURE:	A digital tracing was made of each subject's sternum and spine. Data were corrected for movement during measurement and aligned with reference to bony landmarks.



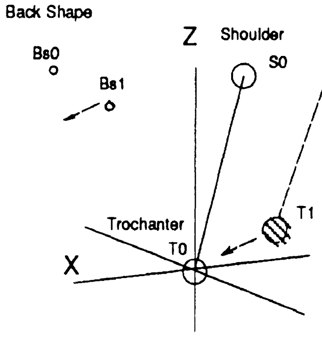
The subject stood in a prescribed spot with his right side toward the digitzer microphone array. Four emitters were fixed to the subject's skin or clothing at the shoulder, the anterior-superior iliac spine, the most superior point on the iliac crest, and the greater trochanter of the femur.

The digitizing probe was used to locate four points: the ankle, the knee, the corner of the eye, and the top of the head. The probe was then moved slowly down the spine from C7 to the sacral area while the emitters and probe location were sampled at regular intervals. Twenty-five points were recorded on the spine. Each time a probe sample was taken, the positions of the fixed emitters were recorded as well. Fifteen points were digitized as the probe was moved down the subject's sternum.

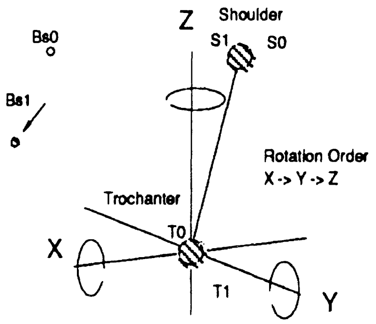
Preliminary investigations indicated that subject movement during the recording session compromised the precision of the data. An aluminum walker was used as a hand-guide to help the subjects stabilize themselves, and the data from the fixed emitters were used to adjust the probe data for movement.

All sternum and spine data were translated along the X axis according to the deviation of the corresponding trochanter sample from the X position of the first trochanter measurement. Then the data were rotated about the X, Y, and Z axes by the amount of the angular deviation of the line connecting the corresponding trochanterion and shoulder points from the initial angle of those two points. The figures below show these rotations.

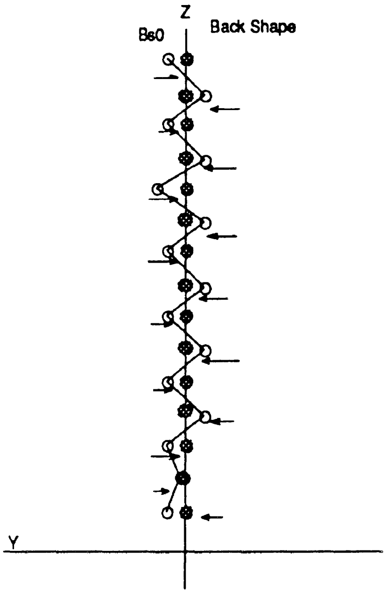
Translation in X



Rotation in X, Y, and Z



Some deviation from the Y axis remained, as shown in the figure below. The data for each series of measurements (sternum and spine) were translated to have identical Y coordinates.



The sternum and spine data were then converted to a planar format, with the origin at the location of the first trochanter sample. A polynomial curvefit was used to smooth the data.

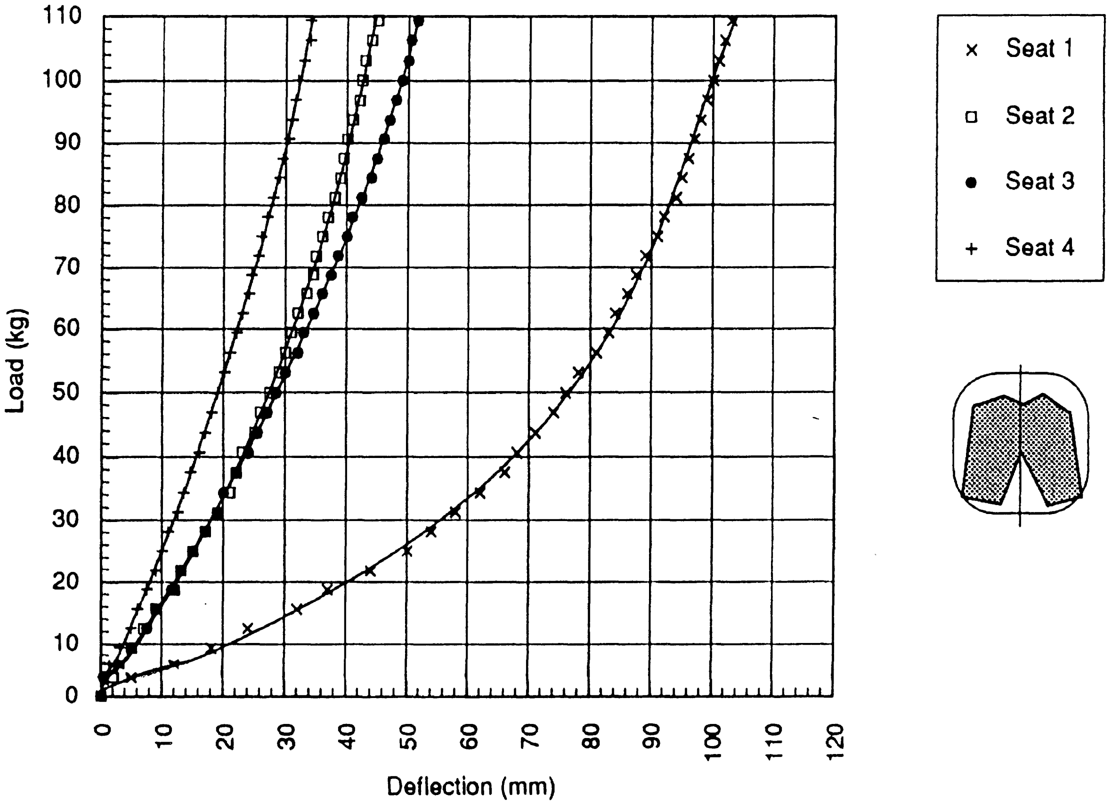
APPENDIX E

STATIC FORCE-DEFLECTION TESTING

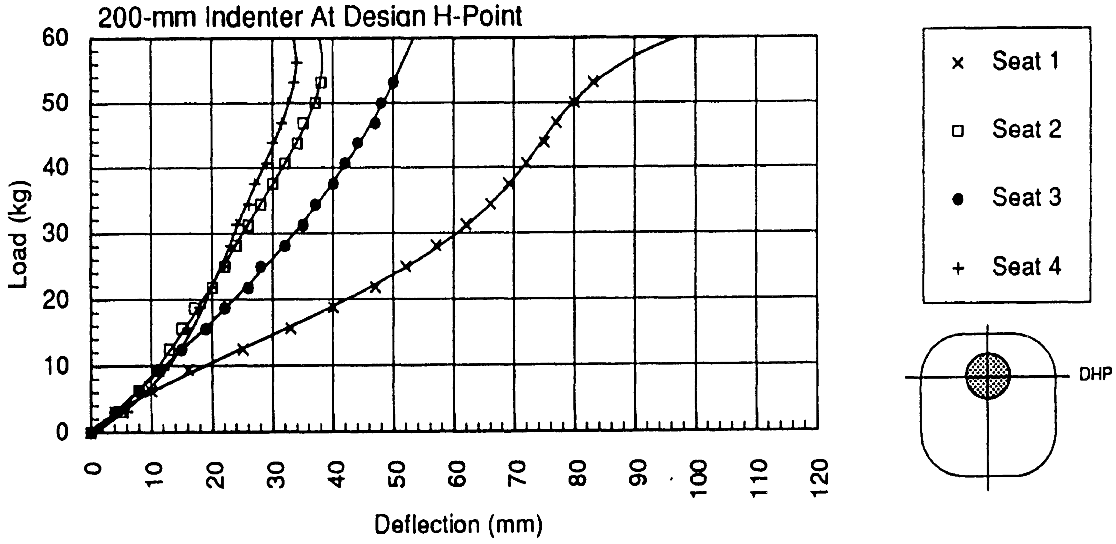
STATIC FORCE-DEFLECTION TESTING

Static deflection testing of each of the four test seats was carried out at Ikeda Engineering Corporation in Farmington Hills, Michigan, by representatives of Ikeda and UMTRI. Testing was performed using a Ueshima Static Load Deflection Tester, with a deflection rate of 600 mm/min for all tests. Each seat was first evaluated using a standard, contoured pan, designed to approximate the indentation pattern of a 50th percentile male. Three repetitions were performed on each cushion and each backrest. The backrests were supported by their frames for testing. Two other series of tests were conducted using flat, circular indenters. The first used a 200-mm-diameter plate in two locations on the cushion and backrest. An 80-mm-diameter plate was used to measure deflection characteristics along the centerline of the seat. Single indentation trials were performed at 50-mm intervals on the centerlines of the cushion and backrest using the 80-mm plate. Data from the tests are summarized in the following figures.

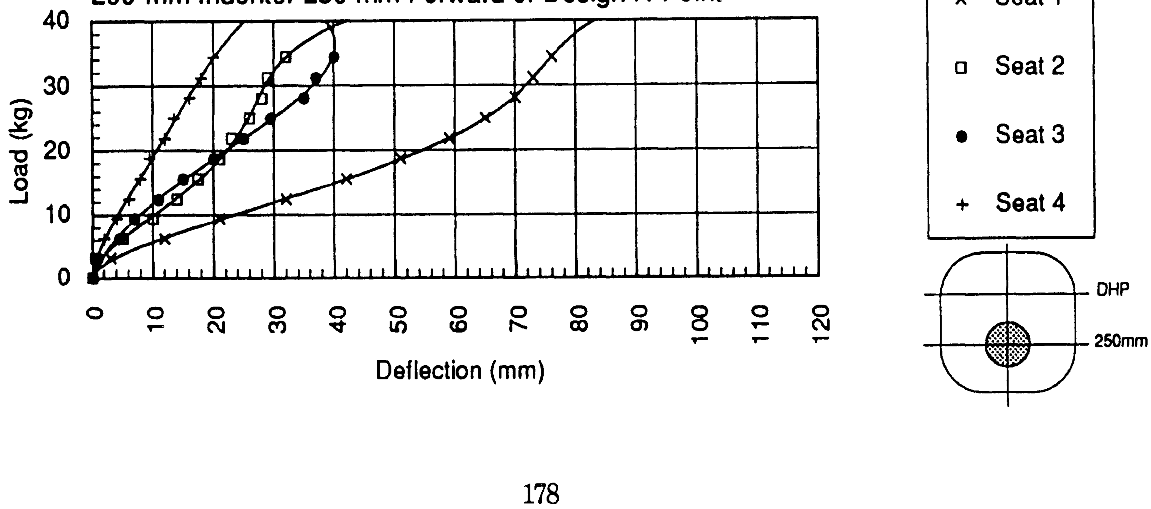
Cushion Pan (Contoured Indenter)

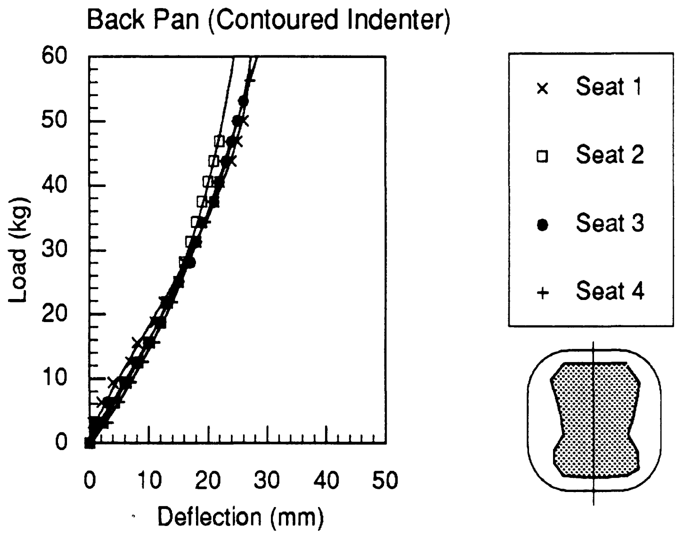


200-mm Indenter At Desian H-Point

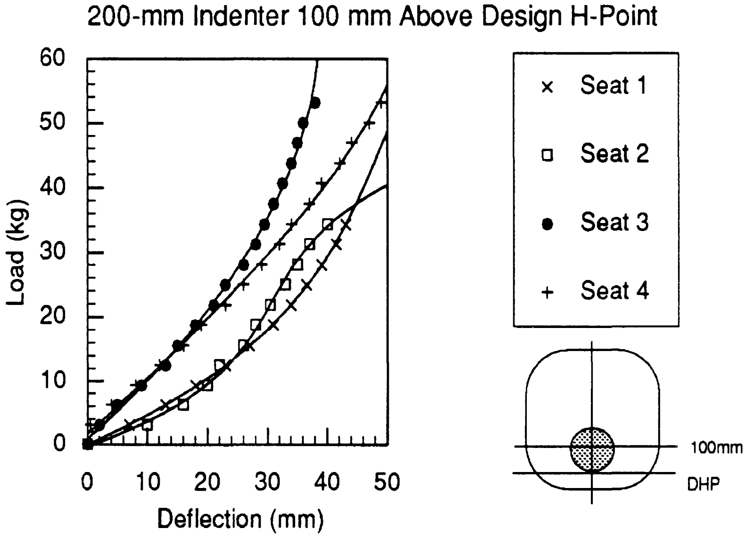


200-mm Indenter 250 mm Forward of Design H-Point

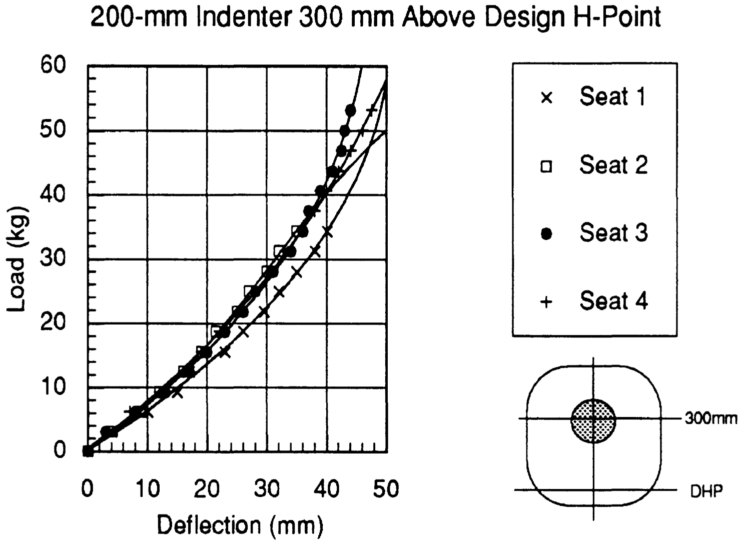




Back Pan (Contoured Indenter)



200-mm Indenter 100 mm Above Design H-Point



200-mm Indenter 300 mm Above Design H-Point

APPENDIX F

QUESTIONNAIRE RESPONSE FORMS

PRELIMINARY QUESTIONNAIRE RESPONSE FORM

ANSWER SHEET

IKEDA SEATING COMFORT PROJECT

DATE: ____________ SEAT#: ________ SUBJECT NO.: ____________________

	SECTION A CHECK ANYWHERE ON THE LINE		SECTION B SATISFACTION CIRCLE ONE OF THE NUMBERS (5 = HIGHEST SATISFACTION)
1. First impression of this seat	BAD	GOOD	
2. Cushion fit under buttock area	LOOSE	TIGHT	1 2 3 4 5
3. Cushion fit under thigh area	LOOSE	TIGHT	1 2 3 4 5
4. Firmness of the cushion padding	SOFT	FIRM	1 2 3 4 5
5. Length of the cushion	SHORT	LONG	1 2 3 4 5
6. Width of the cushion	NARROW	WIDE	1 2 3 4 5
7. Height of the cushion	LOW	HIGH	1 2 3 4 5
8. Cushion angle (angle from horizontal)	SMALL	LARGE	1 2 3 4 5
9. Bounciness of the cushion	STIFF	BOUNCY	1 2 3 4 5
10. Recovery of cushion bounciness	SLOW	FAST	1 2 3 4 5
11. Intrusions through the cushion	NONE	MANY	1 2 3 4 5
12. Feeling of sinking into the cushion	NONE	A LOT	1 2 3 4 5
13. Back-rest fit at shoulder area	LOOSE	TIGHT	1 2 3 4 5
14. Back-rest fit at middle-back area	LOOSE	TIGHT	1 2 3 4 5
15. Back-rest fit at low-back area	LOOSE	TIGHT	1 2 3 4 5
16. Firmness of back-rest padding	SOFT	FIRM	1 2 3 4 5
17. Length of back-rest	SHORT	LONG	1 2 3 4 5
18. Width of back-rest	NARROW	WIDE	1 2 3 4 5
19. Lumbar support	WEAK	STRONG	1 2 3 4 5
20. Location of lumbar support	LOW	HIGH	1 2 3 4 5
21. Constricted feelings on stomach	NONE	A LOT	1 2 3 4 5
22. Back posture (spine curvature)	BOWED	ARCHED	1 2 3 4 5
23. Overall evaluation of the seat	BAD	GOOD	1 2 3 4 5
24. How comfortable is this seat?	UNCOMFORTABLE	COMFORTABLE	1 2 3 4 5

OSGR MODALITY QUESTIONNAIRE RESPONSE FORM

Driving Session Questionnaire

Date: ________ Elapsed Time: ________
Subject No.: ________
Seat No.: ________

CHECK ANYWHERE ON THE LINE

NO DISCOMFORT — UNBEARABLE DISCOMFORT

Middle Back ____
Lower Back ____
Buttock Area ____
Thigh Area ____

EXIT QUESTIONNAIRE RESPONSE FORM

Exit Questionnaire Rev. 3/16/90

Date: ________

Subject No.: ________

Seat No.: ________

Overall Discomfort

Check Anywhere On The Line

NO DISCOMFORT ____ UNBEARABLE DISCOMFORT

Are there any particular body areas in which you feel discomfort? Please list them and describe the discomfort in each. Be as specific as possible.

Is your discomfort caused by any particular seat feature? (For example, side pain caused by too much side support.)

If you could change this seat, how would you make it more comfortable?