Survey of Auto Seat Design Recommendations for Improved Comfort

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PREFACE

This report is a revised and extended edition of an earlier report. In 1994, the present author, with colleagues Lawrence Schneider and Leda Ricci from the University of Michigan Transportation Research Institute (UMTRI), undertook a thorough review of the academic and technical literature relating to automotive seat design, with a particular emphasis on accommodation and comfort. The original work was supported by Lear Seating Corporation and published as UMTRI technical report UMTRI-94-6.

In the intervening six years, attention to seating issues has increased, to judge from the volume of related material published at SAE meetings, in ergonomics journals, and in other forums. Technological advances have increased the use of seat surface pressure distribution in seat design and assessment. Recently, a new H-point manikin was developed at UMTRI under the auspices of the Automotive Seat and Package Evaluation and Comparison Tools (ASPECT) program. As part of the program, several detailed studies of the interaction between vehicle occupants and seats were conducted that led to new insights into how seat geometry and stiffness affects occupant posture.

The updated and expanded version of this report was undertaken to incorporate the findings of the ASPECT program and other studies that have been reported in the open literature since 1994. The anthropometric analyses supporting seat dimension recommendations have been revised with reference to the latest U.S. civilian anthropometry, the third National Health and Nutrition Examination Survey (NHANES III), conducted from 1988 to 1994. Although anthropometric analyses from the survey have not yet been published, the data have recently been made available and were analyzed for this report. Much of the new information in this report is based on research conducted at UMTRI during the past six years under sponsorship of auto industry companies.

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1.0 INTRODUCTION

There is a large body of literature devoted to the study of seating comfort. Åkerblom is widely credited with beginning the modern, scientific study of seating with his 1948 monograph on posture and chair design (Åkerblom 1948), although he cited over 70 previous publications related to his work. Since 1948, hundreds of papers on topics related to seating comfort have been published, many of which include recommendations for seat design to enhance comfort.

The seating literature contains more papers concerned with office and industrial seating than with automotive seating, probably because of the economic costs associated with discomfort and injury in the office and factory. However, the motor-vehicle environment is also a workplace, with the difference between the situations of a commuter and a professional driver being primarily the length of time in the seat, both cumulative and at a single sitting. Epidemiological studies have shown that low-back pain and lumbar disc herniation risk increase with the amount of time spent driving (Kelsey and Hardy 1975). The presence of vibration in the motor-vehicle environment has been suggested as a potentiating factor (Troup 1978).

Most of the research findings concerning industrial and office chair design can be applied to auto seat design. However, there are several important considerations unique to the mobile environment that should influence design recommendations. In particular, the control locations and sight line requirements serve to constrain postures to a greater extent than in most other seated environments. Safety concerns dictate that the driver be alert and continually responding to changing road conditions, and be positioned in such a way that the occupant restraint systems offer maximal protection in a crash. Passenger cars generally require a more extended knee posture than is necessary in other types of seating. This has important implications with regard to the orientation of the sitter's pelvis and lumbar spine. Additionally, vibration imposes tissue stresses that are not generally present in a stationary environment.

When attempting to specify design characteristics of a comfortable seat, it is important to have in mind a functional definition of comfort as it applies to seating. Branton (1969) has pointed out that it is unreasonable to assume, as some researchers have, that comfort extends in a continuum from unbearable pain to extreme feelings of well-being. Since a seat is not likely to impart a positive physical feeling to a sitter, the continuum of interest reaches from indifference to extreme discomfort. The best a seat can do is to cause no discomfort to the sitter. As Branton points out, this definition is useful, not only in the design of subjective assessment tools such as questionnaires, but also in consideration of strategies to improve comfort. The aim of chair or seat design should be to reduce or eliminate factors causing discomfort rather than to elicit feelings of well-being. Recently, Shen and Vertiz (1997) have proposed that comfort and discomfort coexist as separate dimensions, with the possibilities for comfort increasing when discomfort decreases.

Shen has described comfort as the result of a continuous behavioral process of decreasing comfort. This approach suggests that comfort may be influenced by factors that are not strong contributors to the level of discomfort. For example, a broader, more supportive seat may provide better comfort than a narrower seat, even though the narrower seat does not produce a different level of discomfort. Methodologically, however, it is more straightforward to quantify discomfort than to measure comfort. Fairly simple visual analog scales can be used, repeatably and reliably, to gauge discomfort (Reed et al. 1991). Consequently, for the purposes of this report, comfort will refer to the absence of discomfort, so that an increase in comfort implies a decrease of stimuli leading to discomfort. Designs complying with the recommendations herein are expected to result in less discomfort for an occupant population than those that do not.

This report identifies seat design parameters that have been demonstrated to be, or are likely to be, associated with seat comfort, and recommends levels for these parameters. These recommendations are based on the cited sources and the experience of the author. The design parameters are divided into three categories.

1. *Fit* parameter levels are determined by the anthropometry of the occupant population and include such measures as the length of the seat cushion.

2. *Feel* parameters relate to the physical contact between the sitter and the seat and include the pressure distribution and upholstery properties.

3. *Support* parameters affect the posture of the occupant and include seat contours and adjustments.

There is considerable interaction between parameters, both within and among these categories. For example, a change in backrest curvature (Support) will affect the pressure distribution (Feel) and also change the effective cushion length (Fit). However, this parameter categorization is useful because the knowledge required to specify parameter levels in each of these categories comes from distinct areas of research. Fit parameter levels are set with reference to anthropometric measures using data on the distributions of particular body dimensions in the population. Feel parameter levels are set using a combination of subjective assessments and objective measurements made with tools, such as pressure measurement mats and sweat impulse testers. Support parameters, which include lumbar support and backrest angle, are specified with reference to physiological measures related to internal body stresses associated with various postures. Data to support these parameter specifications have come from studies of back muscle activity, lumbar disc pressure, and spine radiographs.

For Fit parameters, there is considerable agreement among various researchers concerning the methodology to select an appropriate design value, if not the actual value. In these cases, the recommendations are adapted from those in two summaries of ergonomic seat design practice: Chaffin and Andersson (1991), and Reynolds (1993). Chaffin and Andersson present recommendations for office and industrial chair design; Reynolds discusses auto seats. As indicated above, there is considerable overlap between these areas. Where necessary, reference is made to the original source materials used in these summaries. Additional consideration is given to a contemporary design guide from General Motors (Maertens 1993). Comparisons are made between the auto recommendations in Maertens and the body of ergonomic literature directed toward general seating. In some cases, deviations from the Maertens design guide are recommended.

The Fit parameter values obtained from these literature sources are supplemented by a new analysis of engineering anthropometry data. Data from the most recent large-scale survey of U.S. adults were analyzed and summary statistics tabulated. The results demonstrate that some changes in seat dimension recommendations can be justified by these new data. The Fit parameter section includes a discussion of how the recommendations can be tailored to particular design situations, particularly those involving gender mixes other than 50/50.

Feel parameters are the least understood because research tools to make objective measurements in this area have only recently become available, and because the subjective and complex nature of these parameters makes them difficult to specify in quantitative terms. One of the most frequently investigated of the Feel parameters is the pressure distribution at the interface between the sitter and seat. There is little agreement in the literature concerning desirable characteristics of a pressure distribution, except that areas of high pressure should be avoided. In Section 3 of this report, the findings and recommendations from a number of researchers are presented, along with the recommendations of the authors for applying the current body of knowledge to seat design.

Transmittance of vibration through the seat is an important contributor to dynamic comfort. Although a complete treatment of this area is beyond the scope of this report, a brief summary of the current state-of-the-art and general design recommendations is included. The bibliography (see Appendix) contains a large number of papers addressing vibration issues.

The most controversial Support parameters pertain to "lumbar support," which generically refers to the contour of the lower half of the backrest that is assumed to provide stabilization to the lumbar portion of the spine. Although some seats are referred to as lacking lumbar support, any seat that contacts the sitter in the lumbar region provides some support to the lumbar spine. Consequently, the question is not whether a seat should have "lumbar support," but rather how the lower part of the backrest should be constructed to support the lower back optimally. Most research in this area has focused on physiological stresses associated with various spine postures. Backrest contours have been recommended that correspond to the back shapes found to result in reduced muscle and spine stress. Recently, research at UMTRI has documented in detail the postural responses of drivers and passengers to changes in lumbar support contour. Section 4 of this report combines this information with the findings from the earlier influential studies concerning lumbar contour, backrest angle, pan (cushion) angle, and a few other seat design parameters related to support. Detailed recommendations based on the research findings are presented. In addition, quantitative information on preferred driver and passenger postures are presented to facilitate seat design to accommodate the wide range of occupant sitting behavior.

The following sections present a discussion of the relevant literature and recommended design values for each parameter. The recommendations are compiled in Section 6.0, along with figures illustrating the parameter definitions. The Appendix contains a large bibliography of literature related to seated comfort and related issues.

2.0 FIT PARAMETERS

The principle that the seat should fit the sitter is the most universally employed concept in seating ergonomics. People had used chairs for centuries before Åkerblom's 1948 monograph, relying on the experience of furniture makers to produce a match between the sitter and the seat. If a chair is to be used by only one sitter, careful measurements of that person's body, and subsequent fit tests, will yield appropriate dimensional specifications for the seat. However, in the passenger car market, where a single seat must accommodate a large percentage of the population, knowledge of population anthropometry is required.

The constraints on Fit parameter design values are usually imposed by the desire to accommodate a sufficient range of the population on one anthropometric measure. A widely used design criterion is that the seat should accommodate the members of the population who lie between the 5th-percentile-female and 95th-percentile-male values on some anthropometric measure of interest. It is important to stress that alternative percentiles could be chosen to accommodate a different fraction of the user population. In fact, modern vehicle marketing requires that more than 95 percent of the potential user population be accommodated.

In general, Fit parameter levels are specified by noting the constraining values among the set of 5th-percentile-female and 95th-percentile-male values for particular anthropometric dimensions. Note that it is not meaningful to refer to accommodating, for example, a 5th-percentile female, without specifying the dimension that is accommodated. For example, a woman who is 5th percentile in sitting height might have thighs that are shorter than 5th percentile for thigh length. She might be accommodated with respect to her view of the instrument panel, but experience uncomfortable pressure on the back of her knees from a seat cushion that is too long. In the case of cushion width, the 95th-percentile-female hip width is commonly used as a specification limit, since this measure exceeds the 95th-percentile-male hip width. The case of cushion width is a good example of how parameter levels might appropriately be selected in practice. Using the methodology described above, the minimum cushion width would be chosen to be greater than the 95th-percentile-female seated hip breadth of 493 mm. However, a larger minimum cushion width would be desirable, mainly because the anthropometric measure does not include clothing.

Other parameters should be considered in the same way as the cushion width. The procedure followed here is to (1) identify the members of the population who represent the extreme of the accommodation range (*e.g.*, small women), (2) select the relevant anthropometric values, (3) determine appropriate values for the selected anthropometric measurements, and (4) provide for *at least* that level of accommodation.

The most detailed anthropometric data are available for military, rather than civilian populations. Recently, data from a large-scale survey of the U.S. adult population have been made available for analyses. The third National Health and Nutrition Examination Survey (NHANES III) includes a sample of over 10,000 adults from all regions of the country. Using U.S. Census data from 1990, the data are weighted so that analyses accurately represent the non-institutionalized U.S. population at that date. Unfortunately, the NHANES dataset contains only a small number of anthropometric dimensions. For example, seated hip breadth, which is an important seat design parameter, is not present in the NHANES database.

To overcome this shortcoming, statistical methods are used to combine the information from the ANSUR survey of military personnel (Gordon et al. 1989) with the NHANES data. ANSUR contains a large number of anthropometric variables and is the most widely used U.S. anthropometric database. However, as is demonstrated below, there are important differences between the military and civilian populations, notably with regard to body weight and related dimensions. Section 2.1 presents summary data from NHANES III that describe the U.S. adult civilian population and lays out a procedure for using linear regression analysis of the military data to estimate the civilian distribution of anthropometric variables of interest.

Assessing seat fit using a small number of linear anthropometric dimensions is, at best, only a rough guide to seat dimensioning. Most of the important characteristics of seat contouring are not currently amenable to an anthropometric analysis, because the needed data are not available. Soon, however, a much more complete analysis of seat dimension and shape requirements will be possible using whole-body scan data. Section 2.9 introduces the potential applications of whole-body scan data.

2.1 Analysis of Anthropometric Data

Table 1 lists the seat dimensions, also illustrated in Figure 1, that will be analyzed with respect to occupant fit. Although most automotive seat recommendations are focussed on driver seats, some of the parameters discussed here are applicable to passenger seats as well. Unfortunately, none of the anthropometric variables listed in Table 1 are available in NHANES, but all are available in ANSUR.

Table 1
Seat Dimensions and Related Anthropometric Measurements

Seat Dimension	Anthropometric Measurement
Cushion Width	Seated Hip Breadth
Cushion Length	Buttock-to-Popliteal Length
Seat Height	Popliteal Height
Backrest Width	Chest Breadth Interscye Distance*
Backrest Height	Shoulder Height

* Distance across back between the armholes of a garment.

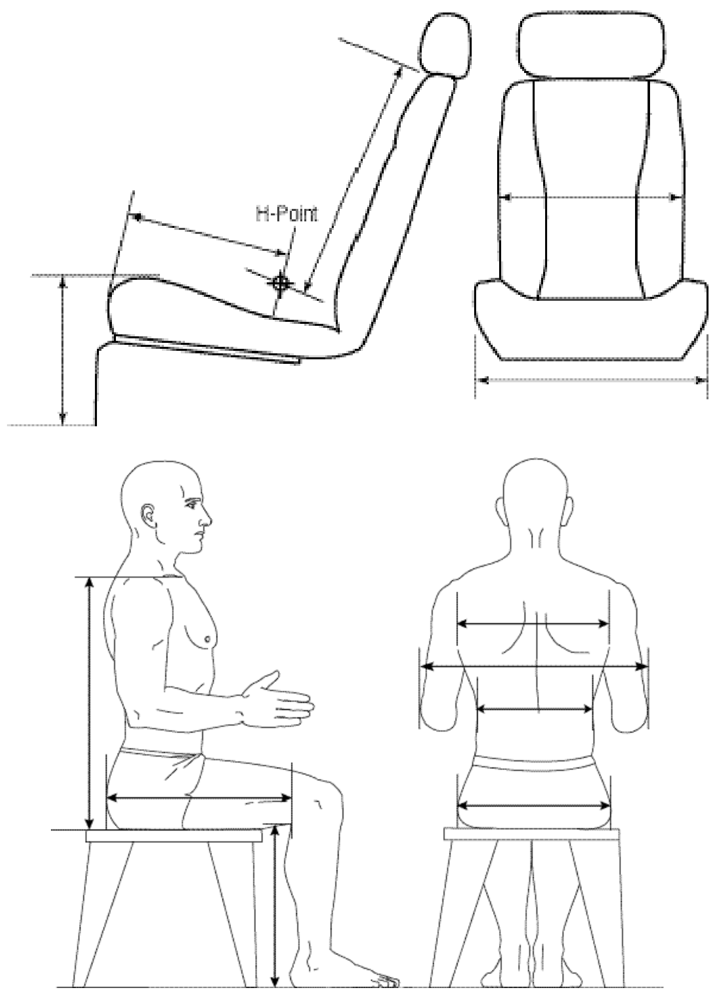

Figure 1. Seat dimensions (top) and related standard anthropometric dimensions (bottom).

The people in the ANSUR database can be viewed as a subset of the more diverse civilian population. In general, the military population is more fit than the civilian population, so the most apparent differences between the groups are found in measures relating to body weight and segment circumferences. A method has been developed to use the distribution information in NHANES for civilians to scale the military data to be applicable to vehicle design.

Using data from ANSUR, linear regressions are constructed to predict each of the anthropometric variables of interest, such as hip breadth, from the overall measures present in the NHANES data. Tables 2 and 3 show these regression results for men and women. Because stature, weight, and sitting height are correlated (known as collinearity), there are problems combining them in the same regression model. Instead, two surrogate variables that capture the same information are used. Body Mass Index (BMI) is calculated by dividing the body mass in kg by the stature in meters squared. A typical value is 25, with thin people having BMIs around 20 and heavy people having BMIs in excess of 30. The ratio of sitting height to stature (SH/S) provides the essential information about body proportions (limbiness), but is much less correlated with stature than is sitting height. BMI and SH/S are also approximately normally distributed, which is generally true of stature and sitting height, but not weight. Table 4 lists the means and standard deviations of stature, BMI, and SH/S for men and women from the civilian NHANES data. These values are used with the regression relationships to obtain estimates of the civilian distributions of the variables of interest.

The sum of two normally distributed, independent random variables is itself distributed normally, with mean equal to the sum of the means of the two inputs. The standard deviation of the sum is equal to the square root of the sum of the squared standard deviations. In other words, the variances add. When a normally distributed random variable is multiplied by a constant, the product is distributed normally with mean equal to the input mean times the constant, and variance equal to the constant squared times the input variance. Algebraically,

$$C = a + b\,A + B$$

where $A \sim N(\mu_A, \sigma_A^2)$, $B \sim N(\mu_B, \sigma_B^2)$, A and B are independent, and a and b are constants. C is then distributed normally, with

$$\mu_C = a + b\,\mu_A + \mu_B$$

$$\sigma_C^2 = b^2\,\sigma_A^2 + \sigma_B^2$$

This provides a means of estimating the civilian distributions of the variables in Table 1. For example, seated hip breadth for women in ANSUR is given by

$$-61.1 + 0.1642\ \text{Stature} + 7.63\ \text{BMI} + e(0, 15.8^2)$$

where e is the normally distributed residual variance from the regression, with mean zero and variance $RMSE^2$ (from Table 3). The estimated mean hip breadth for civilian women is then

$$-61.1 + 0.1642 \text{ Stature} + 7.63 \text{ BMI} =$$

$$-61.1 + 0.1642 * 1627 + 7.63 * 26.3 = 406.7 \text{ mm}$$

using the mean female civilian values for stature and BMI from Table 4. Similarly, the estimated standard deviation of civilian hip breadth is given by

$$(0.1642^2\ 67.2^2 + 7.63^2\ 6.41^2 + 15.8^2)^{1/2} = 52.6 \text{ mm}$$

Using this approach, Tables 5 and 6 compare the estimated civilian means and standard deviations for the measures in Table 1 with the ANSUR values. The biggest differences are found in the width-related measures. For example, the estimated mean hip breadth for civilian women is 22 mm larger than for military women, but the difference in standard deviation is even more striking. The standard deviation of hip breadth for civilian women is over 90 percent larger than for the ANSUR military women. This reflects the general trend of military populations being more fit than civilian populations.

Under the assumption of normality, the means and standard deviations in Tables 5 and 6 can be used to estimate the desired percentiles of each variable. To obtain the desired percentile, multiply the corresponding standard normal quantile by the standard deviation and add to the mean. For example, to obtain the 95^{th} percentile of female hip breadth, multiply 52.6 by 1.64 and add 406.7, yielding 493 mm. Table 7 lists the standard normal quantile values for commonly used percentiles. These values can be easily obtained using the Microsoft Excel standard normal inverse function NORMSINV(*p*), where *p* is the desired quantile (e.g., 0.95) or from tables in any statistics text.

The anthropometric distributions in Tables 5 and 6 are used to estimate the needed percentiles in the Fit parameter analyses that follow. The examples assume that the target population is comprised of U.S. civilians, with 50% males and 50% females. The accommodation boundary is then generally obtained from either the 5^{th} percentile female or 95^{th} percentile male values. Since all of these dimensions are single-sided accommodations (the population is restricted on only one end of the anthropometric distribution), the accommodation provided by the dimensions given in the examples is estimated to be 97.5 percent. Section 2.8 explains how to obtain values for other gender mixes and accommodation levels.

Table 2
Regression Relationships for MEN in ANSUR (mm)*

Variable	Intercept	Stature	SH/S**	BMI	R^2	RMSE***
Acromion Height Sitting	-703.4	0.3786	1222.4		0.75	14.9
Buttock-Popliteal Length	467.1	0.2471	-840.2	1.45	0.80	11.9
Chest Breadth	-29.2	0.1041	****	6.60	0.68	14.4
Forearm-Forearm Breadth	22.9	0.1399	****	10.9	0.61	27.2
Hip Breadth Sitting	-72.4	0.1572	****	6.42	0.77	12.2
Interscye Distance	36.6	0.1244	****	5.76	0.38	24.8
Popliteal Height Sitting	313.4	0.2693	-676.1		0.86	9.2
Waist Breadth Omphalion	-113.2	0.1311	****	7.56	0.73	15.0

* A linear prediction model is constructed by multiplying the stature, SH/S, and BMI coefficients from the table by their respective measurements, summing, and adding the intercept.

** Sitting height/stature.

*** RMSE is the root mean square error, the standard deviation of the residual error from the regression analysis.

**** Not significantly different from zero.

Table 3
Regression Relationships for WOMEN in ANSUR (mm)*

Variable	Intercept	Stature	SH/S**	BMI	R^2	RMSE***
Acromion Height Sitting	-683.7	0.3788	1189.4		0.78	13.4
Buttock-Popliteal Length	510.0	0.2486	-908.9	1.80	0.78	12.4
Chest Breadth	1.5	0.0935	****	5.39	0.59	12.6
Forearm-Forearm Breadth	-27.3	0.1619	****	9.94	0.64	20.9
Hip Breadth Sitting	-61.1	0.1642	****	7.63	0.66	15.8
Interscye Distance	61.2	0.1029	****	5.28	0.32	21.8
Popliteal Height Sitting	371.6	0.2523	-670.5	-1.82	0.86	9.0
Waist Breadth Omphalion	-67.0	0.1045	****	8.0	0.60	18.0

* See notes for Table 2.

Table 4
Civilian Distributions from NHANES III

Variable	Mean	Standard Deviation
MEN		
Stature (mm)	1761	71.9
BMI (kg/m^2)	26.4	4.83
SH/S (mm/mm)	0.524	0.0135
WOMEN		
Stature (mm)	1627	67.2
BMI (kg/m^2)	26.3	6.41
SH/S (mm/mm)	0.529	0.0139

Table 5
Means and Standard Deviations of Anthropometric Variables (MEN)

Variable	ANSUR		Estimated Civilian	
	Mean	S.D.	Mean	S.D.
Acromion Height Sitting	597..8	29.6	603.9	35.1
Buttock-Popliteal Length	500.4	26.6	500.3	25.2
Chest Breadth	321.5	25.5	328.4	35.8
Forearm-Forearm Breadth	546.1	43.6	557.0	60.1
Hip Breadth Sitting	366.8	25.2	373.9	35.2
Interscye Distance	401.5	31.4	407.7	38.3
Popliteal Height Sitting	434.1	24.9	433.4	23.3
Waist Breadth Omphalion	309.3	28.7	317.3	40.6

Table 6
Means and Standard Deviations of Anthropometric Variables (WOMEN)

Variable	ANSUR		Estimated Civilian	
	Mean	S.D.	Mean	S.D.
Acromion Height Sitting	555.5	28.6	561.8	33.2
Buttock-Popliteal Length	481.7	26.6	481.0	26.9
Chest Breadth	279.6	19.7	295.4	37.3
Forearm-Forearm Breadth	468.5	34.7	497.5	67.9
Hip Breadth Sitting	384.5	27.2	406.7	52.6
Interscye Distance	352.0	26.5	367.5	40.8
Popliteal Height Sitting	389.4	23.7	379.5	24.3
Waist Breadth Omphalion	289.7	28.3	313.4	54.8

Table 7
Quantiles of Standard Normal Distribution

Quantile (p)	$\Phi^{-1}(p, 0, 1)$
0.995	2.58
0.99	2.33
0.975	1.96
0.95	1.64
0.9	1.28
(1-p)	$-\Phi^{-1}(p, 0, 1)$

2.2 Cushion Width

Cushion width is specified to accommodate the largest sitting hip breadths in the population, with additional clearance for clothing and movement. The constraining population segment is large females, who have a 95th-percentile seated hip breadth of 432 mm in the Army data. However, Chaffin and Andersson (1991) cite a study of 143 women aged 50–64 years who had a 95th-percentile hip breadth of 457 mm. Schneider et al. (1985), in a study of driver anthropometry, reported an average seated hip breadth of 439 mm in 25 males who were approximately 95th-percentile by stature and weight. This is slightly larger than the 95th-percentile-female hip breadth in the Army data.

Grandjean (1980) recommends 480 mm as a minimum clearance at the hips to accommodate large females with an allowance for clothing. Maertens (1993) recommends a minimum overall cushion width of 500 mm, but does not specify the position at which this dimension is to be measured. Chaffin and Andersson (1991) cite recommendations from a variety of sources for office chair widths between 400 and 480 mm. As noted above, the estimated 95th percentile hip breadth for U.S. civilian women is 493 mm, 61 mm wider than the same percentile in the military population. Since freedom of movement is desired to allow for posture changes, 500 mm is recommended as the minimum clearance at the hips, with 525 mm providing an allowance for clothing.

This does not mean that the seat cushion itself must be 500-mm wide at the hips. An actual cushion width somewhat more narrow might be adequate for a single posture, provided that 500-mm clearance is provided for the hips in the area between 50 and 150 mm above the depressed cushion surface. This requirement primarily constrains the positioning of side bolsters and frame components within 250 mm of the seat centerline. In considering lateral clearance, it is important to make measurements with reference to the depressed seat surface. Seat structures that do not pose a lateral obstruction on the undepressed seat may contact the sitter's hips when the seat cushion is depressed. Further, the seat cushion should deflect evenly across a lateral section at the hips. If the cushion is stiffer at the outer edges because of interference from seat structures, a hammocking effect will constrict the sitter's buttocks, causing the seat to feel too narrow even if the dimensional specifications are met.

The forward part of the cushion should allow the legs to splay at least as wide as the recommended minimum hip clearance of 525 mm. Leg splay can be used by the sitter to change the pressure distribution on the buttocks by redirecting load away from the ischial tuberosities (see Section 3.1) and should not be overly restricted by side bolsters.

Summary

Seat cushions should be a minimum of 500 mm wide, with 525 mm minimum clearance at the hips. The front of the cushion should be a minimum of 525 mm wide to allow for comfortable leg splay.

2.3 Cushion Length

Cushion length is an important determinant of comfort for several reasons. First, a cushion that is too long can put pressure on the back of the sitter's legs near the knee, an area that has many superficial nerves and blood vessels. Pressure in this area will lead to local discomfort and restricted blood flow to the legs. Second, a cushion that is too long will pull sitters forward, away from the backrest, eliminating the possibility of providing appropriate lumbar support. Third, a long cushion can restrict leg splay by interfering with knee movement, and may impede posture changes that alter pressure distributions under the buttocks and upper thighs.

Cushion length is constrained by the buttock-to-popliteal length of the small-female segment of the population. This dimension is measured on the seated subject from the rearmost projection of the buttocks to the popliteal fold at the back of the knee. Gordon et al. (1989) report a 5th-percentile-female buttock-to-popliteal length of 440 mm. From the values in Table 6, the estimated 5th-percentile value for civilian women is 437 mm, only slightly different. For general chair design, Chaffin and Andersson (1991) cite recommendations for cushion length, measured from the furthest forward contact point on the backrest to the front edge of the chair, of 330 to 470 mm. Grandjean (1980) recommends 440 to 550 mm, while Keegan (1964) recommends 432 mm. Maertens (1993) specifies that the cushion should not extend more than 380 mm forward of the H-point (hip point), which is a seating reference point approximating the hip-joint center location of a male sitter who is 50th percentile by height and weight (see SAE J826). Some calculations are necessary to compare the Maertens recommendations with those of other researchers.

In a study of driver anthropometry, Schneider et al. (1985) recorded the postures of small females, mid-sized males, and large males in representative passenger car seats. The small-female sample in that study was approximately 5th percentile by height and weight. Buttock-to-knee length (measured to the *front* of the knee, rather than the popliteal fold) was 527 mm, compared with a 5th percentile for that measure in the Army data of 542 mm. The latter subjects can therefore be considered reasonably representative of the U.S. small-female driver population with respect to thigh length. From the Schneider et al. (1985) measurements taken with small-female subjects in a contoured hardseat, the distance from the H-point to the back of the buttocks on a line connecting the knee joint and hip joint is approximately 135 mm (*cf.* the same measure on the "Oscar" 2-D seating template (Geoffrey 1961) of about 145 mm). Maertens' maximum cushion length recommendation is measured horizontally from the H-point to the forward-most point on the cushion. Assuming a thigh angle of 15 degrees, Maertens' 380-mm horizontal measurement represents 393 mm along the thigh. Adding 135 mm to account for the distance from the H-point to the back of the buttocks, the buttock-to-popliteal clearance is 528 mm as shown in Figure 2. Since 528 mm is substantially greater than the 5th-percentile-female buttock-to-popliteal length of 440 mm, this analysis suggests that the Maertens recommendation is not sufficiently conservative to accommodate smaller drivers. In fact, 528 mm is greater than the buttock-to-popliteal length of 80 percent of the male subjects in the Army survey (80th-percentile male = 523 mm).

The perception of cushion length is likely to be influenced both by seat height and seat cushion angle. At higher seat heights and more inclined cushion angles, the knee angle is reduced, bringing the back of the calf closer to the cushion. Particularly for passengers, high seat heights may necessitate an even shorter cushion to accommodate the legs of short women. The comfort cost of cushions that are too long is substantial for those who are not accommodated. Because the tissue in the popliteal area behind the knee can tolerate almost no pressure, the sitter must either slide forward away from the seatback, or find a footrest to elevate the feet. Either situation provides a substantial comfort problem. This scenario probably arises most frequently in minivans and sport utility vehicles, particularly in second and third seats, which often have higher seat heights than the front seats.

Summary

The cushion length, measured along the thigh line, should not exceed 440 mm from the depressed backrest, or 305 mm from the H-point. An adjustable-length cushion could be used to provide more under-thigh support for larger people, but only a small range of adjustability is needed. The 95th-percentile-male buttock-to-popliteal length is 545 mm, 105 mm greater than the 5th-percentile-female length, so a seat-cushion length increase of 105 mm should be considered the maximum necessary. For sitters with long legs, the cushion may feel too short if the thigh angle relative to the horizontal is substantially greater than the cushion angle, so that only the buttocks are in contact with the seat. These sitters will be accommodated better by an adjustable cushion angle than by a greater cushion length.

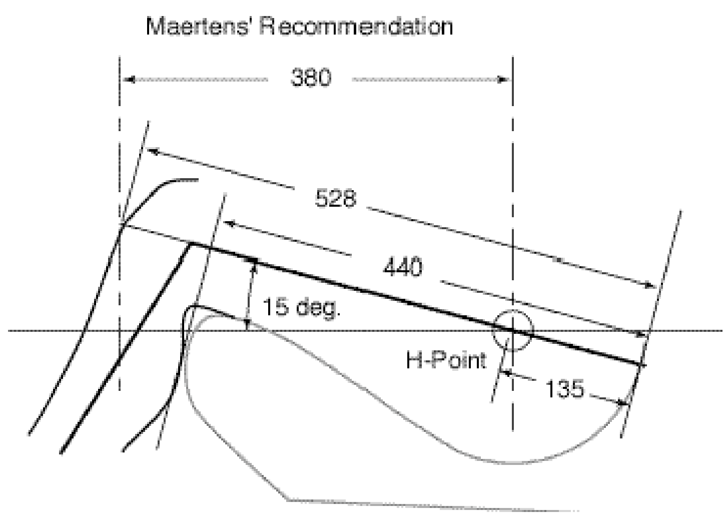

Figure 2. Comparison of Maertens' (1993) and current recommendations for maximum cushion length. (Dimensions in mm -- see text for explanation.)

2.4 Seat Height

Seat height from the floor to the front edge of the cushion should not exceed the seated popliteal height of small women. This parameter is less commonly reported than the height of the seating reference point (e.g., H30 or H31 in SAE notation). As noted above, the undersurface of the distal thigh (popliteal fossa) cannot tolerate substantial surface pressure. Hence, the undeflected surface of the front edge of the cushion (waterfall) should be used as the measurement point for assessing seat height in relation to comfort. The estimated 5th-percentile popliteal height for U.S. civilian women is 340 mm. A substantial percentage of minivan and SUV seats do not meet this criterion. However, popliteal height is measured without shoes, while most vehicle occupants wear shoes. Unpublished data from UMTRI show that the average heel height (difference between stature with and without shoes) for women wearing "comfortable driving shoes" is about 23 mm (s.d. 11 mm). There was no apparent correlation between stature and heel height, indicating that short women did not tend to wear higher heels. This suggests that the maximum height of the front cushion edge could be as high as 363 mm while disaccommodating only 2.5 percent of the population (5 percent of women). However, because an excessive seat height is likely to be extremely uncomfortable, due to pressure on the back of the thighs at the knee, a more conservative value might be calculated. For example, to accommodate 99 percent of women with shoes (and essentially all men), the front-cushion height should be no higher than 346 mm. These design recommendations should be taken into account not just for fixed-height passenger seats, but also for height-adjustable driver seats. Vehicle design assessments sometimes assume that short drivers will adjust the seat to its highest position to maximize eye height. Yet, the leg length, represented by popliteal height, imposes an important constraint on seat height that is increasingly important at high seat heights. Particularly for minivans and sport utility vehicles, the correlation between (lower) leg length and eye height should be investigated when considering the comfort of smaller drivers.

Summary

Seat height from the floor, measured at the highest surface of the undepressed cushion, should not exceed 363 mm. To accommodate up to 99 percent of women, and virtually all men, a more conservative value of 346 mm should be used.

2.5 Backrest Width

Minimum backrest width at the waist level is constrained by the back width of the large-male segment of the population. At waist height, 95th-percentile-male back width measured on a standing subject is 360 mm in the Army survey. The estimated civilian value is 384 mm. In the Army survey data, 95th-percentile-male seated waist height (above the rigid seat surface) is 315 mm. Schneider et al. (1985) report a seated waist breadth of 361 mm for large males (approximately 95th percentile by height and weight). Consequently, the recommended width at the narrowest part of the backrest, 315 mm above the depressed seat cushion or 220 mm above the H-point, measured along the H-point manikin backrest line, is 384 mm, using the larger civilian value. (The vertical distance relative to the H-point was calculated by assuming a 95-mm distance from the point of maximum deflection of the seat surface to the H-point.) In practice, the minimum backrest width should be larger to allow for posture changes and clothing.

The backrest width above and below the waist level should be larger to accommodate the greater hip width below and chest width above. In the upper part of the backrest, the minimum backrest width should provide support for the width of the chest of a large male when reclining. The interscye distance, measured across the back between the posterior axillary folds, is an appropriate anthropometric reference measurement. In the Army data, the 95th-percentile-male interscye distance is 456 mm. (Although this measurement was taken with a tape measure held against the skin, it is sufficiently close to the linear distance to be used for current purposes.) The corresponding civilian estimate is 471 mm. The sitting height of the posterior scye was not measured in the Army survey, but Schneider et al. provide posterior scye height for large males in an automobile seating posture. Using the trochanterion height from Schneider et al. as an approximation of H-point height, the vertical distance from posterior scye to H-point for large males is approximately 295 mm. Assuming a 22-degree back angle, the measurement along the back line is 318 mm. These data suggest a minimum backrest width of 471 mm at a distance of 318 mm above the H-point measured along the manikin back line. As with the seat cushion width recommendations, a value larger than the minimum presented here is desirable to allow for a range of postures.

Since the effective backrest width is integrally tied to the backrest contour, some discussion of lateral contour is necessary in this context. The contour of the backrest behind the shoulders of the sitter should be nearly flat to avoid interference with arm movement. The sitter should be able to extend his or her inboard arm straight to the side without interference from the seat. The maximum height of lateral supports or "wings" on the backrest can be determined by estimating the posterior scye height of small women. Using data from Schneider et al., the posterior scye height for small females (approximately 5th-percentile female by height and weight) is about 30 mm lower along the back line than the large-male scye height, or about 288 mm above the H-point along the back line. Consequently, any lateral contouring or wings should not extend more than 288 mm above the H-point along the manikin back line.

Reynolds (1993) uses the 95th-percentile-male chest width of 367 mm to specify minimum width in the upper part of the backrest. However, the chest width in the Army data cited by Reynolds is an anterior measurement that is smaller than the posterior measurement, which includes the width of the latissimus muscles. Grandjean (1980) recommends 480 mm for backrest width, which is compatible with the upper-back width obtained from the above analysis of large-male anthropometry. Most of the recommended ranges for backrest width cited by Chaffin and Andersson (1991) for office chairs range between 360 and 400 mm. Typically, a narrower backrest would be desired in an office chair than in an auto seat to provide for greater upper-torso mobility in a larger work envelope. In an auto seat, a wider backrest provides more lateral stability for the sitter during cornering maneuvers.

Maertens (1993) specifies lateral radii of curvature rather than widths for the backrest, and specifies different radii for different vehicle types, from sporty to luxury cars. These radii may be compared to the widths specified above by considering a particular body depth and calculating the clearance provided at that depth by the specified radius. For sporty cars, Maertens recommends a minimum lateral contour radius of 300 mm at a lumbar height of 250 mm above the depressed seat surface. From the Army survey, the 95th-percentile-male abdominal extension depth is 290 mm. Taking one-half this value as a representative depth for the widest part of the abdomen gives 145 mm as shown in Figure 3. On a line 145 mm forward of the maximum backrest indentation, the effective backrest width with a 300-mm radius is 514 mm, substantially greater than the 360 mm necessary to accommodate the 95th-percentile-male waist width. Since the Maertens recommendations for other types of cars are 450-mm and 800-mm radii, a large percentage of the population will be accommodated by these recommendations. Maertens also recommends that the thoracic section of the backrest, 321 mm above the H-point along the manikin back line, have a nearly flat lateral contour, specifying a 1-meter minimum radius of curvature for the contour in that area.

Summary

The backrest should be a minimum of 384 mm wide at a point 220 mm above the H-point along the manikin back line, and a minimum of 471 mm wide at a point 318 mm above the H-point. There should be no lateral clearance restrictions (*i.e.*, no side bolsters) extending more than 288 mm above the H-point.

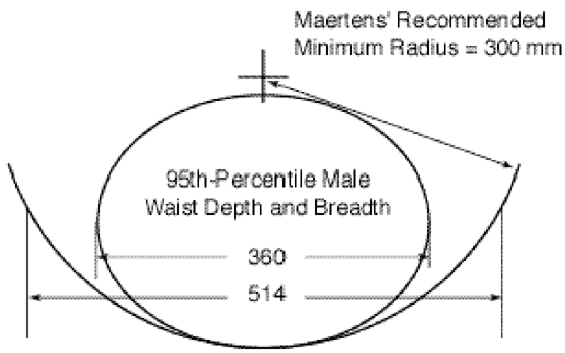

Figure 3. Illustration of compatibility between Maertens' (1993) lateral backrest contour specification for 250 mm above the depressed seat surface and 95th-percentile-male waist dimensions.
Waist cross-section is shown as an ellipse--actual body shape is flatter toward the rear, which may affect the fit between the seat cross section and sitter's back.

2.6 Backrest Height

Backrest height requirements are affected by geometric constraints imposed by FMVSS 202 (U.S. Office of the Federal Register 1992) dealing with head restraints for protection in rear impacts. Within these constraints, there is only a small range of backrest heights that can be specified. From strictly anthropometric considerations, the backrest should be as high as possible without restricting rearward vision for small drivers. The acromial (shoulder) height is a reasonable anthropometric measure to use to set the parameter level. The 5th-percentile-female acromial height is 414 mm above the H-point, while the 95th-percentile-male acromial height is 551 mm above the H-point (Gordon et al. 1989). The civilian values are essentially the same. For comparison, the 5th-percentile-female eye height is 590 mm above the H-point. Thus, backrest heights within the range of 5th-percentile-female to 95th-percentile-male acromial heights will adequately accommodate the population. Note from the previous discussion of backrest width that the 95th-percentile-male posterior scye height is 318 mm above the H-point, so that a backrest designed to the 5th-percentile-female acromial height (414 mm) will still provide substantial upper-back support to a large male.

Maertens (1993) recommends that the termination of upper back contact with the seat (using a design manikin) should be 450 to 500 mm above the H-point, or 545 to 595 mm above the depressed seat surface, depending on the style of the seat. This range will provide adequate upper-back contact for large males. Grandjean (1980) recommends a 500-mm backrest height, or 405 mm above the H-point.

Summary

The backrest should extend 410 to 550 mm above the H-point, measured along the manikin back line.

2.7 Seat Position Width

The lateral space required to seat people side-by-side, such as on a bench seat, can be estimated using the forearm-to-forearm breadth. This is measured with a person sitting erect with the upper arms against the torso and the elbows bent 90 degrees. The width between the outermost parts of the forearm is a good measure of the lateral space required. The upper percentiles of this dimension are larger than the corresponding percentiles for hip breadth or shoulder (bideltoid) breadth. The limiting dimension for a mixed-gender population is obtained from large men. The civilian estimate for the 95^{th}-percentile male value is 656 mm, without accounting for clothing or space for movement. Since the values for women are considerably smaller, this width will accommodate 97.5 percent of a 50/50 male/female population.

Summary

The lateral space required to accommodate 95 percent of men, without a clothing allowance, is 656 mm.

2.8 Gender Mixes and Alternative Accommodation Levels

In the preceding calculations, the 5^{th}-percentile female or 95^{th}-percentile male values have been used, although in some circumstances other values would be more appropriate. Human factors analyses using anthropometry have typically aimed to accommodate 95 percent of a population, but modern designs, particularly of consumer products like automobiles, should strive to accommodate larger percentages. On most Fit parameters, the design limit is one-sided. For example, hip breadth gives a minimum value for seat width, with no limit on how much wider a seat could be. For one-sided accommodation boundaries, 97.5 percent of a 50/50 male/female population would be accommodated by recommendations based on 5^{th}-percentile female or 95^{th}-percentile male values.

In most cases, the corresponding percentiles for men and women are sufficiently different that only one gender needs to be considered in setting the design limit. For example, only about 1 in 1000 men has a popliteal height smaller than the 5^{th}-percentile-female value of 340 mm. However, the gender distributions of some variables, such as hip breadth, overlap more.

The most general way to set design limits, or to assess the accommodation provided by a particular value, is to use both the male and female distributions. This also provides a means of performing assessments when the gender mix is uneven (e.g., 60% female). An example using hip breadth will suffice to illustrate the technique. Begin by considering each gender separately. Find the fraction of each gender who have hip breadth smaller than the candidate design width *w*.

$$(w - \text{Mean Hip Breadth})/\text{Std.Dev. Hip Breadth} = z$$

Then $\Phi(z)$ = fraction accommodated, where Φ is the standard normal distribution. Taking w = 450 mm, the male calculation is

$$z = (450 - 374)/35.2 = 2.16$$

Using the Excel cumulative normal function =NORMSDIST(2.16), the percentage of males accommodated is 98.5 percent. For women,

$$z = (450 - 407)/52.6 = 0.82$$

and the percentage of women accommodated is 79.3 percent. If the target population is 50 percent male, then the accommodated percentage of the population is

$$0.5\ (98.5) + 0.5\ (79.3) = 88.9 \text{ percent}$$

Inserting the appropriate population fractions gives the results for other gender mixes, such as 60 percent women:

$$0.4\ (98.5) + 0.6\ (79.3) = 87 \text{ percent}$$

2.9 Whole-Body Scan Data

Recent advances in scanning technology have led to laser scanners that can rapidly capture the three-dimensional shape of the entire body (Jones and Rioux 1997). This technology is now being applied in a new cooperative program involving government and industry partners to gather a new database of human body shapes. The Civilian American and European Survey Anthropometry Resource (CAESAR) program is using whole-body scanners as well as conventional anthropometric techniques to scan up to 2500 men and women in the U.S. and an equal or greater number in the Netherlands and Italy. The CAESAR program is coordinated by the Society of Automotive Engineers' Cooperative Research Program, which has secured the support of over 30 industry partners. The U.S. portion of the program is being supported primarily by the U.S. Air Force and led by researchers at the Computerized Anthropometric Research and Design (CARD) Laboratory. At this writing, scan data from over 600 U.S. adults are available for analysis.

Participants in the U.S. CAESAR program have been measured at a number of sites around the country, including Los Angeles, Detroit, and Ames, Iowa. Data collected from each participant include 45 standard anthropometric measures and descriptive demographic data, such as occupation, age, and place of birth. For body scanning, each participant wears a set of close-fitting shorts, and the women wear a sports bra. Small contrast targets are placed on the participant's skin to mark the location of 73 body landmarks. The three-dimensional locations of these targets are extracted from the body scan data.

Each participant is scanned in three postures, shown in Figure 4. In posture A, the participant stands with the arms and legs spread to allow the scanner to record the inner surfaces of the arms and legs, and to reduce the shadowing of the torso by the arms. Posture B is a relaxed but unsupported sitting posture, with the arms at the sides and the palms resting on the thighs. Posture C is a “coverage” sitting posture, with the limbs oriented to achieve maximum coverage of the body surfaces by the scanner.

Scanning in the U.S. CAESAR program is conducted using a Cyberware whole-body scanner. The scanner and associated software are effective for extracting both traditional anthropometric measures as well as new measures that require three-dimensional body shape information. The scanner uses lasers to record body shape in horizontal slices at 2-mm increments. The scanning heads travel vertically on a frame surrounding the subject, completing a whole-body scan in about 17 seconds. The data from a scan consist of 150,000 to 300,000 three-dimensional surface points linked in a polygonal mesh. Each vertex also has color information that can be used to render the surface and to detect the locations of the contrast landmark markers. Semi-automated procedures are used to extract the three-dimensional coordinates of the landmarks.

Because the whole-body scan data capture a large portion of the body surface, virtually any body shape parameter of interest can be measure on the scans. For example, instead of being limited to a small number of two-dimensional back breadth measurements, detailed contour information can be obtained at any seat or anatomical location.

The tools and methods for using these data are still in their infancy. Tools to extract information automatically from scans are needed. These tools might include an automated anthropometer that could be programmed to make a particular measurement, which would then be carried out on each scan in the database. Equally important, statistical methods to quantify fit using complex shapes must be developed. The preceding analyses using one-dimensional measures must be generalized to handle the fit between the three-dimensional shapes of the sitter’s back and the seat, both of which are deformable. Finally, subjective models must be developed to relate the fit between the sitter and seat to subjective assessments. Using ratings from study participants, quantitative guidelines need to be developed to express the difference between a fit that is too tight and one that is too loose. Although these are substantial challenges, the payoff will be seats that are designed to fit the target population more comfortably.

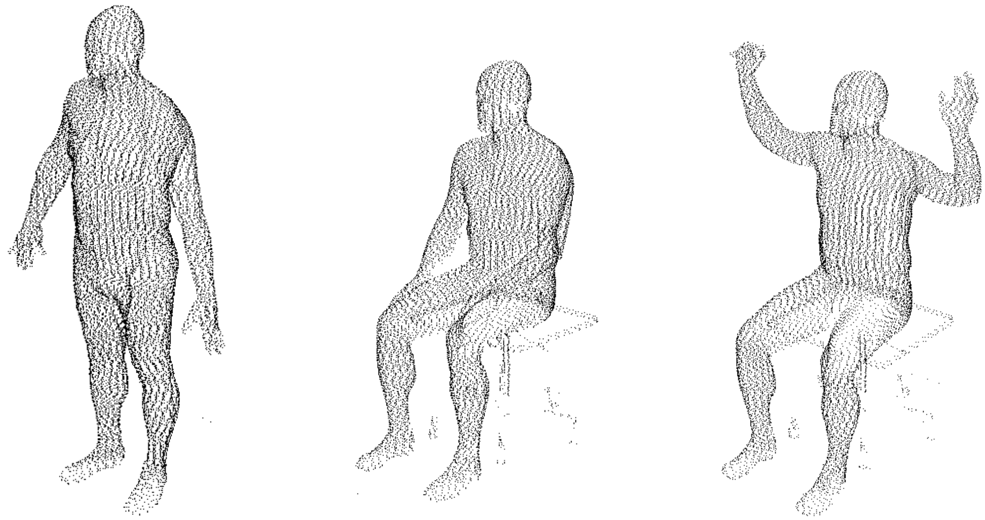

Figure 4. Postures used for CAESAR scans (from top, A, B, and C), shown as point cloud data (approximately one tenth of data points are shown).

3.0 FEEL PARAMETERS

Design parameters that affect the local sensation of comfort at the interface between the sitter and seat are called Feel parameters. As noted above, this analysis assumes that comfort is the absence of discomfort, so that optimal levels for Feel parameters are those that minimize discomfort. The possibility that the surface texture of the seat may promote, for example, a feeling of luxury, is not considered here because no quantitative information on this type of comfort-inducing feature is available.

The effects of Feel parameters are detected primarily by nerve receptors in the skin and superficial underlying tissues. Five stimuli applied to the skin surface are important contributors to local tissue discomfort.

Pressure (force directed normal to the skin surface) is generated whenever the tissue bears external load. Of course, the skin is continually under hydrostatic pressure from the atmosphere, but this pressure does not cause discomfort. In fact, the skin and underlying tissues are remarkably impervious to hydrostatic pressure (equal components in all directions) as when submerged in water. Body tissues can readily tolerate up to 240 psi (12400 mm Hg) hydrostatically, equivalent to 500 ft under water. However, uniaxial local pressure of as little as 1 psi (50 mm Hg) can cause pathological changes in body tissues (Chow and Odell 1978; Husain 1953). The physiological effects of surface pressure in seating are due to deformation of the skin and underlying tissues, resulting in occlusion of blood vessels and compression of nerves. Pressure on nerves can cause discomfort immediately, while loss of blood circulation leads to discomfort as cell nutrition is interrupted and metabolites build up in the tissues. The state of stress in body tissues produced by application of external pressure can be decomposed into a combination of hydrostatic and shear stresses. Chow and Odell (1978) point out that since body tissue is relatively impervious to hydrostatic stress, it is the shear stress and accompanying deformation that are harmful.

Shear stress results internally whenever a uniaxial load is applied to the skin, as is the case in sitting when pressure is applied to the dorsal surfaces of the buttocks and thighs. As indicated above, the primary cause of discomfort associated with external pressure is the shear stress and deformation that result internally. Shear stresses applied externally (surface friction) have a compounding effect, producing larger tissue deformations than the surface pressure alone. External shear stress often occurs in seating, particularly under the buttock area when the torso is reclined.

Temperature can affect the local feeling of discomfort, with both high and low temperatures being perceived as uncomfortable. Both the foam padding and surface material of the seat affect the skin temperature at the interface.

Humidity interacts with temperature to influence discomfort. Perspiration that is trapped against the skin by the upholstery can produce a sticky feeling if the skin is warm, or a clammy feeling if it is cold. Both the foam padding and the surface covering of the seat are important determinants of local humidity on the seat.

Vibration is transmitted through the seat to the occupant whenever the vehicle is operating. The extent to which the seat attenuates or amplifies vibrations can have important effects on dynamic comfort. Vibration is the most studied of the feel parameters, yet, in some ways, the recommendations are analogous those relating to pressure distribution. High levels of vibration transmitted to the occupant are undesirable, but the relationships between comfort and vibration magnitude, frequency, and direction are not yet well understood.

The Feel parameters described above are discussed in greater detail in the following sections. Pressure and shear stress are considered together because their discomfort-causing mechanisms are closely related. Similarly, local temperature and humidity are usually measured simultaneously and are discussed together. Because of the difficulty in measuring the objective levels of these stimuli, as well as the relationships between the stimuli and discomfort, the recommendations in this section are more qualitative than in those sections dealing with Fit and Support parameters. The exception is vibration, which is amenable to study using precise quantitative methods.

3.1 Pressure and Shear

Seat surface pressure has been pursued for decades as an objective measure that might be suitable to predict the comfort of seats (*e.g*., Lay and Fisher 1940; Ward and Southall 1993; Park and Kim 1997; Cohen 1998). Measurement equipment has included a matrix of spring-loaded nails (Reswick 1961), strain gages (Thier 1963), inductive force transducers (Diebschlag and Müller-Limmroth 1980), a light-transmission pedobarograph (Treaster and Marras 1989), and flexible tactile sensors (Podoloff 1993). Pressure distribution measurement methods have recently been evaluated by Gyi et al. (1998), among others. Ng et al. (1995) described an "intelligent" seat system that attempts to improve comfort by continuous monitoring and modification of the seat surface pressure distribution. Hughes et al. (1998) examined the relationship between pressure distribution and foam stiffness in an effort to improve seatback comfort.

The appeal of the seat surface pressure distribution as an objective measure of the comfort of a seat is that (a) pressure sensors produce data with high numerical resolution, (b) excessive pressure is anecdotally and experimentally associated with discomfort, and (c) excessive pressure can cause pathology (*e.g*., decubitus ulcers or bedsores). Consequently, there appears to be a simple linkage between the stimulus, the physiological response, and the psychological response. However, the actual relationship has been found to be more complex.

There are two primary methods by which researchers have attempted to link discomfort and pressure distribution. The first and most common procedure is to measure the pressure distribution for a variety of seats or sitting conditions for which subjective comfort assessments are also obtained (*e.g*., Lay and Fisher 1940; Kamijo et al. 1982; Date 1988; Lee and Ferraiuolo 1993; Park and Kim 1997; Gyi and Porter 1999). Regression analysis can be used to identify relationships between discomfort and pressure levels in particular body areas, *e.g.,* under the ischial tuberosities. An alternative method is to evaluate the comfort of a large number of seats and then to compare the overall pressure distributions of seats judged to be “comfortable” with those considered “uncomfortable.” Kamijo et al. (1982) present an example of the latter method. The pressure distribution produced by a mid-sized Japanese male was recorded on 40 seats that were previously evaluated subjectively by a panel of fifteen people. The authors do not report the duration of the discomfort evaluation trials. The differences in the pressure distributions between seats categorized as “comfortable” and “uncomfortable” were used to recommend levels of pressure at particular seat locations.

There are some important limitations to the method of Kamijo et al. First, there is little evidence that the specific aspects of the pressure distribution that were selected for emphasis (*e.g.*, the pressure in the lower-back area) contributed substantially to the overall comfort of the seats. Second, comfort ratings obtained during a short-duration, static assessment may not be representative of the long-term comfort of the seat, which might be affected more strongly by the pressure distribution. These limitations are inherent in the regression method since a linkage between local pressure and discomfort is assumed, but a mechanism is not demonstrated. Park and Kim (1997) and Gyi and Porter (1999) have conducted similar analyses. In both cases, an attempt is made to uncover relationships between parameters of pressure distributions and subjective assessments. While Park and Kim reported “approximate” correlation, “a clear, simple, and consistent relationship between interface pressure and driving discomfort was not identified” in the Gyi and Porter study. Unfortunately, that statement sums up the success of efforts to date to use pressure distribution as an objective measure of comfort.

The second approach to specifying appropriate pressure distributions is to consider the physiological response of the skin and underlying tissue to the application of pressure. This area of investigation has received considerable emphasis in the medical and rehabilitation literature because of the clinical importance of pressure sores for insensate and paralyzed patients (*e.g.*, Bader et al. 1986; Chow and Odell 1978; Drummond et al. 1982; Hobson 1992; Rosemeyer and Pförringer 1979; Sacks et al. 1985; Shields and Cook 1992). Application of guidelines developed for these purposes to the design of vehicle seats for the entire driving population is problematic for several reasons. Able-bodied sitters detect interference with blood flow as discomfort and shift their postures, if possible, to reduce the discomfort by relieving the pressure. People at risk for pressure sore formation are generally insensate or incapable of voluntary pressure-relieving movement, so the duration of application of high pressures is greater. The duration of pressure application determines the maximum pressure that can be sustained without tissue damage. People who remain in one posture for longer periods of time, *e.g.,* wheelchair users, require lower maximum pressure levels than able-bodied sitters to avoid pressure sore formation. In general, able-bodied sitters can tolerate higher pressure loading, provided they are able to shift postures to relieve pressure. Hence, different criteria should be used to design seating for the able-bodied and insensate/immobile populations.

The aspects of the medical studies of pressure sore formation that are most applicable to seating for the general population concern the physiological effects of surface pressure and shear on tissue ischemia (Husain 1953; Kosiak 1961). Surface pressure has been found to occlude blood vessels in the underlying tissues, particularly near bony prominences such as the ischial tuberosities. The level of pressure necessary to cause occlusion depends on many factors, including the structure of the tissue (muscle, fat, etc.) and the shape of the loading surface.

It may seem that the most reasonable way to use seat surface pressure data to improve seat design would be to modify the seat to reduce the peak pressures and pressure gradients to the extent possible. Underlying such an approach must be an assumption that the various body regions in contact with the seat have equal tolerance to pressure. This, however, is not the case. Many researchers have sought to identify "physiologic" pressure distributions that direct the load to the various body tissues proportionate to their ability to withstand that load without discomfort (*e.g.*, Lay and Fisher 1940; Åkerblom 1948; Rosemeyer and Pförringer 1979; Diebschlag and Müller-Limmroth 1980). The primary finding has been that the tissue over the ischial tuberosities, typically the site of the peak pressure in sitting, is better suited to carrying load than the other tissues of the buttock and thigh.

When a person is seated, the large gluteal muscles are pulled to the side of the ischial tuberosities by flexion of the hip joint and pressure from the seat surface, leaving a flesh margin of only a few centimeters over the ischii. These areas will bear a substantial part of the body weight if the seat surface is flat and firm. Local pressures at the tuberosities have been reported as high as 60 psi for heavy, lean subjects on a flat, rigid pressure measurement device (Hertzberg 1972). Although sustained high pressure over the tuberosities will cause discomfort, the overlying tissue is less sensitive to pressure than the muscle tissue surrounding the tuberosities. Muscle responds to pressure with ischemia and a burning sensation at lower pressure levels than does the skin and fat tissue overlying the tuberosities.

A desirable seat cushion pressure distribution will therefore maintain the peak pressures in the area of the ischial tuberosities. There are few recommendations in the literature for the magnitude of the peak pressure. Diebschlag et al. (1988) specify that pressures under the tuberosities should be 1–3 N/cm^2 (10–30 kPa, 1.4–4.3 psi) and 0.8–1.5 N/cm^2 (8–15 kPa, 1.2–2.2 psi) in the area around the tuberosities. Large variance in peak pressure across sitters can be expected since peak pressure is strongly dependent on body weight and build. For example, heavier people will generally exhibit higher pressure peaks, but heavy people with substantial fat tissue in the buttock area may experience lower pressure peaks than lighter, but leaner, sitters. Because of this variability, it is probably unreasonable to specify a target value for peak cushion pressure without also including a description of the population for which that value is appropriate. Further, some sitters with little internal padding will be more sensitive to peak pressures than others because they will experience greater internal tissue stresses under the same pattern of external stress.

As noted above, surface pressure that is not evenly applied over the skin surface (nonhydrostatic) produces shear stress and strain in the tissue (Chow and Odell 1978). This resultant shear, rather than the normal stress, is probably responsible for the ischemia and discomfort produced by sustained pressure. When shear is applied directly to the surface of the skin, the problem is compounded. Hobson (1992) reported that the application of surface shear can reduce the pressure required to occlude blood vessels by nearly half. Surface shear results when the support force generated by the seat is not normal to the skin surface. The most common site of surface shear is under the buttocks, where a rearward-directed shear force acts to keep the sitter from sliding forward out of the seat. Hobson (1992) investigated the effects of posture on the pressure distribution and aggregate seat cushion shear force for twelve spinal-cord-injured and ten able-bodied subjects. Reclining the backrest while holding the seat-cushion angle constant was found to increase the shear on the seat cushion. For example, a flat seat cushion coupled with a 20-degree back angle increased the cushion shear by 25 percent over the erect seated condition. Angling the seat pan upward as the back angle is increased reduces this effect.

Since back angles in auto seats are typically 20 to 25 degrees, substantial surface shear will be generated on the seat pan if the cushion is not angled and contoured appropriately. When the cushion is angled up, or the cushion is contoured to achieve the same net effect, the normal force against the buttocks and thighs has a rearward component that acts to reduce the surface shear required to maintain the posture. However, the cushion should not be angled excessively because the trunk/thigh angle may become uncomfortably small and posture change (as well as seat ingress/egress) may become difficult. Preferred angles for cushion and backrest in the automotive environment are discussed below in Section 4.

Summary

The lack of consensus regarding the relationship between pressure distribution and discomfort, even after decades of research, may be discouraging for the seat designer. However, there are several seat design guidelines relating to pressure distributions that are justified by the current state of knowledge.

1. A good seat cushion will produce pressure distributions for sitters with a wide range of anthropometry that show peaks in the area of the ischial tuberosities with gradual decreases in pressure toward the front and sides of the cushion. The pressure under the distal half of the thigh (*e.g.*, from 200 mm forward of the H-point to the front of the seat) should be minimal. Åkerblom (1948) and others have pointed out that the under-thigh tissue has minimal resistance to deformation until the tissue nears its compression limit against the femur, leading to considerable restriction of circulation and consequent discomfort. Particular attention should be paid to the pressure distributions of short persons, who are more likely to encounter interference from the front edge of the cushion.

   A reduction in the pressure gradient is also desirable, since the pressure gradient is likely related to internal shear. Typically, a high pressure gradient would be observed near the tuberosities on a very firm cushion. Softening the cushion slightly would reduce both the peak pressures and the gradients.

2. Backrest pressure distributions should show peaks in the lumbar area. Kamijo et al. (1982) found lumbar pressure peaks of about 2.5 kPa in seats judged to be

comfortable compared with lower values in uncomfortable seats. A backrest with adequate lumbar support will produce pressure peaks in the lumbar area, but excessively high pressures due to a very firm lumbar support can lead to discomfort in long-term sitting (Reed et al. 1991a, 1991b).

3. Some sitters will produce relatively even pressure distributions, even on hard seats, because of ample physiological padding, while other more lean subjects will produce high pressure peaks even on a well-padded seat. Since the former are not likely to experience discomfort because of excessive local pressure, it is reasonable to restrict many pressure distribution investigations to specific subpopulations who are particularly sensitive to changes in seat cushioning, namely, heavy, lean subjects, and small subjects for whom cushion-leg interference is more likely. Seats designed to meet the pressure requirements of these sitters are likely to be acceptable to others as well.

4. The use of excessive seat padding to reduce peak pressures by more evenly distributing pressure on the seat pan is likely to contribute to discomfort by restricting pressure-relieving movement (Åkerblom 1948; Grandjean 1980). The design of the seat cushion should allow easy transitions to multiple postures so that sitters can adjust their pelvis placement to alter the pressure distribution patterns. If the cushion is too soft, changing the pelvis position within the constraints imposed by the driving task will not substantially alter the pressure distribution.

Once a pressure distribution with peaks near the tuberosities surrounded by a smooth gradient has been obtained, subjective assessments by sensitive subjects over a long-term sitting session should be used to determine if peak pressure reduction accomplished by the seat padding is sufficient. No local maxima should be found in the pressure distribution outside the tuberosity and lumbar areas.

3.2 Temperature and Humidity

The microclimate at the interface between the sitter and seat is important to the overall comfort of the seat. Glassford and Shvartz (1979) estimate that the metabolic heat production of a driver is approximately 191 W. Considering a typical driver to have 1.81 m^2 of skin surface area, Glassford and Shvartz estimate that the average surface heat flux must be about 105 W/m^2. Heat is transferred away from the body surface by conduction, convection, radiation, and evaporation. At the interface between the sitter and seat, conduction and evaporation are the primary means of removing heat from the skin surface.

The skin temperature in body areas contacting the seat will approach body core temperature because of the insulating effect of the seat padding and covering. Glassford and Shvartz report that an acceptable skin temperature range is 92 ± 2.6 degrees F (33±1.4 degrees C). However, the most important aspect of the microclimate is the humidity, which is determined by the amount of moisture released by the skin and the water vapor permeability of the seat. A buildup of humidity at the skin surface can lead to discomfort, partly because of an increase in the coefficient of friction when the skin is moist. This is particularly important during conditions of high heat loading on the occupant, for example, when driving on warm, sunny days.

Several researchers have addressed the vapor permeability of seat padding and covering materials. Glassford and Shvartz investigated 45 trim-cover materials, 16 trim pads, and five foam-cushion pads for impedance to body heat loss using a laboratory apparatus designed to simulate the temperature and water vapor production of the skin. The authors established a minimum desirable heat flux of 75 W/m^2. The heat flux of the typical seating materials they investigated ranged from 20 W/m^2 to 110 W/m^2, indicating that some of the materials would be unacceptable as seat coverings. Glassford and Shvartz found that small perforations in the surface of an otherwise unacceptable covering could bring the heat transfer capabilities into an acceptable range.

Temming (1993) introduced an advancement of the Glassford and Shvartz technique that utilized a “sweat impulse test” to assess the suitability of car seats for warm-weather use. A heated pad moistened with a fixed amount of water was placed against the seat surface for a period of three hours. Temperature and humidity sensors between the pad and the seat monitored the microclimate as the water diffused into the seat. A weight placed on the pad loaded the surface to a pressure approximating that produced by a seated occupant. The water vapor permeability was evaluated for different seats by comparing the rate at which the humidity at the test site decreased. Large differences in permeability were found among production car seats. The backrests of seats were generally found to have higher permeability than the seat cushions, probably because of thinner foam padding on the backrest. Temming does not specify a particular level of vapor permeability that is acceptable, but suggests that higher permeabilities will lead to greater comfort, particularly under high heat load (summer) conditions.

Diebschlag et al. (1988) report studies of the effect of foam type, thickness, and compression on vapor permeability and the resulting effect on the microclimate against the skin. Although different foam compositions varied in their permeability, water vapor transfer increased with foam compression up to about 80 percent of full thickness, above which the permeability dropped markedly. As the foam is compressed, the shorter diffusion distance speeds vapor transfer until the compression is sufficient to occlude the minute passages in the foam and block the water vapor. Diebschlag et al. also found that perforations greatly increased the vapor permeability of covering materials. The authors suggest that the vapor permeability of upholstery can be increased up to 85 percent by appropriately placed perforations representing a total of only 10 percent of the seat surface area.

Efforts are now being made to actively control the microclimate at the seat surface. Madsen (1994) reports on the effects of ventilating car seats using forced air inside the cushion and backrest. Many seats for vehicles sold in cold climates now include seat heaters. Brooks and Parsons (1999) report on a system that uses an encapsulated carbonized fabric heater to obtain a more even distribution of heat.

Summary

Few studies have reported quantitative assessments of the microclimate at the sitter-seat interface that can be used to design more comfortable seats. The key findings are:

1. Body heat and water vapor must be allowed to pass through the seat. Seat coverings that substantially impede heat or water vapor transfer are to be avoided.

2. The total heat flux through the seat, including heat transfer due to evaporation, should be about 75 W/m^2. Perforated cover materials are desirable because of reduced resistance to water vapor diffusion.

3. "Bottoming out" of foam padding should be avoided because of the large increase in resistance to water vapor diffusion that occurs when foam compression exceeds 80 percent. Careful investigation of areas where padding is thin, for example, in the lower-back region, should be made to ensure that acceptable vapor permeability is maintained under a wide range of sitting conditions.

3.3 Vibration Transmission

The vehicle seat functions as part of a system, including the tires and vehicle suspension, that is intended to reduce the effects of irregularities in the road surface on occupant accelerations. Simply stated, the seat is a key component of ride comfort. Seats are usually bolted to the floor of the vehicle, which is connected through metal components to the suspension, tires, and then to the road. As a vehicle moves down the road, the road imparts displacements to the surface of the tires, primarily in the vertical direction. As these motions are transmitted through the suspension and into the vehicle chassis, some frequencies are attenuated and others amplified, depending on the resonances of the structures. Different displacements applied to the four wheels result in lateral and fore-aft accelerations that are transmitted along with the vertical vibration into the seat.

It might seem that an ideal seat would attenuate all acceleration inputs and completely isolate the occupant from the road. Of course, this cannot be the case, since the seat must move with the vehicle, and further, because some feel for the vehicle motion is generally desirable, especially for the driver.

Extensive experiments have been conducted in laboratory settings to determine the sensitivity of humans to vibration. A thorough review of this literature can be found in Griffin (1990), which is mandatory reading for anyone concerned with human exposure to vibration. The human body is comprised of structures with widely varying compliances and damping characteristics, ranging from stiff bone to the soft, loading-rate-sensitive viscera. These parameters vary widely across individuals and different seating configurations.

A complete summary of the literature concerning seat vibration is beyond the scope of this review. Instead, a number of key points of emphasis for seat design is presented. The interested reader is directed to Griffin (1990) for a thorough introduction to this subject area.

- People show a resonance in vertical vibration between 2 and 10 Hz, usually reported as 4 to 8 Hz. This resonance is produced by the primary flexion mode of the trunk.

- Vehicle seats, because of the desire to have a seat that feels soft in a static evaluation, yet restricts vertical dynamic deflections to less than 50 mm, tend to produce a resonance in the same area. That is, the constraints on vehicle seats tend to result in seats that amplify, rather than attenuate, vibration around 4 Hz, the primary human resonance for vertical vibration. Yet, seats vary widely in vibration performance, and the effort to produce better vibration control is worthwhile from a comfort perspective.

- Mechanical devices to simulate the human occupant in the seat/human system have not proven very effective. Isolated reports of such systems have appeared periodically, but the lack of a standardized device in spite of the substantial need suggests the magnitude of the problem in producing such a device.

- Among the factors that affect transmissibility of vibration through the seat, among the most important is posture. Changes in recline angle, in particular, have large effects on vibration transmissibility. Vibration transmitted through the seatback contributes importantly to comfort, and may even influence the transmission of vertical vibration through the seat cushion.

- People vary widely in their perception and tolerance of vibration. General guidelines have been developed that suggest minimizing vibration transmission in the 4 to 8 Hz range. However, systematic models that relate the vibration at the seat surface (i.e., input to the person) to subjective assessments of comfort or ride quality are not available in the open literature.

Summary

Vibration transmissibility is an important component of dynamic seat comfort. Quantitative guidelines are available that call for minimizing the transmission of vibration, particularly in the 4 to 8 Hz range. However, mechanical design tools that accurately simulate the human part of the seat/human system are not yet in wide-spread use. Quantitative models relating vibration transmission to seat comfort are also not available. Both subjective and objective testing with volunteers remains necessary to quantify seat performance.

4.0 SUPPORT PARAMETERS

Support parameters are defined to be those that are intended to influence the posture of the sitter. These parameters include the contour of the seat and the relative position and orientation of the seat cushion and backrest. Clearly, there is substantial interaction between the Support parameters and the Fit and Feel parameters. For example, a change in backrest contour will change the backrest pressure distribution and may affect sitters differentially depending on anthropometry. In spite of these interactions, it is useful to consider these parameters with respect to their effects on posture, since the specifications are generally driven by a desire to promote, or to provide for comfort in, particular postures.

Although any aspect of seat surface contouring could be considered as a Support parameter, few are quantified in the literature, and most have more importance in consideration of body pressure distribution rather than posture. An important exception is the longitudinal backrest contour, particularly in the lower-back region, where the contour is frequently referred to as the lumbar support because the reaction forces generated by the seat are directed in the vicinity of the sitter's lumbar spine. Lumbar support has become a controversial subject of research, primarily because of the widespread prevalence of lower-back discomfort associated with sitting, particularly in vehicle seats. Section 4.1 summarizes the salient research findings concerning the appropriate function and specification of lumbar support for car seats.

The overall body posture can be characterized by angles at the various joints that divide the body into a mechanical linkage. Several authors have recommended target postures based on these joint angles. Section 4.2 summarizes these recommendations and discusses the physiological motivation behind them. Seat adjustments that can be provided to the sitter for customization of the seat support are also discussed.

Research in the ASPECT program and other research at UMTRI has provided considerably more information on vehicle occupant posture than is available in the open literature (Reed 1998; Schneider et al. 1999, Reed et al. 1999a, 1999b, 1999c; Manary et al. 1999). The findings from these studies are included in this section, with a particular emphasis on (1) the effects of seat design parameters on posture and (2) the variability in posture in relation to anthropometry.

4.1 Lumbar Support

There are four primary methodologies that have been used to infer proper lumbar support configuration.

1. *Anthropometry*. Targeting a support to the lumbar area requires an accurate and precise description of the position and orientation of the lumbar spine for a wide range of anthropometry.

2. *Electromyography*. Back muscle activity, as measured by electromyography (EMG) has been used to examine the physiological reactions to various lumbar supports. The hypothesis is that less back muscle activity is desirable because it may lead to reduced muscle fatigue and reduced discomfort.

3. *Intradiscal Pressure Measurement*. In-vivo measurements of lumbar intradiscal pressure have been made to study the effects of different postures and lumbar support configurations on axial spine loading. Lumbar support configurations that reduce intradiscal pressure have been recommended as a result of these experiments. Precise measurements of stature have also been used to infer disc loading in experimental comparisons of different chairs and postures (Althoff et al. 1992).

4. *Subjective Evaluations*. Many researchers have solicited subjective evaluations of lumbar supports to determine configurations that sitters prefer. However, the large variance in these measurements has been responsible for the appeal of the “objective” measures described previously, which may provide a physiological explanation for the subjective assessments. Ultimately, however, the primary goal of seat design is comfort, so the subjective assessments are the standard against which the objective measures should be compared, rather than the reverse.

The lumbar support recommendations resulting from each of these methodologies are considered in turn, although many studies include more than one of these methodologies.

Anthropometry

The most important characteristic of a lumbar support is that it should be located in close proximity to the lumbar spine of the sitter. Precisely where in the lumbar area the support should be located is the subject of both physiological and comfort studies (see below), but the location of the lumbar spine of the sitter is the subject of anthropometric studies. The data most applicable to the automotive environment are found in Schneider et al. (1985). Stereophotogrammetry was used to record the three-dimensional locations of body landmarks, including targets on the pelvis and spine. Twenty-five subjects were selected in each of three categories: small female, mid-sized male, and large male. The small-female subjects were approximately 5th percentile by stature and weight for U.S. females, the mid-sized males were approximately 50th percentile by stature and weight for U.S. males, and the large males were approximately 95th percentile by stature and weight for U.S. males.

Data were recorded with each subject seated in a wooden seat shaped to be representative of the indented contour of a production car seat for similar-size drivers (see Schneider et al. 1985 for methods). The positions of the L2 and L5 spinal processes were recorded and averaged for each subject group. The data are presented in Table 8. Coordinates are expressed relative to the H-point (estimated hip joint center), with X positive forward and Z positive upward. Y-axis coordinates (medial-lateral dimension) are all zero since the points lie on the seat centerline. To obtain a useful dimension for locating a lumbar support, the locations of the L2 and L5 surface landmarks are expressed as distances up the torso line from the H-point. The torso line is defined as a line in the midsagittal plane connecting the H-point and shoulder (greater tubercle of the humerus). For each of the subject groups, the torso line is 22 degrees. Table 9 and Figure 5 show the distance up the torso line for L2 and L5 by group.

Table 8
Location of Surface Landmarks Relative to H-point
(Schneider et al. 1985)

Landmark	Small Female		Mid-Sized Male		Large Male	
	X	Z	X	Z	X	Z
Shoulder (greater tubercle humerus)	-152	380	-173	421	-185	469
L2	-180	79	-217	87	-246	95
L5	-154	23	-174	13	-202	19

Table 9
Location of L2 and L5 with Respect to Torso Line
(Dimension in mm)

Dimension	Small Female	Mid Male	Large Male
Torso Angle (H-point to shoulder from vertical)	21.8°	22.3°	21.5°
L2 distance up torso from H-point*	158	181	197
L5 distance up torso from H-point*	97	96	110
Range (L5 to L2) from depressed seat cushion*	192 – 253	191 – 276	205 – 292

* Includes 18-mm distance added to correct pelvis position (see text). Calculated using 95-mm distance from H-point to depressed cushion along torso line (see text).

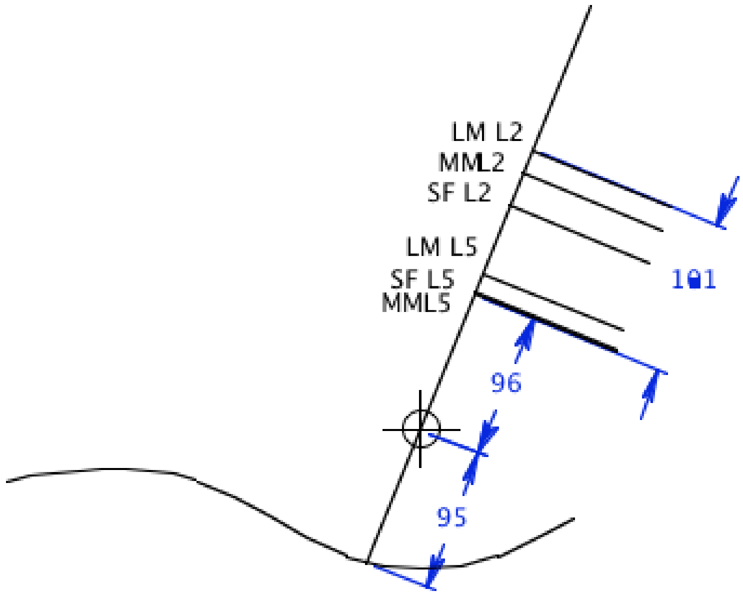

Figure 5. Lumbar surface landmark locations on torso line from Schneider et al. 1985.
SF = Small Female, MM = Mid Male, LM = Large Male. Dimensions in mm.

Some corrections to the Schneider et al. (1985) data have been made in this analysis. The distance from the H-point to the seat surface along the torso line in the Schneider et al. data for the mid-sized male is approximately 113 mm, but data collected at UMTRI (Manary et al. 1994) suggest that the appropriate dimension is about 95 mm, a difference of 18 mm. Thus, 18 mm was added to the lumbar distances from the H-point measured along the torso line (*i.e.*, the H-point was lowered relative to the spinous processes). A similar adjustment has been made by Haas (1989) to make the Schneider et al. lumbar-spine length consistent with Snyder, Chaffin, and Schutz (1972), who performed an x-ray study of seated subjects. The adjusted Schneider et al. data for lumbar spine locations are reasonably consistent with other work (*cf*. Snyder et al. 1972; Nyquist and Patrick 1976). Several other researchers have used the UMTRI data to make recommendations for lumbar support locations (Hubbard and Reynolds 1984; Robbins 1986).

Another useful anthropometric relationship noted by Cleaver (1954) is that the center of the lumbar spine in a sitting subject is approximately coincident with elbow height. In Gordon et al. (1989) the 5th-percentile-female to 95th-percentile-male range for erect seated elbow height above a rigid seat surface is 176 to 274 mm, or 81 to 179 mm above the H-point, using the 95-mm H-point-to-seat-surface offset. The median male elbow height is 232 mm above the seat surface, or 137 mm above the H-point. These estimates are in good agreement with the UMTRI data for lumbar spine location. Porter and Norris (1987) found the average height of L5 above a rigid seat surface of ten men and ten women to be 210 mm, or approximately 115 mm above the H-point. This compares favorably with the average over the three subject sizes in the UMTRI data of 101 mm above the H-point. The vertical measurements taken from subjects in an erect seated position should be compared to measurements made along the back line of the manikin.

Having located the lumbar spine, the questions remain: where in that range should the support be centered and how prominent should the support be? Answers to these questions have been addressed through investigation of back muscle activity and spine loads, as well as by subjective assessments.

Electromyography

Electromyography (EMG) is the recording of the electric impulses in the body generated by the process of muscle activation. Although these signals can be monitored by needle electrodes inserted in the muscle tissue, surface electrodes attached to the skin over the muscle belly are most frequently used in seating research and provide more reliable measures of aggregate muscle activity. The EMG signal amplitude has been found to vary approximately linearly with the muscle force, although it is very difficult to isolate the force produced by many muscles, for example, those in the back. Chaffin and Andersson (1991) presented a review of EMG methods.

The hypothesis behind EMG studies of sitting posture and chair design is that lower levels of muscle activity will result in less muscle fatigue and discomfort, so chair designs that result in lower EMG levels are desirable. The most important EMG studies of sitting postures were conducted by Andersson and coworkers (1974a, 1974b, 1974c, 1974d, 1974e), who measured back muscle activity in a variety of seats, including a specially constructed laboratory chair, an office seat, and an automobile seat. Andersson et al. (1975) provided a useful summary of this work.

Of the seat parameters studied, backrest angle and lumbar support prominence were found to have the greatest influence on back muscle activity. Increasing the angle of the backrest relative to the horizontal from 90 degrees to 110 degrees reduced muscle activity in the lumbar spine area by about 40 percent. In these studies, backrest angle was described as the angle of the backrest surface, which for the rigid experimental chair was well defined. For the automobile seat, the angle of the backrest surface, presumably measured in an undepressed condition, may not be identical to the seatback angle measured by the H-point manikin (SAE J826), but the trend toward reduced back muscle exertion at increased recline angles is clear, regardless of the angle measurement method.

The prominence of the lumbar support was also found to affect back muscle activity. In studies on a car seat (Andersson et al. 1974b), increasing the lumbar support prominence from 0 to 50 mm reduced the EMG amplitude at the L1 level by about 50 percent, with the absolute magnitude of the reduction dependent on backrest angle. The definition of the lumbar prominence on the car seat is not clear, but the definition used in other papers by the same research group is probably applicable. The lumbar support prominence on the experimental chair was measured perpendicular to the plane of the backrest, which the subject's buttocks and thorax contacted during testing. This method of measurement appears to be equivalent to the depictions of the lumbar curve in the specifications provided by Maertens (1993).

Hosea et al. (1986) examined the effect of lumbar support prominence and backrest angle on back muscle activity in an on-the-road experiment. The results are consistent with

Andersson et al., in that increasing the backrest angle from 100 degrees to 120 degrees resulted in large decreases in the amplitude of lumbar muscle EMG. Lumbar support prominences of 30, 50, and 70 mm were tested. The 30- and 50-mm prominences produced equivalent back muscle activity in the lumbar and thoracic regions, while the 70-mm prominence resulted in an increase in EMG amplitude. The lumbar support prominence was not clearly defined, but references in the paper to Andersson's work suggest that a similar interpretation is appropriate.

Recently, Reed (1998) examined back muscle activity using an approach similar to that employed by Andersson et al. and Hosea et al. when studying car seats. Reed measured back extensor activity at three spine levels as sitters sat in driver and passenger postures at a range of seatback angles centered on their preferred seatback angle. In all previously published experiments, subjects were tested only at imposed seatback angles, whereas most front vehicle seats now allow the sitter to choose a seatback angle. As in previous studies, muscle activity decreased with increasing recline. However, Reed demonstrated that both drivers and passengers tend to select the most upright seatback angle (and hence torso recline) that allows them to sit without using their back extensors. The data also showed that driver and passenger postures, as well as muscle activity, were not substantially affected by the addition of a prominent lumbar support.

Intradiscal Pressure

Andersson et al. (1974a, 1975) noted that, although the etiology of low-back pain is often unclear, there is considerable evidence that persons with chronic low-back pain suffer more when the mechanical stresses on their lower backs are increased. Reduction in lower-back stress is therefore desirable to aid those with existing back pain, and may help to prevent its occurrence in those currently asymptomatic. Because internal stresses on body tissues are generally difficult to measure, there is considerable research emphasis placed on those measurements that are feasible. One of these methods, EMG, which relates to the stresses produced by muscle activity, has been discussed above. Another method that yields information on spine loading is intradiscal pressure measurement.

The vertebral bodies are separated by flexible discs that provide for the articulation of the spine. Each vertebral disc is comprised of a semigelatinous nucleus pulposus in the center of the disc surrounded by the annulus fibrosus, which consists of layers of collagen fibers. In the lumbar region of the spine, the discs are taller anteriorly, producing the characteristic lordotic curve. The nucleus pulposis in the center of the disc has been found to behave hydrostatically in healthy individuals so that the pressure in the nucleus may be used as a measure of the axial load on the spine. The disc pressure has been found to be affected primarily by three factors: the weight supported above the spine level of interest, the paraspinal muscle activity, and the posture of the spine in the area of measurement. Each of these factors is important in the analysis of disc pressure changes produced by variations in seat design parameters.

Andersson et al. (1974a, 1974b, 1974c, 1974d) conducted disc pressure measurements in conjunction with the EMG analyses discussed above. For each test, a needle containing a pressure transducer was inserted into the nucleus of the disc below the L3 vertebra. The disc pressure was recorded simultaneously with EMG signals from back extensor muscles as the subject assumed various postures. In general, disc pressures were found to be substantial higher in sitting than in standing. The type of sitting posture had a strong influence on the disc pressure.

In studies on a laboratory chair (Andersson et al. 1974a), the disc pressure decreased as the backrest angle was increased from 90 degrees to 120 degrees. Disc pressure also decreased as the lumbar support prominence was increased from –20 mm to +40 mm (negative lumbar support measurements indicate that the apex of the support was rearward of the plane of the backrest). The amount of change in disc pressure due to changes in lumbar support was independent of backrest angle. Studies on a car seat (Andersson et al. 1974b) produced similar results, with disc pressure decreasing as the backrest recline angle and lumbar support prominence were increased.

The disc pressure and EMG data can be interpreted with respect to the stresses placed on the lower back in the various postures examined. When the backrest angle is increased, a greater proportion of upper-body weight is transferred to the backrest, reducing the amount of load carried by the lumbar spine. Additionally, the center of mass of the upper body moves rearward, reducing the restorative (extension) moment that must be produced by the back muscles. Since the back muscle tension is applied approximately parallel to the lumbar spine, reduction in back muscle activity is seen directly as a reduction in disc pressure. The curvature of the lumbar spine also influences the disc pressure. When the normal lordosis of the lumbar spine is flattened, the discs are wedged anteriorly, compressing the anterior aspect of the disc while stretching the posterior aspect. These forces act to increase the pressure in the disc. Thus, moving the lumbar spine away from lordosis toward kyphosis increases the disc pressure even if the muscle activity remains constant.

In the Andersson et al. studies, the lumbar support reduced disc pressure by producing a more lordotic lumbar curvature and by slightly reducing back muscle exertion. These findings resulted from changes in the lumbar spine curvature produced by the lumbar support. In a later study, Andersson et al. (1979) examined radiographically the influence of backrest angle, lumbar support prominence, and the vertical position of the lumbar support on lumbar lordosis. Neither backrest angle (80 degrees to 110 degrees) nor the vertical position of the lumbar support (L1 to L5) had a significant effect on lumbar lordosis. The prominence of the support did have a strong influence on lumbar curvature. When the lumbar support prominence was 40 mm, the lumbar curve closely resembled the standing lordosis.

The lumbar support used in the Andersson et al. (1979) study was constructed to be used as an indicator of position rather than as an actual support surface, so the postural responses of the subjects to the experimental support might not be representative of their responses to actual seats. In particular, the rigid, small-diameter support probably was not conducive to relaxed postures with substantial pressure exerted on the support. Nonetheless, the findings suggest that the rotation of individual vertebral bodies is strongly linked to the motion of the adjacent vertebra, so that the vertical position of the lumbar support may not strongly influence the resulting spine curvature. Consequently, decisions about appropriate lumbar support height might reasonably be based on other considerations, such as the differential sensitivity of back areas to pressure.

In more recent studies (e.g., Althoff et al. 1992), precise measurements of stature have been used to infer disk loading. Researchers have noted that increased load on the spine causes spine shrinkage, leading to a typical diurnal variation in stature. People are generally taller when measured in the morning than in the evening, primarily because their lumbar discs have been compressed by standing and sitting. Since invasive disk pressure measurements are no longer acceptable, stature measurement has been used as a surrogate measure of spine load.

Unfortunately, the information from stature measurements is difficult to interpret with respect to spine loading. For example, spine shrinkage is generally slower in sitting than in standing, yet the spine loading associated with sitting is widely believed to be more injurious to the spine than standing. The reduced rate of shrinkage in sitting is probably due in part to the transfer of some of the upper body weight to the seatback from the lumbar spine, but the role of lumbar spine posture in changing the stresses on the intervertebral disks is not well understood. Taken together, however, the findings with respect to spine shrinkage do not clearly support any particular lumbar support configuration.

Subjective Evaluations

Decisions regarding lumbar support design should ultimately be made to optimize the experience of the sitter. Although EMG and intradiscal pressure measurement can be used to estimate the mechanical stresses produced in back tissues by various seat designs, the success of a design can be judged by two criteria: (1) reduction in pathology due to sitting, and (2) reduction in discomfort. In practice, the first criterion is extremely difficult to employ because of the complex etiology of chronic lower-back disease and the difficulty in ascribing medical outcomes to subtle changes in seat parameters. Subjective evaluations of discomfort are, therefore, the standard by which lumbar supports should be judged. A reasonable hypothesis is that lower-back stresses are manifest in discomfort before producing injury, so that a reduction in discomfort should lead to a reduction in the potential for injury.

Few published studies have obtained carefully controlled lumbar support evaluations. As noted above, a lack of standardization in the characterization of lumbar support prominence makes comparisons among studies difficult. Grandjean (1980) cited comfort ratings of auditorium seats to recommend a lumbar support positioned 100 to 140 mm above the depressed seat surface. These values are the lowest found in the literature. It is likely that the posture assumed in this seat results in a substantial rearward tilt of the pelvis and support for a slightly kyphotic lumbar curve. Kamijo et al. (1982) found that auto seats rated as comfortable showed backrest pressure peaks in the area from 140 to 180 mm above the H-point, or about 235 to 275 mm above the seat surface, suggesting that the center of lumbar support should be located in that area.

Porter and Norris (1987) investigated subject preferences for lumbar support height in a laboratory chair, simulating a driving environment by placing the subjects in a chair with a 30-degree backrest angle, a 15-degree pan angle, and an extended-knee position. This study was specifically designed to replicate the postures investigated by Andersson et al. (1974a) to determine if the lumbar support configurations recommended on the basis of EMG and disc pressure minimization criteria coincided with those preferred by sitters. Thirty-seven male and twenty-five female subjects indicated their preferred lumbar support position. The average preferred support height above the seat pan was 215 mm, or approximately 120 mm above the H-point. The support used in this study was rectangular in cross section, 97-mm tall, and protruded 20 mm from the plane of the backrest. The 20-mm support was preferred over the 40-mm support, suggesting that the preferred lumbar support configuration is less prominent than that which produces the lowest disc pressures.

Reed et al. (1995) and Reed and Schneider (1996) examined the effects of lumbar support prominence on driver posture. In previous studies of lumbar support, postures were not measured, or were measured when the sitters were sitting unrealistically. A seat was constructed that allowed the lumbar support prominence and location to be varied over a wide range. In an initial study, twenty-four participants operated a driving simulator for one hour while their posture was measured at 10-minute intervals. Testing was conducted with three lumbar support prominences. Only small differences in posture were noted between a flat lumbar support and one with a convex prominence of 35 mm.

In a follow-on study, thirty-two men and women were measured in their preferred driving postures using four lumbar support prominences ranging from zero to 45 mm. The participants were tested both with the vertical lumbar support position fixed and after they had selected their preferred vertical positions. As in the preceding study, only small changes in posture were produced by large increases in lumbar support prominence. Increasing the prominence from zero (flat) to 45 mm reduced average lumbar spine flexion by only about six degrees, compared with an average change from standing to sitting of 55 degrees. When permitted to adjust the vertical position of the lumbar support, the subjects chose positions averaging 152 mm above the H-point along the J826 H-point manikin back line, with a standard deviation of 23 mm. Preferred lumbar support positions were approximately normally distributed.

The most important finding from the Reed et al. studies from 1995 and 1996 was that longitudinally convex lumbar supports do not, in general, induce lumbar lordosis in auto seats. The changes in lumbar spine contour resulting from the addition of a prominent lumbar support were small. Testing with a prescribed sitting procedure demonstrated that the participants were physically capable of attaining a more lordotic posture in the seats, but did not voluntarily selected such postures. These findings show that seats should not be designed for substantially lordotic postures, and that the rationale for lumbar support design should not rely on inducing a particular, "optimum" lumbar spine posture. Posture testing during the ASPECT program supported these findings, and found, in general, even smaller effects of seat contour on posture (Manary et al. 1999). One important finding was that the vertical position of the lumbar support did not substantially effect the posture. This implies that the rationale for selecting a vertical lumbar support position, or an adjustment range, should be based on subjective and anthropometric data, rather than on posture goals.

One interesting innovation recently proposed is a dynamic lumbar support that cycles the back contour automatically (Reinecke et al. 1994). This technology has the potential to vary the stresses in the lumbar spine during prolonged sitting, which may delay the onset of discomfort. However, more testing in an automotive setting will be necessary to determine if the comfort effects justify the substantial additional cost compared to conventional lumbar support systems.

Other studies of lumbar support preference have likely been conducted by seat manufacturers and others. These studies are rarely published because of the potential competitive advantage associated with the information. The codification of design recommendations for lumbar support has been hampered by the lack of a standardized method for defining and measuring lumbar support in a way that is related to the sitter's experience. The newly developed ASPECT manikin measures lumbar support prominence under realistic loading, providing a way to quantify comfortable lumbar support contours.

Recommendations

The research findings cited above have been used by a variety of authors to justify recommendations of particular lumbar support configurations. However, the most recent recommendations based on the literature (*e.g.*, Reynolds 1993) do not differ substantially from the design specifications suggested decades earlier (*e.g.*, Åkerblom 1948; Keegan 1953).

Furthermore, recommendations in the literature are difficult to compare because, as noted above, there is a lack of standardization with regard to the specification of the lumbar support parameters. The problem is compounded by the fact that the seat contour of interest is that which results when the sitter is seated in a comfortable, self-selected posture. Since sitter anthropometry and preference vary, a particular lumbar support may produce different effective prominences or vertical positions relative to the lumbar spine depending on the sitter and the posture.

Another issue in lumbar support specification is the stated purpose of the support. Some researchers specify that the intent of the lumbar support is to induce (or retain) lordosis in the lumbar spine (*e.g.*, Hubbard and Reynolds 1984). Andersson (1980), in a summary of the work discussed above, recommends that the lumbar support be used to preserve lordosis because lower disc pressures are observed with lordotic lumbar curvature. As noted above, posture measurements from people in auto seats show that lumbar supports in auto seats do not induce lordosis, although they can reduce the maximum amount of lumbar spine flexion observed. Keegan (1964) specifies that support should be directed in the area of L4 and L5, because the discs below those vertebrae have the greatest association with low-back pain. In Keegan's view, the purpose of the lumbar support is to prevent the flattening of the lumbar lordosis. He recommends that the seat design should promote a neutral lumbar spine curvature about midway between the standing lordosis and a flattened spine. However, even Keegan's neutral posture is more lordotic than those generally observed in auto seats, even with prominent lumbar supports.

Grandjean (1980), Kamijo et al. (1982), Porter and Norris (1987), and others have used subjective preferences to recommend lumbar support configurations without reference to desired physiological outcomes. Robbins (1986) follows Hubbard and Reynolds (1984) in recommending centering of the lumbar support at the apex of the lumbar lordosis, midway between T12 and L5. Robbins found that this mid-lumbar point for people ranging in size from small females to large males lies within 33 mm of a point 250 mm from the depressed seat surface, and recommended that the 250-mm dimension be used to locate the lumbar support. Maertens (1993) follows the recommendation of Robbins and also specifies that the support should be centered 250 mm above the depressed seat surface.

Lumbar height recommendations relative to the H-point are summarized in Table 10. Note that all recommendations fall between the average L2 and L5 locations given by Schneider et al. (1985).

Table 10
Summary of Recommendations for Vertical Location of Lumbar Support

Reference	Lumbar Support Position above H-point on Torso Line (mm)
Keegan (1964) (mean L5 position in Schneider et al. 1985)	101
Andersson (1980)	155
Robbins (1986)	155
Kamijo et al. (1982)	160
Porter and Norris (1987)	120
For Reference: L2 mean (Schneider et al. 1985)	178
Reed et al. 1996 (mean preferred)	152

The prominence of the lumbar support is more difficult to specify than the vertical position because of a lack of standardization in measurement. For this discussion, the method used by Andersson, Porter and Norris, Reed, and others will be used. These researchers have constructed laboratory chairs with rigid, planar backrests and measured the protrusion of the lumbar support from that plane. This measurement can be approximated for a padded seat by measuring perpendicular to a line tangent to the thoracic curve and the rear of the buttocks (*cf.* Robbins 1986; Maertens 1993).

Andersson et al. (1979) measured the effect of lumbar support on lumbar lordosis and concluded that 40 mm was an appropriate prominence. Porter and Norris (1987) found that a 20-mm support was preferred over a 40-mm support in all test conditions. Robbins (1986) recommended 15 to 25 mm prominence while Maertens (1993) indicates that an acceptable range is from 20 to 50 mm. Some researchers specify a longitudinal radius of curvature along with, or instead of, a prominence. Grandjean (1980) recommended a 450-mm radius. Floyd and Roberts (1958) recommend not less than 300 mm and preferably 400 to 460 mm. Robbins (1986) recommends a 250-mm radius, Maertens (1993) specifies 255 mm. Reynolds (1993) cited lumbar curvature radii for cadavers in erect seated postures from 206 to 348 mm, implying that similar radii would be appropriate for drivers.

The ASPECT program developed a new H-point manikin that measures lumbar support prominence, using a definition similar to that used above (Reed et al. 1999a). For the first time, a standardized method is available to quantify lumbar support prominence using a deflected seat measure that is closely related to how people experience a seatback contour. Measurements of a wide range of production seats show that seats that are generally perceived to be comfortable have lumbar support prominences ranging from about 5 to 25 mm. It is likely that a midrange value of around 15 to 20 mm will be most comfortable, although considerably more research using the new manikin will be necessary to determine how the manikin readings relate to comfort. Sporty seats tend to have higher lumbar support prominences than luxury seats, although this may not correspond to a difference in subjective preference.

One important point that the ASPECT manikin makes clear is that the prominence of the lumbar support is strongly dependent on the contour of the seatback below the lumbar support. If the sitter's buttocks are constrained from moving rearward by the design of the lower part of the seatback, the effective prominence of the lumbar support is reduced. The ASPECT manikin measures the lumbar prominence with the buttock area of the manikin pushed firmly against the seatback. Providing greater relief in this area may be a more effective way of increasing lumbar support prominence than adding additional padding or support in the lumbar area.

Summary

Lumbar support should be firm but sufficiently padded to avoid discomfort due to high pressure. Ideally, the support should be adjustable in prominence and vertical position. The depressed contour should adjust from flat to convex up to approximately 30 mm prominence, as measured by the ASPECT manikin, with a radius adjustable from about 250 to 400 mm. The vertical position of the apex should be adjustable between 100 and 200 mm above the H-point along the manikin back line, or between 195 and 295 mm above the depressed seat cushion. If a fixed lumbar support is to be provided, the prominence should be 15-20 mm and the radius 300 mm for a mid-range or higher seat height (*i.e.*, higher than about 240 mm). The apex should be positioned about 150 mm above the H-point along the manikin back line. Use of the ASPECT manikin to define and measure lumbar support will ensure that sufficient relief is provided in the sacral area below the lumbar support.

4.2 Body Segment Angles and Seat Adjustments

The posture of the body is described by the relative orientations of the various articulating segments that make up the body linkage. Reynolds (1993) stresses the usefulness of abstract linkage representations of the human body as design tools. Hubbard et al. (1993) discuss computerized kinematic models that increase the fidelity of simple link models by including descriptive geometry for the links, *e.g.*, legs, torso, and arms. Such link models are used to define joint angles that are associated with improved comfort. Recently, Reed et al. (1999b) published a complete measurement and representation method for automotive occupant postures based on a synthesis of data from preceding studies. Figure 6 shows a linkage representation of the vehicle occupant along with the definition of posture variables based on the linkage.

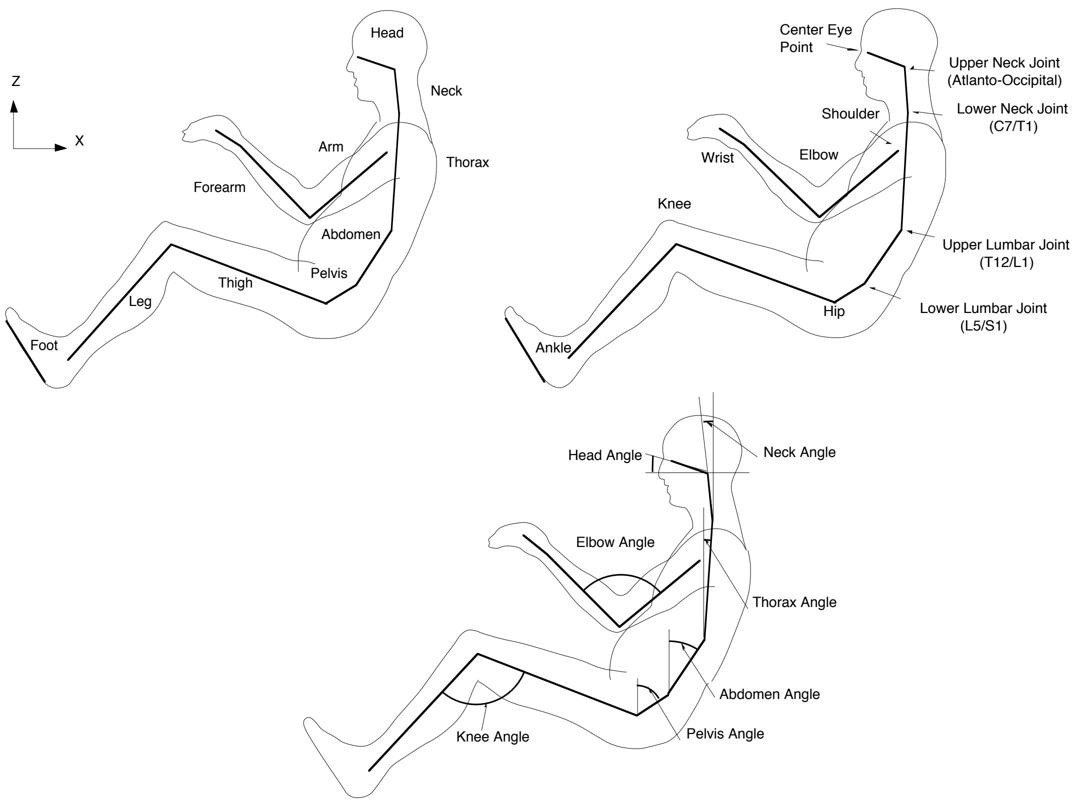

Figure 6. Definitions of kinematic linkage and posture measures (Reed et al. 1999b). Angles referenced to horizontal or vertical are XZ (sagittal) plane angles. Angles between segments (elbow angle, knee angle, and ankle angle) are measured in the plane formed by the segments (included angles). Note: Neck angle is negative as shown. All other angles are positive as shown.

The assumption implicit in joint angle recommendations is that the least discomfort will result when all joint angles are within a neutral range for which tissue stresses are minimized (Keegan 1953). These ranges are typically in the middle of the full passive range of motion for the joint, where muscles are approximately at their resting lengths. Rebiffé (1969) presents a summary of recommendations for body segment angles in the automotive environment. Recently, Porter and Gyi (1998) presented new recommended ranges based on a laboratory study, and summarized values from Grandjean (1980).

Figure 7 shows the definitions of body segment angles for which recommendations are listed in Table 11. The recommendations are very similar, having in general large ranges that are probably not very useful for design purposes.

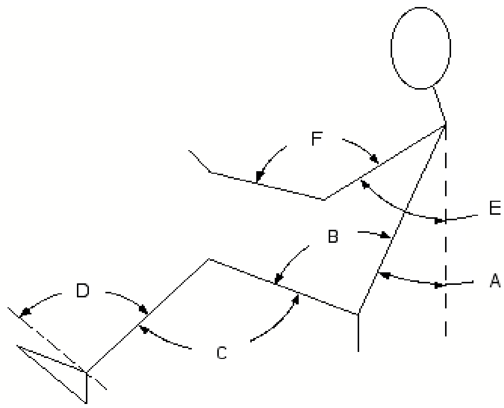

Figure 7. Definitions of posture angles in Rebiffé (1969).

Table 11
Recommended Ranges for Body Segment Angles from Rebiffé (1969), Grandjean (1980), and Porter and Gyi (1998)
(See Figure 7 for angle definitions.)

Angle	Rebiffé (degrees)	Grandjean (degrees)	Porter and Gyi (degrees)
A. Back	20 – 30	--	--
B. Trunk/Thigh	95 – 120	100 – 120	89 –112
C. Knee	95 – 135	110 – 130	103 – 136
D. Ankle	90 – 110	--	81 – 105
E. Upper Arm*	10 – 45	20 – 40	16 – 74
F. Elbow	80 – 120	--	80 – 161

*These values are dependent on hand support and seat-back configuration.

The Rebiffé linkage expresses body posture in terms of line segments in a sagittal plane connecting joint centers. The trunk angle is represented as a line connecting the shoulder joint with the hip joint. The most important angles for comfort are the back, trunk/thigh, and knee angles, which represent the relative orientations of the trunk, thigh, and leg. The research summarized in Section 4.1 demonstrated the importance of maintaining a reclined trunk posture to reduce spine and back muscle loads. The Rebiffé recommendations for 20- to 30-degree recline angles are consistent with the EMG-based recommendations of Andersson et al. and contemporary practice. Angle B is the trunk/thigh angle, which Keegan (1953) demonstrated to have a strong effect on the lumbar curve. The Rebiffé recommendations for trunk/thigh angle fall short of the 135-degree angle cited by Keegan (1953) as producing a neutral spine curvature, but are in keeping with the recommendation by Grandjean (1980) of 100 degrees to 120 degrees. With specific reference to auto seating, Keegan (1964) specified a trunk/thigh angle of 105–115 degrees, with 115 degrees preferred for long-term comfort.

The determinants of trunk/thigh angle are the backrest angle and the seat cushion angle. Backrest angle can be adjusted on almost all current driver seats, while seat cushion angle adjustment is generally available only on more expensive models. Front passenger seats usually have back angle adjustment, but most rear passenger seats lack either back or cushion angle adjustment. Seatback angle and cushion angle are defined and measured using the SAE J826 H-point manikin and procedure. The ASPECT manikin also provides these measures.

Knee angle is an important determinant of comfort. Rebiffé recommends that the angle not exceed 135 degrees. When the knees are extended (*i.e.*, knee angle increases) tension can develop in the hamstring muscles in the back of the thigh. Because these muscles are attached both below the knee and above the hip joint (on the pelvis), tension in these muscles resulting from extended-knee positions constrains motion at the hip joint (Stokes and Abery 1980). If the pelvis is forced to rock rearward because of tension in the hamstrings, then a lumbar lordosis is difficult to obtain without extreme seat recline angles. Thus, knee angle is an important factor to consider in the specification of a lumbar support (see Section 4.1).

The preceding presentation of "comfort angles" is based on literature that does not include a rigorous measurement of posture and examination of postural variance. The recent studies conducted in the ASPECT program provide a more thorough understanding of posture preference (Manary et al. 1999). In several experiments, men and women with a wide range of body size selected their preferred driver and passenger postures in seats with adjustable seatback angles. There are several key observations:

- Drivers adapt to changes in vehicle package layout primarily by changes in limb posture, while torso posture is relatively unaffected.

- Changes in posture associated with changes in seat geometry are small compared to intersubject variability.

- Torso posture is not strongly affected by anthropometry, and there is a large amount of variance in torso posture that is not predictable from anthropometric, vehicle, or seat factors.

- Driving postures are very similar to passenger postures, with differences arising only with extreme forward or rearward steering wheel positions.

These observations indicate that the passenger postures observed in seats with adjustable seatback angles can be taken as representative of sitters' preferred postures. These, in effect, define the "optimum" postures for vehicle occupants, in the sense that these are the postures that sitters choose when subject to few constraints. Table 12 lists the mean and standard deviation of a range of posture variables.

Table 12
Means and Standard Deviations of Posture Variables (degrees) for Passengers in Seats with Adjustable Seatback Angle*

Variable**	Mean	Standard Deviation
Thorax Angle	3.8	6.7
Abdomen Angle	32.7	9.7
Pelvis Angle	60.4	11.7
Torso (Hip-to-Shoulder) Angle	28.2	5.8
Hip-to-Eye Angle	9.9	4.6
Thigh Angle (side view, with respect to horizontal)	15.8	5.0
Thigh Angle (top view, with respect to forward)	8.3	5.7
Leg Splay Angle (rotation of leg and thigh around hip-to-ankle vector with respect to vertical)	9.0	7.9
Knee Angle (in plane of leg and thigh segments)	122	10.6

* Based on data from 48 men and women with a wide range of stature in the ASPECT Seat Factors study.
** See Figure 6 for variable definitions.

The values in Table 12 can be compared to the recommendations from Rebiffé and others. Torso angle averages about 28 degrees, within the 20 to 30 degree range recommended by Rebiffé. Mean observed knee angles are similarly within the wide range recommended by Rebiffé.

The values in Table 12 can be used in seat design in two ways. First, design specifications based on three-dimensional computer manikins can be set using the posture angles. For example, the mean values can be used to posture a computer manikin for use in assessing seat dimensions. Second, the variance can be used to determine if a particular design adequately accounts for the range of preference. Thigh angles, for example, might be restricted by bolsters or other components. The values in Table 12 indicate the range of preferred positions in a situation with minimal constraints, so a design that does not accommodate a substantial percentage of the observed range of postures might produce discomfort for some people. Of course, the extent to which posture restrictions cause discomfort must be quantified using subjective assessments.

Package and Seat Effects on Posture

As noted above, the effects of package and seat variables on posture are small compared to the intersubject variability. However, it is useful to understand the effects when designing seats for different vehicles and seating positions. In the ASPECT Package Factors study, seat height, fore-aft steering wheel position, and cushion angle were varied over a wide range. Table 13 shows regression equations relating these parameters to several driver posture variables. Note that the hip-to-eye angle, a primary measure of torso recline, is affected only modestly by fore-aft steering wheel position. A change in fore-aft steering wheel position of 100 mm changes torso recline by only about 1.5 degrees. Perhaps more interesting is the observation that torso recline is not significantly related to seat height. This is contrary to conventional practice in the auto industry, which generally assumes that drivers sit more upright in high seat vehicles and more reclined in low seat height vehicles. Based on evaluations using in-vehicle data, the results in Table 13 are expected to be valid throughout the Class A vehicle range (up to 405 mm H30).

Table 13
Effects of Package and Seat Factors on Driver Posture*

Variable (mm or deg)	Intercept	Stature (mm)	Sitting Height/ Stature	Seat Height (SAE H30) (mm)	Steering Wheel Position aft of Ball of Foot (SAE L6) (mm)	Cushion Angle (SAE L27) (deg)	R^2_{adj}	RMSE
HiptoEyeAngle	-72.7	0.00642	115.7		0.0147	0.11	0.20	3.9
Knee Angle	69.1	-0.0071	61.3	-0.0321	0.0829	-0.59	0.44	7.7
Neck Angle	16.1	-0.01197			0.0109		0.04	7.7
Thorax Angle	-42.7	0.00497	45.2		0.0128		0.03	6.1
Abdomen Angle	-94.5	0.0109	184.5		0.0222		0.09	9.7
Pelvis Angle	-16.3	0.0102	90.2		0.0177	0.39	0.04	10.0

*Linear model created by multiplying each term in the table by the value of the column variable and adding the intercept.

Posture Change with Seatback Angle

Most seat design recommendations assume that the posture is static, and focus on designing for a single optimum posture. As noted above, there is considerable posture variance, most of which is not related to vehicle or seat parameters. However, in modeling individual occupants, it is often useful to consider how the posture will be affected by changes in the posture constraints. The seat parameter that has the strongest effect on posture is the seatback angle, when it is imposed rather than set by the sitter. The hip-to-eye angle produced by a particular seatback angle, as measured by the SAE J826 manikin, is given by

$$HipToEyeAngleJ826 = -12.4 - 0.0135\ S + 62.1\ SH/S + 0.559\ BA,$$
$$R^2 = 0.54,\ RMSE = 2.41$$

where S is stature (mm), SH/S is sitting height divided by stature, and BA is the SAE J826 manikin back angle. As the hip-to-eye angle changes, the relative orientation of segments in the torso changes as the lumbar and cervical spines flex and extend. Table 14 shows how each segment changes orientation as the hip-to-eye angle changes. Starting from the average posture from Table 13, the head remains level while the segments from the neck to the pelvis change angle. The relative distribution of flexion in the lumbar spine changes with increasing recline, with flexion at the lower lumbar area decreasing while upper lumbar flexion increases. These relationships may be used to model the effects of changes in seatback angle on passenger posture in rear seats.

Table 14
Average Change in Segment Orientation with Change in Hip-to-Eye Angle

Segment	Slope Estimate*
Head	-0.62†
Neck	0.477
Thorax	0.739
Abdomen	1.437
Pelvis	1.198

*Estimated change in segment orientation (degree/degree)
†Head orientation slope is not significantly different from zero (p = 0.32). All other slope estimates are significantly different from zero with p<0.001.

Adjustments

Seat adjustments are supplied to provide for some customization of the interior environment to the preferences of the occupant. The minimum set of adjustments for driver seats in passenger cars is the seat track, which adjusts fore-aft position, and the seatback recliner. The range of seat track travel is recommended to be about 150 mm (Grandjean 1980; Rebiffé 1969), but data collected at UMTRI indicate that 200 mm or more may be necessary to accommodate short and tall drivers (Flannagan et al. 1998). Most seat tracks are angled several degrees to the horizontal so that moving the seat forward also raises the seat. This is appropriate, since occupants with shorter legs usually also have shorter torsos, and the added height helps to achieve good eye position. However, a flatter cushion angle is usually necessary to preserve a comfortable reach to the pedals.

Cushion angle adjustment is also useful in conjunction with height adjustment. Smaller drivers may find it preferable to flatten out the seat as it is raised, while long-legged drivers might increase the cushion angle to allow a more reclined backrest angle while preserving reach to the steering wheel. Many problems of occupant positioning relative to the controls could be solved more satisfactorily from the driver's perspective if the steering wheel and dashboard remained fixed relative to each other while both the seat and pedals moved fore and aft. The technology to move the pedals exists and might result in greater comfort and more flexible occupant packaging. Drivers could sit at a more comfortable and safe distance from the steering wheel, since the shoulder-to-wheel distance could be adjusted independent of the hip-to-pedal distance. Recently, several manufacturers have begun to offer adjustable pedals, largely because of concern about driver proximity to the airbag. Further research will be necessary to determine how adjustable pedals affect driver posture and comfort.

The seatback recline mechanism should allow trunk angles up to 30 degrees behind the vertical with a larger range preferred. Although most drivers will not use the full range, the extra adjustability is useful for those with long arms or for those who prefer large recline angles. The standard deviation of preferred torso recline is about five degrees, suggesting that a range of about 20 degrees is needed to accommodate drivers and passengers in preferred torso postures.

In seats that lack seatback angle adjustment, seatback angles should be selected to allow most occupants to sit either at their preferred torso recline angle or slightly more reclined. As noted above, imposed postures more upright than preferred induce back extensor activity that is likely to lead to discomfort. In contrast, sitting more reclined than preferred does not lead to increased muscle activity, until the recline is so great that anterior neck flexor activity is required to hold the head up.

Summary

Body joint angles should be maintained near the center of the passive range of motion for the joint. Values for these neutral angles can be inferred from the distribution of driver and passenger postures observed in conditions with minimal constraints. The most important angles related to auto seat comfort are the trunk angle relative to the vertical and the knee angle. Reclining the trunk 20 degrees with respect to vertical substantially decreases back muscle activity and opens the trunk/thigh angle, decreasing the necessity for lumbar flexion. Posture research findings demonstrate the effects of seat, package, and anthropometric factors on occupant posture and should be considered, along with the residual posture variance, in selecting seat design parameter values.

5.0 DISCUSSION

Research related to seating comfort has been conducted for over 100 years, and chair-makers have worked for centuries to increase the comfort of their products. Åkerblom (1948) provides a thorough review of work that preceded his own. In spite of the large body of research published in the intervening decades, recent recommendations on seat design echo those published in articles from the 1940s and early 1950s (*e.g*., Lay and Fisher 1940; Åkerblom 1948; Keegan 1953; Cleaver 1954). And yet the number of journal articles published on seating research shows no sign of abating. What has been learned in the past few decades? Is there an advantage to using recommendations from, say, Reynolds (1993) rather than Åkerblom (1948)?

Some ergonomic knowledge is being applied in automotive seat design. Most current seats appear to be designed more in keeping with ergonomic recommendations than seats from previous decades. For example, at the time Keegan (1964) raised the issue of lumbar support in auto seats, most seats had fixed backrest angles and a uniform stiffness along the vertical length of the backrest or "squab" as it was then called. Keegan pointed out that such seats produced kyphotic lumbar postures and were more likely to cause back discomfort than seats that provided a firm lumbar support in the lower-back area. But Åkerblom (1948, 1954), Keegan (1953), Cleaver (1954), and others had specified a decade earlier that firm support should be directed to the lumbar area. Indeed, Lay and Fisher (1940) measured the pressure distribution preferences of 250 people in an auto-seat mockup and reported that preferred backrest pressure distributions contained peaks in the lumbar area similar to those reported by Kamijo et al. (1982). One reason for continuing seating research must certainly be that the recommendations that are made are not always followed by those designing seats. In recent years, however, there has been an increased design emphasis on seat comfort in automobiles, partly because of epidemiological data showing that prolonged driving is associated with increased risk of lumbar disc herniation (Kelsey and Hardy 1975), but primarily because driver and passenger comfort have been seen as an increasingly important aspect of the competitive marketing of vehicles.

Of the design recommendations discussed in this report, those related to *Fit* parameters are the most readily applied. Although most current vehicle seats fit a large percentage of the driving population well, two parameters on which many seats could be improved are cushion length and width. As discussed in Section 2.1, cushion width should be sufficient to avoid constricting hips as wide as the 95th percentile. This means an unobstructed width of about 525 mm at a distance of 100 mm above the depressed seat surface. The continued rapid increase in body weight among U.S. adults has resulted in an increase in seat width recommendations of about 25 mm since the first edition of this report. Although this is an increase of only about five percent (for hip width, as an example), the additional 50 mm of lateral clearance across the car (counting a driver and passenger) represent a substantial change in occupant space requirements.

Some seats have the required clearance but have cushion side bolsters that constrict the buttocks of larger drivers as the cushion deflects, reducing the effective cushion width below that required. Although it may be reasonable to trade off accommodation of larger drivers for a more sporty feel for others, all drivers are likely to find a narrower seat more uncomfortable because it restricts posture change more than a wider seat. Shifting the pelvis laterally allows drivers to change the pressure distribution on their buttocks, potentially delaying the onset of discomfort.

Many car seat cushions are too long and too high. As the data in Section 2.2 indicate, a seat in which the distance from the depressed seatback to the front edge of the cushion is more than 440 mm is likely to restrict the postures of small drivers and reduce their comfort. Although some small sitters may not report that the seat cushion is too long, they may nonetheless be prevented from using the backrest properly by the need to sit further forward on the seat to avoid uncomfortable pressure behind the knees. Shorter cushions are advantageous even for those whose thigh lengths are closer to the population median. Shorter cushions allow for greater flexibility in leg posture and, in particular, allow the legs to splay to a greater extent than does a longer cushion. Leg splay changes the pressure distribution under the buttocks and can be a useful way of delaying the onset of buttock discomfort. One way to make a short cushion more comfortable for long-legged subjects is to include a cushion angle adjustment. Long-legged subjects can tilt the cushion up to obtain the desired contact pressure on their thighs, rather than obtaining similar support by sinking into a longer, softer cushion. Excessive seat height has an effect similar to long cushions for occupants with short legs. This is particularly a problem for short women in rear seats of minivans and sport-utility vehicles. The issue also arises in driver seats with vertical adjustment, where some short-statured drivers are prevented from using the full range of vertical adjustment because of their leg length.

Feel parameters, particularly body pressure distribution, have received substantial attention in recent years because advances in sensor technology have made it possible to measure the pressure at the interface between the sitter and production car seat without substantially interfering with the normal performance of the seat. Early systems required extensive seat modifications that made it difficult to apply the findings to production seats and to compare results among different seat designs. The primary appeal of pressure distribution studies is that they give an objective measurement of some of the stresses applied directly to the skin. Since pressure distributions are clearly related in general ways to discomfort (*e.g.*, high pressures lead to discomfort more quickly than lower pressures), it is tempting to conclude that an ideal pressure distribution can be described that will produce minimal discomfort. However, the research evidence suggests that the pressure distribution alone does not give enough information about the discomfort stimuli perceived by the sitter to serve as an objective measure of the potential for discomfort. For example, the pressure distribution measurement does not give a useful measure of surface shear, which has been determined to be an important factor in determining the critical pressure at which blood vessel occlusion will occur (see Section 3.1). Two identical pressure distributions accompanied by differing surface shear exposures would probably have different outcomes with respect to tissue ischemia and discomfort.

In spite of these limitations, the emerging pressure measurement technology has the potential to be a useful tool in assessing the interaction between sitters and seats. For example, seat-cushion firmness can affect long-term buttock comfort, but will affect heavy sitters with little fat tissue more than lighter sitters with more substantial fat tissue in the buttock area. Pressure distribution measurement could be a useful way of selecting subjects for seat-cushion comfort testing that are likely to be sensitive to changes in foam density. Another important use for pressure measurement is the assessment of lumbar support function. The support forces produced by a lumbar support can be observed on a pressure map of the backrest. The optimal lumbar support configuration for a particular sitter might be identified by the pressure distribution in addition to the contour of the seat.

Support parameters, particularly lumbar support location and curvature, will probably continue to receive the greatest emphasis, both from researchers and manufacturers, because of the importance of low-back pain to consumers and the importance to seat makers of alleviating that pain. The research findings presented in Section 4.1 show considerable consensus with respect to the location of a sitter's lumbar spine and the desirability of providing a firm reactive surface to prevent excessive flexion in that area. There is also general agreement in the literature that the protrusion of the lumbar support should be between 20 and 40 mm, with adjustability provided for different anthropometry and preference, and that the height above the depressed seat surface should be between 200 and 250 mm. These recommendations, however, are based primarily on physiological assessments of spine biomechanics. Lumbar support was found to have only a small effect on back muscle activity. Reclining the backrest by an additional 10 degrees produces a greater reduction in back muscle activity than addition of lumbar support. Changes in spine posture due to lumbar support reduce lumbar intradiscal pressure, but lumbar supports in auto seats do not produce the large changes in spine posture necessary to cause large changes in disk pressure. Further, no link has been established between the low levels of disc pressure associated with quiescent seated postures and disc pathology.

The appropriate design for lumbar support in auto seating is not currently clear because of incongruities between spine postures that have been identified as physiologically desirable and those postures that are prevalent and possible in automobiles. One defining characteristic of passenger car seating is the extended-knee position that results from low seat heights (compared to office seating) and the driver's requirement to operate the foot controls. Knee extension places a restriction on the forward rotation of the pelvis through the action of the hamstring muscles that extend both below the knee and above the hip joint. Stokes and Abery (1980) demonstrated that the knee position alters the range of motion of the pelvis in sitting postures. Boughner (1991) developed a computer model to describe the constraints that the resting hamstring muscle length imposes on pelvic orientation. When the knees are extended, an upright pelvis orientation can put passive tension on the hamstrings. The extended knee posture therefore constrains the pelvis angle, which in turn constrains the lumbar spine posture. Particularly for low seat heights, a lordotic lumbar curvature may not be possible for many drivers. Consequently, the appropriate function of a lumbar support in such seats cannot be to maintain a lordosis, and thus a convex lumbar support contour would be inappropriate. A lumbar support designed for a flat spine curve might be more comfortable in such seats.

The first edition of this report noted that a primary limitation of previous physiological research on lumbar support was that realistic postures were not studied. Since then, a large amount of data have been gathered on the postural effects of seat geometry, including the effects of lumbar support on spine posture. The data indicate that lumbar supports in auto seats do not generally induce lordosis, but they can prevent the sitter's lumbar spine from flexing maximally. This may reduce the stresses on the spine and paraspinal tissues to a sufficient extent that discomfort may be delayed or prevented. Indeed, subjective data suggest that seatbacks with a moderate prominence, located near the middle of the lumbar spine, are judged to be more comfortable that flatter or more contoured seats. The passive tissues of the lumbar spine are highly nonlinear, so that even a modest reduction in flexion may reduce tissue stresses significantly. Together, these findings suggest that seats should be designed to accommodate sitters in the postures that they prefer. Lumbar supports should be designed to minimize lumbar spine flexion to the extent practical without producing uncomfortable pressure in the lumbar area.

6.0 SUMMARY

The recommendations discussed in the previous sections are summarized here in tabular and graphical form. The reader is referred to the body of the report for more detail and the rationale behind the recommendations.

6.1 Fit Parameters

Fit parameters are linear dimensions related to sitter anthropometry.

Table 15
Summary of Fit Parameter Recommendations

Parameter	Recommendation (mm)	
	Should not be less than:	Should not be more than:
Cushion Width		
• Actual width at H-point	500	--
• Clearance at H-point	525	--
• Width at front of cushion	525	--
Cushion Length		
• Forward of H-point on thigh line	--	305
Backrest Width		
• At waist (220 mm above H-point)	384	--
• At chest (318 mm above H-point	471	--
• Height of side bolsters above H-point	--	288
Backrest Height	410	550
Seat Height at Front of Undepressed Cushion	--	346
Seat Position Width	656	--

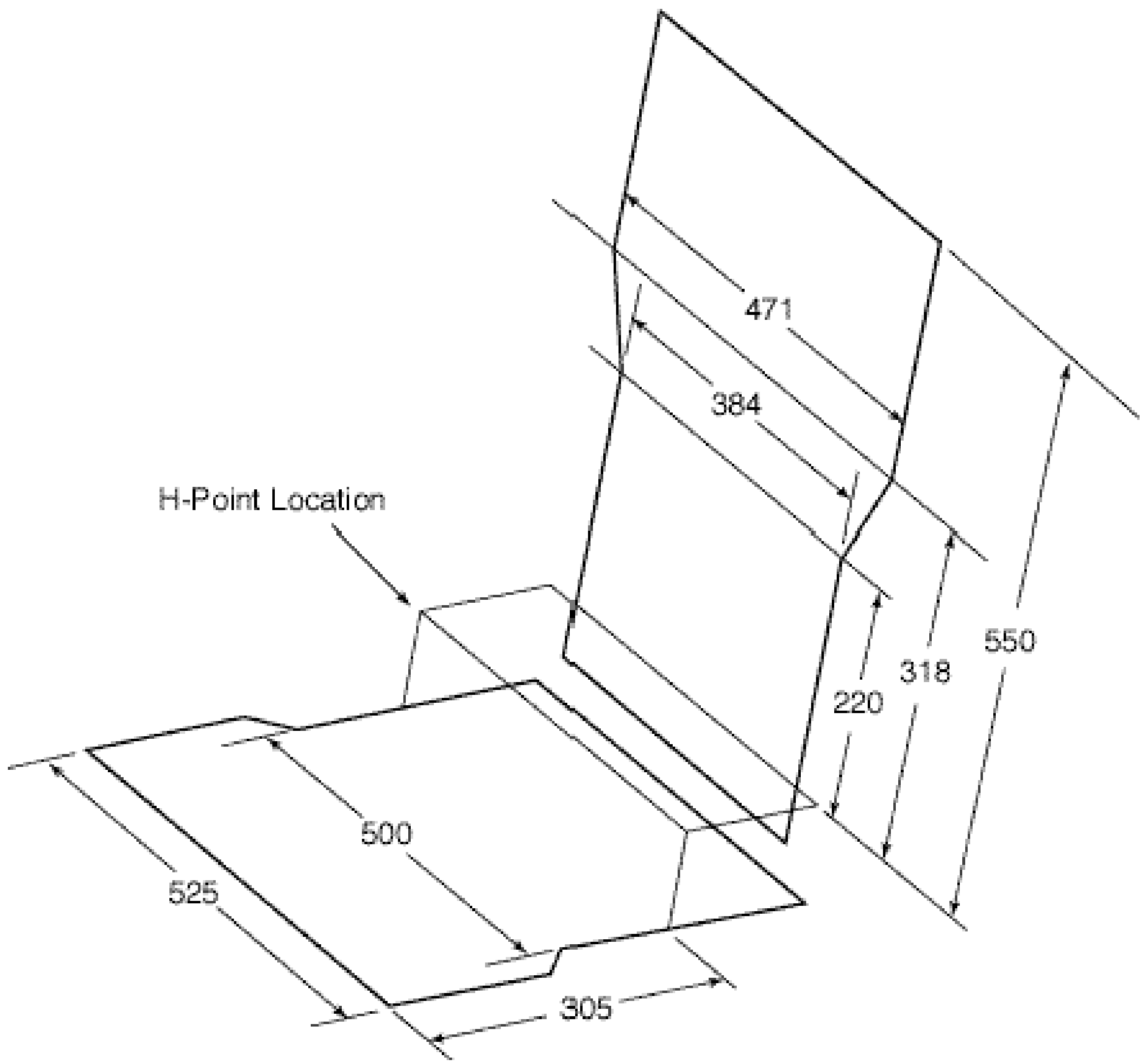

Figure 8. Schematic representation of Fit parameter recommendations.

6.2 Feel Parameters

Feel parameters affect local comfort and are related to stimuli detected primarily in the skin and subcutaneous tissues.

Table 16
Recommendations for Feel Parameters

Parameter	Recommendation
Pressure Distribution	
• Seat cushion patterns	Peaks should be located only in the areas of the ischial tuberosities. No other local maxima should be found.
• Backrest patterns	Peaks should be located only in lumbar area. No local maxima should be found in the shoulder area.
• Peak levels	Peak levels should be determined by subjective comfort testing with target populations. Large differences in pressure distributions and sensitivity among individuals make specifying a quantitative “optimal pressure distribution” difficult.
Surface Shear	Surface shear on the seat cushion should be minimized by increasing the cushion angle and/or by contouring the cushion to achieve the same effect.
Temperature and Humidity	The seat covering should allow heat transfer of at least 75 W/m^2 by conduction and diffusion of water vapor. Foam should not be compressed to more than 80% to allow for maximum vapor diffusion.
Vibration	The seat should minimize the transmission of frequencies between 4 and 8 Hz.

6.3 Support Parameters

Support parameters are intended to influence the posture of the sitter and are related to body segment angles.

Table 17
Recommendations for Support Parameters

Parameter	Recommendation
Lumbar Support (Fixed)	
• Vertical position	Locate apex 200–250 mm above depressed seat surface, or 105–155 mm above H-point along back line. Mean preferred height is 150 mm above the H-point.
• Prominence	Support should protrude 15 to 20 mm in front of backrest plane (see Figure 9), yielding a lumbar support prominence measure of 15 to 20 mm using the ASPECT manikin.
• Radius	The 20-mm support should have a depressed-contour, convex radius of about 300 mm.
• Sacral Relief	Adequate relief should be provided below the lumbar support for the sitter's buttocks. Measurement of lumbar support prominence with the ASPECT manikin includes the effectiveness of sacral relief.
Lumbar Support (Adjustable)	
• Vertical position	Apex should be adjustable between 100 and 200 mm above the H-point along back line.
• Prominence	Prominence should be adjustable between 0 and 30 mm, as measured by the ASPECT manikin.
• Radius	Radius should be adjustable between 250 and 400 mm. If only a prominence adjustment is provided, higher prominences should be achieved with smaller radii.
Knee Angle	Included angle between leg and thigh should be less than 135˚. Mean preferred angle is 122 degrees.
Trunk/Thigh Angle	Angle formed by the knee, hip, and shoulder joints should be larger than 90˚. Mean preferred angle is about 105 degrees.
Trunk Angle	Angle relative to the vertical of line from hip joint to shoulder joint should be between 10–30˚. Mean preferred angle is 28 degrees. Mean preferred angle of line from hip to eye is about 10 degrees.

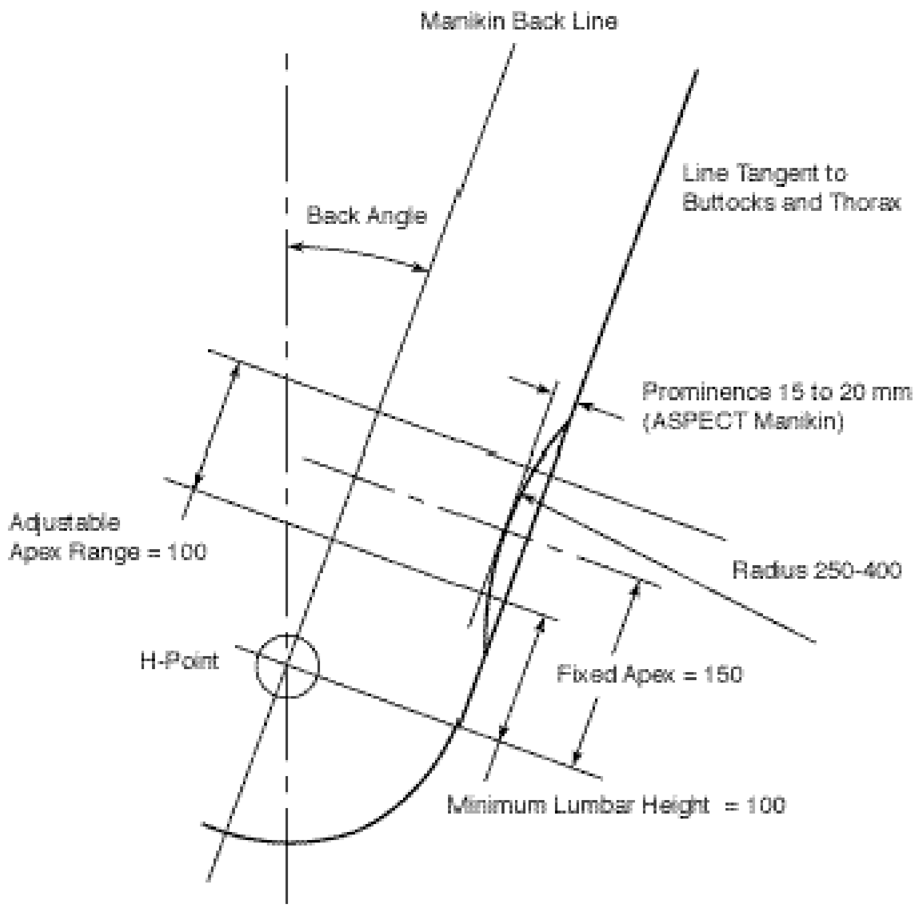

Figure 9. Schematic illustration of lumbar support recommendations (dimensions in mm).

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