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REVIEW OF SELECTED LITERATURE RELATED TO SEATING DISCOMFORT

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16. Abstract

This literature review incorporates published research of anatomical, behavioral, biomechanical, and physiological studies related to automotive seating comfort. It summarizes key literature related to seating design and criteria and reviews comfort issues in automotive seating. The report is divided into five sections: Driving Posture, Pressure Distribution and Hemodynamics, Vibration, Subjective Evaluation, and Practice in Industry.

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INTRODUCTION

Automotive seats need to accommodate a wide range of driver sizes over relatively long periods of time and provide isolation from vehicle vibration and shock. To fulfill these requirements, there have been remarkable advances in automotive seat design during the past decade incorporating seatback recliners, lumbar support, motorized multi-axes adjustments, and foam cushions. However, these added features have resulted in increased cost and have been used in only a limited number of seating environments. Even with the progress that has been made, however, many drivers continue to experience significant discomfort in automotive seating, and the factors that contribute to long-term discomfort or improved comfort are still not clearly understood.

Thus, in spite of abundant research studies in automotive seating, many questions still remain about what really contributes to seating comfort. As stated by Corlett (1989):

> One of the most difficult, though apparently simple, problems in ergonomics is the evaluation of the quality of seating, and perhaps the one dimension which is most difficult is comfort of seating.

Studies of seating comfort are particularly difficult to conduct due to a large number of interacting factors involving the driver, the seat, and the driving tasks as shown in Table 1. The most difficult challenge in such studies is that of accurately and consistently measuring the subjective perception of discomfort. Though Hertzberg (1958) defined comfort as *the absence of discomfort*, there is no universally accepted operational definition of discomfort. Furthermore, there is no agreed upon, reliable method for quantifying the sensation of comfort or discomfort.

TABLE 1
FUNCTIONAL FACTORS IN SITTING (Corlett 1989)

The Task	The Sitter	The Seat
Seeing Reaching (arm and leg)	Support weight Resist accelerations Under-thigh clearance Trunk-thigh angle Leg loading Spinal loading Neck/arm loading Postural change Long-term use Acceptability Comfort	Seat height Seat shape Backrest shape Stability Lumbar support Adjustment range Ingress/egress

In order to provide direction for additional research, a literature review was conducted of anatomical, behavioral, biomechanical, and physiological studies related to seating comfort. The goals of this review were:

1. to determine factors important to automotive seating comfort;
2. to understand the interaction between the human and the seat;
3. to establish preliminary seat design guidelines;
4. to review test methodologies useful for evaluating the comfort of a seat;
5. to establish future research direction in automotive seating comfort.

This document reviews comfort issues in automotive seating as well as other relevant information not necessarily specific to automotive seating. The material is divided into five chapters: (1) Driving Posture, (2) Pressure Distribution and Hemodynamics, (3) Vibration, (4) Subjective Evaluation, and (5) Practice in the Industry. Each chapter contains annotated abstracts of literature reviews in chronological order.

KEY REFERENCES

The following references provide a good overview and perspective on seating comfort issues.

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

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

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

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

Pheasant, S. (1986) Chapter 8: Posture. In *Body space: Anthropometry, Ergonomics and Design*. Taylor and Francis, Ltd., London, England.

Pheasant, S. (1986) Chapter 11: Seating. In *Body space: Anthropometry, Ergonomics and Design*. Taylor and Francis, Ltd., London, England.

Pheasant, S. (1986) Chapter 12: Driver's workstation. In *Body space: Anthropometry, Ergonomics and Design*. Taylor and Francis, Ltd., London, England.

Corlett, E. N. (1989) Aspects of the evaluation of industrial seating—The Ergonomics Society Lecture. *Ergonomics*, 32:257–269.

KEY REFERENCES

A. DRIVING POSTURE

Driving posture is a restricted seated working posture in which the driver must interact with and operate vehicle components. The driving posture is therefore determined and influenced by seat characteristics such as surface shape, amount of cushion, seat back and pan angles, lumbar support, and adjustability as well as the locations of controls (steering wheel and pedals), field of vision, and available head room.

Rebiffe (1966) reported joint angles for comfortable driving posture and demonstrated comfortable zones for the steering wheel and pedals to accommodate small- and large-size drivers simultaneously. Similar research was done by Preuschen and Dupuis (1969) and Verriest (1986). Although the results showed wide ranges of preferred angles, and only provided two-dimensional (planar) joint angles instead of real three-dimensional angles, they have provided important guidelines for car interior designers. Drury and Searle (1965) reported the preferred locations of seating and controls for the truck driver, but the ranges of optimum locations were widely distributed. Verriest (1986) introduced a variable-geometry test rig to measure the preferred seating parameters. Schneider et al. (1979) suggested a complex interaction between pedal location and steering wheel location in determining a driver's preferred seat location which also showed a significant relationship with stature.

Geoffrey (1961) developed a 2-D manikin for seating design based on X-rays of seated subjects which became the basis for the SAE J826 3-D automotive seat calibration device that defines the location of the 50th percentile male hip point. Because these manikins (the 2-D and SAE manikin) do not reflect lumbar shape, discrepancies are inevitable between real seating posture and manikins (Hubbard and Reynolds 1984). Kohara and Sugi (1972) stated that seating comfort is determined not by the external shape of the seat but by the final stable posture in which a seated person settles himself. In order to evaluate the final stable posture of a given seat, he developed a 3-D manikin which has a unique joint-spring mechanism analogous to the human lumbar.

The most well known biomechanical aspect of sitting is flattening of the lumbar curvature as the pelvis rotates backward (Akerblom 1948; Keegan 1964; Andersson et al. 1979). Lumbar flattening brings at least 50% higher intervertebral pressure in the unsupported sitting posture than in the standing posture (Nachemson and Morris 1964; Andersson et al. 1974). In order to support the lumbar area and redistribute trunk weight, lumbar supports and back recliners have become the most recommended devices for improved seating comfort. Andersson et al. (1974) showed that the driver's seat position which minimizes myoelectric activity and intervertebral pressure is 120° of backrest inclination, 4 cm of lumbar support, and 5° of seat pan. Back inclination was the most important parameter affecting both myoelectric activity and disc pressure: myoelectric activity and disc pressure decreases with an increase of inclination (Andersson et al. 1980). Hosea et al. (1986) obtained similar results during actual driving. However, evidence of muscular fatigue was not identified over a 3.5-hour driving period, and it was concluded that paraspinal muscle activity may not play the predominant role in disc herniation related to driving.

There is little doubt about the need for lumbar support in a comfortable automotive seat. However, design guidelines (size, shape, or location) for lumbar support are not clear because of the large variability in the size and shape of the human body (Branton 1984) and the complex and poorly understood relationship between body size and weight and seat compression. The most widely recommended amount of lumbar support is a depth of 4 cm located at the level of L3. However, the location of lumbar support with respect to the level of the lumbar spine has been found to be of little importance to the shape of the lumbar curve (Andersson et al. 1979). A variety of posture measurement methods have been adopted and X-ray has been widely used to understand skeletal geometries (Akerblom 1948; Geoffrey 1961; Keegan 1964; Kohara and Sugi 1972; Nyquist and Patrick 1976; Andersson et al. 1979). Although radiography is the most ideal tool, it is no longer an acceptable experimental technique because of radiation exposure problems.

Stereophotogrammetry has been used to provide surface landmarks and precise information on the 3-D location of palpated skeletal landmarks during automotive seating (Robbins et al. 1983). Diebschlag and Mueller-Limmroth (1980) used a simple back contour transcripting machine to measure the back shapes (profiles and cross sections) of relaxed, upright seated male and female drivers and found no marked difference between male and female drivers of similar size. This information may be used to design backrest surface and lumbar support contours appropriate for both male and female drivers.

The function of hamstring muscles may also be a factor in seating comfort. Because the hamstring muscles cross two joints (the knee and the hip), movements of the lower limb can affect pelvic rotation and influence the posture of the spine. People who have tighter hamstrings tend to show a larger change in spinal curvature when sitting or extending the lower leg (Stokes and Abery 1980; Bridger et al. 1989).

One of the most important factors contributing to discomfort is sitting duration. Branton (1969) observed resting postures using time-lapse films and showed that the seat slowly and repeatedly ejected the sitter. Two generic approaches are possible to improve postural comfort in a prolonged driving situation. One way is to increase the driver's freedom by removing postural restrictions using automatic shift or cruise control (Rebiffe 1980). Another approach is provision of support and accommodation of movement in seat design (Lueder 1983). However, these dual criteria may conflict. Accommodation of movement frequently curtails the potential for support and, enhancement of support limits the ability to shift one's body weight.

General guidelines for thigh, trunk, thorax, or head support are not well defined and there is little understanding about how to relieve postural stress. Fidgeting is regarded as the body's defense against postural stress. Drivers fidget before they become consciously aware of discomfort (Branton 1969; Pheasant 1986). Postural changes on a given seat may be a clue to understanding seating discomfort and stress relief mechanisms and are therefore a possible measure for evaluating and comparing seating comfort.

The following questions need to be investigated further to gain a better understanding of seating posture:

1. How can seating posture be optimally stabilized?

2. How can support and movement during prolonged sitting be effectively accomplished?

3. What is good "final stable posture?"

4. What is good back shape?

5. Is it possible to accommodate the entire driver population with a single seat-back contour?

Geoffrey, S.P. (1961) **A 2-D manikin—The inside story.** *SAE paper no. 267A.* Paper presented at the 1961 SAE International Congress.

The purpose of this study was to develop a seated-male, 2-D, side-view template as a seating design and automotive interior dimensioning tool. Based on this document, SAE J826 (*Devices for Use in Defining and Measuring Motor Vehicle Seating Accommodations*) was established.

In order to determine the dimensions of the template, the effective link lengths of the 90th percentile driver were estimated from the results of Gleser and Trotter (1958) and Dempster (1955). The effective link length between hip joint and shoulder joint was determined by an x-ray survey of twelve male subjects with 80th percentile weight and sitting height. Using basic linear relationships, link length was translated from 80th percentile to 90th percentile values. The X-rays were taken at two different seated postures: an erect sitting posture and a driving posture on a typical automobile seat.

The slump factor (0.84 inches) was determined from the difference between the erect and the normal postures. A slump of 0.57 inches occurred between the hip and shoulder joint; the remaining 0.27 inches occurred between the shoulder joint and the top of the head. The average back angle (angle between the line formed by the hip and the shoulder joints and the horizontal) of the seated subjects was 22.5° for the normal driving posture.

In this study, the authors assume that the posture that was found most frequently on the survey seat is an optimum posture. As a result, the final back contour of the template represents the average of the slumped back of the subjects.

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

This is one of the classic papers which explains seating discomfort, especially low back pain, by lumbar spine flattening. It also includes intuitive seating design recommendations.

Lumbar curvature (lordosis) is an essential mechanism for upright walking. It allows pelvis rotation and gives straight alignment between trunk and lower extremities and it supports the trunk weight. X-rays show that lumbar curvature is greatly flattened when sitting. As a result, anterior wedging pressure is increased on the discs between lumbar vertebral bodies and discs may bulge or protrude rearward in extreme cases.

From X-ray observation, it was found that a sitting posture with a trunk-thigh angle of about 115° with lumbar support gives the nearest approximation to the normal lumbar curve (Figures 8 and 10).[1] Lumbar support should be curved and placed low enough to give support over the 4th and 5th lumbar vertebrae and discs, where 95% of lumbar disc trouble develops, not at the mid-lumbar region.

Provision of an open or recessive space for the buttock is important to fit the lumbar-to-lumbar support. Moderate contouring and cushioning of the seat are helpful to transfer some of the trunk weight from the buttock area, but excessive contouring or cushioning transfers too much weight and restricts needed changes of position.

The height of the seat from the floor is important and is related to seat length for optimal comfort. With a 16-inch length seat the height should not be more than 16 inches for short men and most women to reach the floor comfortably without excessive pressure on the underside of the legs.

According to this paper, ten factors which affect seating comfort are listed below in order of decreasing importance:

	Factor	Estimated Importance
1.	Vertically-curved lower lumbar support	20%
2.	Minimum trunk-thigh angle	15%
3.	Length of seat	10%
4.	Height of seat	5%
5.	Open front of seat	5%
6.	Tilt of seat	3%
7.	Free space for sacrum and elbows	
8.	Front and top borders rounded or soft	
9.	Moderate contouring or cushioning	
10.	Porous cover cloth	

[1]NOTE: Figure and table numbers throughout this report have been maintained as in the original paper.

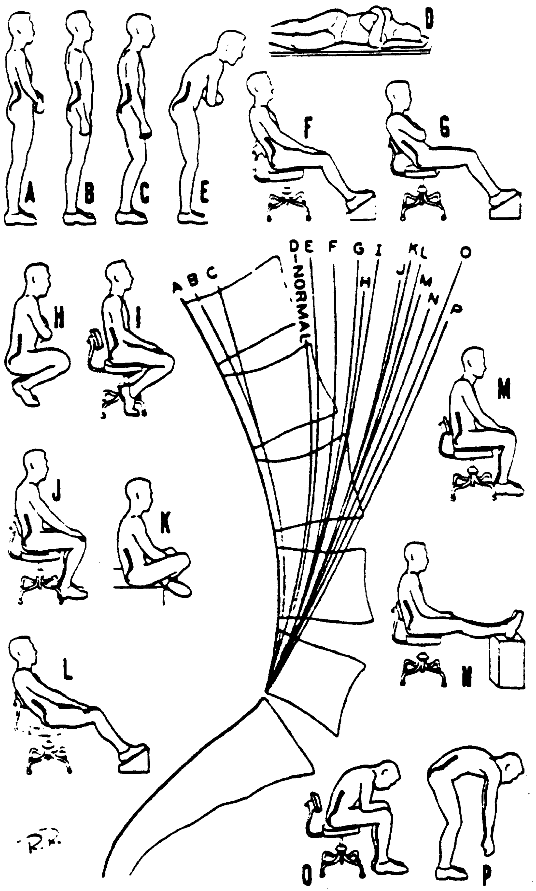


FIGURE 8. Subject III. X-rays of lumbosacral spine in 16 positions to show progressive flattening of lumbar curve from erect standing to maximum stooping, interpreting the normal curve in the lateral recumbent position.

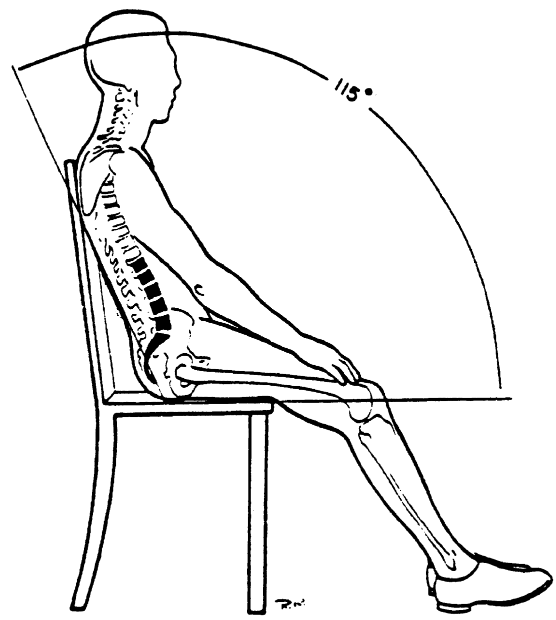


FIGURE 10. Position commonly taken by men for comfort in right-angled chair.

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

This paper deals with the development of a manikin that can simulate the final stable posture of a driver to evaluate seat comfort quantitatively and to analyze the biomechanical characteristics of seats.

The factors that influence the static comfort of seats can be broken down into the following: dimensions of a seat, final stable posture, body pressure distribution, cushion characteristics, and body shape of individual.

Obviously, movement is essential to human beings. Therefore, *a seat without any freedom would never be a good seat. But a good final stable posture in a standard sitting position is a necessary condition for seat comfort*. The authors define six prototypes of final stable posture depending on the types of seating.

The authors classify the back shape into three different patterns based on a curvature measure (Figure 4). The proportion of flat, normal, and round back persons was 11%, 64%, and 25%, respectively, of the surveyed population. A person with a round back feels more comfortable in a seat with a large curvature of the seat back, while a person with a flat back feels comfortable in a seat with a flatter seat back. Also, the most comfortable shape of the spinal column was measured at three different postures (standing, sitting, and lying). It was found that the distances between the most lordotic point of the lumbar and the most prominent point in the back (scapular, etc.) were 10–15 mm in the sitting posture (Figure 5).

A three-dimensional manikin which has a spinal column analog was developed and compared with a human subject (Figures 19 and 20). Using the distance between each spring bracket, one can judge the quality of the spinal support of a seat. A rough criterion for seat comfort is the length sum of L2 and L3 which should be 150 mm when the manikin is mounted on that seat.

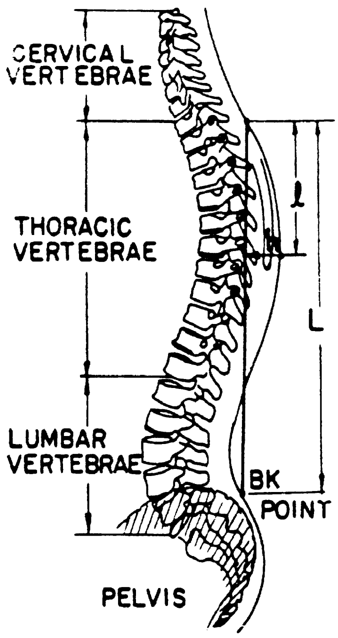


FIGURE 4. Parameter presenting body shape.

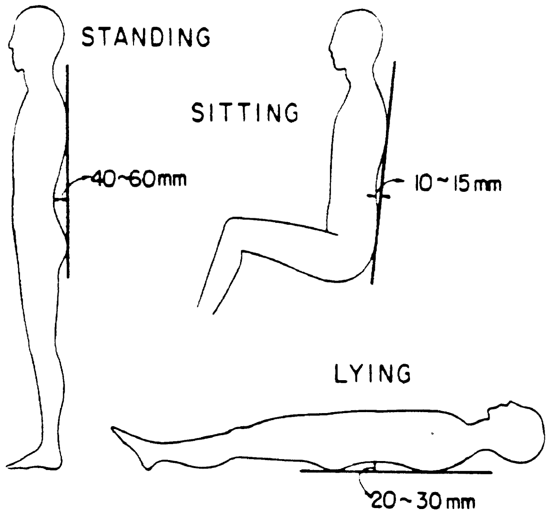


FIGURE 5. Comfortable spinal curves in three typical postures.

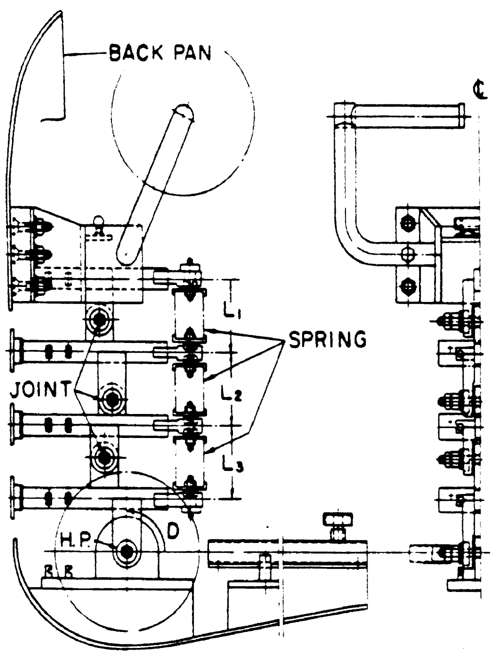


FIGURE 19. Plan of 3-D manikin, Model III.

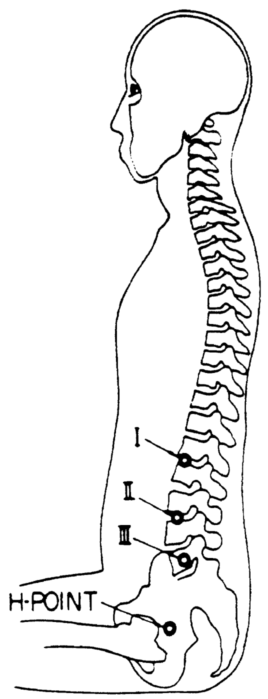


FIGURE 20. Relative joint locations of a 3-D manikin.

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

The myoelectric (EMG) activity of several muscles of the back and the lumbar disc pressure were measured simultaneously (see Figure 1 and Table 1) while subjects (N=4) were sitting on a driver's seat.

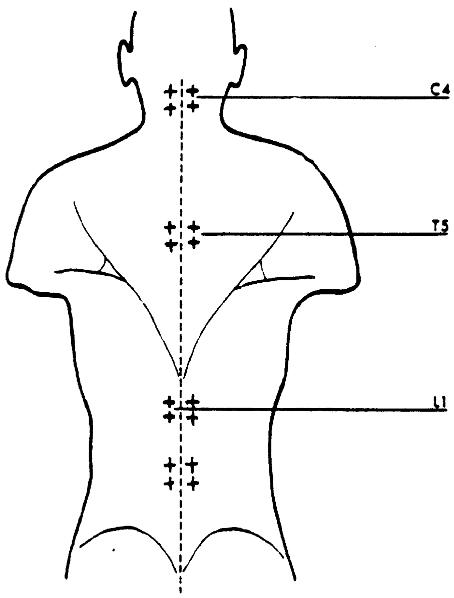


FIGURE 1. Locations of EMG electrodes.

TABLE 1
LOCATIONS OF EMG SURFACE ELECTRODES, DISC PRESSURE MEASUREMENT NEEDLE, AND TEST CONDITIONS

EMG Electrode Locations	C4 T5 L1 L3 T8 & T10	Both sides of the spine, 2.5–3.0 cm from midline and parallel to the spinous process electrode and disc pressure needle Left side only
Test Conditions	Backrest inclinations Seat inclinations Lumbar supports Driving postures	90°, 100°, 110°, 120° 10°, 14° 0 to 5 cm Relaxed, Depressing the clutch pedal, Shifting gear

Disc pressure and the myoelectric activity decreased with increases in the backrest angle and the amount of lumbar support. The lowest disc pressure was found when the backrest inclination, the lumbar support, and seat inclination were all as large as possible (B=120°, L=5 cm, S=14°).

When the backrest inclination increased, a larger proportion of the body weight was transmitted to the backrest thereby reducing the stresses on the spine resulting in less disc pressure and less muscle activity. However, the effect was less pronounced at larger recline angles because the neck must be flexed to maintain eye position.

A large backrest to seat cushion angle increases the angle of the hips and forces the pelvis to rotate backwards (suitable hip angles are between 95–120°). To preserve the suggested hip angles, it is necessary to *increase the inclination of seat cushion and backrest simultaneously*.

The authors point out that the level of the lumbar support is important. If it is too high, a lumbar support forces the lumbar spine into kyphosis. If it is too low, it pushes the occupant forward on the seat. The authors recommended the level of L3 as an optimum location for lumbar support.

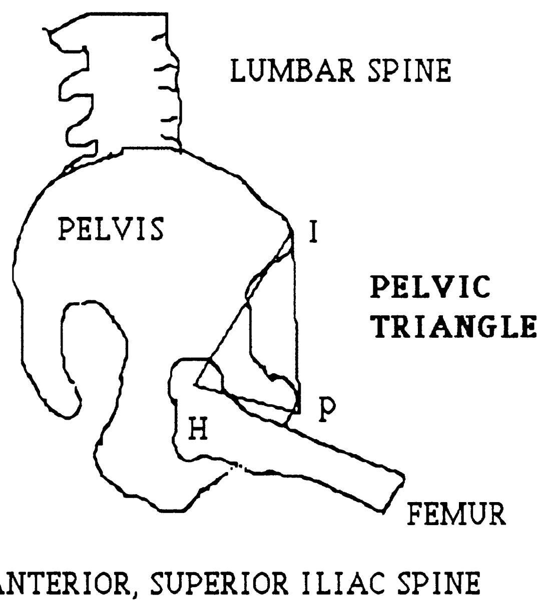
Nyquist, G.W.; and Patrick, L.W. (1976) **Lumbar and pelvic orientations of vehicle seated volunteer.** *SAE paper no. 760821.*

The purpose of this study was to gain insight into the lower torso skeletal geometry associated with seated postures in a vehicle. Radiograms of the lumbar, pelvis, and femur configuration were taken from two adult male volunteers.

To solve the seat cushion interference problem (because the lower torso submerges into the seat), a wooden seat was sculptured using a thin plaster cast of the volunteer/seat interface.

From two radiograms, each vertebral body center was identified and various angles were measured. In order to define the position and orientation of the lower torso, the authors defined the pelvic triangle formed by the anterior-superior iliac spine (ASIS), the pubic crest, and the H-point (Figure 10). By definition, this plane lies on the mid-sagittal plane.

For the seating configuration in this study, the lumbar spine was nearly flat. Examination of the radiograms allowed researchers to determine the location and orientation of the subjects' pelvis and spine. Because of radiation hazard, the authors recommended the direct observation of subject posture by palpation technique (Nyquist and Murton 1975).



I : ANTERIOR, SUPERIOR ILIAC SPINE
P : PUBIC CREST
H : H-POINT

FIGURE 10. The pelvic triangle.

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

This paper explains the symptoms and causative factors of back pain due to prolonged driving.

Primary back pain stems from a local state of irritation which can be due to muscular fatigue or postural stress, to injury, and/or to degenerative disease or local pathological changes in the spine. The pain may be local or spread up or down the spine and is often referred to the buttocks and thighs. Because there are no nerve supplies, intervertebral discs and cartilaginous facet of the synovial joints can be injured without pain.

Secondary pain in the back or lower limb is due to mechanical disturbance of, or degenerative changes in, the nerves which supply the back or legs. The significance of minor injuries is that, if repeated, they have a cumulative effect leading to an early onset of degeneration.

There is epidemiological evidence that *those who spend more than half of their working lives driving are three times more likely to suffer back trouble than the rest of the population*. Apart from individual susceptibility to back trouble, the causes would appear to be mainly mechanical such as postural stress, vibratory stress, muscular effort, and shock or impact.

If the spine is exposed to postural stresses for long enough, it stiffens as well as shortens (creep effect—when the compressive load exceeds the osmotic pressure in the disc, fluid is slowly expelled and the disc becomes less compliant and shortened). Therefore, neuromuscular control of spinal posture and reaction to external forces are likely to be modified. Also, muscular activities required to maintain given postures may induce symptoms of fatigue. Figure 1 shows the most common forces which are applied to the L5-S1 joint.

To prevent postural overload, 110° or more of backrest angle, 6° of seat inclination, and lumbar support at L3 level are recommended. These reduce the postural stress, and also reduce the stresses arising from road shock and vibration. To prevent vibration in the range of 4 to 8 Hz, soft cushions should be replaced with firm ones, and the seat should be suspended to get a natural frequency of less than 1.5 Hz. The line of action of pedal-force should pass from the foot through the hip joint, and the backrest should firmly resist pelvic rotation.

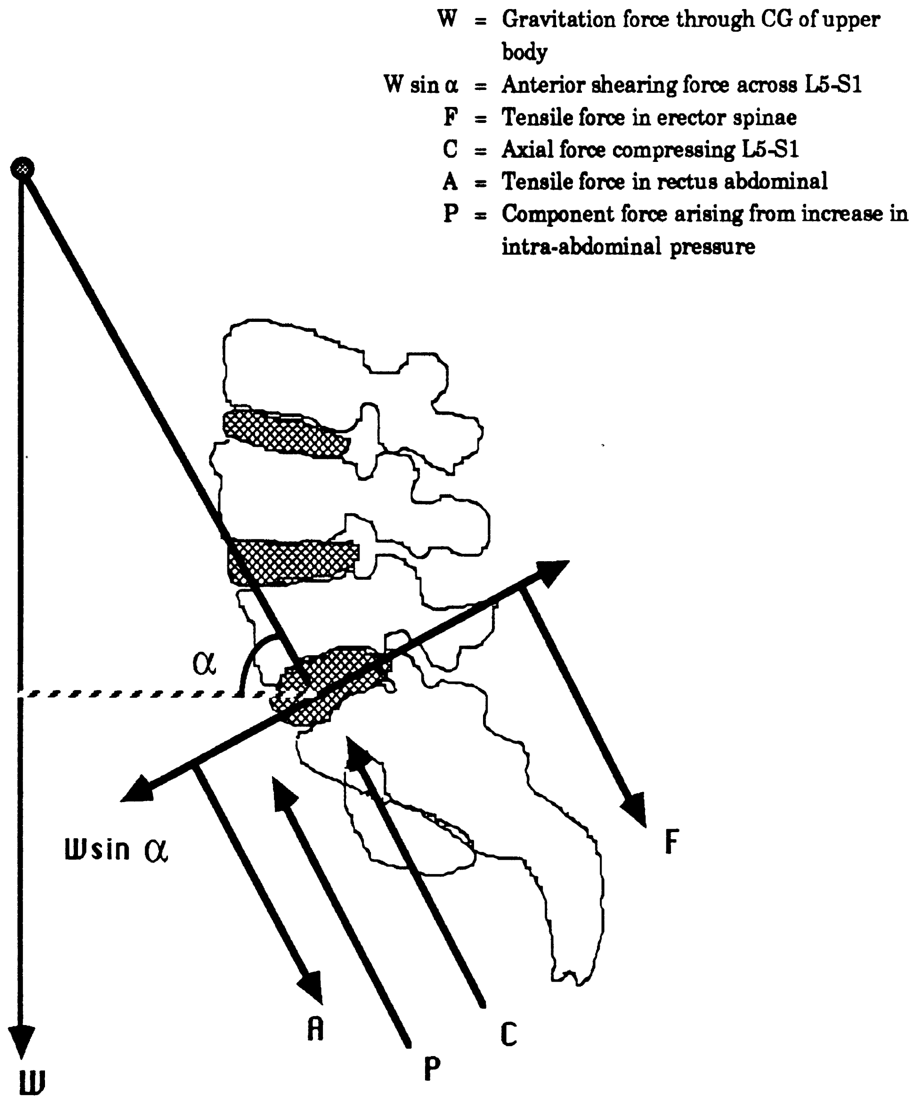


FIGURE 1. Diagrams of forces in the sagittal plane at the L5-S1 intervertebral disc arising from muscular activity and the effects of gravity on the upper part of the body.

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

The influence of backrest inclination and lumbar support on the shape of the lumbar spine in sitting posture has been studied radiographically. Spinal X-rays were taken from four different groups of subjects at four different sitting conditions on an experimental chair:

1. standing and unsupported sitting posture;
2. 80° to 110° of seatback angle, without lumbar support;
3. 90° of seatback angle, –2 to +4 cm of lumbar support, relative to the plane of the seat back;
4. 110° of seatback angle, +4 cm of lumbar pad, and L1, L3, and L5 as support locations.

Nine different angles, including total lumbar angle, were evaluated from X-rays (Figures 3 and 4). The measurements showed an average of 38° reduction of total lumbar angle (i.e., decrease of lumbar lordosis). This reduction is mainly due to the rotation of the pelvis (28°) and changes in the vertebral body angles of the two lower lumbar segments (10°).

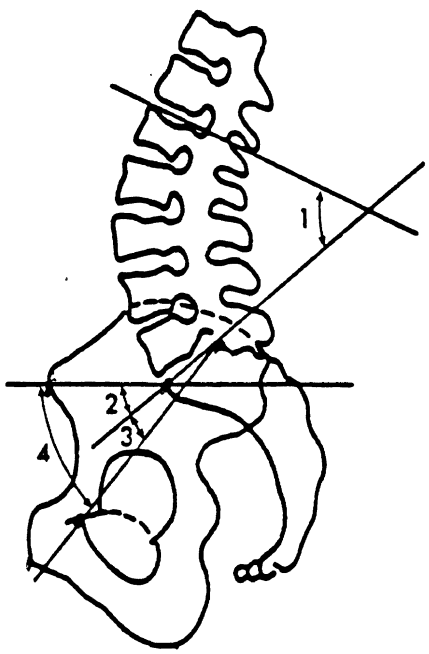


FIGURE 3. Angles measured from the radiographs of subjects in the study: 1=total lumbar angle; 2=sacral-horizontal angle; 3=sacral-pelvic angle: 4=pelvic-horizontal angle.

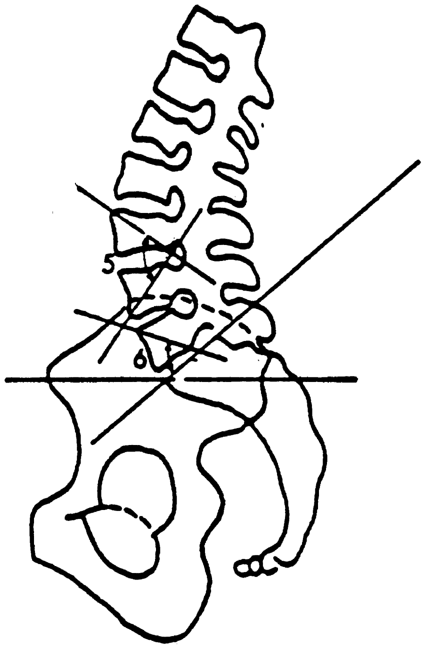


FIGURE 4. Angles measured from the radiographs of subjects in the study: 5=vertebral body angles L1–2, L2–3, L3–4, L4–5, and 6=the L5-S1 angle.

With +4 cm lumbar pad, the lumbar curvature closely resembles the lumbar curve of the standing posture. The location of the lumbar support with respect to the level of L1 to L5 did not significantly influence any measured angles.

A simple geometric calculation shows that the lumbar support moves about 4.5 cm upward with respect to the lumbar spine when the backrest angle increases from 90 to 105°. Therefore, it is necessary to increase the inclination of the seat and backrest simultaneously.

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

This paper deals with the special problems in automotive seat design, and also contains seat design guidelines generally agreed upon by experts in orthopedics and ergonomics.

1. Side Support: Side supports would be favorable to the back by keeping the spine in the appropriate vertical position. Preuschen and Dupuis (1969) proposed a small space between trunk and side support to allow body movement for fatigue relief. Grandjean et al. (1973) found that the subject felt more comfortable when the backrest was gently curved (45-cm radius at the lumbar level and 60-cm radius on the upper part of the backrest).

2. Lumbar Support: Grandjean et al. (1969) found that the highest comfort rating was obtained when the center lumbar support was 10 to 14 cm above the depressed seat surface (corresponding to L5, including the upper part of the sacrum and L4).

3. Inclination of Seat Surface: For the driver's seat, Andersson et al. (1974) recommends a backrest angle of 120° and seat surface angle of 14°. In the case of passenger seats, slightly different values (Grandjean et al. 1969) can be applied (i.e., seat surface angle of 21° and 24° with seatback angle of 122° and 128°).

4. Profile and Shape of the Seat Surface: Grandjean et al. (1973) concluded that a backrest which is slightly concave in the thoracic region 45 to 55 cm above the depressed seat surface allows a larger portion of the back muscles to relax. The concavity in the upper part of the backrest provides a better neck position and therefore reduces the risk of fatigue in the neck area.

The following are recommended guidelines for automotive seat design.

- A comfortable body posture requires the following angles:

Ankle	90 to 110°
Knee	110 to 130°
Arms versus Vertical Line	20 to 40°
Hip	100 to 120°
Head-Neck Axis to Trunk Axis	20 to 25°

- A fore-aft adjustment (minimum range of 15 cm) and adjustable backrest angle between 90° and 120° are essential.
- The seat cushion depth should not be shorter than 44 cm and not exceed 55 cm.
- The seat cushion angle should not be smaller than 10° and not exceed 22°.
- The backrest should have a lumbar support.
- Side supports to seat cushion as well as to the backrest are advisable to improve the position of the hips and trunk.

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

The hamstring muscle can restrict hip flexion, especially when the knees are extended, as is the case in the driving posture. It was hypothesized that individuals with short or tight hamstrings would have abnormal tilting of the pelvis in some seated postures, with greater flattening or reversal of the lumbar lordosis.

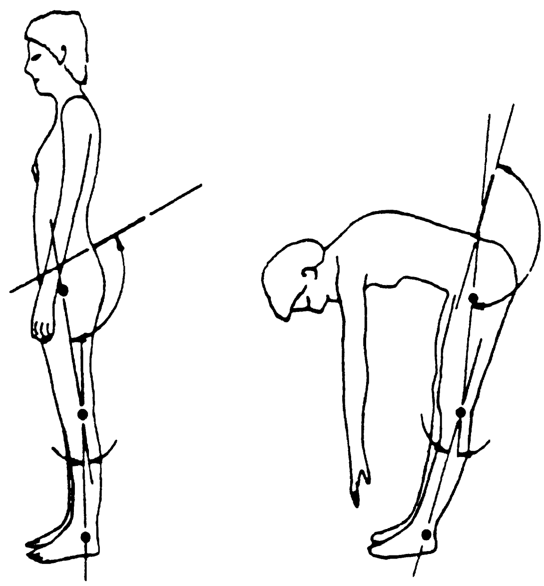


FIGURE 2. Tracings from photographs show the method of measuring the straight-leg range of hip movement. The pointer on the pelvis and markers on the leg allow measurements of joint movements.

As a measure of tightness of hamstring muscle, hip-flexion range was measured by a toe-touch test. The back shapes of subjects were recorded by a hand-held stylus over the spinous processes in standing, sitting with knees flexed, and in sitting with knees partially extended.

Large individual variations in hip flexion were found. Subjects (N=29) with more than 40° of hip flexion show a correlation between hip flexion angle and change in spine curvature (i.e., a subject who has less hip flexion angle due to tighter hamstring muscles tends to show a larger change in spinal curvature). It appears that individuals with very tight hamstrings have already flexed the lumbar considerably in sitting, so that extending the knees does not produce much further loss of lordosis.

It is concluded that attention should be given to the effect of the hamstrings on the lumbar spine in workplace design.

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

This study arose from the practical need for data on back shapes in the design of railway passenger seating.

The backshapes of 114 subjects were measured at the most upright posture using a TEMCO Formulator. Based upon visual inspection, 71.1% of subjects were lordotic in the lumbar region, 17.5% of subjects were straight, and 11.4% of subjects were kyphotic.

From a designer's view, it is disappointing to find that the range in driver stature is so great that there is considerable overlap between the height of the nape (innermost point) of neck curvature of a large person and the occiput (rearmost projection of head) of a small person. Therefore, the head or neck rest has to be adjustable over a wide range and even then it is not likely to satisfy more than about 25–30% of the population.

Another apparent difficulty is that the horizontal variation of thoracic curvature is from about 4 to 6 cm, and thus is too large to be compensated for by cushion softness (Figure 1 below).

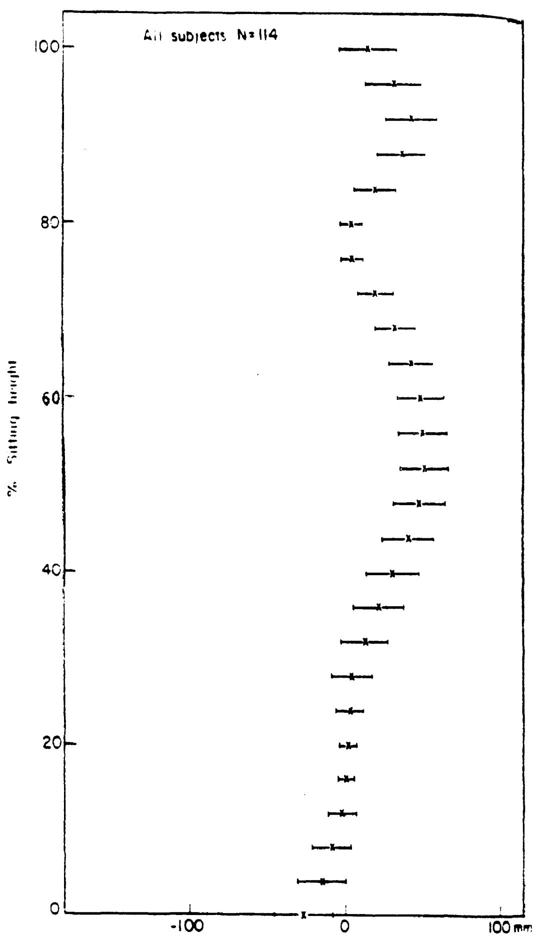


FIGURE 1. A-P back shape (mean ± 1 SD) in millimeters [abscissa] plotted against height as a percentage of sitting height.

Corlett, E.N.; and Eklund, J.A.E. (1984) **How does a backrest work?** *Applied Ergonomics*, 5:2, 111–114.

The authors explain the difference in force distributions between standing posture and several sitting postures. When standing erect, the vertical line through the body's center of gravity (CG) passes through the trunk and the feet, and the muscular activity of the trunk muscles is minimal. Also, reduction in trunk muscle activity is aided by the lumbar lordosis. This forward curve brings the lumbar vertebrae close to or below the CG of the trunk, arms, and head.

Because of the backward rotation of the pelvis when seated, the moment arm between the CG and the lumbar vertebrae increases, and more tension is produced in the erector spinae muscles and other passive ligament structures. A lumbar support makes the upper part of the trunk rotate backwards and relax the posterior muscles of the lumbar spine. The backrest also provides a supporting moment which reduces the need for muscle activity to counteract against gravity.

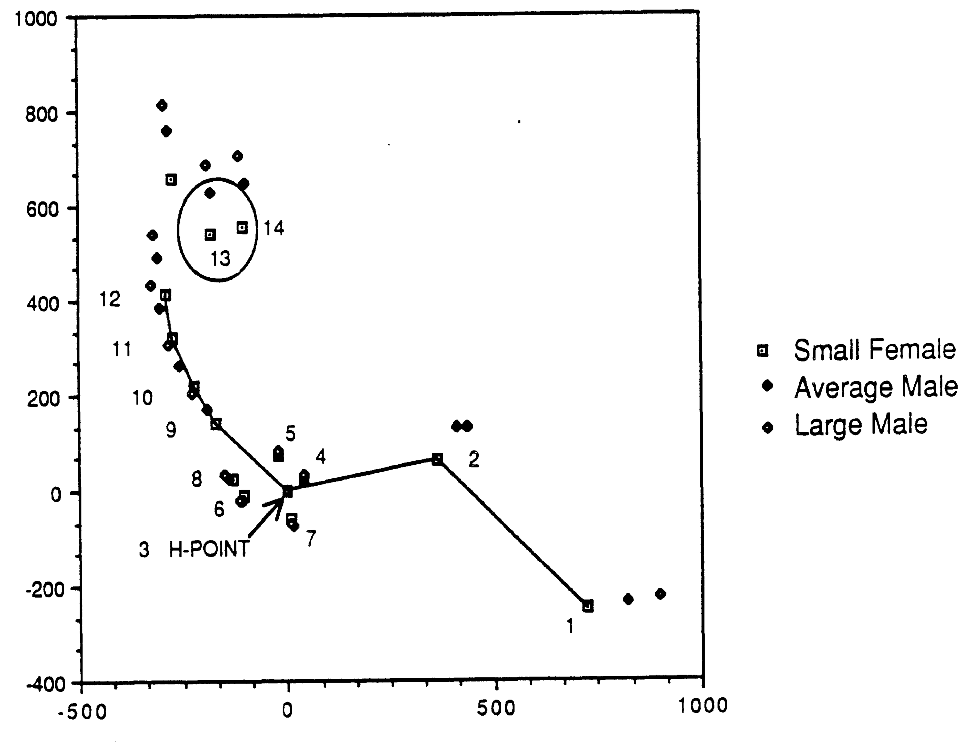
Hubbard, R.P.; and Reynolds, H.M. (1984) **Anatomical geometry and seating.** *SAE paper no. 840506.*

To improve seating comfort, the following factors must be considered:

1. human skeletal geometry and its position in a seat;
2. human movement capability and preference;
3. human mass distribution;
4. human dimensions for work space clearance and seat support surface shape.

In this paper, three different body size groups (small female, average male, and large male) and two different driving postures (erect and reclined) were defined, and the kinematic properties of the body and its important segments are reported in a usable form for seat design.

Body structures which are particularly important considerations for automotive seat design are the femur, pelvis, spinal column (lumbar, thoracic, and cervical), and head. Figure 1 shows the idealized postures of each body-size group. Table 1 contains the authors' idealized geometry for lumbar curvature in each of the different body-size groups.



1.	Heel Point	2.	Knee Point	3.	Hip Point
4.	Symphysion	5.	Ant/Sup Iliac Spine	6.	Post/Sup Iliac Spine
7.	Ischiale	8.	L5 Spinous Process	9.	T12 Spinous Process
10.	Spinous Process	11.	T4 Spinous Process	12.	C7 Spinous Process
13.	Ear Point	14.	Eye Point		

FIGURE A1. Locations of anthropometric landmarks in an automotive seat with a 26.5° seatback angle (figure generated by author from Tables 1–3 in Hubbard and Reynolds 1984).

TABLE 1
RADII AND CENTERS OF LUMBAR SURFACE CURVATURE

Radii	Small Female	Avg. Male	Large Male
Rearward of H-point (mm)	168	220	422
Above H-point (mm)	163	183	208
Radius (mm)	195	249	444

The authors made an assumption that the most desirable lumbar spine configuration in an erect seated posture would be similar to the configuration in an erect standing posture. All values were obtained by manipulating the authors' unpublished data and many other sources of data.

The authors note striking differences between the SAE J826 practice and body configuration based upon this study.

1. The erect body posture requires seat contours to provide support of the lower thorax and lumbar curvature—designs based upon SAE-2D templates will force the upper thorax forward and produce slumped postures. When the body is slumped, the pelvis rotates rearward, the lumbar spine flexes which straightens the low back curvature; the thorax rotates forward throwing the shoulder forward; to keep the head level, the head rotates rearward with cervical extension producing a lordotic neck curvature.

2. In erect body posture, the eye positions are changed rearward and upward.

3. When reclining in any of the currently marketed automobile seats, the seatback tends to move upward relative to the seated persons' back and pull on their clothing. Seatback motion does not follow torso motion (Figure 1).

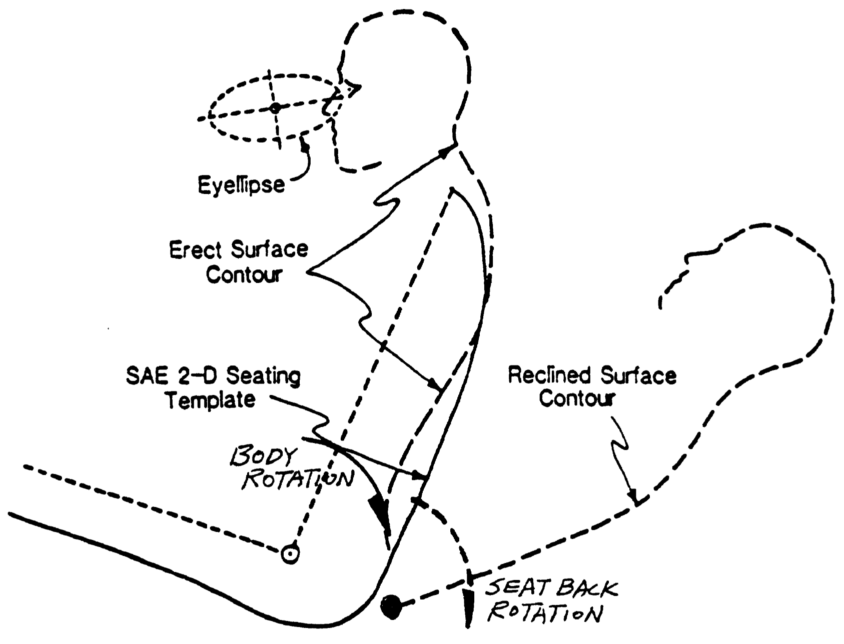


FIGURE 1. Erect and reclined body surface contours for an average adult and SAE 2-D seating template contour and eyellipse.

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

The purpose of this study was to examine the influence of subject variables such as sex, age, and musculo-skeletal health upon the subjective evaluation of vehicle seating.

Seventy-two subjects were carefully selected from a stature range common to both British males and females. This sample was composed of three age ranges (18–24, 30–40, 50+ years), each range containing three stature groups (156–164, 165–171, 172–178 cms) consisting of equal numbers of males and females, half of whom experienced persistent back problems.

Each subject sat on the same seat for a continuous period of 2–1/4 hours in the laboratory. Subjects were allowed to adopt postures normally assumed when traveling as a passenger in a car. A video monitor was used to ensure that the subject looked forward for the majority of the time and also to reduce boredom. All subjects completed discomfort ratings over 14 body areas using a five-point scale after 15, 45, 75, 105, and 135 minutes of sitting. The data were analyzed in terms of the number of subjects reporting discomfort at each of the above times, and the number of minutes of discomfort over the whole period of sitting. The number of minutes of discomfort was calculated by summing 30 minutes of discomfort for each report of discomfort at the intervals above. The final interval allocated was 15 minutes. The maximum number of minutes of discomfort was 135 minutes.

Analysis of variance was performed on the comfort data, averaged over the fourteen body areas. The summarized data are shown in Table 2.

No significant differences were found among age groups, although the 50+ age group reported a mean of 21 minutes discomfort per subject over all body areas, whereas both the younger groups reported similar discomfort at a 50% longer duration. There were no effects of stature in the mean discomfort rating over fourteen body areas except for neck area (the shortest group did report a significantly longer duration). No significant differences due to sex or back trouble were found.

The results of this study suggest that *the assessment of sitting comfort is not critically dependent upon the age, sex, or back pain experience of the subject sample selected in a stature group.*

TABLE 2 MEAN DURATION OF REPORTED DISCOMINT FOR OVERALL BODY AREAS (14 AREAS) AND FOR FOUR MOST FREQUENT AREAS OF DISCOMFORT

Factor	Mean Duration of Reported Discomfort (minutes) (Maximum=135 minutes)				
	All Body	Low Back	Neck	Buttock	Thighs
Age					
18–24 yrs.	30	66	74	32	31
30–40	31	60	46	50	32
50+	21	40	39	35	30
Stature					
156–164 cm	29	46	80*	37	21
165–171	29	70	42	35	39
172–178	23	50	36	45	34
Sex					
Male	25	55	42	36	30
Female	29	56	63	42	32
Back Trouble					
Sufferer	29	67	59	43	40
Non-Sufferer	25	43	47	35	22

*$p<0.05$

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

In this study, the myoelectric activity of twelve paraspinal muscles of ten male subjects aged 18 to 24 were recorded to examine the effects of backrest inclination, lumbar support, and seat inclination in driving. In total, 24 test conditions per subject were evaluated over a 3.5-hour period of driving in a single day.

EMG activities of 12 back muscle groups were monitored for 24 different conditions (Table 1). EMG signals were sampled at 500 Hz and converted with 12-bit resolution. Each channel was bandpass filtered with a passband of 20–250 Hz. Two measures of EMG amplitude were calculated from 6-second recordings. The mean of the absolute value (rectified EMG) of sampled signals, and its root mean square (rms) value were adopted to compare the muscle activities.

TABLE 1
LOCATIONS OF EMG SURFACE ELECTRODES AND TEST CONDITIONS

EMG Electrode Locations	C4 T5 L1 L3 Trapezius T1 and T8	Both sides of the spine, 2.5–3.0 cm from midline and parallel to the spinous process. 2 cm above the spines of scapular. Left side only.
Test Conditions: 12 Locations & Ground Electrode at T6–7 Area (24 Combinations)	Backrest inclinations Seat Inclinations Lumbar Supports	110°, 110°, 120°, 130° 14.5°, 18.5° 3 cm, 5 cm, 7 cm

No evidence of muscle fatigue after 3 hours of driving was found based upon spectral analysis of EMG signals (no changes in spectral shape and mean power frequency). In static tests, higher EMG mean activity and greater variability were found in all cases compared to dynamic tests. No significant differences in muscle activities between before test and after test under various testing conditions were found. Because of this, the authors recommend dynamic tests for evaluation of seating comfort. Minimum muscle activity for the different muscle groups were generated for the seat configurations as shown in Table 2.

TABLE 2
THE MINIMUM EMG CONFIGURATION

Muscle Group	Minimum EMG Configurations		
	Backrest Angle	Seat Pan Angle	Lumbar Support Size
Cervical	130°	18.5°	3 cm
Trapezius	120	18.5	7 cm
Thoracic	130	14.5	3 cm
Lumbar	130	18.5	5 cm

B. PRESSURE DISTRIBUTION AND HEMODYNAMICS

A seat cushion should ideally distribute body weight properly, and should absorb shock and vibration. As Dempsey (1963) has pointed out, 75% of body weight is supported by the buttock and especially high pressure is concentrated on 25 sq. cm of the ischial tuberosity and the underlying flesh. Drummond et al. (1982) showed that 18% of body weight is distributed over each ischial tuberosity. This load is sufficient to reduce the blood circulation through capillaries, and results in sensations of ache, numbness, and pain (Chow and Odell 1978; Bader et al. 1986). Therefore, the pressure distribution between body and seat surface has been considered as one of the most important factors affecting seating comfort (Thier 1963; Hertzberg 1972; Kohara and Sugi 1972; Kamijo et al. 1982; Diebschlag and Mueller-Limmroth 1980; Diebschlag et al. 1988). Also, a recent roadside survey (Schneider and Ricci 1989) suggests that pressure under the buttock is the second largest source of driver seating discomfort (lumbar discomfort is the largest source).

Despite a long-term interest in seated pressure distributions, it is still not known what specific distributions of pressure are optimal given intervening factors such as seat features (dimensions, angles, surface shape, cushion firmness, and cover material) and driver characteristics (body weight, shape, and tissue composition). However, general guidelines do exist (Hertzberg 1972; Diebschlag and Mueller-Limmroth 1980; Diebschlag et al. 1988; Weichenrieder and Haldenhangner 1985). It is believed that seat pan and back angle are important since they redistribute the trunk weight and reduce the pressure under the buttock, that excessive contour is not helpful, and that overall pressure should be kept low by providing enough contact area to support the load, etc.

Pressure distribution is difficult to measure in the real world. Thier (1963) estimated a pressure distribution using a dummy (Comfort-Oscal) which had humanlike mass distribution and strain gauges. Reswick (1961) demonstrated a pressure distribution using 150–300 nail heads supported by calibrated springs. Hertzberg (1972) measured the maximum loading area under the buttock using a Pediscope. Garber et al. (1978) devised a pressure evaluation pad (PEP) which had a 12x12 matrix of pneumatically-controlled contact switches. Drummond et al. (1982) developed a microcomputer-based pressure scanner composed of sixty-four strain-gauge transducers to create a contour map of seated pressure distribution. Treaster and Marras (1987) introduced an optical-reflection technique which provided continuous pressure measurement.

Most of these methodologies cannot directly measure pressure between a driver and a contoured seat surface. In recent years, several types of pressure sensors have been developed. A new and promising sensor is the conductive elastomer sensor (such as the Force Sensitive Resistor) which consists of a force-sensitive organic film screen printed on a Mylar sheet (available from Interlink Electronics, Santa Barbara, California). A force applied on the top increases the contact area. This reduces the resistance of the force-sensitive film. Though the pressure-resistance relationship is not linear (log-linear), it has full-scale repeatability of ±1%, and it is thin and small enough not to effect the seat characteristics.

Studies related to pressure soreness provide the basic understanding of pressure problems. A pressure sore is an ulceration of the skin and/or deeper tissue due to unrelieved pressure, shear forces, and/or frictional forces. Pressure soreness is usually found in patients or wheelchair users who cannot move their bodies voluntarily (cannot relieve pressure effectively).

Generally known results are: *Body tissue is more susceptible to shear forces than to equivalent normal forces*. Tangential forces of 6.7 kPa or 1.33 N/mm are sufficient to induce pathological changes in body tissue. Chow and Odell (1978) showed the shear pressure development inside the buttock due to surface friction using a finite element model. Reddy et al. (1982) evaluated several cushion materials using a PVC-gel buttock model. Medium foam generated a minimum shear stress, and doubling the thickness of the foam considerably decreased the high pressure region.

Driver body shape also determines pressure distribution. Kadaba et al. (1984) measured the shape of the buttock-cushion contour of different sizes of subjects due to reduced surface area of the buttock. The results showed that the subject with the lowest body weight indented deeper into the cushion than heavier subjects. This shows that not only body weight but also shape of the body determines pressure distribution.

Extended periods of sitting can decrease the lower body hemodynamics (Pottier et al. 1969; Glassford 1977; Winkel 1981, 1986). Foot swelling was also observed. Pottier et al. reported 2.8% of foot swelling after 2 hours of normal sitting. Also, an increase in temperature accelerated foot swelling. Winkel (1986) found similar results and suggested leg movement to reduce foot swelling. Montgomery and Glassford (1978) attempted to pulsate the seat cushion to improve the hemodynamics of the lower body.

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

In order to measure the contact pressure distribution on body surfaces, subjects were instructed to sit or lie on nail heads supported by calibrated springs placed 2 cm apart on perforated plywood. By measuring the protruding length of each nail, the degree of spring compression was calculated and converted to pressure values. One hundred and fifty to 300 points under the buttock area were measured from a sitting posture. Figure I-3 shows the obtained static pressure distributions. The method of spring compression, however, could not be used for "dynamic" pressure measurements and could not be measured on different supporting surfaces.

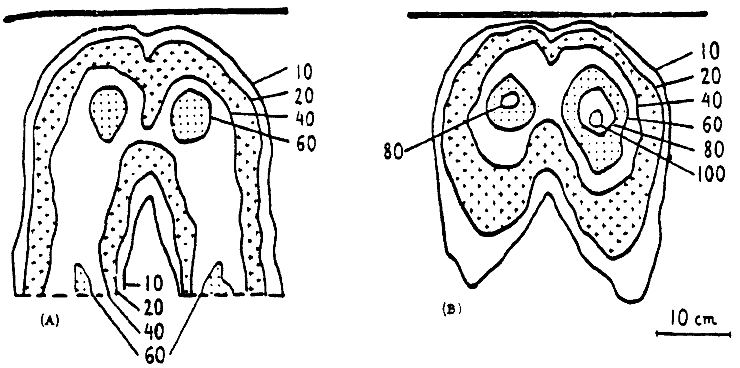


FIGURE I-3. Pressure distribution under the buttocks of a seated subject with (a) feet hanging freely, and (b) feet supported (mm Hg).

The Isobar transducer was designed to avoid the previous drawbacks. This is a pressure measuring sheet made of plastic layers enclosing a large number of small air cells. Each air cell has an electrical contact on the roof of the cell and another on the floor of the cell. If the pressure within the sheet is greater than the outside pressure, the cell will inflate, causing the contacts to separate. When the pressure within the cell is less than that of the pressure outside the cell, the cell wall will collapse causing the contacts to close. By controlling the pressure inside the sheet, the response sensitivity of each switch can be adjusted. Therefore, at a given inside pressure, the array of sensors gives isobaric contours. Figures I-4 and I-5 show the configuration of the Isobar transducer.

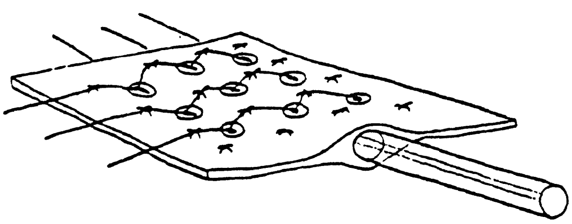


FIGURE I-4. A 3x3 contact pressure Isobar transducer.

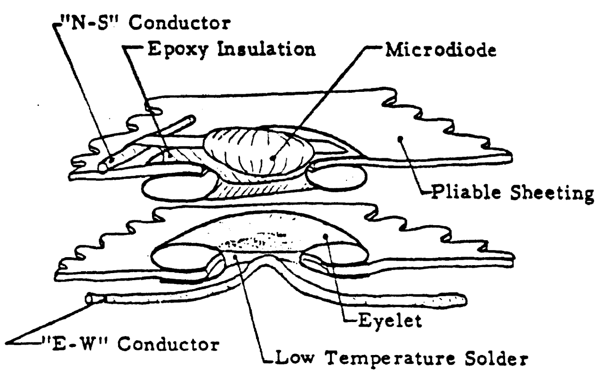


FIGURE I-5. Cross-section detail of eyelet and diode contact.

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

The Comfort-Oscar has three components: a light metal seat pan, a backrest pan, and a lower part of the leg, including the foot. Each of these three main parts was loaded corresponding to the weight distribution of body segments. On the seat pan and back pan, three rows of holes were made, and contact pressure was measured through these holes using a simple compression spring-type pressure gauge. The inclination of the seat cushion and backrest could also be measured by this device.

The author summarized the requirements for a comfortable vehicle seat as follows:

1. good support for the thighs without hard pressure restricting the blood circulation in the hollow of the knees;

2. sufficient lateral support of the buttocks when the vehicle is taking a curve;

3. the avoidance of painful pressure on the lower end of the spine;

4. good support of the back in the region of the lumbar to avoid slipping or damage to the vertebral discs;

5. a concave backrest in the region of the shoulder, without hard spots, for good lateral location.

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

Volume changes of the foot were recorded under three different conditions using a constant water level plethysmograph: normal sitting posture, sitting posture with increased temperature (from 32°C to 40°C), and sitting with thigh compression.

Foot volume increased 2.3%, and 2.8% after 1 and 2 hours of normal sitting. Also temperature increase resulted in a 2.1% increase in volume before 1 hour of sitting, and a 1.5% increase after 1 hour of sitting. Compression under the thighs caused significant differences in volume after 33 minutes (female) and 37 minutes (male) of sitting.

The authors point out that three distinct factors are responsible for foot volume increase: hydrostatic pressure due to sitting posture, vaso-dilation due to temperature increase, and venous return obstruction due to compression under the thighs. The authors also recommend: (1) the introduction of short and frequent pauses during sitting work, and (2) the use of height-adjustable seats.

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

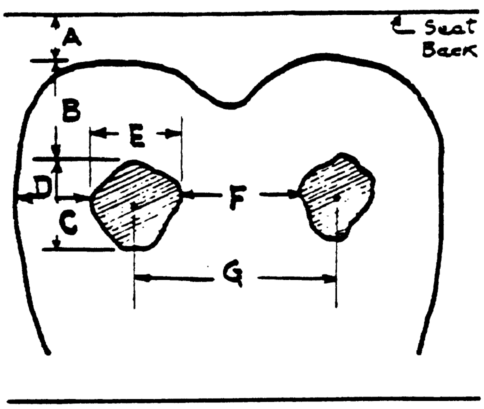
The author presents data on buttock size, tuberosity locations, and other dimensions needed for improved seat design (Table 1.) These dimensions were measured from a sample of 35 young males chosen to approximate the range of USAF flying personnel using a modified McGrath C-Ray Pediscope. The data were taken in the body position expected to yield maximum load on the tuberosities and the flesh surrounding them.

Based upon these data, the curved cushion shape shown in Figure 1 was recommended (tuberosity depression was assumed at 3.8 inch from the back). The contoured surface spreads the load that is normally on the tuberosities to some of the surrounding tissue, greatly reducing the peak pressure.

To reduce the discomfort of long continued sitting, the following suggestions were added:

1. Adequate lumbar support is essential.
2. Excessive contour is not helpful.
3. Cushion cover must be elastic enough to pass local loads directly through to the cushion.

TABLE 1
SUMMARY VALUES, TUBEROSITY AREA LOCATIONS, N=34*



Dimensions	Mean (M)	Standard Deviation (S D)	M-2SD	M+2SD
A–Seat back to rear of buttock	0.8	0.4	0.0	1.6
B–Rear of buttock to rear of tuberosity area	2.8	0.7	1.4	4.2
C–Depth (A-P) of tuberosity area	1.4	0.5	0.4	2.4
D–Lateral edge of buttock to lateral edge of tuberosity area	3.5	1.1	1.3	5.7
E–Breadth of tuberosity area	1.4	0.5	0.4	2.4
F–Distance between medial edges of the tuberosity areas	2.4	0.5	1.4	3.4
G–Computed distance between tuberosity centers; G=E+F**	3.8	(0.5)	(2.8)	(4.8)

*One negative of this subsample was lost.
**Values in parentheses computed from the SD of F.

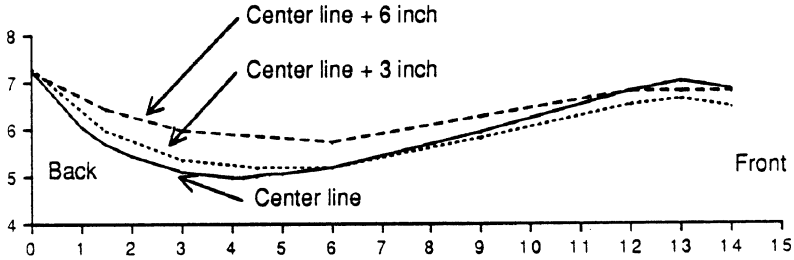


FIGURE 1. A proposed profile of seat cushion (used for the USAF MD-1 survival kit top).

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

An approach which relates physiological changes with subjective judgements of discomfort was proposed as a means to understand discomfort factors better. Two physiological indices were recorded: (1) the blood flow index,[2] and (2) the blood accumulation index.[3] These indices were monitored by an air-displacement plethysmograph (Figure 1).

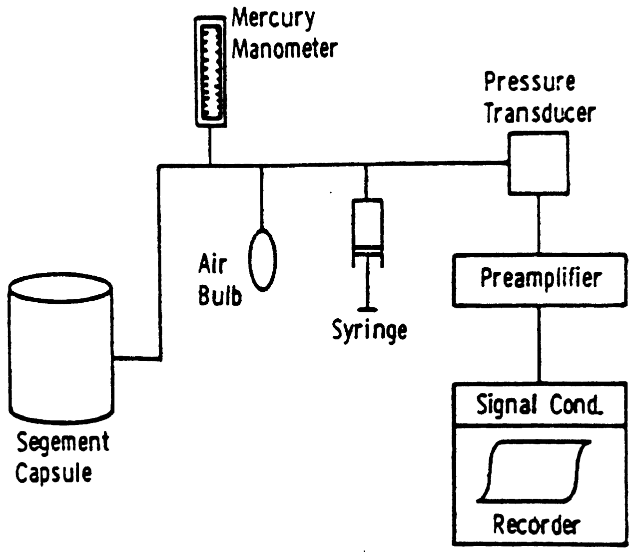


FIGURE 1. A schematic diagram of the displacement plethsymograph.

For subject judgement, 30 items of semantic differential scales and body area discomfort ratings were used (Habsburg and Middendorf 1977). As a result of canonical analysis between physiological indices and subjective factors, several significant and stable relationships were found.

1. Blood accumulation has a positive correlation with *secure*, *restful*, and *deep* sensation.
2. Blood accumulation has a negative correlation with *overall comfort*, *supporting back*, *unsafe*, *height*, and *for me*.

This paper also shows the effect of posture and inter-subject differences on blood flow index. Figure 2 shows hemodynamic variation due to posture and Figure 3 shows individual differences. Both subjects were the same age, height, weight, and were healthy. Subject No. 1 maintained a better blood flow index, suggesting that subject no. 2 would be more intolerant to the sitting posture. The most important finding was that the redistribution of blood from the central pool was associated with the absence of subjective comfort.

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[2]Blood flow ml/min/100 ml body segment.

[3]Blood accumulation ml/100 ml body segment.

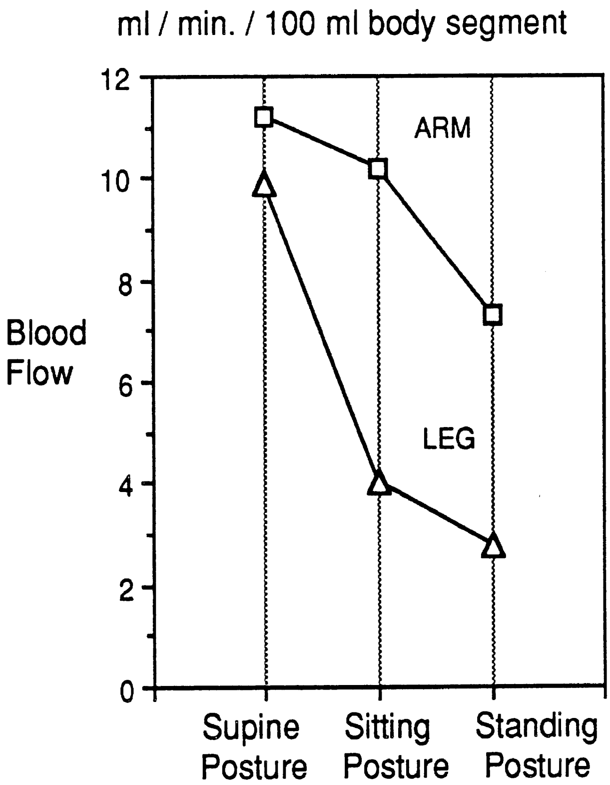


FIGURE 2. Postural effect on the blood flow in the arm and leg (N=72).

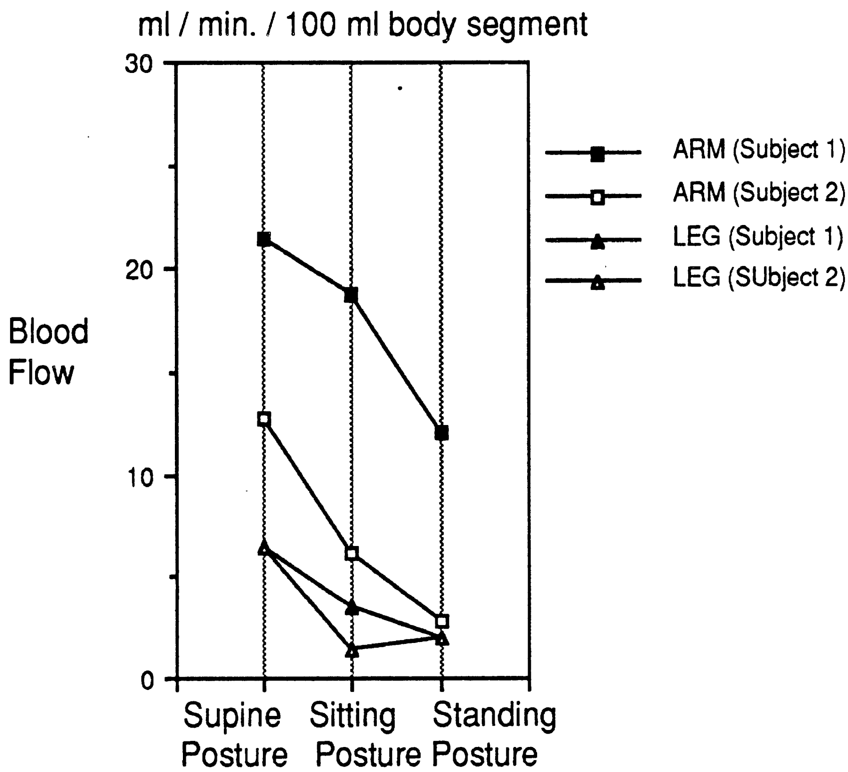


FIGURE 3. Individual difference in blood flow index.

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

Pressure exerted over a long period of time can cause mechanical damage in tissues and cut off blood supply to the tissue. A good cushion distributes the pressure more uniformly over the skin area. Thus it decreases the incidence of ulcers and lengthens the tolerable time period at a given posture.

The following information was found from previous research on pressure sores:

1. There is an inverse relationship between the tolerable pressure level and the time duration of the pressure. For example, for a pressure of 20 kPa (2.9 psi or 150 mm Hg), the tolerable time period is about 2 hours, but the endurance time increases to 4 hours at 10 kPa (1.45 psi or 75 mm Hg).

2. It is known that skin and tissue can tolerate much higher cyclic pressures than constant pressure.

3. The friction between body and seat surface has been identified as a significant factor in the formation of ulcers.

4. Localized pressure can cause deformation, mechanical damage, and blockage of blood vessels because soft body tissues are very deformable but are nearly incompressible.

5. Body tissue can tolerate 1655 kPa (240 psi, 12.4 m Hg, 500 feet deep under water) of hydrostatic pressures with no difficulty. Whereas, a uniaxial pressure of less than 6.7 kPa (1 psi or 50 mm Hg) will induce pathological changes in body tissue.

6. The stress observed in the buttock can be decomposed into a combination of shear stress and hydrostatic stress. Hydrostatic pressure is relatively harmless to biological tissues. Shear stress is more important and may impair the integrity of capillary structure.

The authors analyzed the deformation and stresses in the buttock area using a hemispherical buttock model and finite element method. The buttock model was assumed a typical adult weighing 779 N (175 lb) and having a hip width 400 mm (15.75 in). Each half of the buttock area assumed to bear 38.5% of the body weight. Thus a vertical force of 300N (67.4 lb) is transmitted through one half of the cushion-buttock interface. The model is composed of a 100-mm radius hemisphere of soft tissues with a rigid core which represents the ischial tuberosity (Figure 2). Body tissue parameters of 15 kPa for Young's modulus and 0.49 for Poisson ratio were used.

Figure 10 shows an X-ray picture of a physical (gel) model and it shows the deformation of buttock and the shear strain inside the buttock model.

Figures 11 and 12 show the calculated stress distributions. Friction between the buttock and the cushion generates shear stresses. Analysis with a frictionless assumption does not show any shear stress.

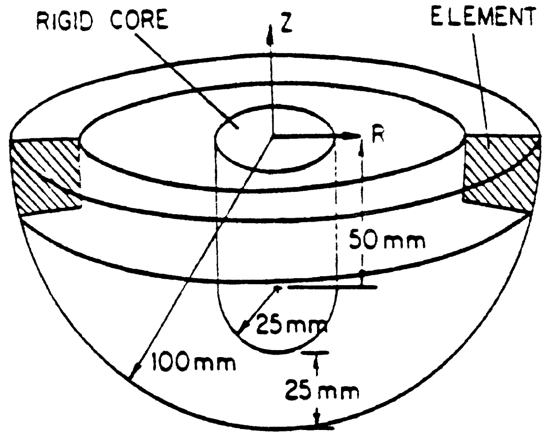
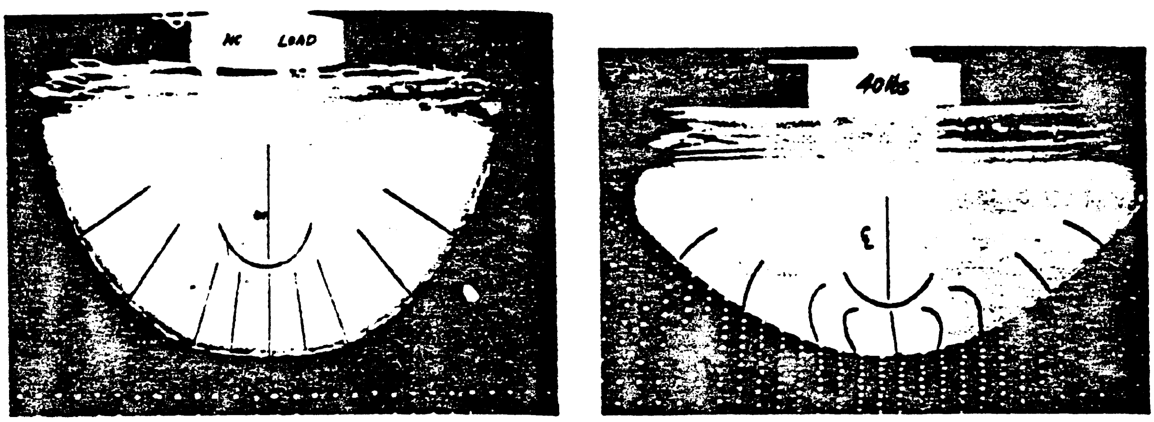


FIGURE 2. The model is a 100 mm radius hemisphere with a right core.



(a) (b)

FIGURE 10. X-ray pictures of a gel model (a) no load, (b) 40 lbs load. In (b), the model is pushed into a foam cushion, and embedded lead sticks inside the model show the shear strain at the surface of the hemisphere.

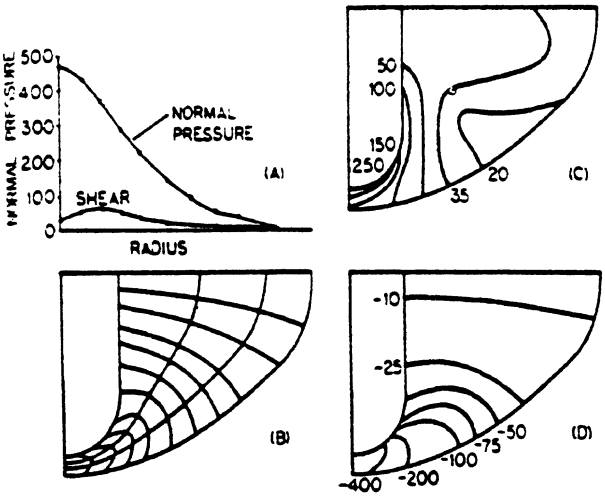


FIGURE 11. The model pushed into a 4-inch foam cushion. All stresses are in X100 Pa (0.0145 psi, 0.75 mm Hg). (a), (b), (c), and (d) same arrangement as in Figure 4.

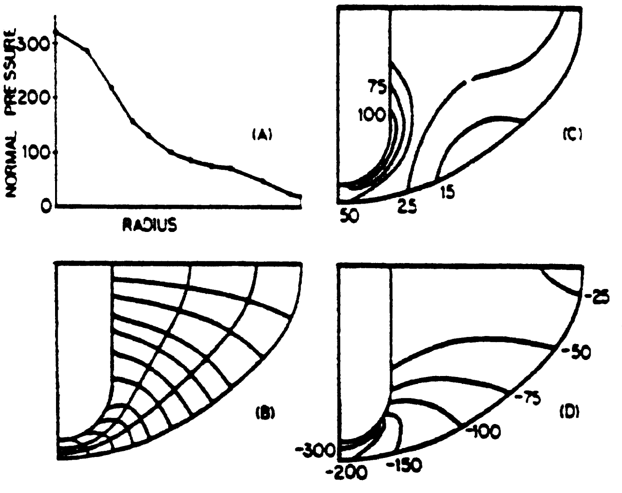


FIGURE 12. The model pushed into a foam cushion with frictionless interface. All stresses are in X100 Pa (0.0145 psi, 0.75 mm Hg). (a), (b), (c), and (d) same arrangement as in Figure 4.

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

The effect of a pulsating cushion on lower body hemodynamics was investigated using Impedance Plethysmography (Figure 1). Blood flow index and venous clearance were measured in the lower leg, knee, thigh, and buttock with/without pulsation on a truck cushion (Table A-1).

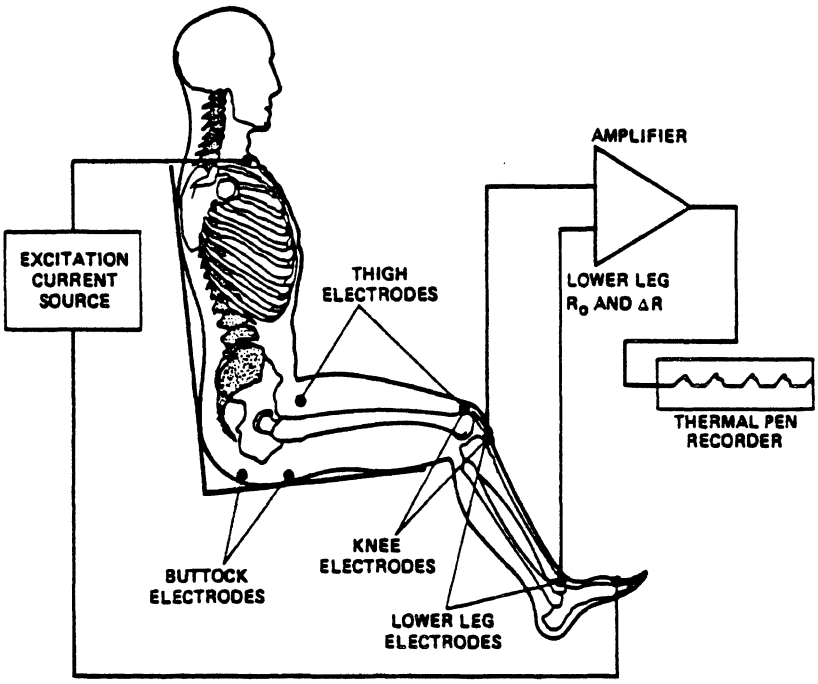


FIGURE 1. Impedance plethysmographic electrode locations.

TABLE A-1
HEMODYNAMIC RESPONSE OF BODY SEGMENTS
(Table generated by author from Figures 3–6 in Montgomery and Glassford 1978)

Body Segments	Blood Flow Index (ml/min)			Venous Clearance (ml/cycle)
	Before	After	% Increase	
Calf	83.16	89.78	8.03	2.95
Knee	36.41	38.72	8.31	5.93
Thigh	201.73	217.98	10.42	15.58
Buttock	99.09	133.90	27.85	

Mean hemodynamic indices increased significantly in all measured body areas following a five-minute activation of the pulsating cushion. Also, the cushion assisted venous clearance in all segments of the leg during each inflation cycle. These hemodynamic responses were more pronounced in body areas which were closer to the pulsating location. This device may be desirable to reduce fatigue and increase performance during prolonged driving.

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

This study was conducted in an attempt to demonstrate the influence of the properties of mattresses and their coverings on body/support interface conditions.

Body/support interface pressure, temperature (at the trochanter and the sacrum), and body movement were monitored to compare the characteristics of standard hospital mattresses and covers. Signals from electropneumatic pressure sensors and an ITT-type M52 thermistor were sampled every 10 minutes (Figure 1). Body movements were filmed using a 35-mm camera with IR-sensitive films. Also, the pressure relief frequency of healthy volunteers and patients were compared.

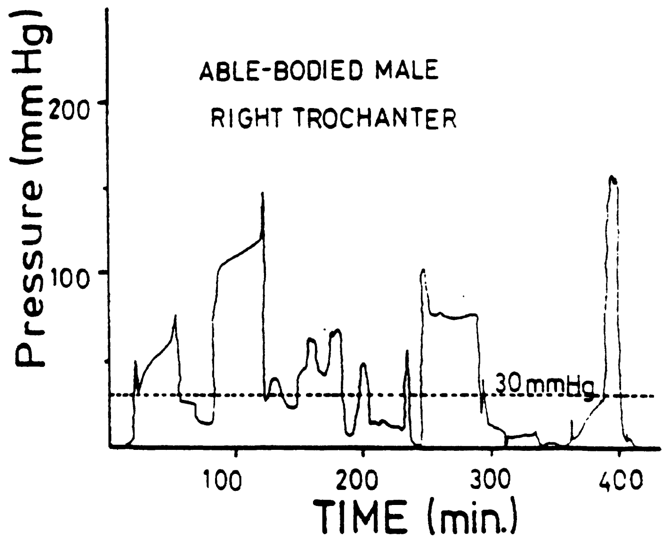


FIGURE 1. Variation in interface pressure at body/mattress interface during sleep. Scan interval=1 min. Mattress=polyether foam + proofed nylon cover.

A group of 13 healthy volunteers were monitored on five different mattress conditions throughout the night. Figure 3 shows load-deflection curves of mattress/cover configurations.

Figure 4 shows pressures measured on different mattress/cover configurations with (a) normal volunteers using variable capacitance pressure sensors, (b) normal volunteers using electropneumatic sensors, and (c) spinal injury volunteers using the electropneumatic sensors.

Measurements on normal volunteers indicated that pressure in excess of 30 mm Hg (4.0 kPa) were endured on average for periods of 40 minutes. An average pressure of 75 mm Hg (10.0 kPa), which is sufficient to disrupt tissue nutrition, occurred only occasionally (less than 20% of measurements exceeded 100 mm Hg, 13.3 kPa). The spinal injury volunteers showed significantly higher pressure levels than normal volunteers (109 mm Hg vs. 63.5 mm Hg). Results also show that the biaxial stretchable mattress cover could reduce the pressure and drawsheets were found to increase pressure.

A: DS184 Standard 5" medium density (32–34 kg/m^3) polyether foam with extensible knitted cover
B: As in "A", fitted with drawsheet
C: As in "A", fitted with inextensible proofed nylon cover
D: Polyflotation mattress, 6" thick with grooved surface
TSE: Spring interior mattress with waterproofed cover

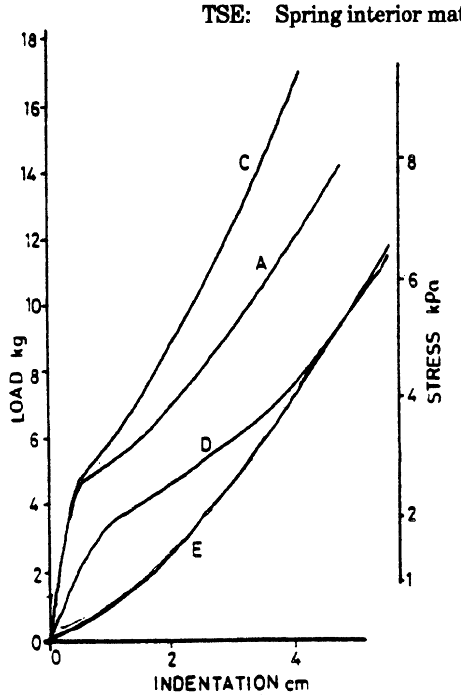


FIGURE 3. Load indentation properties of hospital mattresses. (Indentation rate = 5 cm/min, indentor diameter = 15 cm)

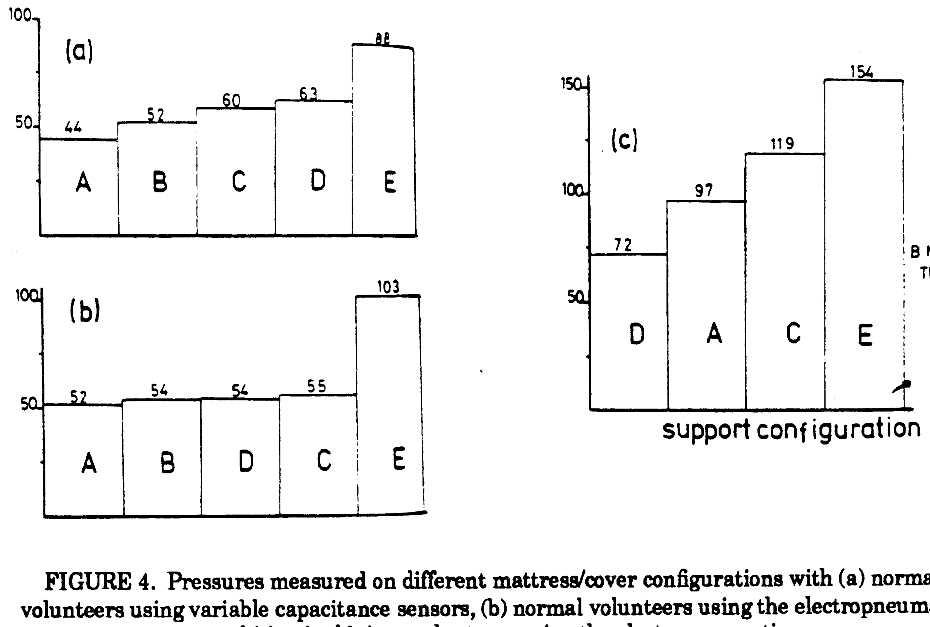


FIGURE 4. Pressures measured on different mattress/cover configurations with (a) normal volunteers using variable capacitance sensors, (b) normal volunteers using the electropneumatic sensors, and (c) spinal injury volunteers using the electropneumatic sensor.

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

This study was conducted to investigate the pressure relief patterns under the ischial tuberosities in a group of paraplegic subjects who had not exhibited any significant problems with ulcers.

The pressure-time pattern and the temperature were recorded from twelve paraplegic subjects. In the morning the subjects were instrumented using an Entran Model ESP-200 pressure transducer (1-mm thick, 5-mm diameter) and Yellow Spring Model 427 thermistor and were allowed to go about their normal activities for the day sitting on a 4-inch foam cushion in their wheelchair.

The following terms were defined to analyze the pressure-time patterns (Figure 1).

Pushup:	A pressure relief motion which reduces pressure below 30 mm Hg.
T_{150}:	The time period in which the pressure remains over 150 mm Hg.
T_{90}:	The time period in which the pressure remains over 90 mm Hg.
T_{30}:	The time period in which the pressure remains over 30 mm Hg.
T_0:	The time period in which the pressure remains below 30 mm Hg, i.e., pushup time.

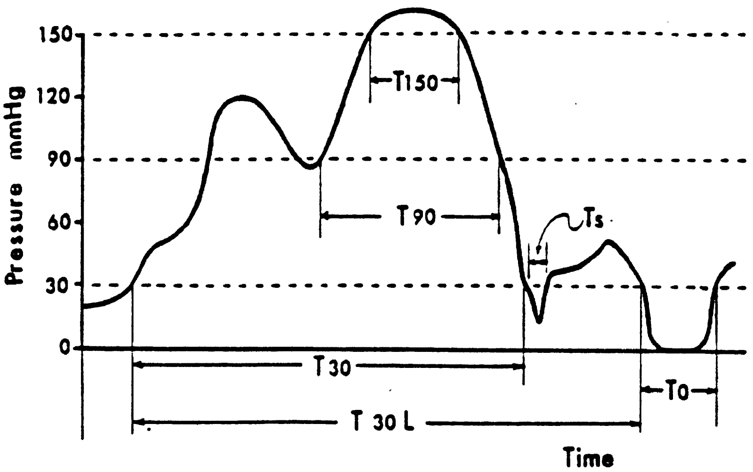


FIGURE 1.
A sample pressure record indicating the pressure levels chosen to generate the pressure-time histograms. T150, T90, and T30 indicate the time periods in which the pressure is above 150 mmHg, 90 mmHg, and 30 mmHg, respectively. T_0 is the time period in which the pressure is below 30 mmHg. T30L is the time period in which the pressure is above 30 mmHg (neglecting the short-duration fall in pressure below 30 mmHg of < 1 sec or < 5 sec, as indicated by time T_s).

The subjects sat for 17.6% of their day at pressures above 150 mm Hg (T_{150}). T_{90} accounted for 53.5%, and T_{30} 91.8%. (Note that T_{30} subsumes T_{90} and T_{150}). On the average, the subjects sat for 10.1 minutes without doing longer than one second of pressure relief ($T_{p>1}$), and for 29.6 minutes without doing a longer than 5 seconds of pressure relief ($T_{0>5}$). The average time between pushups was within the generally accepted limits to prevent ulcers—10–30 minutes.

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

Prolonged driving postures can decrease the lower body hemodynamics. This kind of discomfort is described as numbness, burning feet, swollen feet and legs, and leg cramps. Hemodynamic shift from the central venous pool to the peripheral pool can cause drowsiness, dizziness, and mental fatigue.

The purpose of this study was to (1) measure the amount of swelling of the lower leg and the perception of discomfort, and (2) investigate whether "activity pauses" affect the swelling and the perception of discomfort in the lower legs.

The left leg volume of two healthy, female subjects was measured every 30 seconds using plethysmography. The subjects were asked to express their level of discomfort by marking on an eight-point scale.

A lower leg swelling of 3.4–5.5% was observed while sitting 8 hours on a standard office chair. Lower leg swelling and discomfort during prolonged sitting can be reduced by intermittent leg exercise. Figure 6 shows a postulated cause-effect model of venous disorder due to prolonged sitting.

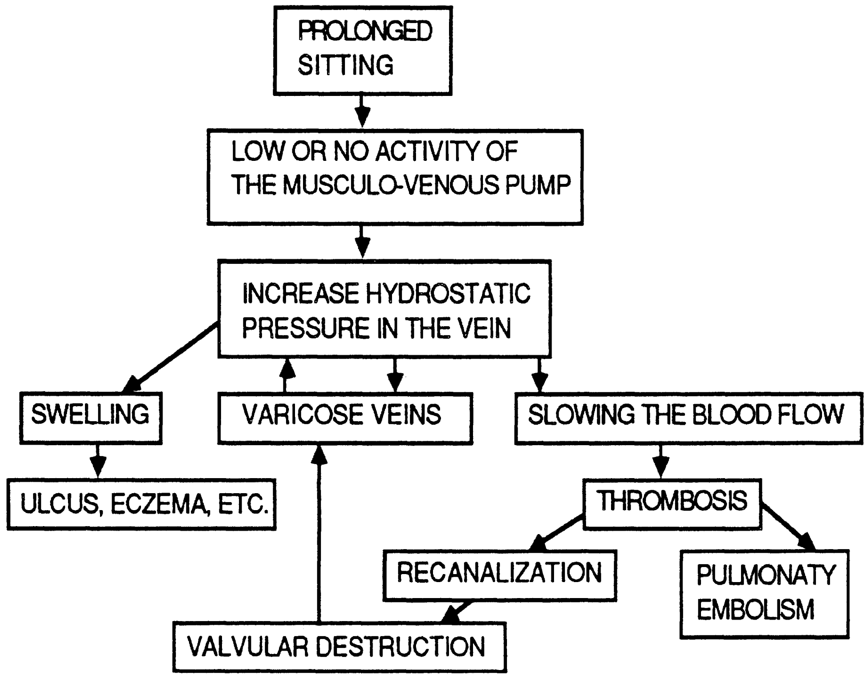


Figure 6. A model of peripheral venous disorder.

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

Sixty-four special strain-gauge transducers were fabricated on an aluminum plate. Using this instrument, pressure distributions of normal and unbalanced sitting were measured.

Analysis of the distribution of pressure during sitting in 15 normal subjects showed that 18% of body weight is distributed over each ischial tuberosity; 21% over each thigh, and 5% over the sacrum (Figure 3). Three paralytic patients showed foci of unequal pressure which are enough to cause decubitus ulceration.

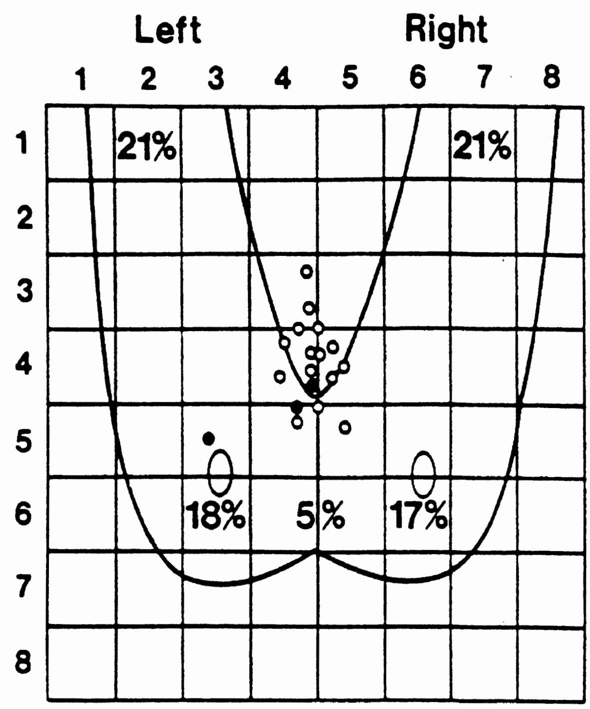


FIGURE 3. Center of seating. The open circles represent the center of seating for fifteen normal subjects and the solid circles are for the patients described under Case Reports. The ischial tuberosities and outline of the buttocks and thighs, typically positioned, can be seen.

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

In this investigation, a two-dimensional physical model of the buttock-cushion system was developed. The model consisted of PVC gel simulating flesh, cast around a wooden core simulating the ischium bone. A grid etched on the gel permitted measurement of strains via photographs of the undeformed and deformed model buttock supported by various cushion materials. The displacement field was analyzed using finite strain theory to obtain the maximum shear stress (τ_{max}) and compressive stresses.

The effect of cushion material was evaluated using four different foam cushions and the PVC gel cushion of the same thickness (3.8 cm) (Table 2). Stresses in the buttock model were compared under a vertical load of 20.2 N.

TABLE 2
PEAK VALUES OF COMPRESSIVE AND SHEAR STRESSES GENERATED IN THE BUTTOCK MODEL WITH VARIOUS CUSHION MATERIALS

Cushion Type	Thickness (cm)	Young's Modulus (Cushion stiffness) (kPa)	Max. Compressive Stress (kPa)	Max. Shear Stress (kPa)
Soft Foam	3.8	9.5	5.7	2.8
Medium Foam	3.8	11.8	4.7	2.6
Viscoelastic Foam	3.8	15.5	10.9*	3.4
PVC Gel	3.8	21.8	8.3	5.0*
Stiff Foam	3.8	25.5	10.3	3.6
Medium Foam	7.6	11.8	3.9**	2.0**
Viscoelastic Foam	7.6	15.5	6.4	2.9

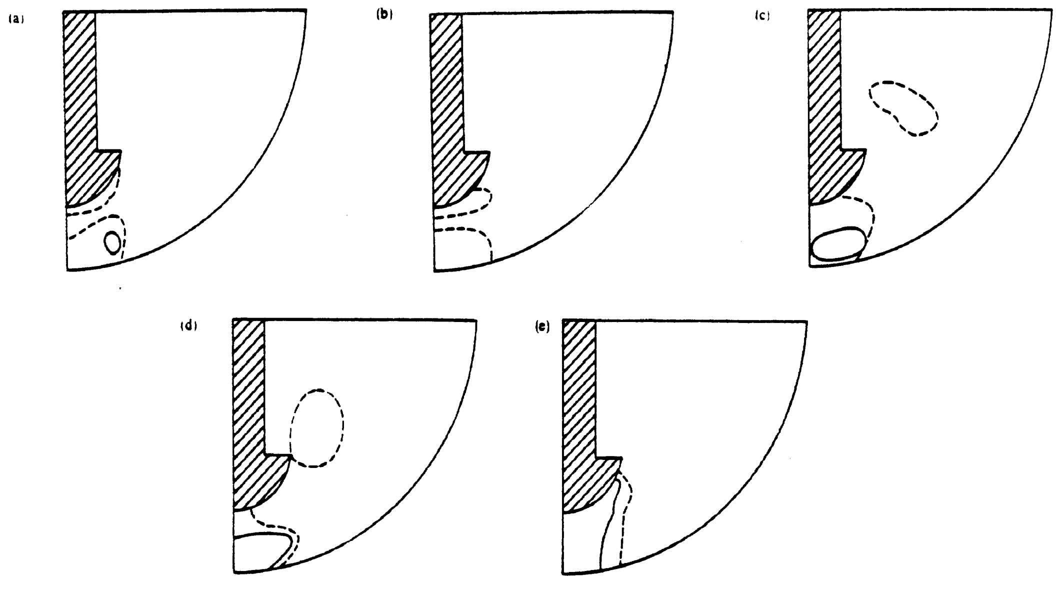


FIGURE 6. Comparison of high shear stress region developed in the buttock model with various seat cushions: (a) soft foam, (b) medium foam, (c) viscoelastic foam, (d) stiff foam, (e) PVC gel. Solid lines are contours of τ_{max}=2.7 kPa and broken lines are contours of τ_{max}=2 kPa.

The following conclusions were drawn from the comparison of five different cushion materials:

1. Five tested cushion materials produced widely different magnitudes and distributions of compressive and shear stresses.

2. High stress regions occurred at two general locations in the buttock model (a) beneath the rigid "bone" core along the central axis, and (b) at an internal location lateral to the rigid core of the model.

3. With regard to the maximum shear stress generated in the model, the cushion material can be ranked as follows in the order of increasing maximum shear stress magnitude: (a) medium foam, (b) soft foam, (c) viscoelastic T-foam, (d) PVC gel, and (e) stiff foam (Table 2).

4. Doubling the thickness of foam cushions from 3.8 cm to 7.6 cm considerably decreased the high stress region.

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

Pressure distributions were measured in solid tissue near bony prominences of pigs using a silicon pressure transducer connected to a hypodermic needle at different skin depths and lateral distances from the 5-cm-diameter indentor.

The results showed that tissue pressure increases closer to bony prominences in both depth and lateral distance. The results were in accord with the previous finite element model approach. The data indicated that internal pressure near the bony prominences is three to five times higher than pressure at the skin over the prominence, and it is high enough to cause ischemia if it is not relieved. Figure 10 shows pressure values as high as 270 mm Hg directly under the bony prominence at the depth of 1.25 cm from the skin, while skin pressure at the corresponding location is only 47 mm Hg.

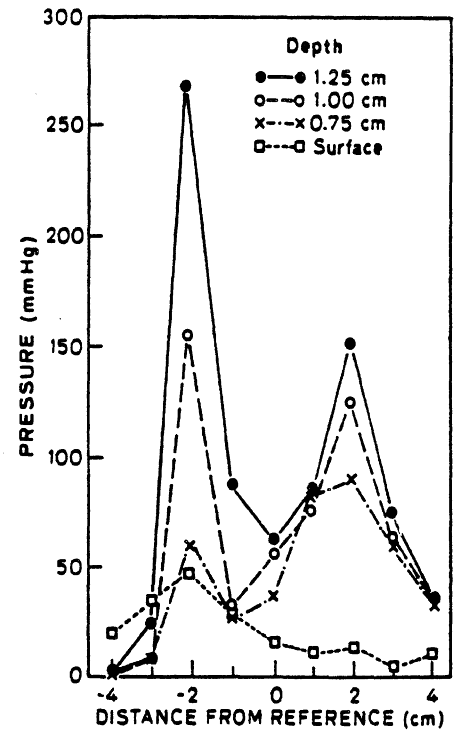


FIGURE 10. Pressure distribution measured at different depths in the tissue under the ischium and at the surface (◊).

Kadaba, M.P.; Ferguson-Pell, M.W.; Palmieri, V.R.; and Cochran, G.V.B. (1984) **Ultrasound mapping of the buttock-cushion interface contour**. *Archives of Physical Medicine and Rehabilitation*, 65:467–659.

To measure the shapes of the contact surface between cushion and buttock, a prototype ultrasound contouring system has been developed. The technique is based on the fact that an ultrasonic pulse traveling in a multilayered medium is reflected and refracted at each interface between two layers with dissimilar acoustic impedances. Using this principle, it is possible to accurately determine the thickness of the layer by measuring the temporal location of the reflected echoes originating from various interfaces with respect to the transducer excitation pulse (Figure 1).

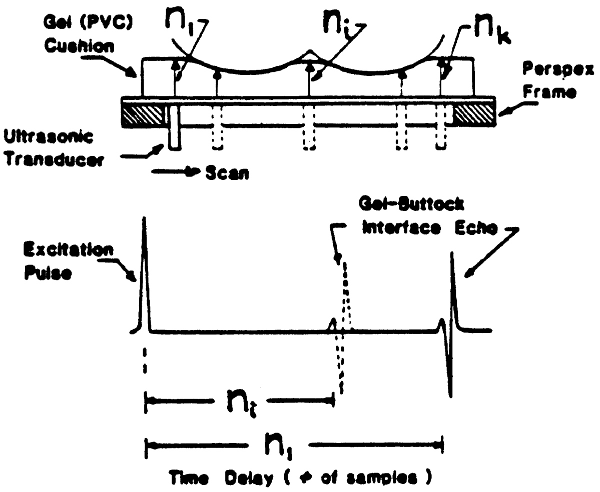


FIGURE 1. Schematic of scanning system.

The shape of the buttock-cushion contour of three subjects (Figure 3) demonstrated different indentation contours. The subject with the lowest body weight indented deeper into the cushion than the other two heavier subjects. Also, indentation tended to be asymmetrical despite careful attempts to position and balance the subject. Repeated mappings of the buttock-cushion interface contour yielded similar shapes.

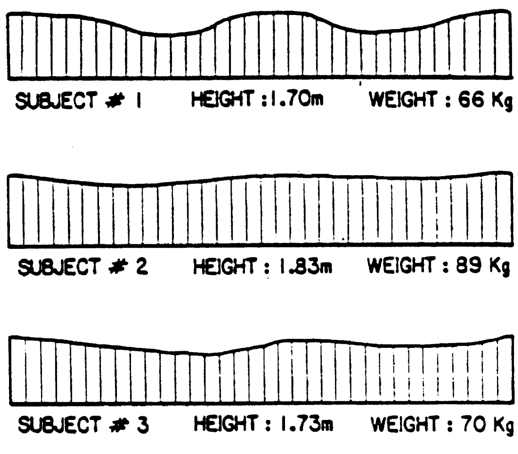


FIGURE 3. Buttock-cushion interface contours for three test subjects of approximately equal height but of unequal weight; the lightest subject showed the deepest indentations.

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

Pressure at the seat surface produces stresses and strains within the soft tissues that affect blood supply and lymphatic drainage. Shear stresses arise from localized pressure, surface shear, or tangential forces and are potentially more damaging than hydrostatic components. The pressure levels which cause disruption of blood flow can be half as high when shear forces are present.

The effect of tangential forces (generated by skin stretching) on the morphologic pattern of skin capillaries was examined on the anterior surface of the forearm of ten healthy volunteers. While tangential forces applied on the skin were increased using a skin-stretching device, tissue vascular collapse was observed by vital capillary microscopy (a non-invasive technique which can observe the structural changes of the nutritional capillaries of the skin).

Critical force intensity for collapse of all vessels in the subjects' forearm ranged from 0.94 N/mm uni-axial tension to 1.99 N/mm with a mean of 1.33 N/mm. Application and relaxation of force showed reproducible vascular collapse and subsequent return of blood flow. This reversibility was still observed after 6 minutes of critical force application. However, if this stress is maintained for a prolonged period, tissue ischemia eventually leads to cell breakdown.

In order to demonstrate the real possibility of capillary collapse in the clinical situation, the authors showed the rough calculation of the maximum shear force at the sacrum when a patient is supported on an inclined surface (a patient lying on a surface inclined 30° and 300 mm of contact width at the sacrum was assumed). It was approximately 0.6 N/mm and this value is sufficient to significantly reduce capillary blood flow.

C. VIBRATION

One of the most striking differences between automotive seats and other types of seats is their dynamic environment. Vibration is transferred to a passenger at all points of contact between the passenger and the vehicle. Therefore, vibration has been considered as one of the major factors affecting passenger comfort (Oborne 1978; Griffin 1978).

When vibrations are attenuated in the body, the vibration energy is absorbed by tissue and organs. Vibrations lead to both voluntary and involuntary muscle contraction and can cause local muscle fatigue especially at resonant frequencies. Vertical vibrations in the 5–10-Hz range generally cause resonance in the "thoracic-abdominal" system (at 4–8 Hz in the spine, at 20–30 Hz in the head-neck-shoulder, and at 60–90 Hz in the eyeball (Chaffin and Andersson 1984). There are many studies which suggest the risk of low-back pain due to the effect of vibration (Rosegger and Rosegger 1960; Kelsey and Hardy 1975; Troup 1978).

However, it is difficult to evaluate the dynamic characteristics of a seat because the effect of vibration needs to be analyzed with respect to the whole vehicle-seat-passenger dynamic system and the perception of vibration is a very subjective matter.

Although ISO 2631 (1974) provides guidelines for evaluating whole-body vibration, problems still remain with vibration discomfort and measurement. New measurement devices and evaluation methods, however, have been developed (see Griffin 1978; Parsons and Griffin 1980, 1983; Kozawa et al. 1986).

A general guideline with regard to seat design for vibration is to keep the vertical natural frequency (f_n) of the seat away from 4–8 Hz and to keep the peak value of the transfer function as low as possible for frequencies of 4–8 Hz (f_n of torso) and 10–12 Hz (f_n of back-slap) (see Varterasian and Thompson 1977; Troup 1978; Parson and Griffin 1983; Kozawa et al. 1986).

In order to attentuate the vibrational problem, new suspension systems using air-oil (airdraulic) have been devised (Harder 1972). Another method that has been suggested is to introduce damping into the seat system to dissipate the unwanted vibrational energies. This can be accomplished by using high-energy dissipating viscoelastic material (tuned damper) designed to vibrate at approximately the same frequency as that of the seat back (Foley and Allemang 1988).

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

In order to identify the dynamic characteristics of the seated human, the seat/occupant system was excited vertically with random vibration.

One of the most important functions of a seat is its ability to isolate the occupant from road vibration. This isolation characteristic of the seat can be defined by the transfer function (or transmissibility)) which is the ratio of the output of the seat to the input as a function of frequency. When the transfer function is unity (F_1), the seat transfers floor vibration directly to the occupant. At the natural (or resonance) frequency (F_n), the seat amplifies the input acceleration maximally. Thus, the output acceleration reaches the maximum at f_n (Figure 1).

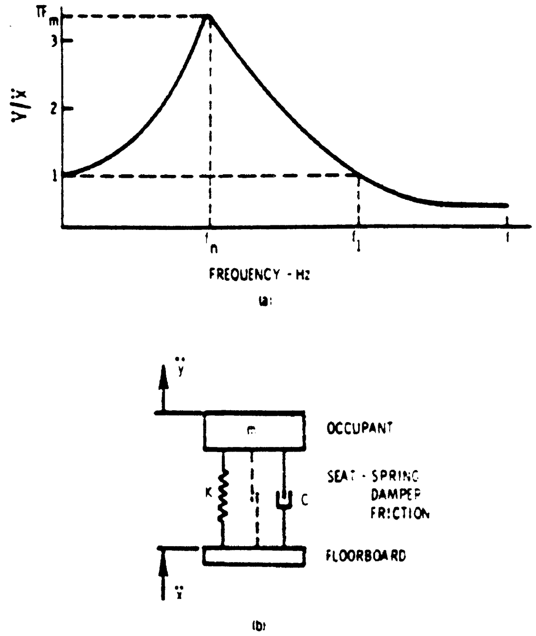


FIGURE 1(a) and 1(b). Simplified representation of an automotive seat.
(a) transfer function on transmissibility, and (b) corresponding mechanical model.

Fifteen subjects were tested in a 1976 full-size two-door car. Vertical accelerations were measured at the floor (d^2x), the seat surface (d^2y), and the occupant's head (d^2h). The following transfer functions were computed with a PDP 11/05 Fourier analyzer.

(1) $G_{xy}(f) = d^2y/d^2x$ (the loaded seat vertical transfer function)
(2) $G_{yh}(f) = d^2h/d^2y$ (the seated occupant vertical transfer function)
(3) $G_{xh}(f) = G_{xy}G_{yh} = d^2h/d^2x$ (the total system vertical transfer function)

The mean natural frequency of the transfer function of the loaded seat (G_{xy}) was 3.9 Hz, and the transmissibility (amplification ratio) was 2.8 at this frequency. At over 5.28 Hz (mean value), the transmissibility was less than the ratio of 1.0. Because the variation of natural frequency was small enough (0.28), in spite of the large variation in the occupant's body weight, the seat and occupant can be represented by a simple mass, spring, and damper system.

Seated human occupants are characterized by a transfer function (G_{yh}) with three resonance frequencies at 3.0 Hz (head), 5.6 Hz (torso, neck), and 11 Hz (back-slap). Back-slap occurs due to the resonance of the seat back. The author presumed that back-slap frequency is important in subject ride ratings, since it is in the range of automobile wheel-hop frequencies, 10–12 Hz.

As a result, the optimized seat should have a loaded natural frequency less than 5.6 Hz and greater than 1–1.5 Hz, the seat transfer function should be kept to a low peak value, and the transfer function at wheel-hop frequencies (10–12 Hz) should also be kept low.

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

The purpose of this study was to evaluate alternative objective methods of predicting passenger vibration discomfort. Figure 1 shows a model of vibration discomfort prediction.

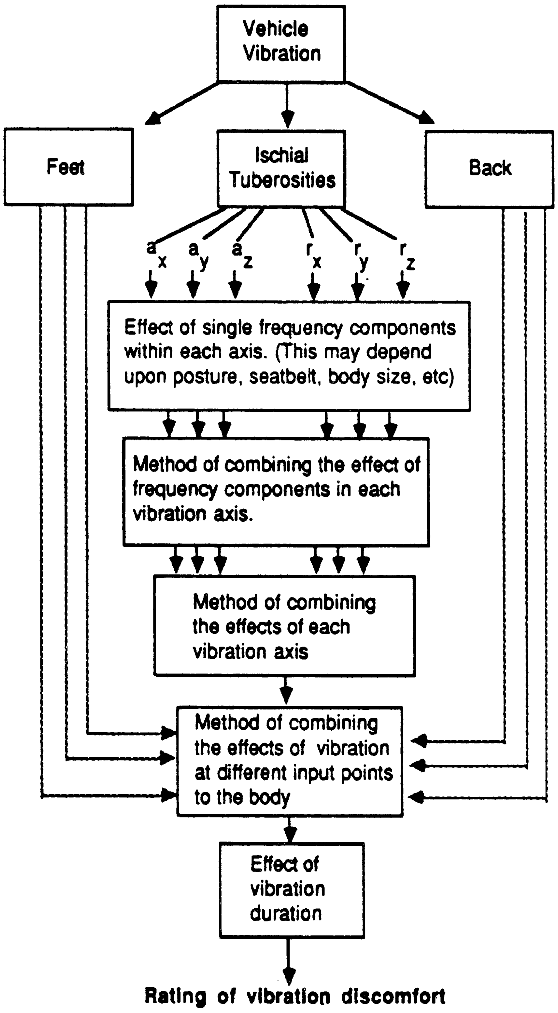


FIGURE 1. Model of vibration discomfort prediction.

A series of laboratory experiments was conducted to determine discomfort due to complex vibration (multiaxis, multiple input, random, and impulsive vibration). Twelve vibration inputs to the body were considered: fore-and-aft (x-axis), lateral (y-axis), and vertical (z-axis) vibration input to the subjects' feet, ischial tuberosities, and back (9 inputs), and the roll (r_x), pitch (r_y), and yaw (r_z) vibration at the subjects' ischial tuberosities (3 inputs). Translational vibration was measured using Endevco 2265/20 piezo-resistive accelerometers, and rotational vibration was measured using Schaevitz ASMP-100 angular servo-accelerometers.

For all twelve inputs, individual equivalent comfort contours were obtained by laboratory experimentation from eight male subjects with reference to a 0.8 m/s^2 rms, 10 Hz sinusoidal vertical vibration input to the seated subjects' ischial tuberosities. These contours provide individual frequency weighting functions.

Each of the eight subjects drove six passenger vehicles on a route that contained twelve different road conditions. Subjects were asked to rate the vibration discomfort they experienced by marking on a 100-mm line with ends labelled "little discomfort" (on the left) and "much discomfort" (on the right).

Because subject discomfort sensations differ at vibration frequencies, the vibration power spectrum must be weighted and combined based upon the equal-sensation contour to get a representative value of vibrational effect of an axis. As a method of weighting and combining vibration frequencies of a single axis, weighted maximum frequency level ($W_{max}f$), weighted rms level (W_{rms}), and weighted rmq level (W_{rmq}) were considered. Each value of the twelve inputs and twelve roads were calculated for each subject using the following equations:

$$W_{max} = \left[\int_F^{F+\Delta F} G_{X_W}(f)\, df \right]^{\frac{1}{2}}$$

$$W_{rms} = \left[\frac{1}{T} \int_0^T X_W^2(t)\, dt \right]^{\frac{1}{2}}$$

$$W_{rmq} = \left[\frac{1}{T} \int_0^T X_W^4(t)\, dt \right]^{\frac{1}{4}}$$

where:

$X_w(t)$ = time history of vibration input

$G_{xw}(f)$ = weighted power of spectrum of $X_w(t)$

F = lower frequency boundary which contains the maximum level of the weighted psd(ΔF=0.5 Hz)

T = the total vibration duration

Evaluation of the total effect of multi-axis input also had to be addressed. Three methods of combining twelve vibration inputs were investigated: most severe component method (MSC), root sums of squares (rss), and root sums of quads (rsq). MSC chose one maximum axis value from twelve weighted input values, and rss and rsq were calculated using the following equations:

$$\text{rss of inputs} = \left[\sum_{i=1}^{12} W_i^2 \right]^{\frac{1}{2}}$$

$$\text{rsq of inputs} = \left[\sum_{i=1}^{12} W_i^4 \right]^{\frac{1}{4}}$$

where W_i = weighted value of ith axis.

Nine values [three methods of combining vibration frequencies by three methods of combining vibration inputs (3x3)] were calculated for each subject in each vehicle at twelve road conditions. Discomfort ranking of road condition was assigned based upon these values. The rank order of the predicted discomfort was correlated with the rank order of subjective discomfort ratings. It is assumed that higher correlations imply a more efficient method of predicting discomfort (Table 1). Global rank-order was decided by summing the ranks over the eight subjects over six vehicles (8x6).

TABLE 1
OVERALL RANK-ORDER OF EFFICIENCY OF PREDICTION PROCEDURES

Within Axes	W_{rmq}			W_{rms}			$W_{max}f$		
Cross Axes	msc	rss	rsq	msc	rss	rsq	msc	rss	rsq
Rank Order	8	2	4	5	1	3	9	6	7

It was found that the root sums of squares (rss) of twelve weighted rms level (W_{rms}) of each vibration axis input gave the best correlation with subjective ratings of vibration discomfort. This result corresponds to the method of combining frequencies in the ISO 2631—the weighted rms values of the vibration stimuli.

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

Though the ISO 2631 is suitable for evaluating the influence of vibration on the human body, it is difficult to apply to the evaluation of ride comfort because of the following vibrational characteristics of a passenger car:

- Vibration is transferred to a human body through a soft seat.
- The dominant vibration frequency ranges are 0.5–2 Hz, 3–6 Hz, and 10–20 Hz.
- A human body in a car is exposed not only to vertical vibration but also to lateral and fore-aft vibrations.

A new portable ride comfort meter and a new index, *VN* (vibration number), were developed based upon vibrational discomfort evaluation experiments. Through these experiments, the relationships between subjective ratings of ride comfort and physical measurements of vibration were found. Experimental results were as follows:

- The principal vibrations and frequencies which affect ride comfort are the seat cushion vertical vibration (4–8 Hz), the seat-back lateral vibration (8–16 Hz), and the foot vertical vibration (8–16 Hz).
- When lateral vibration including components of 8–20 Hz is added to vertical vibration, the whole vibration becomes similar to that in passenger cars. If the portion of lateral vibration increases, ride comfort is degraded significantly (see Figure 8).

Figure 10 shows a block diagram of the ride comfort meter. Acceleration signals from the seat cushion, seat back, and foot were amplified and filtered. The overall evaluation index, *VN*, is defined as below:

$$VN = 18 \log_{10} (K_1 \cdot 10^{Ac} + K_2 \cdot 10^{Ab} + K_3 \cdot 10^{Af}) - 20$$

where:

K_1, K_2, K_3 =	Contribution factor of each vibration
A_c, A_b, A_f =	Weighted vibrational intensity of each input (A_c: seat cushion vertical, A_b: seat-back lateral, A_f: foot vertical)

VN corresponds to the reduced comfort limit for 24 hours of exposure to vibration under ISO 2631 when only the seat cushion vertical vibration is applied, and *VN*=100 corresponds to a one-minute tolerance limit for the same condition. The correlation coefficient between the *VN* index and the subjective rating was –0.83 (Figure 12).

The authors conclude that: (1) ride comfort is correlated not only with acceleration of the seat cushion but with acceleration of the seat back, the foot, etc.; (2) ride comfort is primarily affected by vertical vibration when the ratio of lateral vibration to vertical vibration is smaller than a specified value, but lateral vibration strongly affects ride comfort when the ratio becomes larger than a certain value; (3) the *VN* index is strongly correlated with the subjective rating.

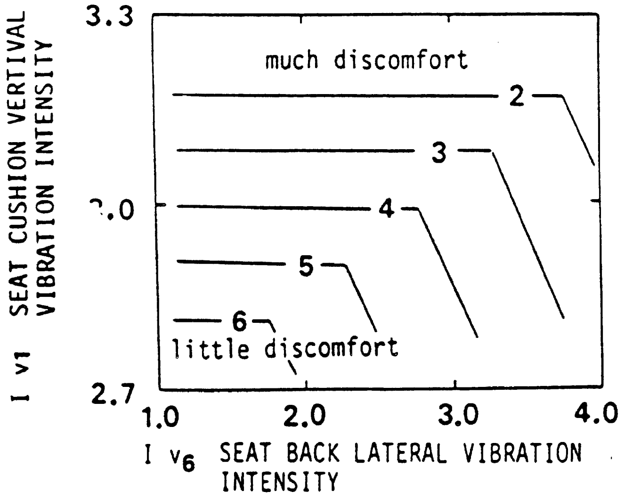


FIGURE 8. Simplified equidiscomfort curves.

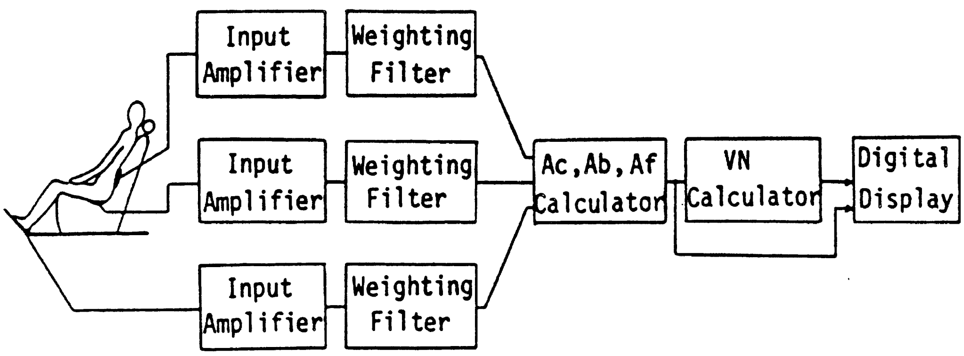


FIGURE 10. Simplified schematic block diagram of the ride comfort meter.

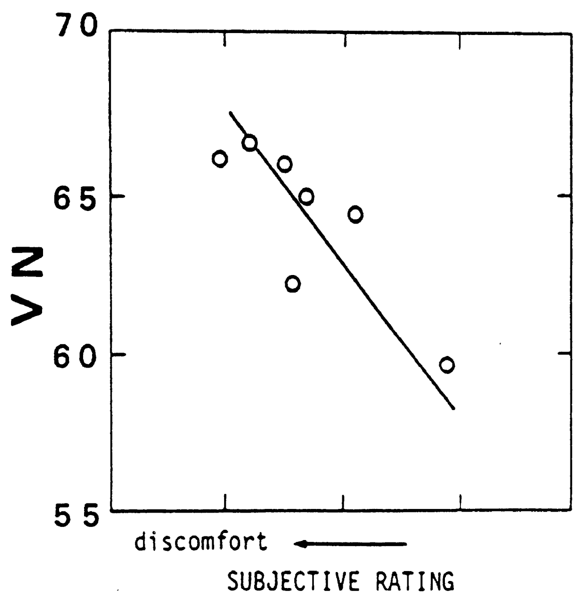


FIGURE 12. Correlation of subjective rating vs. *VN*.

D. SUBJECTIVE EVALUATION

Subjective evaluation of seating comfort is the most common way to evaluate seat performance. Several subjective approaches have been used in conjunction with overall comfort rating (Shackel et al. 1969; Oliver 1970; Habsburg and Mittendorf 1977; Drury and Coury 1982). Corlett and Bishop (1976) preferred to focus on discomfort, asking subjects either to rank, or rate, body areas perceived as suffering discomfort.

The question of focus is important. Wachsler and Learner (1960) found that the only factors which had a high correlation with feelings of comfort were comfort of the back and buttock. The same results were reported in a recent roadside interview conducted by the University of Michigan Transportation Research Institute under Ikeda Engineering Corporation sponsorship (Schneider and Ricci 1989). Habsburg and Middendorf (1977) used semantic differentials like "for me/not for me." This question focuses the response more sharply and provides instructions for subjects to consider more explicitly. Apart from focusing attention on body parts, subjects can be asked to focus on attention to the seat characteristics as, for example, in Shackel et al. (1969) the chair feature checklist (CFCL).

Subjective rating or ranking has limitations because the following conditions need to be satisfied when the subjective evaluation method is used (Branton 1969; Oborne and Clark 1975).

1. The respondents should be aware of their feelings of comfort. Certainly, individuals differ widely in such awareness.
2. Feelings of comfort should be verbalized. But, postural discomfort is very primitive and not readily accessible to introspection and verbalization (Branton 1969).
3. The respondents should be able to identify seat characteristics which cause (dis)comfort.
4. One's sensation of (dis)comfort should be maintained in memory sufficiently long to compare it with the (dis)comfort sensation resulting from other seats or different times.
5. Similar verbal expressions should represent similar experiences.

Poulton (1982) listed common biases in subjective judgement. Newstead et al. (1987) and Brigham (1975) also demonstrate subjects' limited capability in subjective evaluation. Leuder (1983) comments that the lack of accepted measures of comfort frequently cause comfort to be a low priority in decision making which affects comfort.

In order to bypass the above limitations, Branton (1969) attempted to use a hand dynamometer for a cross-modality match (CMM) with feelings of body tension. Although unsuccessful, he considered it a potential evaluation method and thought it would facilitate the subject's ability to evaluate responses to the seat. Gregg (in Corlett 1989, p. 264) attempted to quantify the pressure sensation under the buttock using a blood pressure cuff as a cross modality, and demonstrated a highly significant reliability between repeated trials for estimating perceived pressure.

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

Various subjective measures were introduced to evaluate the seating comfort of upright chairs.

1. *General Comfort Rating.* The following 11-point scale was constructed by having users rank order twenty statements about comfort and choose responses which gave the most consistent equal interval scale.

   I feel completely relaxed.
   I feel perfectly comfortable.
   I feel quite comfortable.
   I feel barely comfortable.
   I feel uncomfortable.
   I feel restless and fidgety.
   I feel cramped.
   I feel stiff.
   I feel numb (or pins and needles).
   I feel sore and tender.
   I feel unbearable pain.

2. *Body Area Comfort Ranking.* Subjects were instructed to choose "three most comfortable" body areas among a list of 15 body areas. After eliminating these three areas from the list, the next "three most comfortable" body areas were ranked until all the body areas were selected sequentially. In the same manner, discomfort areas were ranked, i.e., forced-choice ranking method (Bennett 1963).

3. *Chair Feature Checklist (CFCL).* The checklist contained the following items.

Seat height	Too high	Correct	Too low
Seat length	Too long	Correct	Too short
Seat width	Too narrow	Correct	Too wide
Slope of the seat	Slopes too far down to the back	Correct	Slopes down at front too much
Seat shape	Poor	Adequate	Good
Back support	Too high	Correct	Too low
Backrest shape	Fits the back	Adequate	Poor fit
Back curvature	Too curved	Correct	Too flattened

4. *Direct Ranking.* Each subject was asked to sit in each chair in turn and to divide the chairs roughly into three comfort groups. The subject then sat in the chairs again and ranked them within each group, comparing adjacent chairs to decide a final ranking.

5. *Body Posture Change Frequency.* By film analysis, posture changes were counted.

Ten chairs were evaluated by 20 male and female subjects using the above methodologies. There were no significant differences between gender. There was a clear trend of decreasing comfort rating with time. The poorer ratings of the two worst chairs were obvious from the start, but the others only seemed to separate clearly after 1 to 1.5 hours. A high correlation between the comfort rating and the direct ranking was also found.

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

Twenty-one front-passenger car seats were evaluated based upon objective and subjective measurements of seating comfort under dynamic and static test conditions.

In a short-term dynamic test (2-mile driving), the vertical acceleration measured on the surface of seats and the subjective preference rankings were compared. No correlations were found between the ranking and vertical acceleration magnitude. Written comments on the subjective rating questionnaire showed that the appearances of the seats strongly influenced subjects' judgement. In a long-term dynamic test (60-miles driving), differences in road conditions were perceived on the same seat (e.g., the same seat received an equal number of preferences for significantly different levels of acceleration—0.56 and 1.69), and two hours of driving did not affect comfort ratings.

In static tests, the preference rank-order was obtained from the 10-point comfort ratings (1: very comfortable, 10: very uncomfortable).

Very Comfortable	1
	2
	3
	4
	5
	6
	7
	8
	9
Very Uncomfortable	10

This was compared with the load-deflection characteristics. Stone (1965) reported that the judgements of seating comfort were apparently being made on the basis of the initial stiffness of the cushion as the subject sat in the seat. However, in this investigation, no relationship was found between subjective rating and the initial slope of the load/deflection curve.

It was expected that a journey of longer duration would accentuate the subjective effects of differences in seat vibration, but it was apparent from the results that vibrational effect was overshadowed by other aspects such as individual differences or complex road situations, although for 75% of the preferences expressed, the most preferred seat of any pair was that with the lower estimated vibration level.

The preferred seat dimensions were as follows:

Cushion Width	20–22" (508–559 mm)
Cushion Length	19–20" (483 mm)
Seat-Back Width	20–22" (508–559 mm)
Seat-Back Length	20–21" (508–533 mm)
Seat-Back Angle	24–30°
Seat-Back Lateral Curvature	1.3–2.6"

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

The author points out that, despite the fact that most of the problems involved in questionnaire design are well known, the quantitative aspects of questionnaire design and analysis are frequently given too little attention. The following design principles are addressed:

1. Ambiguity in question content must be avoided.
2. Length and content of the questionnaire should be appropriate to maintain the interest of the respondent.
3. Verbal descriptions which support the scale must be involved in a single continuum of sensation and the magnitude of verbal description should be tested.
4. The resolutions of scale must be within the respondents' discrimination capability.
5. Interval between two points in scale should be calibrated (Figure 3).
6. Zero or indifference point in scale need to be considered.

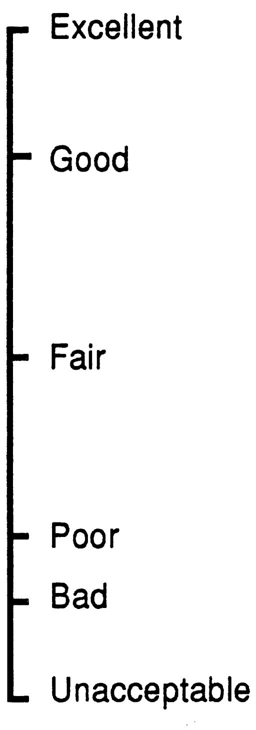


FIGURE 3. Representation of the interval scale positions of a six-point rating scale for the estimation of telephone transmission quality. GOOD and FAIR is more than three times the size of the interval between POOR and BAD (Duncanson 1968).

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

Two types of rating scales were compared and examples of each were provided. The *Graphic Rating Scale* uses descriptive phrases that are placed at intervals along the rating line to guide the rater. The *Numerical Rating Scale* uses phrases only at each end of the rating line.

1. The phrases positioned along the line (verbal representation) may change a previous uni-dimensional scale into a multi-dimensional scale, as in Shackel's general comfort scale which includes "relaxability," "comfort," "restlessness," "fidgets," "cramp," "stiffness," "numbness," "soreness," or "pain." Asking the subject to rate the object in terms of so many different dimensions could cause problems in the interpretation of the ratings.

2. Guiding phrases give a "centering" effect of the subject's response (Figure 4).

3. The reliability and the validity of scales rely on the fact that the guiding phrases are at least ordinally positioned, and that all subjects agree on this ordering of phrases.

The authors concluded in favor of the numerical scale because of the many difficulties encountered in the interpretation of the graphic rating scale.

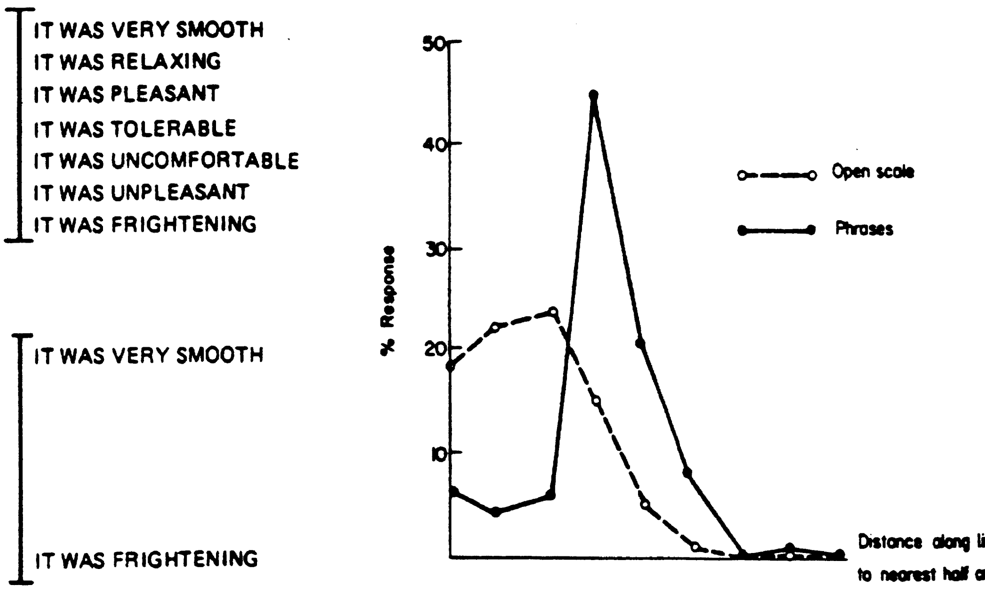


FIGURE 4. Comparison of comfort ratings when an open scale or phrases are used (from BEA helicopter survey 1970).

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

The purpose of this study was to find a good estimate of seat comfort using combinations of subjective and other physiological measures such as blood flow index and total segmental accumulation.

Twenty seats were evaluated (see Evaluation Sheet below) by three body size groups of subjects using rating scale, body discomfort rating, and adjective checklists. Among the adjectives used were: *Soft, Long, Accommodating, Deep, Restful, Comfortable, For Me*. Other ratings such as *Shoulder Comfort, Seat Rank, Overall Comfort Rating* provided a means for grouping seats as relatively good or bad. Each evaluation took an average of 15 minutes.

Four significant relationship patterns were extracted by canonical analysis of two sets of subjective variables—*Overall Comfort, Secure, Cool, Long* vs. all other subjective measures (Table 1).

TABLE 1
RELATIONSHIP PATTERNS OF SUBJECTIVE MEASURES (N=40)

Relationship Pattern	1 Rc=0.89 χ^2=707.39	2 Rc=0.57 χ^2=216.62	3 Rc=0.39 χ^2=98.02	4 Rc=0.38 χ^2=48.31
Subjective Factors Set 1				
Overall Comfort	98	−50		−40
Secure		85	39	
Long			−92	
Cool				91
Subjective Factors Set 2				
Comfortable	40	−59	−50	−35
Accommodating	23			
Safe		49		
Supporting Back		40	32	
Restful		36	31	
Spacious		−31		
Thigh Comfort		−27		
For Me			38	
Deep			−74	
Thick				49
Sticky				31
Soft				−31

A major finding of this study was that exterior appearance did not influence comfort judgements. Rather, functional interactions determined whether the seat was comfortable or not. Physiological measurements were done for 31 subjects. Only the total segmental accumulation showed a canonical relationship (Rc=0.79) with *Secure* (71), *Supporting Back* (−41), *Cool* (−47), *Overall Comfort* (−44).

Table 2 shows that good overall comfort rating is correlated with *Comfortable, Supporting Back*, and *For Me*. Also, it shows that subjects become sensitive to particular features of the seat and these features appear to be determined individually (no overlap in subjective variables was found among the worst seats).

TABLE 2
THREE BEST- AND WORST-RATED SEATS

Seat Type	*Overall* Comfort Rating		Subjective Variables Which Have High Correlation With *Overall* Comfort Rating
	Mean	SD	
Volvo 144	5.31	1.30	*Comfortable*, Accommodating, Restful, *Supporting Back, For Me*, Thick
Opel Rekord	5.22	1.26	Back Comfort, *Comfortable, Supporting Back, For Me*, Secure
Buick Electra	5.00	1.23	*Comfortable*, Restful, *For Me*, Thigh Comfort, *Supporting Back*
Hardwood	0.56	0.73	Insecure, Tiring, Cool, Buttock Discomfort, Uncomfortable
Range Rover	2.40	2.86	Unsafe, Rough, Shallow, Tiring, Uncomfortable, Not for Me
Recaro Bucket	2.44	1.90	Short, Insecure, Low, Buttock Discomfort, Constricted

The authors recommend further study that will clarify the relationship between seat dimensions and corresponding comfort factors in a dynamic seat evaluation study.

EVALUATION SHEET
(from Habsburg and Middendorf 1977)

EVALUATION OF SEAT

OVERALL COMFORT RATING	COMFORTABLE						UNCOMFORTABLE
BODY AREA RESPONSE	NECK						
	SHOULDER						
	BACK						
	BUTTOCK						
	THIGH						
	LEG						
	TIME						
SEAT PROFILE	SPACIOUS						CONSTRICTED
	SOFT						FIRM
	UPRIGHT						RECLINING
	ADJUSTABLE						NON-ADJUSTABLE
	SUPPORTING BACK						NON-SUPPORTING BACK
	SECURE						INSECURE
	COOL						HOT
	HIGH						LOW
	LONG						SHORT
	QUITE						NOISY
	SAFE						UNSAFE
	SMOOTH						ROUGH
	ACCOMODATING						STIFF
	DEEP						SHALLOW
	STICKY						SLIPPERY
	RESTFUL						TIRING
	THICK						THIN
	COMFORTABLE						UNCOMFORTABLE
	FOR ME						NOT FOR ME
	RANK						

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

This paper illustrates the biases that can be involved in quantitative judgement. The following possible biases are discussed.

1. *Stimulus and response contraction biases.* A person tends to underestimate large sizes and differences or overestimate small sizes and differences.

2. *Sequential contraction biases.* When a person judges one stimuli directly after another, the previous stimulus becomes an additional reference magnitude against which the next stimulus is judged. The person tends to underestimate the size of the difference between the previous stimulus and the next stimulus.

3. *Unit unfamiliarity biases.* If a person has no familiar physical units that he can use to check his judgement, the additional bias is likely to be large.

Unfortunately, there is no way to avoid biases in quantitative judgements. All the experimenter can do is to be aware that quantitative judgements are likely to be biased. Subjects can be trained to avoid the bias, but the training may not transfer from one kind of judgement to another. Thus, training is not necessarily a dependable method of preventing bias.

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

The authors investigated how people interpret quantifiers of amount commonly used in rating scales. The results shown in Table 2 indicated that the interpretation of certain quantifiers varies depending on the context. Low-magnitude quantifiers (e.g., "few," "several") were interpreted as a much greater proportion when they described small set sizes than when they described relatively large ones. This means that it is virtually impossible to find quantifiers for use in rating scales which achieve the desirable property of interval scaling. Despite this, it was found that some quantifiers are clearly more consistent in their interpretation than others. The following recommendations are made:

1. Five quantifiers including the end terms are:
   All, Many, Half, Some, None
2. Six quantifiers including the end terms are:
   All, Most, Many, Some, Few, None
3. Five quantifiers excluding the end terms are:
   Most, Many, Half, Some, Few

TABLE 2
PROPORTION OF ITEMS CHOSEN IN EXPERIMENT 2
AS A FUNCTION OF QUANTIFIER AND SET SIZE

Quantifier	Set Size					Mean
	12	60	108	1000	(10 000)*	(exclud. 10 000)
All	1.00	1.00	1.00	1.00	(.96)	1.00
Most	.81	.84	.84	.86	(.84)	.83
Lots	.74	.76	.76	.78	(.74)	.76
Many	.74	.76	.72	.75	(.70)	.74
Some-not	.64	.66	.78	.69	(.77)	.70
Half	.50	.50	.50	.50	(.50)	.50
Several	.47	.32	.33	.27	(.17)	.35
Some	.37	.33	.32	3.0	(.27)	.33
A few	.30	.20	.15	.12	(.11)	.19
Few	.26	.21	.16	.12	(.09)	.19
None	.00	.00	.00	.00	(.00)	.00

*NOTE: The data for set size 10 000 are from a separate study.

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

Eight principal components were extracted from 22 items of subjective rating (see Evaluation Sheet) by principal component analysis (PCA). Extracted components are: *cushion fitness, left-right tightness, spring feel, seat-back fitness, lumbar support feel, front-back tightness, hardness, vibration attenuation feel.*

These components were regressed with *Overall Comfort* (R^2=0.77). Also, linear models between physical measurements (based upon JASO B407) and each comfort component were developed.

EVALUATION SHEET
(from Iwasaki et al. 1988)

				Unsatisfactory (us) Satisfactory (s)
0. What is your first impression?				+-+-+-+-+ us s
CUSHION				
1. Cushion hardness			+-+-+-+-+ soft hard	+-+-+-+-+ us s
2. Bottomness feel			+-+-+-+-+ no yes	+-+-+-+-+ us s
3. Large deflection feel under buttock area			+-+-+-+-+ no yes	+-+-+-+-+ us s
4. Spring feel of cushion			+-+-+-+-+ no yes	+-+-+-+-+ us s
5. Vibration attenuation feel			+-+-+-+-+ no yes	+-+-+-+-+ us s
6. Cushion shape fitness	a direction b direction	ⓐ ⓑ	+-+-+-+-+ not fit good +-+-+-+-+	+-+-+-+-+ us s +-+-+-+-+
7. Thigh pressure			+-+-+-+-+ low high	+-+-+-+-+ us s
8. Lateral tightness of thigh due to cushion wing			+-+-+-+-+ loose tight	+-+-+-+-+ us s
9. Lateral tightness of hip due to cushion wing			+-+-+-+-+ loose tight	+-+-+-+-+ us s
10. Surface slippery			+-+-+-+-+ sticky slippery	+-+-+-+-+ us s
SEAT BACK				
11. Seat back hardness			+-+-+-+-+ hard soft	+-+-+-+-+ us s
12. Seat back shape fitness	a direction b direction	ⓐ ⓑ	+-+-+-+-+ not fit good +-+-+-+-+	+-+-+-+-+ us s +-+-+-+-+
13. Lumbar support height			+-+-+-+-+ low high	+-+-+-+-+ us s
14. Pressure on lumbar area			+-+-+-+-+ low high	+-+-+-+-+ us s
15. Thightness at underarm due to trunk support			+-+-+-+-+ loose tight	+-+-+-+-+ us s
16. Thightness at waist due to trunk support			+-+-+-+-+ loose tight	+-+-+-+-+ us s
17. Support feel when turn the corner			+-+-+-+-+ no yes	+-+-+-+-+ us s
18. Over-extended back feel			+-+-+-+-+ no yes	+-+-+-+-+ us s
19. Hunchback feel			+-+-+-+-+ no yes	+-+-+-+-+ us s
20. Pressed feel on stomach related to hip angle			+-+-+-+-+ no yes	+-+-+-+-+ us s
21. Overall evaluation				+-+-+-+-+ us s

E. PRACTICE IN INDUSTRY

Kozlowski (1988) provides an historical perspective on the work done to date in automotive seating. In the 1930s, seats used individually wrapped coil springs. These coils were then replaced with sinous wire and later, in the 1950s, with form wire. Until the urethane foam topper pad was introduced in the mid 1950s, cotton was the primary padding material. The six-way power track, introduced in the mid 50s, was the first optional comfort feature available to the customer. The recline feature was then added in the 60s. Until the 1980s, these were the only comfort adjustment options. Lumbar support has become a standard device since 1964. In the 1980s, fully-articulated, high-performance seats were introduced.

Even though there is agreement in the seating industry on the final goals of seat making, different companies have different design philosophies and manufacturing technologies. In addition, every country has distinct design preferences since consumer preference differs regionally (Figure 10 and 11). In 1978, Bohlin et al. presented the Volvo's seat with lumbar support and completely separated damping and suspension elements. Babbs (1979) reported a double-fitting trial using manikins of both small-sized females and large-size males. Relevant dimensions were adjusted simultaneously in the design process to accommodate the range of driver size. Maertens (1985) prepared seat design guidelines depending on car body type. Weichenrieder and Haldenwagner (1985) presented the Audi's design concepts—static, orthopedic, and dynamic functions of a seat. The Jaguar XJ40 seat development stressed the importance of feedback from customers when a new seating system is developed (Arrowsmith 1986). Matsuoka and Hanai (1988) introduced a new design concept for the front passenger's seat by separating it from the driver's seat. Diebschlag et al. (1988) introduced a backrest length adjustment to accommodate the back shape of a larger population and pointed out the importance of microclimate.

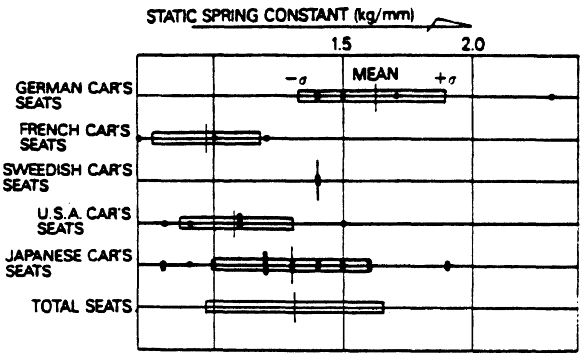


FIGURE 10. Static spring constants of seats classified by country.

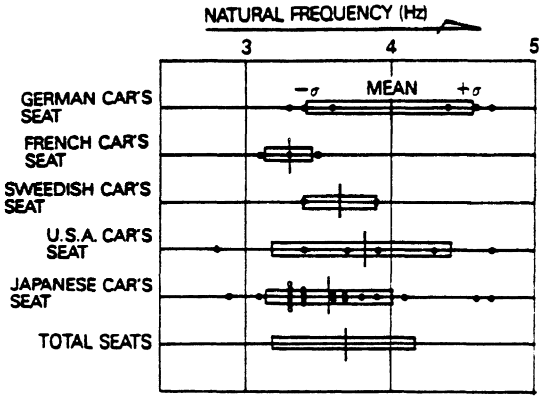


FIGURE 11. Natural frequencies of seats classified by country.

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

Lockheed's JetStar seat was introduced as a result of its seating design criteria that are based on both long- and short-term seating considerations.

The *back cushion* is precisely contoured to the lumbar curve of the spine, and the design allows a variety of relaxing positions. This is in contrast to the popular bucket seat which allows one comfortable position, but severely limits the number of other positions. Lockheed's seat back encompasses the following design characteristics:

1. vertical contour with maximum convexity at approximately 10 in. above the depressed seat cushion;
2. horizontal contour to fit the rounding of the lumbar region;
3. flattening in the upper part to open chest and straighten shoulders;
4. a gradual bend centering at 16 in. above the depressed seat cushion and with an upper portion angled forward at 15°;
5. net sloping of approximately 53° in the fully reclined position when the seat back is set at a 38° incline (chord line);
6. seat back height of 30 in.;
7. no contouring at neck level;
8. a "butterfly" pillow to stabilize head.

The *seat cushion* is flat and firm. This is contrary to both the bucket and the big spongy armchair which roll the thighs inward, distributing the weight over other areas sensitive to strain and muscular tension. The seat cushion has the following design characteristics:

1. A semi-rigid sandwich fiberglass platform sandwiched between a firm foam cushion on top and a thicker, softer foam cushion underneath.
2. The platform stops 3 in. from the front edge of the seat bottom.
3. The seat height is 16.25 in. to the floor at the front of the free cushion.
4. The seat length is 18 in. and the seat width is 20 in.
5. The seat pitch is 7° when empty.

A specially designed pad works as a lumbar support. The upper part of the seat back at the shoulder blade level is flat in the horizontal plane allowing the shoulders to set back, opening the chest.

Excessive pressure on the underside of the thigh normally results when (1) the seat height at the front is too great, (2) the seat bottom is too soft in the center relative to the front, or (3) the seat bottom is pitched backward without elevating the feet or lowering the seat height at the front. To eliminate these conditions, the JetStar seat cushion is curved downward at the leading edge and does not come too far forward along the lower thigh (18 in.), and the seat height is reduced.

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

This article reviews aircrew seating problems and suggests solutions for their specific concerns. There are many who would claim that the progress of seat development for a cockpit has not been fast enough, taking into account the availability of ergonomic knowledge, the incidence of pilot back complaints, and their economic consequences. Evidence suggests that the incidence of low back pain among aircrew is abnormally high and so the question of seat design may be of particular significance.

The aircrew seating problem has become more pronounced since pilots are not allowed to leave their seat except for operational reasons, and therefore must remain strapped in, usually in a slumped posture and in one position throughout their duty period. It has been suggested that discomfort factors are often associated with poor design in the following areas:

1. Seat height from floor (of primary importance)
2. Height and adjustability of armrests
3. Seat back recline adjustability (this also influences the spinal curvature)
4. Seat cushion and cover material characteristics, particularly ventilation
5. Seat cushion hardness
6. Seat cushion contouring
7. Seat back contouring
8. Footrest facilities
9. Pressure distribution
10. Seat rigidity
11. Seat controls
12. Seat geometry/rudder pedal/control column/reference eye position
13. Ingress and egress
14. Headrest facility
15. Seat belt and hardness

As a solution for these problems, the author recommends the following design considerations:

1. *Lumbar Support*: One of the most needed features is a variable lumbar support which can be easily adjusted by the individual. The optimum area of support is between the 2nd and 4th lumbar vertebrae which is near the average waist or belt line.

2. *Thigh Support*: An adjustable thigh support is related both to blood restriction beneath the thigh as well as proper pressure distribution under the buttock.

3. *Seat Pan Contour*: There should not be too much of a bucket effect in order to avoid discomfort from side pressure on the outside of the hip joint.

4. *Seat Cushion and Fabric*: The cushion should be firm but deformable to conform to the occupant's contour. The cushion and fabric should permit air circulation, and fabric should be elastic enough to pass local load directly to the cushion. A sheepskin cover which gives a warm feel when it is cold, and a cool feel when it is hot have received good responses from the crew.

5. *Seat Armrest*: In order to prevent the shoulders from being forced up and to take a proper share of body weight, the armrest height must be adjustable over an adequate range.

6. *Footrest*: A footrest is essential to ensure seated comfort over long periods by allowing the leg to be raised occasionally so as to relieve pressure under the thigh and reduce blood pooling in the leg.

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

This paper explains the design philosophy of the Volvo seat. Since 1945, individual front seats have been used as a standard to adjust preferred driver position independent of the front seat passenger. Lumbar support has also been a standard device since 1964 when it was found to provide the most support and comfort in long-term driving.

The current Volvo seat can be adjusted 200 mm (8 in) fore-aft, has 90° of seat-back angle adjustment, 38 mm of height, and 14° of seat-pan angle to cover anthropometric variability. In some cases, drivers of the same stature show 100 mm (4 in) difference in fore-aft seat location.

The Volvo seat has almost completely separate damping and suspension elements. The damping element is a seat cushion (molded polyurethane), and the suspension element is a wire frame which covers the bottom of the cushion and is connected to the seat frame by short coil springs. The position of the seating reference point (SRP), particularly the height, is a primary comfort factor. It is a decisive consideration for entry and exit comfort. The SRP for both rear and front seats should be positioned as high as possible for comfortable entry and exit.

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

This paper describes an empirical study of seating layout performed by T.I. Cox Ltd. To design a better vehicle seating environment, (1) optimum seat/body pressure distribution and three-dimensional profiling, and (2) positioning of seat support surface were considered based upon subjective seating comfort rating experiments.

Two primary issues were considered. One is that pressure distribution changes as the three-dimensional seat/driver interface shapes vary with the sizes of the occupants. The second is regarding the accommodation of the various sizes of occupants under the geometric restrictions. If only fore-aft adjustment was used, 4 inches of eye-height variation was expected.

To accommodate different-sized occupants with respect to locations of various controls and geometric restrictions of car bodies, a 2-D plastic manikin was initially used, and then a 3-D manikin was developed to obtain a complete seating profile design. The manikin fitting trials gave optimum postures and twelve locations of adjustable points were defined (Figure 2). This configuration resulted in 2.5 inches of eye height variation.

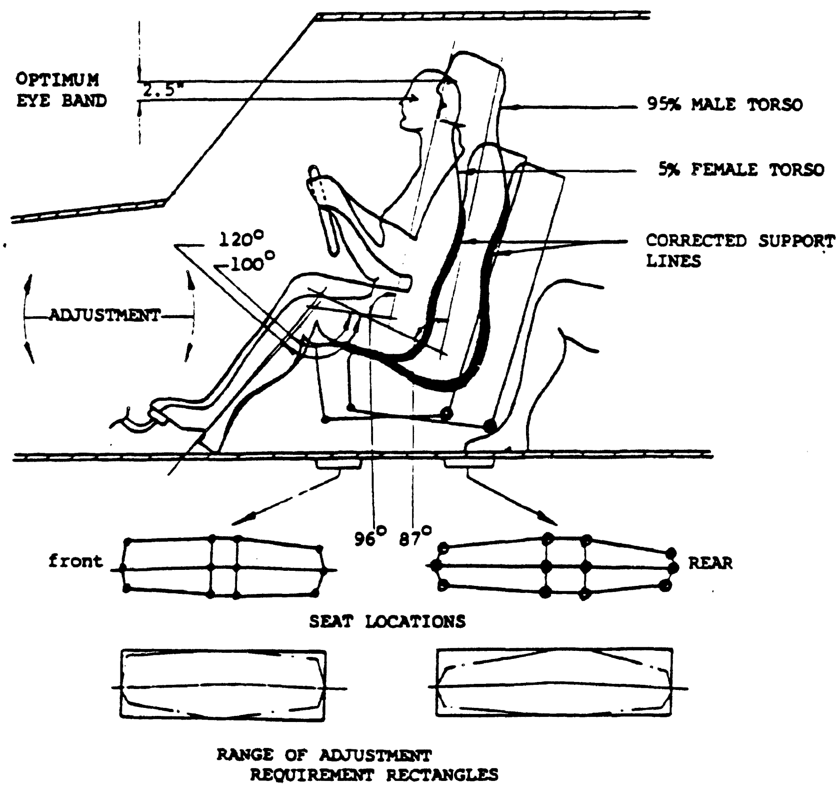


FIGURE 2. Layout method: Positioning the manikins.

The paper goes on to clarify why the main support should be provided at and forward of the ischial tuberosity point. If pressure is allowed to build up to the rear of the ischial tuberosity, compression of muscle fiber (such as gluteus maximus in Figure 7) becomes painful. It is noted that muscle fiber areas are more susceptible to pressure discomfort than skin and fat areas such as the ischial tuberosities.

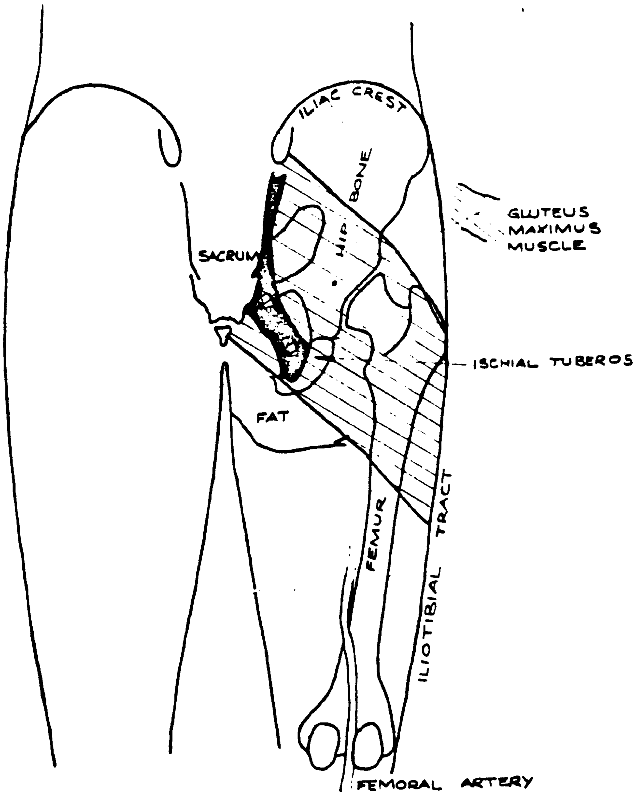


FIGURE 7. Gluteus maximum muscle rises over the ischial tuberosity when one is sitting.

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

This report contains the GM design guidelines for production seats. Different criteria are used depending upon three car-body types: sport-type (level 1), family-type (level 2), and luxury type (level 3).

Seats for a sports car body-type require a firm feel with maximum lateral control and assorted adjustable features. Some compromise in comfort may be inevitable to achieve a sport seat-type feel and control. Seat design for a family-type car requires a softer feel and has a less dramatic seat contour. A luxury-type car has a plush or softer seat which still provides support.

The following recommendations have been made for seat design (see Tables 1 and 2):

1. Maintain the 50 mm "body to metal frame" clearance line under the occupant.
2. Seat contour surface should avoid dramatic changes.
3. Penetrating at the sacrum should be minimal.
4. Provide a 150 mm relatively flat area in the central portion of the D-point.
5. Wings should be kept to a minimum.
6. Seat back contour should be smooth and have a parallel nature when comparing it with the occupant's depressed back line.
7. Seating comfort is difficult to achieve without contour as a primary consideration.

The following factors can also influence seating comfort and should be considered:

1. the complexity of the construction of the cover (location and number of buttons, welts, and pipes, etc.);
2. the softness/firmness of the foam;
3. the type of fabric chosen for the cover;
4. the choice of suspension to support the occupant.

TABLE 1
DESIGN RECOMMENDATIONS FOR A SEAT CUSHION

	Sport type	Family type	Luxurious type
Penetration at the Ischial Tuberosities (IT)	40-60 mm	60-80 mm	80-100 mm
Penetration at seat front -300 mm forward from the IT	10-15 mm	30-40 mm	60-75 mm
Length of the thigh contact from the IT	Minimum 350 mm		
Cushion length from H point	Maximum 380 mm		
Clearance thickness	Minimum 50 mm from the deflated surface It should be remain free of deflecting obstruction such as frame.		
Contour surface	150 mm width area should remain relatively flat under IT		
Seat width	Minimum 500 mm		

TABLE 2
DESIGN RECOMMENDATIONS FOR A SEAT BACK

	Sport type	Family type	Luxurious type
Deflection at the lumbar region	20 mm	35 mm	50 mm
Upper body contact from H-point along the back angle	450 mm	475 mm	500 mm
Horizontal back shape	Parallel with the depressed occupant back line.		
Lumbar section shape	300 mm radius	450 mm radius (bucket) 810 mm radius (bench)	
Thoracic section shape	1000 mm radius A lesser radius will cause discomfort due to the act of rounding the shoulder.		
Clearance thickness	At least 50 mm is required (65 mm is recommended).		

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

This paper discusses functions of automotive seats and design concepts which can fulfill these functional requirements. Also, the advantages of the all-foam seat cushion are presented. Design criteria for three major seat functions—static, orthopedic, and dynamic—are discussed.

1. Static Function

As shown in Table 1, design dimensions need to be considered in order to suit the various body proportions to the necessary operating and movement ranges of the hands, feet, and vision. There are four methods of adjustment to accommodate various sizes of drivers.

According to the authors' findings, the occupant becomes aware of a change in seat position if the seat is moved 10 mm horizontally, 5 mm vertically, or the seat base or backrest angle is moved 2 degrees.

2. Orthopedic Function

The occupants of an automobile are forced to adopt an almost unchanging body posture for quite lengthy periods of time. In addition, the seated posture is different from the standing posture because (a) the load imposed by the body on the legs now rests on the bones of the pelvis, (b) the spinal curve changes from lordotic to kyphotic curvature, (c) back muscles are elongated, and (d) the abdominal area is compressed by the raised thighs.

The following design recommendations should be considered in order to enhance the orthopedic function of a seat.

(a) The overall pressure should be kept low by providing enough contact area to support the loads. The highest pressure should be built up below the ischial points (1–3 N/cm^2). The pressure should fall gradually around the ischial support area (0.8–1.5 N/cm^2) and towards the boundary of the contact area (0.2–0.8 N/cm^2).

(b) To prevent backwards pelvic rotation and unwanted spinal curvature, both must be restrained in the ischial support. A "healthy" seated posture cannot be achieved simply by providing lumbar support. Supports at the iliac crest are also recommended.

(c) The shape of the backrest should be designed to give minimum muscular retention and low pressure on the intervertebral disks. Because back configurations differ considerably in curvature, vertical shaping of the backrest should be highly adjustable.

(d) In addition to the iliac crest support, the principal support should be applied at the lower edges of the two shoulder blades.

3. Dynamic Function

The dynamic function of an automotive seat is to protect occupants from vibration. In this sense, the seating design objective is to minimize the total transmission of vibration, especially at the sensitive vibrational frequencies. (ISO 2631 shows that the human is most sensitive at frequencies of 4–8 Hz.)

In general, as the foam thickness increases, the resonance frequency is lowered to the less critical range, and acceleration amplitude is reduced. The authors find that an all-foam seat cushion, like other spring cushions, transmits vibration at a selective frequency range. Because this all-foam cushion can be regarded as an infinite number of spring-damper systems, it is possible to tune the cushion by controlling the local thickness and hardness.

Softening of the seat upholstery reduces the vibrational comfort at low frequencies, but gives unpleasant effects due to body displacement when acceleration or deceleration occurs.

TABLE 1
REQUIRED ADJUSTABLE RANGES FOR ACCOMMODATING 5th PERCENTILE FEMALE AND 95TH PERCENTILE MALE DRIVER RELATED TO THE FIXED POINT

Fixed Point	Seat Adjustment	Wheel Adjustment	Pedal Adjustment	Eye Position Difference (V)
Pedal	190 mm H 10 mm V	120 mm H	—	120 mm
H-Point	—	70 mm H 80 mm V	190 mm H	100 mm
Steering Wheel	70 mm H 80 mm V		120 mm H 95 mm V	20 mm
Eye Point	20 mm H 120 mm V	80 mm H 30 mm V	210 mm H 130 mm V	0 mm
Pedal/Steering Wheel	190 mm H 10 mm V	—	—	120 mm

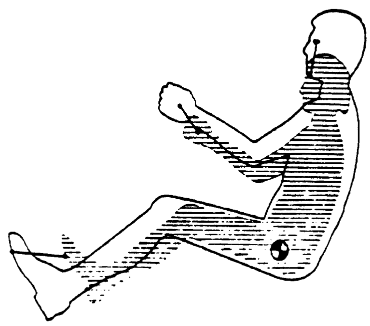


FIGURE 8. Fixed H-Point.

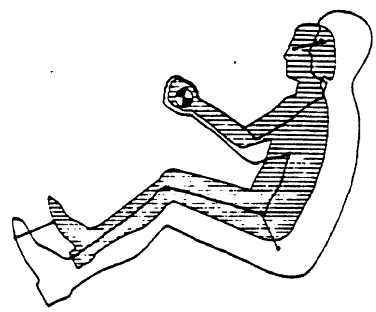


FIGURE 9. Fixed steering wheel holding point.

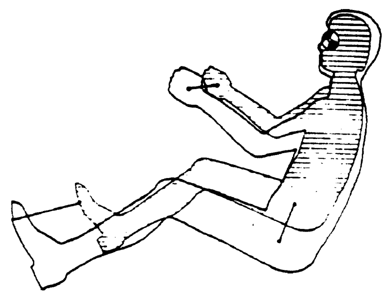


FIGURE 10. Fixed eye point.

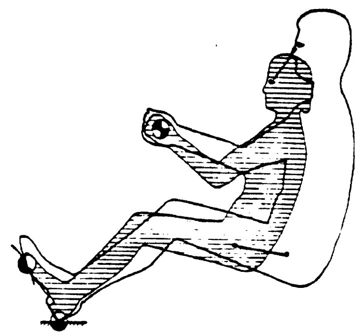


FIGURE 11. Fixed pedals and steering wheel.

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

This paper describes the research, design, and development processes involved in the creation of the Jaguar XJ40 seating system (Figures 4, 5, 6, and 7).

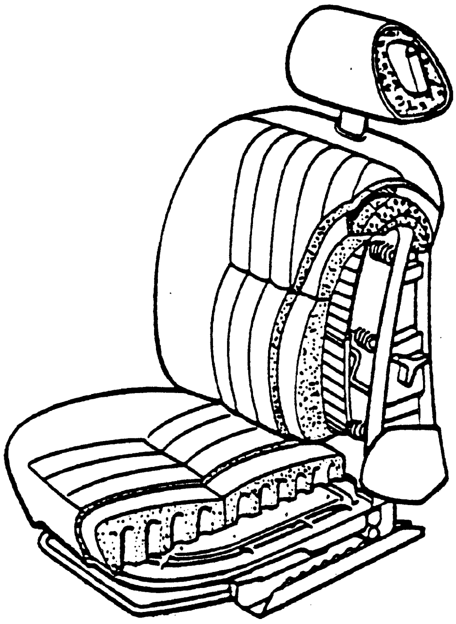


FIGURE 4. Series III front seat.

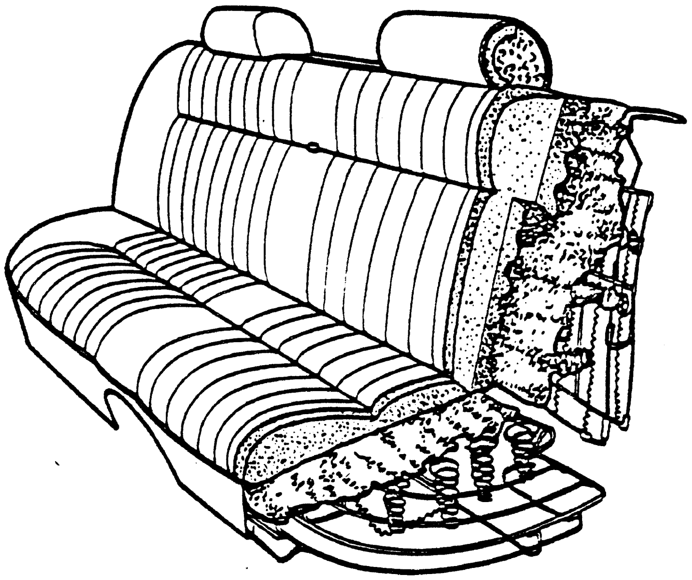


FIGURE 5. Series III rear seat.

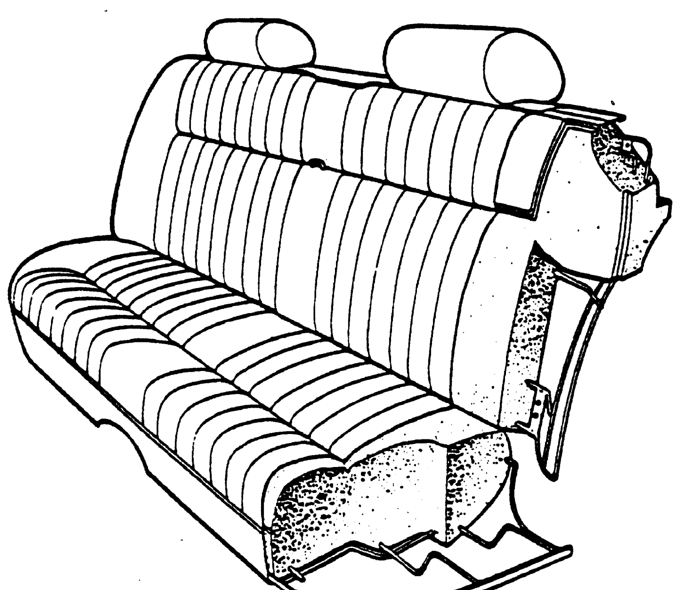


FIGURE 6. XJ40 rear seat.

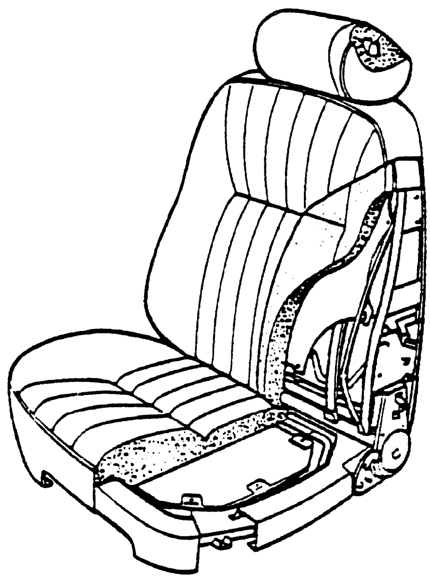


FIGURE 7. XJ40 front seat.

Before starting the design of a new seating system, the current Series III saloon seat was evaluated using a postal questionnaire and a group of subjects representing the driving population. Subjects were first questioned after 15 minutes of sitting in the car in order to assess the showroom condition. They were then asked to assess the seat every 30 minutes during 2 hours of driving. The correlation between the experimental results and the questionnaire survey was good. The following were found or changed as a result:

1. The piping across the front edge of the cushion was lowered to reduce contact with the underside of the thigh.
2. The rear of the cushion was stiffened by reducing the size of the cavities in the foam. This part of the cushion supports the bulk weight of the torso, but usually the thinnest section in a cushion. Support capabilities are increased by eliminating the cavities.
3. Seat height adjustment was found essential to provide a comfortable posture for the full range of stature.
4. The rear seat showed significantly poorer dynamic characteristics than the front seat. (The difference is due to different seat suspension systems. The front seat consists of a foam pad supported by a rubber diaphragm. The rear seat is of sprung-steel construction.) The rear seat uses a full-depth foam and the body seat pan as a base.

The following were included in new seat design and in the prototype XJ40 seat development:

1. For the front seat, a rubber diaphragm was chosen to support the foam.
2. "Cold Cure" polyurethane foam was chosen since it is lightweight and has good repeatability of foam properties. Also, its hardness and density can readily be adjusted to tune for seat comfort.
3. Tubular frame was adopted to reduce lead time, costs, and because of seat characteristics and easiness of design modification.
4. Even though high-strength steel offers the advantage of lighter weight, mild steel was chosen because of manufacturing ease.
5. During the seat cushion tuning process, H-point is carefully checked by placing a standard weighted manikin on the seat.

To test the prototype seat, "clinics" were held in the U.K. and the United States. As a result of the clinics:

1. There was frequent criticism of inadequate lateral support and excessive lumbar pressure in the front seat. "Submarining" was evident in the rear seat, i.e., the tendency for the passengers to slide down and forward along the cushion. To reduce submarining, the cushion rake (angle) was increased.
2. The original design of the XJ40 lateral flutes were changed to vertical flutes which is a more traditional trim style. The vertical fluting allows a more concave squab (seat back) section in both front and rear seats and improves lateral support.
3. Further improvement to the lumbar support was made by using a mechanical adjustment system in place of the screw-tensioned strap.

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

A new prototype seat was developed focusing on (1) surface shape and adjustability of a seat, (2) force and pressure distribution under thigh, buttock, and back, and (3) microclimate on the contact areas.

1. Shape and Adjustability

The following adjustabilities were found to be primarily related to seating comfort:

1. forward/rearward adjustment;
2. backrest inclination;
3. height of the seat;
4. seat cushion length.

However, the back profile measurement results showed large variations in back contours (the location and amount of cervical and lumbar lordosis). The considerable difference between vertical back profile of 5th percentile women and 95th percentile men (Figure 2) requires *backrest length adjustment* to accommodate the length of the driver's torso. This length adjustment involves the entire backrest and the support pads in the area of neck and lumbar lordosis. Figure 3 shows the following extra adjustabilities:

1. total length of backrest adjustable;
2. support of the cervical lordosis, adjustable in height and depth;
3. adjustable height and depth support of the iliac crest and the lumbar lordosis;
4. integrated head and neck support, angularly adjustable.

Also, the *recliner's center of rotation* was relocated according to the anatomic center of rotation of the upper body in order to avoid a displacement between back and backrest while inclining the backrest (130–180 mm in front of the compressed backrest, and 20 mm under the compressed seat cushion in the tuberosity area, Figure 3).

With regard to seat cushion design, the following points were considered:

1. molding of the buttock area;
2. slight lowering of the surface height under ischial tuberosity with respect to the upper thigh area;
3. widening of the seat cushion towards the front due to the opening of the thighs during relaxed sitting;
4. proper size of the side support for ease of ingress/egress.

2. Upholstery of Seats

In order to achieve the lowest pressure values under the tuberosities and to ensure a suitable pressure distribution, polyurethane foams with linear force-deflection characteristics are specially suitable because a resulting force is transferred throughout the area of utilization.

3. Microclimate

Temperature and humidity of the contact surface has an essential influence on comfortable sitting. The following factors are related to microclimate:

1. Material and texture of the cover material
2. Thickness and density of the cushion
3. Compression of the cushion
4. Perforations of the cushion and of the seat/backrest shell

Generally, water vapor permeability increases with increasing compression due to the shorter diffusion thickness, but starts to decrease sharply with 75–85% of compression due to the increase of foam density. In order to avoid a warm and humid microclimate, the listed components (cover fabric, foam, and seat shell) should be optimized with regard to their water vapor permeability (Figure 7).

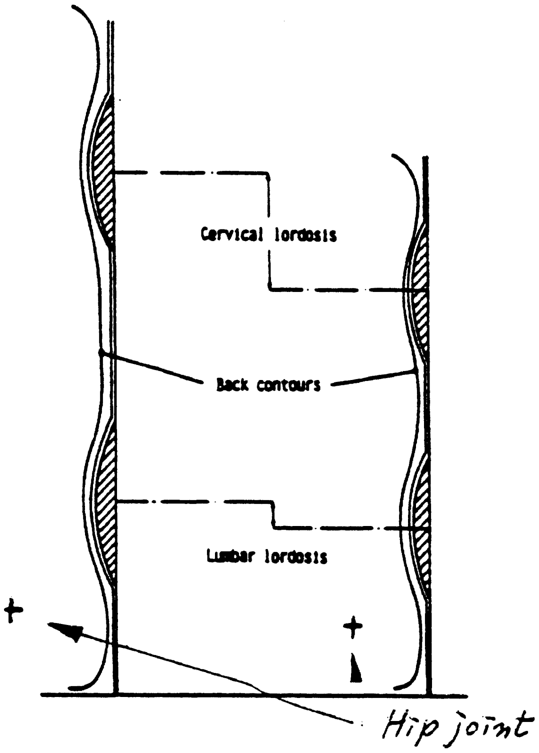


FIGURE 2. Vertical back profiles of a 95th percentile male and of a 5th percentile woman (schematic).

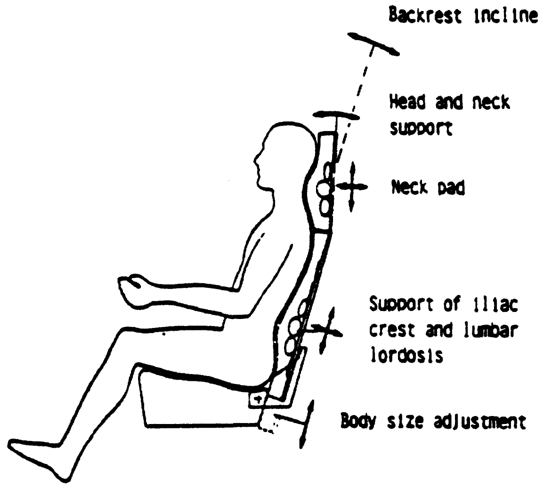


FIGURE 3. Seat concept, adjustable to torso length.

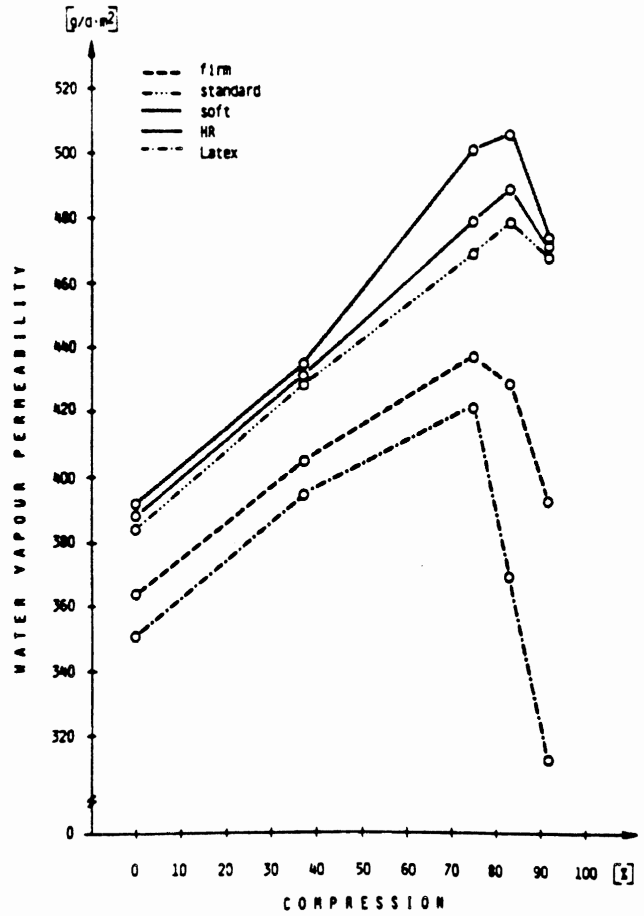


FIGURE 7. Water vapor permeability of different polyurethane foams depending on compression.

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

In order to design more comfortable and functional passenger and rear seats for passenger cars, new design concepts were introduced based upon systematic analyses of passenger behavior and posture in the vehicle.

The most frequent occupant behaviors in a passenger or rear seat were observed as (1) watching outside scenery, (2) relaxing, or (3) assisting the driver. Related to these behaviors, occupant postures and complaints due to lack of design features were also collected as part of the study. New design concepts for passenger and rear seats were developed from these behavioral requirements (Figure 1) and include:

1. *Side Support*. The amount and height of side supports have been reduced to provide a greater degree of lateral movement while maintaining suitable support to the trunk. The height of trunk supports (on the seat back) was slightly lowered to reduce the large lateral pressure at reclined postures which are found more frequently than in the driver's seat (Figures 3 and 4).

2. *Shape of seat cushion*. To compensate for the gap between the body and the borderline of the seat back and cushion at the reclined position, the back-end of the seat cushion was inclined upward. This provides a better contoured fit between the body and the passenger seat.

3. *Forward tilt of upper part of seat back* (Figure 5). The upper half of the seat back can be tilted forward and up to 30°. This function maintains the normal eye position with reclined postures and also enhances the degree of comfort by supporting the upper trunk properly. The maximum tilt angle was determined based on the subjective measurement of comfort angle using various sized groups of subjects, and the height was determined with reference to the height of the 10th vertebrae because the 11th and 12th thoracic vertebrae are relatively more flexible than the others.

4. *Upward swing*. This allows the entire seat cushion to slide forward and upward. This function is helpful to prevent sliding or rotation of the pelvis which reduces the lumbar lordosis. The range of swing was determined based on the relationship between comfortable angle and hip-slip range (Figure 13).

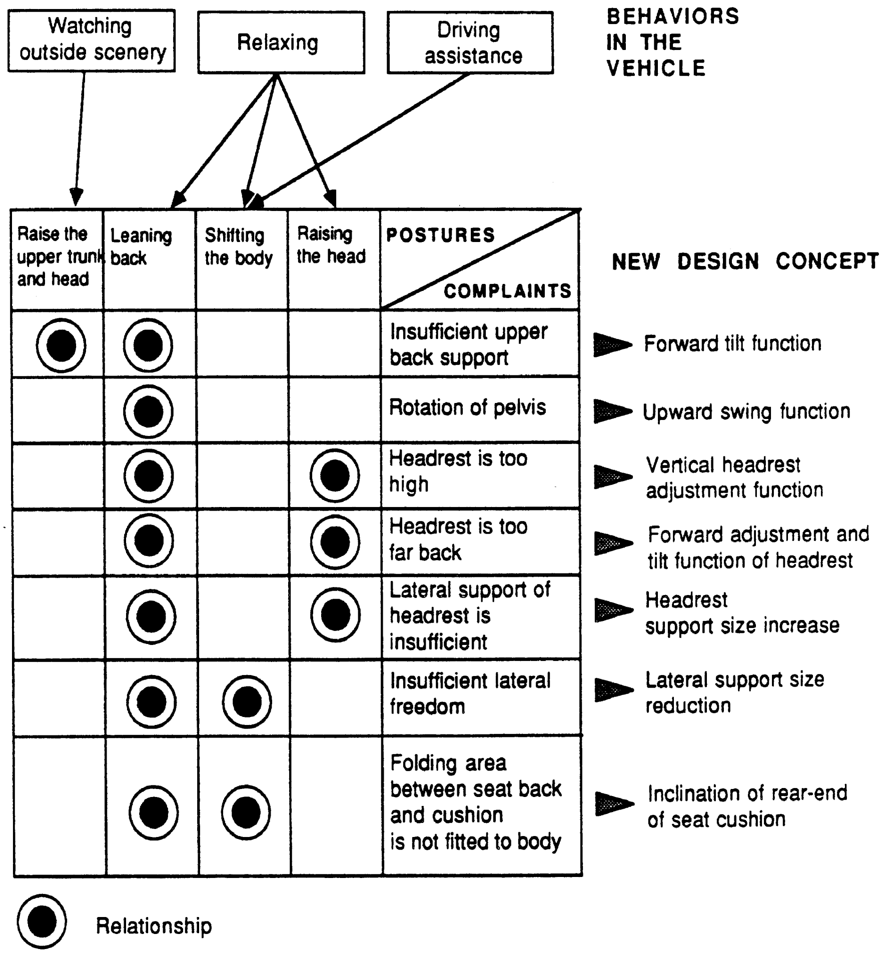


FIGURE 1. A new design concept for passenger seats.

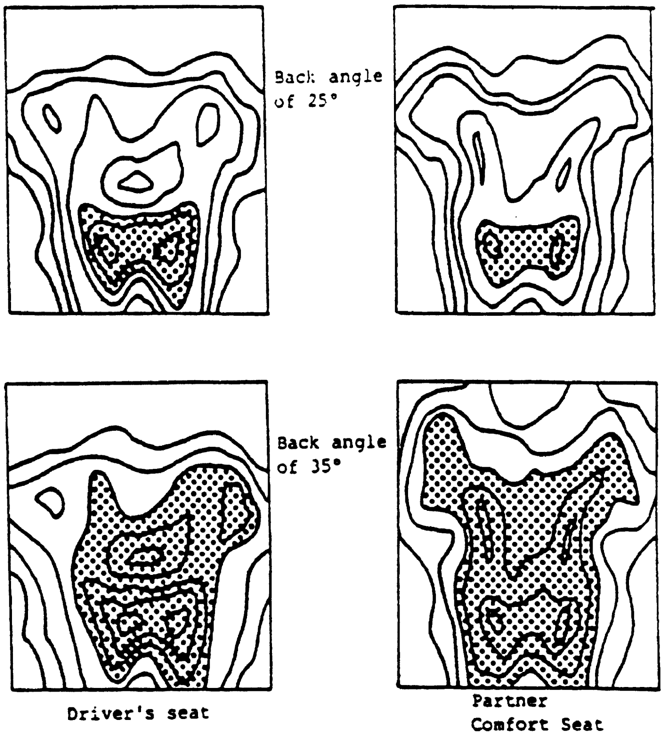


FIGURE 3. Changes in body pressure distribution for different back angles.

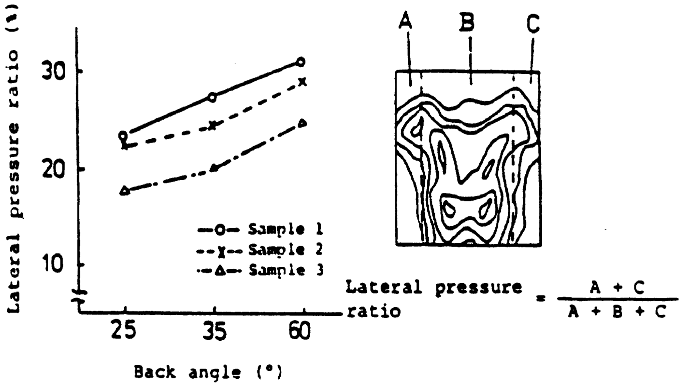


FIGURE 4. Change in lateral pressure ratio.

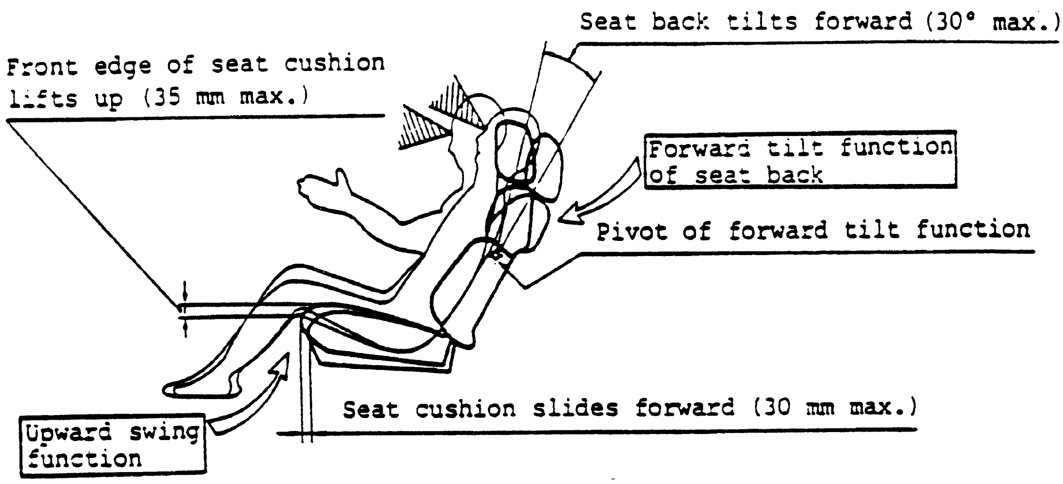


FIGURE 5. Function features.

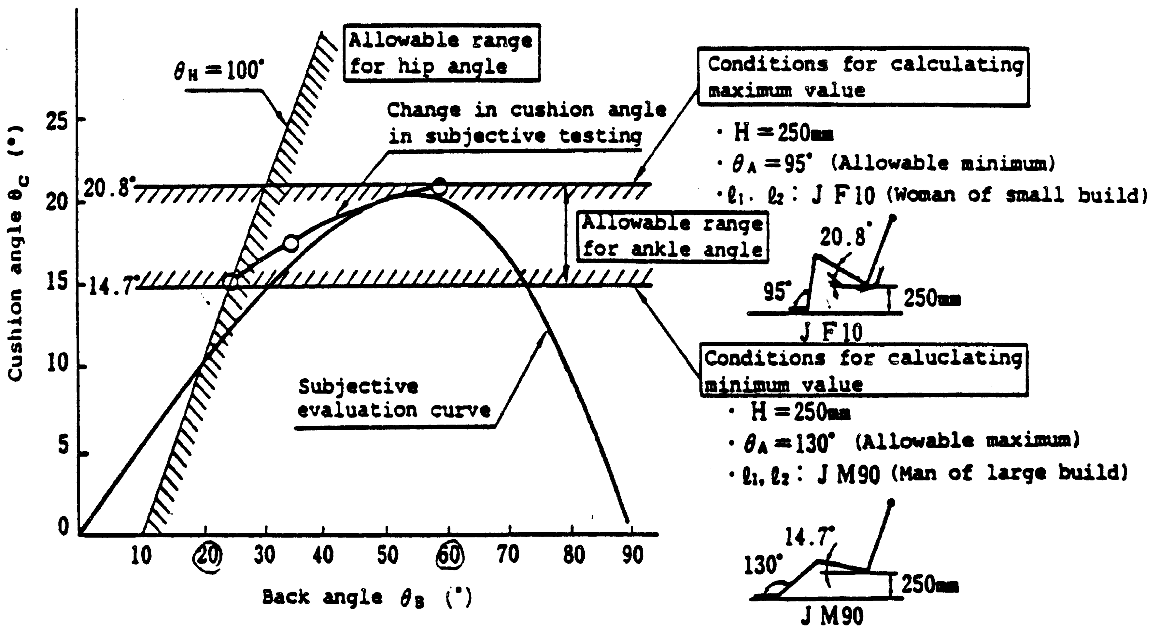


FIGURE 13. Allowable range for cushion angle.

Rossiter, R.E. (1989) **Interior of tomorrow.** *Automotive News.*

The following future trends are forecasted by Lear Siegler Seating Corporation:

1. As family size shrinks, the front bench seat will gradually disappear.
2. An increased number of convenience features such as built-in trays, shelves, cup holders, etc. will make optimum use of interior space.
3. Options such as entertainment and communication consoles will become a standard.
4. Thinner, lower-profile seats (accomplished through changes in foam resiliency and more advanced seating suspension systems) will provide even more interior space and greater comfort.
5. Pressure-sensing transducers monitoring road conditions and automatically adjusting seat suspension systems will be available.
6. "True ventilation systems" will be more common and will mean climate-controlled seats. There will be no more sweltering in the summer and freezing in the winter.
7. Built-in safety features such as child carriers and passive restraints will be standard. Seat belts will be an integral, load-bearing component of the total seat system, attached to the seat rather than the vehicle frame. Airbags will also become commonplace, as consumers gain confidence in the technology.
8. There will be increased interior differentiation—no more cookie-cutter interiors that satisfy the average but ignore special needs and tastes.
9. Memory adjustment systems will be standard as the cost of existing technology comes down.
10. There will be a decrease in interior part numbers. More options will become standard and affordable because of advanced design, manufacturing and assembly-line techniques.
11. More attention will be paid to rear-passenger comfort such as rear headrest, recliners and individual comfort adjustments. The back seat won't be just for short-legged children or talented contortionists any more.
12. There will be more luxury, sporty truck interiors. Consumers have obviously decided that pick-ups aren't simply utility vehicles. They are a desirable, affordable means of general transportation.
13. Ingress/egress features will accommodate an aging population with swivel seats and easily accessed, well-lit push-button controls.

BIBLIOGRAPHY

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Dempsey, C.A. (1963) Chapter 9: Posture and sitting, pp. 165–180. McGraw-Hill, New York. [Reference incomplete; for copy, contact author.]

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

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

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

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

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

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

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

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

Geoffrey, S.P. (1961) *A 2-D manikin: The inside story.* paper presented at the 1961 SAE International Congress.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Parsons, K.C.; and Griffin, M.J. (1980) Predicting the vibration discomfort of seated passengers. In *Human Human Factors in Transport Research. Volume 2—Factors: Comfort, the Environment and Behaviour*, pp. 114–122. Edited by D.J. Oborne and J.A. Levis. New York, Academic Press.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Stone, P.T. (1965) An approach to the assessment of the comfort of foam cushioning. *Automotive Body Engineering*, January.

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

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

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

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

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

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

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

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

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

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