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The biomechanical assessment and prediction of seat comfort

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Introduction

The widespread use of computers has been accompanied by a heightened interest in the ergonomics of office seating. In addition to improving the well-being of the worker, a comfortable seat may contribute to productivity (e.g., Dainoff and Dainoff, 1986).

Until recently, much remained unknown about how to design ergonomic seats. We have been limited by the lack of a viable operational definition for comfort and a difficulty in relating comfort to seat design parameters.

As a result, many researchers have used the notion of discomfort to understand comfort. Discomfort is caused by biomechanical stress acting on the body. One cause of stress on the body is the result of the static muscle activity required to hold the body in a near stable position.

Good seating supports the user within a minimum of cumulative stress on the back, shoulders, and legs. When the body is not properly supported, several muscle groups act together to restore stability, and may cause static muscle loading*. Branton (1969) suggested that people trade off stability with freedom of movement (e.g., crossed legs). This suggests that no single posture will provide comfort for prolonged sitting activities.

In this paper, we attempt to define the ubiquitous term 'comfort' by analysing a biomechanical correlate to sitting comfort; that is the pressure distribution between the seat surface and its occupant. A variety of approaches can be

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* This does not imply that proper support to the body should be achieved by an anatomical seat pan which conforms to the shape of the body as this restricts body movement and presents sizing problems.

used to measure the pressure distribution. Traditional force measurement devices are of little value as they interfere with comfort. The steps for measuring the pressure distribution and quantifying 'comfort' requires:

1. An unobtrusive measurement interface between the seat and occupant. We developed such a system which included the supporting electronics and software necessary to drive, display and calculate the load distribution.
2. Information on how seat pressure relates to comfort. To this end, we conducted over 1100 short-term (5–10 minutes) seat-subject evaluations of 50 seats that compared load distributions with subjective comfort ratings. We found that comfort ratings can be predicted from patterns of weight distribution over a seat surface. To improve our comfort prediction capacity we constructed multiple regression equations to predict interval level comfort from seat pressure variables (r^2 greater than 90 per cent).

Although we have related seat comfort to a biomechanical variable, to be of most use this information must now be applied in the seat design process. This chapter will review the measurement of seat pressures and describe the developments for the next generation of seating—the intelligent seat.†

Seat comfort research

Studies on quantifying seat comfort have typically approached the problem in two ways:

1. Compare the dimensions and postures of seated individuals with seat measurements.
2. Relate the occupant's weight distribution on the seat to seat geometry, contour and firmness.

The approaches used for assessing the comfort in automobiles have been different from those used in office seating. A brief review of the two approaches will be presented first, followed by the common element, sitting pressures.

Anthropometric and postural studies

Industrial and office seating

Eklund (1986) has shown that when the feet support one third or more of the body weight, discomfort is experienced because continuous muscle activity is required. The force transmitted to the ground through the feet depends on many factors. One factor is the seat height, which is closely related to popliteal height.

A well-designed seat should fit all sizes and shapes of users. Size differences may be accommodated through adjustability. Many designers view sitting as a static activity and design seats based on anthropometry.

However, sitting is a dynamic activity and seat design should be based on the required changes in postural and anthropometric characteristics of the user over time. Anthropometric accommodation is necessary but not sufficient for comfort.

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† Note: The *Intelligent Seat* and the transparent interface for recording pressures and calculating comfort are both BCA patented.

When changing from a standing to a sitting posture, the hip angle decreases from 180° to approximately 90°. Anatomically, this is a fairly complicated movement; about 60° of the bending takes place in the hip joint and the remaining 30°–40° is due to the flattening of the lumbar curve (i.e., the lordosis of the spine tends to flatten out because the pelvis rocks posteriorly). Most of the spinal shape changes occur between the third, fourth and fifth lumbar discs. Ergonomic seats typically attempt to help restore lumbar lordosis and minimize disc pressure with reclining seat backs as recommended by Andersson (1974) or the forward tilting of the seat pan as recommended by Mandal (1981).

Seated comfort while working has been studied primarily through the assessment of anatomical and physiological characteristics. A few ways that seats have been evaluated include the following:

1. Body height shrinkage, using a stadiometer (Corlett, 1990) to measure loads on the spine.
2. Cross-modality matching. This technique relates the seat discomfort to pressure distributions measured on the seat and the back rest (Wachsler and Learner, 1960; Habsburg and Mittendorf, 1980).
3. Spinal disc pressures and muscle loading (e.g., Andersson, 1974; Eklund and Corlett, 1984).
4. Psychophysical rating or ranking scales are the most commonly used subjective techniques for evaluating seats. The general comfort rating scale and Chair Feature Checklist (CFC) developed by Shackel *et al.* (1969) and the Body Part Discomfort Scale (BPDS) of Corlett and Bishop (1976) have been widely used.
5. Evaluation of pressure distributions.

Fleischer *et al.* (1987) adopted a different approach by studying the image patterns of weight displacements of seated subjects. They suggested that seats be designed to avoid restricting movement rather than conform to the total body. Lueder (1983) has provided a review of the many approaches used to assess seat comfort.

Car seats

The basic reference source for designing automobile seats in the United States is the SAE Handbook (1990). This handbook specifies (among other data) the dimensions, adjustability, and the configuration of automotive seating. All dimensions are determined by using a two-dimensional H-point template and a three dimensional H-point machine (Figure 18.1).

The H-point machine is one which has a seat back and seat pan representation of a deflected seat contour for adult males. This machine simulates the human torso and thigh and is mechanically articulated at the H-point. The lower leg and thigh segments can be adjusted to the 10th, 50th and 95th percentile adult male dimensions. The H-point of a seat is determined when this machine is placed in a prescribed manner with the 95th percentile male leg and thigh segments.

Earlier recommendations (Van Cott and Kincade, 1972; Rebiffe, 1969) are obsolete as the configurations of the driver's seat and the position of the eye with respect to the windscreen have changed dramatically over the past decade. Hence, only the more recent work on automotive seat comfort will be reviewed.

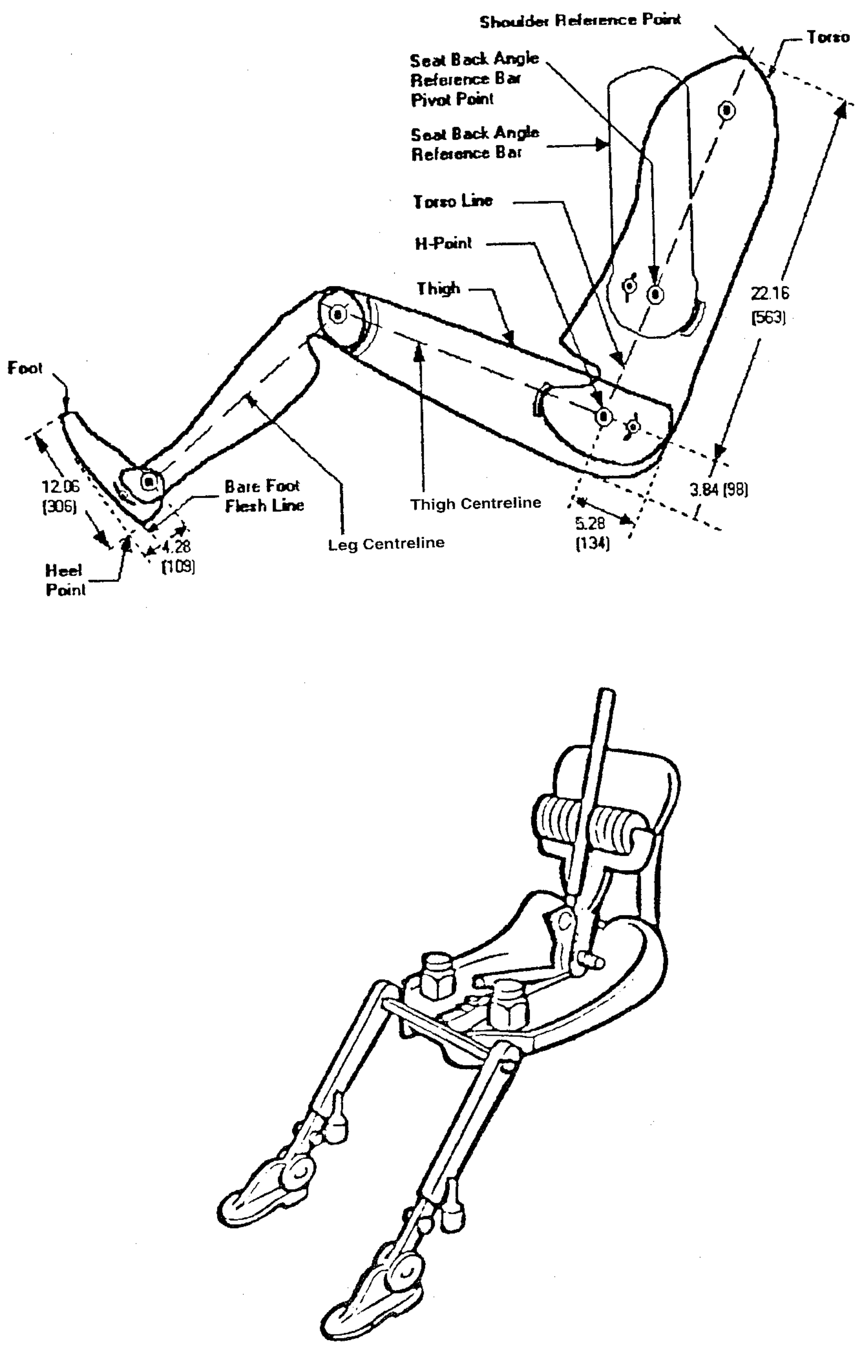

Figure 18.1 (a) H-point template; (b) H-point machine

The methodology used by a major automobile company to assess the comfort of the driver's seat is based on contour/dimension scores, subject preference scores and body pressure scores. The contour/dimension scores are based on dimensional guidelines shown in Table 18.1 for a family car, luxury car, and sports car.

Occupant preference scores were assessed by administering a seat comfort questionnaire. During the test, the subjects wore standard test clothing, sat in the driver's side of the vehicle, adjusted the seat to a comfortable driving position and rated their short-term comfort level. The subjects rated nine features of the seat, namely: fore/aft control; recliner; lumbar control; front cushion tilt; seat back wings; thigh adjustments; lower back support; seat firmness and overall comfort on a 3-point scale (poor, fair or good).

The body pressure scores were evaluated by comparing the seat pressure contours against comfortable seat back and seat cushion contours (Figure 18.2).

In another study Hubbard and Reynolds (1984) interpreted existing data on the external car body configuration and skeletal geometry to determine body positions for small women (5th percentile), average men (50th percentile), and large men (95th percentile). They note that the SAE design method of using 2-D and 3-D templates does not necessarily fit the people who will use the seat, nor predict how a person will fit a proposed seat design. They estimated the co-ordinates of 16 anthropometric landmarks for the small, average and large users, but point out the need for synthesizing basic information about seating biomechanics into a predictive model for seat design.

Seating research at Audi (Weichenrieder and Haldenwanger, 1986) led to recommendations for dimensions and postural angles to accommodate the 5th percentile female and the 95th percentile male. The postural recommendations were based on comfort levels that varied from −5 to +5. A comfort rating of 0 corresponds to an optimum value for passenger cars while +5 and −5 corresponds to the anatomical boundaries. They accounted for the differences between the sexes by considering that women on average:

1. are 10 cm smaller than men
2. weigh 10 kg less

Table 18.1 Seat dimensional guidelines

Dimensions	Family car	Luxury car	Sports car
Maximum cushion length (from H-point)	380 mm	380 mm	380 mm
Minimum cushion width	500 mm	500 mm	500 mm
Deflection at D-point	60–80 mm	80–100 mm	40–60 mm
Flat cushion surface width	150 mm	150 mm	150 mm
Centre of lumbar region (up from D-point)	230 mm	230 mm	230 mm
Radius of lumbar (plan view contour)	450 mm	800 mm	300 mm
Radius of thoracic (plan view contour)	1000 mm	1000 mm	1000 mm
Back height	510–560 mm	510–560 mm	510–560 mm

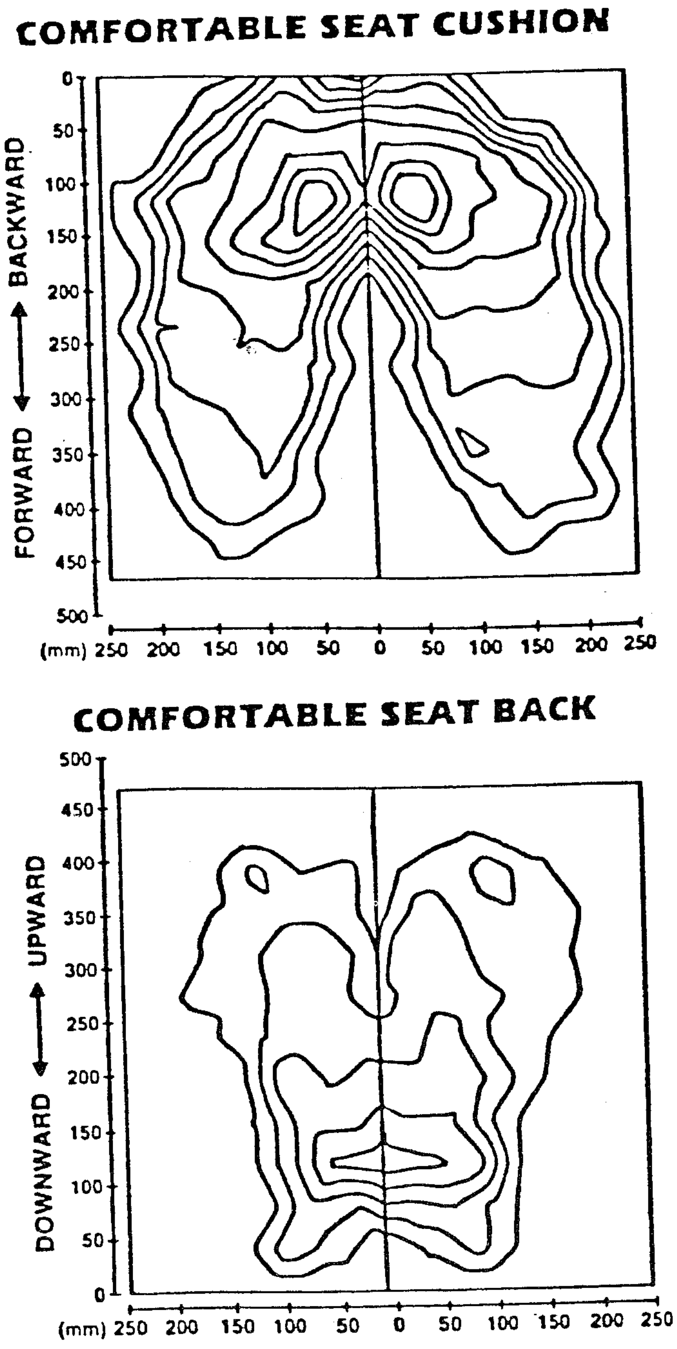

Figure 18.2 Comfortable pressure contours from automobile company study

3. have approximately two-thirds of a man's arm and leg strength
4. have more flexible limbs
5. have a thicker and more uniform layer of body fat
6. have shorter limbs turned slightly inward.

Pressure during sitting

Most of the sitting pressure is borne by the ischial tuberosities. Pressure between the seat and the body can be changed by adopting different postures, e.g., crossing one's legs or leaning forward or backward. Pressure on the body tissue restricts blood flow and may impact the nerves.

Wheelchair users who sit for long periods of time are prone to develop ischemic ulcers, usually over weight-bearing protuberances. When seated, the areas under the ischial tuberosities and the sacrum are most susceptible. Normal cellular metabolism depends on adequate circulation. Any condition which interferes with the circulation which provides nutrients and eliminates waste products, may lead to changes in the cell causing pain and discomfort. For the disabled, prolonged obstruction of the local capillary circulation eventually kills the cells. Ischemia caused by pressures greater than capillary pressure is the primary factor in the formation of ulcers (Brand, 1979; Kosiak, 1976; Landis, 1930). It has been suggested that pressures below 20–30 mm mercury are required to prevent capillary occlusion (Houle, 1969; Peterson and Adkins, 1982). When different seat cushions were used, the pressure under the ischial tuberosities ranged from 41 mm and 86 mm mercury (Mooney *et al.*, 1971; Souther *et al.*, 1974). Drummond *et al.* (1982), using a microcomputer based pressure scanner, showed that approximately 18 per cent of the body weight is distributed over each ischial tuberosity; 21 per cent over each thigh; and 5 per cent over the sacrum. These values may be modified with changes to the seat geometry and foam durometer.

Floyd and Roberts (1958) concluded that most people feel comfortable when the weight of the body is carried primarily by ischial tuberosities. Alternatively, Sanders and McCormick (1987) suggest that the weight be distributed rather evenly throughout the buttocks area, but minimized under the thighs. Such a distribution can be achieved by contouring the seat pan and varying cushion density.

Researchers may now collect point pressures from the seat back rest and the pan cushions, using a data collection and analysis apparatus consisting of pressure sensitive mats on the seat pan and back rest connected to an amplifier and analogue-to-digital converter. During testing, subjects sat on a seat with both hands on the steering wheel, the right foot on the accelerator, and the left foot on the dead pedal. The peak pressures and load distributions in each area of the seat were computed and compared to their recommended guidelines for pressure distribution (Table 18.2).

Arrowsmith (1986) performed a study in which the seat cushioning was changed in the Jaguar XJ40 seat. The study was based entirely on subjective responses to seat comfort. The subject population consisted of both sexes, a variety of social and economic groups with statures ranging from the 5th to the 95th percentile. They were required to rate the comfort of the seat on a five-point scale (very comfortable, moderately comfortable, neutral, moderately uncomfortable and very uncomfortable). Subjects rated their comfort

Table 18.2 Preferred seat pressure distribution

Region	Proportion of pressure
Lumbar	16 per cent
Shoulder	4 per cent
Back lateral	2 per cent
Ischial	54 per cent
Thigh	22 per cent
Cushion lateral	2 per cent

level after sitting for 15 minutes (showroom comfort); after 30 minutes (representing a short test drive), and at half-hour intervals for a drive of one and a half hours (representing an extended test drive). The study results were incorporated into the Series III design. Even though the changes were minor, the authors claim that they had a significant beneficial effect on passenger comfort. Some changes were the lowering of the piping across the front edge of the cushion to reduce contact with the thigh and stiffening of the rear of the cushion by reducing the size of the cavities in the foam.

Designers at Audi (Weichenrieder and Haldenwanger, 1986) used published data to distribute the weight of the driver over the entire contact area, and thus keep the overall pressure low. The highest pressure was below the ischial support points, and fell off gradually towards the boundary of the body's support area.

Seat comfort assessment

Comfort is a subjective measure and is not easily quantified. However, if comfort can be related to objective measures, then the best combination of seat adjustments may be determined. As such, distribution of sitting pressures could be directly linked to perceived comfort.

Pressure measurement

A major consideration for the seat comfort is the force exerted on the seat surface. In a manufacturing environment, force can be measured using dynamometers. However, force measures are of little use in seating research because the force acts over the entire body-seat contact surface area. Instead, pressure measurements (force per unit area) are required. When changes in posture occur, real time pressure measurements are needed.

Different techniques are used to measure force and pressure. A force sensing device will respond identically to two equal forces, regardless of the area over which the force is applied.

Alternatively, a true pressure sensor will produce an output for a given force which is inversely proportional to the area.

Sitting pressures were first measured using mechanical valves and compressed air tanks (Kosiak, 1959; Houle, 1969). More recently, optical techniques have been used based on the prototype built in 1934 by Elftman (Hertzberg, 1972; Mayo-Smith and Cochran, 1981; Treaster and Marras, 1987). Other techniques include pressure-sensitive chemicals (Frisnia *et al.*, 1970), thermographs (Trandel *et al.*, 1975), capacity sensors (Ferguson-Pell, 1976) and mechanical springs (Lindan *et al.*, 1965). The main problem with most of these techniques is the validity and the reliability of the measurements.

Recent developments in electronics technology allow for more precise measurements. Any electronic sensing device used for seat pressure measurement should have the following characteristics:

- transparent to the seated subject (i.e., cannot be felt)
- insensitive to vibration, temperature and noise
- durable
- repeatable
- optimum sensitivity and range
- low hysteresis (i.e., similar electrical characteristics during loading and unloading)
- flexible
- configure to any seat shape or size
- deformable
- linear in the pressure resistance relationship over a high range
- simple and cost-effective.

The pressure measurement system developed by BCA uses a special 'mat' comprising 225 sensors (15 × 15 matrix) on the pan (covering an area of approximately 6.3 × 6.3 cm) and 225 sensors (15 × 15 matrix) on the seat back covering an area of approximately 5.5 × 8.3 cm (Figures 18.3, 18.4, 18.5).

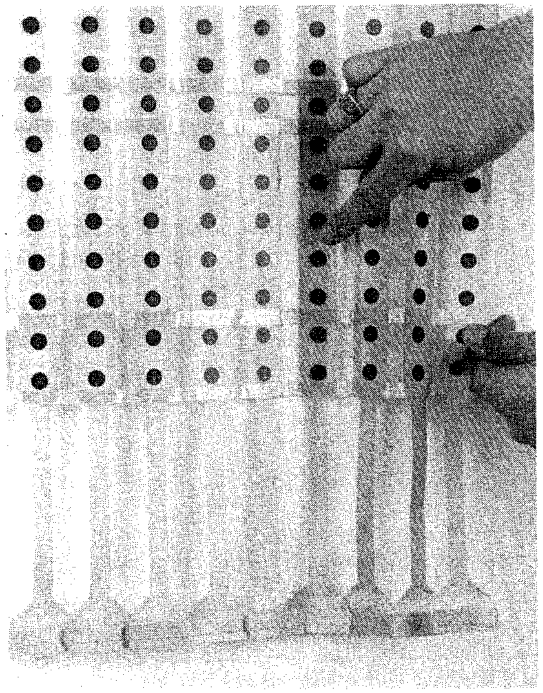

Figure 18.3 Segment of seat pressure mat

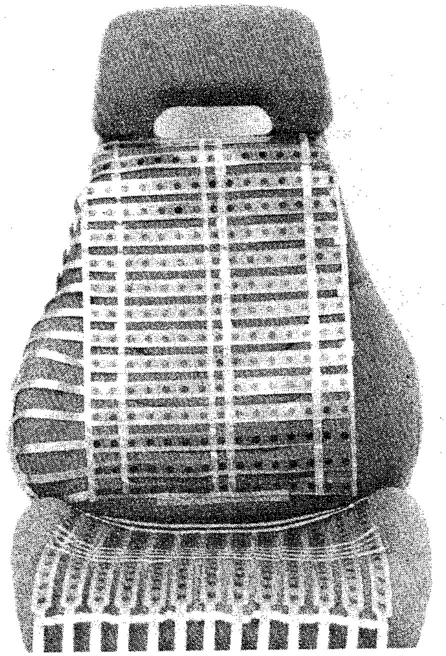

Figure 18.4 Seat pressure mat superimposed on experimental seat

At zero or very low pressures, the sensors act as an open circuit. After the pressure reaches a low threshold, increasing force rapidly reduces electrical resistance. The sensors are all connected to a 5-volt power supply through a current-limiting resistor. The voltage measured at the output end is proportional to the force as the device and the current limiting resistor form a voltage divider. To incorporate a higher current and low source impedance, operational amplifiers are used. The pressure mat is connected to a microcomputer through an analogue-to-digital data acquisition system. Proprietary BCA software is used to measure and display pressure in real time (Figure 18.6).

Modelling comfort

To quantify the factors that contribute to the perceived comfort of a car seat, the following categories of data were collected:

1. The subjective ratings of comfort for each part of the seat. Using Likert scales, the subjects rated the comfort of 12 aspects of the seat after it had been adjusted to the most comfortable position. Subjective ratings are selected on a continuous scale from one to five, where one represents very poor and five represents very good with neutral corresponding to a value of three.

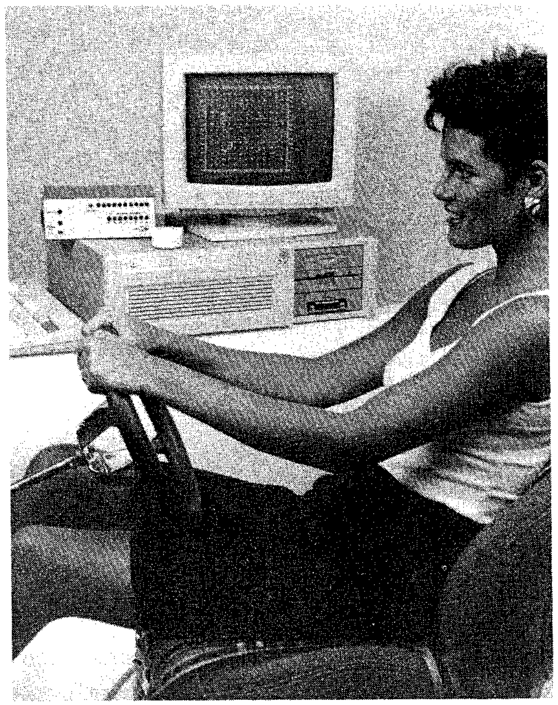

Figure 18.5 Seated subject driving evaluation

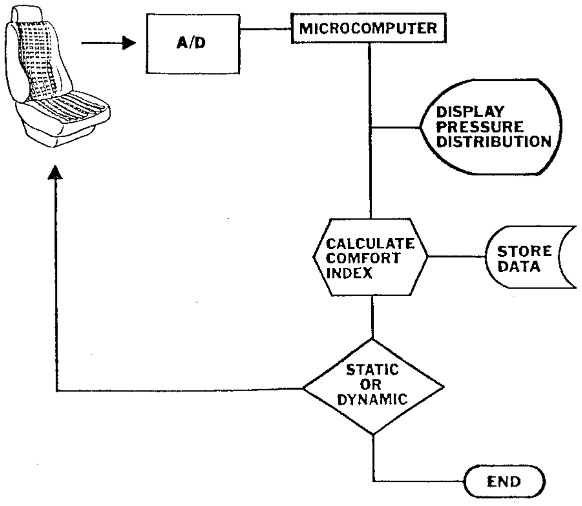

Figure 18.6 Block diagram of seat pressure measurement system

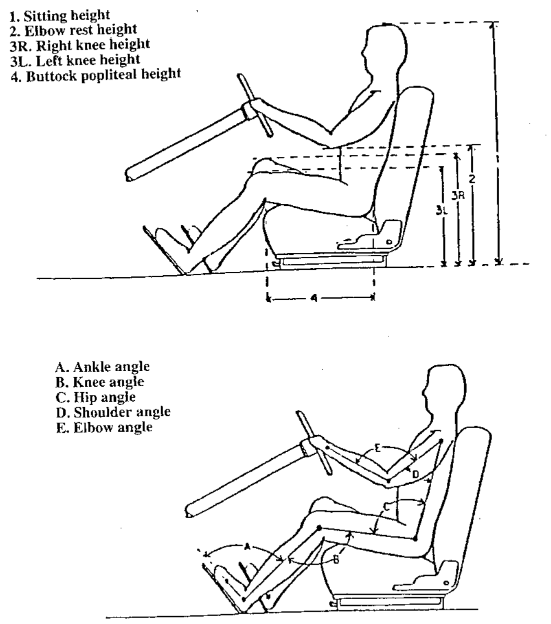

Figure 18.7 Anthropometric dimensions of seated subject

2. The anthropometric dimensions of the driver. The subjects' anthropometric characteristics were measured while seated and standing. The seated dimensions were taken with the seat adjusted to the most comfortable position. The body angles that defined the subjects' posture were measured with a goniometer. The leg and foot angles were measured separately on the left and right side as the accelerator and dead pedal were placed at different angles (Figure 18.7).
3. The dimensional and angular characteristics of the seat. Back rest height and width, seat cushion width, seat cushion length, seat cushion angle, and seat back angle were recorded (Figure 18.8).
4. The force exerted by the seated driver on the seat surface and its force distribution. The seat pan was divided into eight regions: two halves (fore and aft), two buttocks, two thighs and two bolster regions. The seat back was divided into eight regions: two halves, two lumbar, two thoracic and two bolster regions. The force measures in each of the regions were determined and analysed statistically, defining location and pressure dispersion.

More than 1100 seat-subject combinations (50 seats) were tested for short term trials (5–10 minutes). Although recordings were continuous, 20-second windows of time within these trials were used for data analysis.

The subjects were stratified by size and gender. Sample pressure plots for luxury, sports and economy seats for seat back and seat pan are shown in Figures 18.9–18.14. Pressure gradients at different points were calculated using a discrete approximation of the partial derivatives of a two-dimensional function:

$$df(x, y) = \delta f(x, y)/\delta x + \delta f(x, y)/\delta y$$

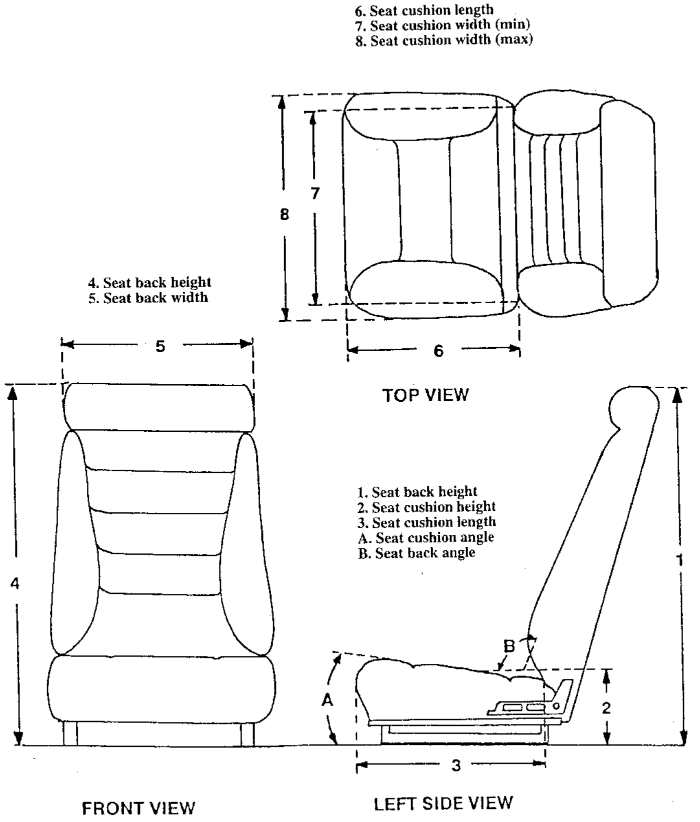

Figure 18.8 Seat dimensions and angular characteristics

The discrete approximation for the two terms in the derivative are given by:

$$\delta f(x, y)/\delta x = [f(x, y) + f(x, y+1)] - [f(x+1, y) + f(x+1, y+1)]$$
$$\delta f(x, y)/\delta y = [f(x, y) + f(x+1, y)] - [f(x, y+1) + f(x+1, y+1)]$$

Two convolution filters were used to calculate the partial derivatives. The gradient at each point is the sum of the absolute value of the derivatives. The two filters used were:

$$\begin{matrix} 1 & -1 \\ 1 & -1 \end{matrix} \qquad \begin{matrix} 1 & 1 \\ -1 & -1 \end{matrix}$$

These two operators were applied to the pressure readings at each sensor and the absolute value of the responses added to define the gradient. The maximum pressure gradient for each subject on each seat was determined by using the maximum value on the matrix that was passed through the two operators shown above.

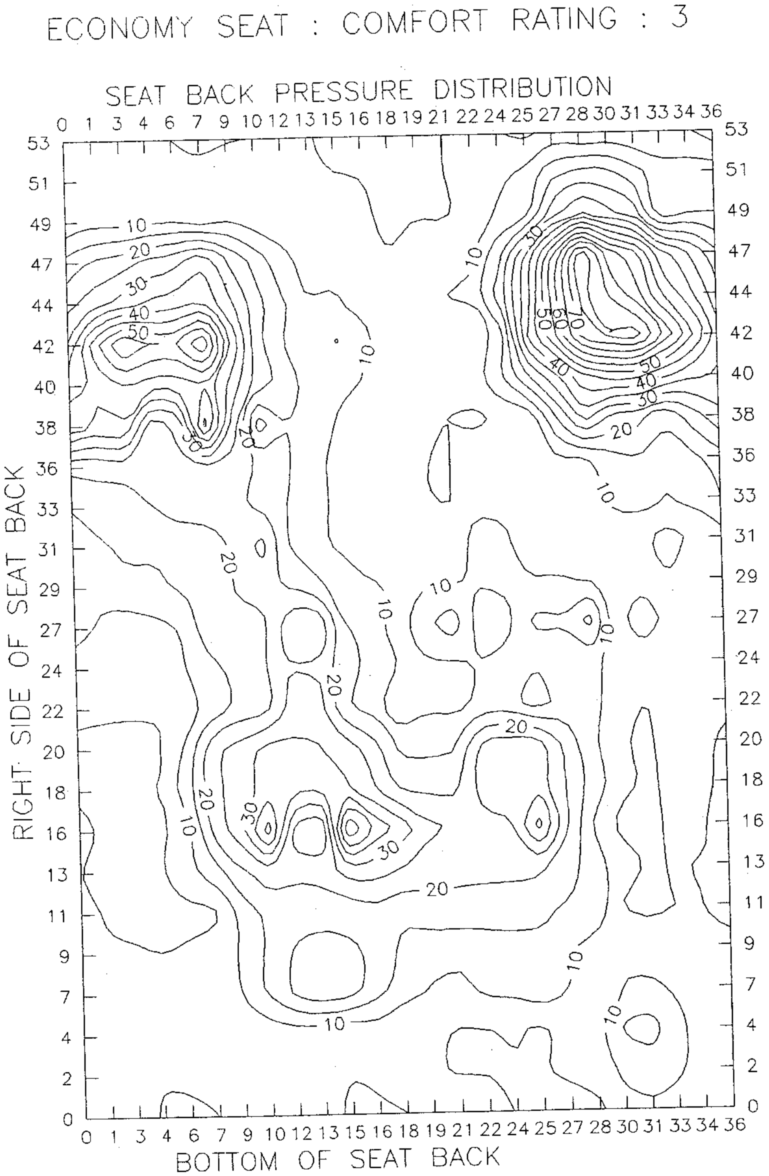

Figure 18.9 Sample pressure contours for different automotive seat classes (comfort rating is on a scale from 1 to 5). Data are normalized to peak pressure

A multivariate analysis of the data related the pressure distribution of the driver's weight on the seat surface with seat comfort (see Figures 18.15, 18.16, and 18.17 for a sample load distribution on seat pan and seat back). Statistics computed from the pressure data were strongly related to perceived comfort

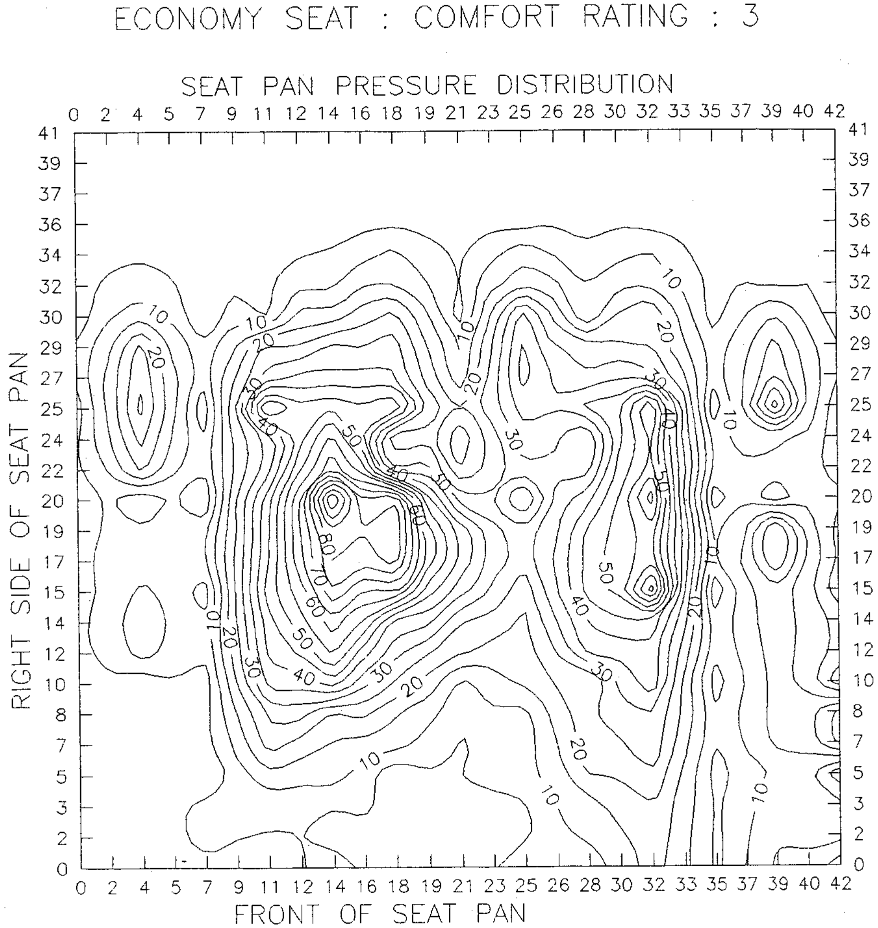

Figure 18.10. Sample pressure contours for different automotive seat classes (comfort rating is on a scale from 1 to 5). Data are normalized to peak pressure

Table 18.3 Calculation of perceived comfort

Seat number	Subjective comfort	Predicted comfort	95 per cent Confidence Interval Lower limit	 Upper limit
1	3.8	3.8	3.7	4.0
2	3.8	3.5	3.3	3.7
3	3.4	3.3	3.2	3.4
4	3.7	3.7	3.6	3.9
5	3.6	3.5	3.4	3.7

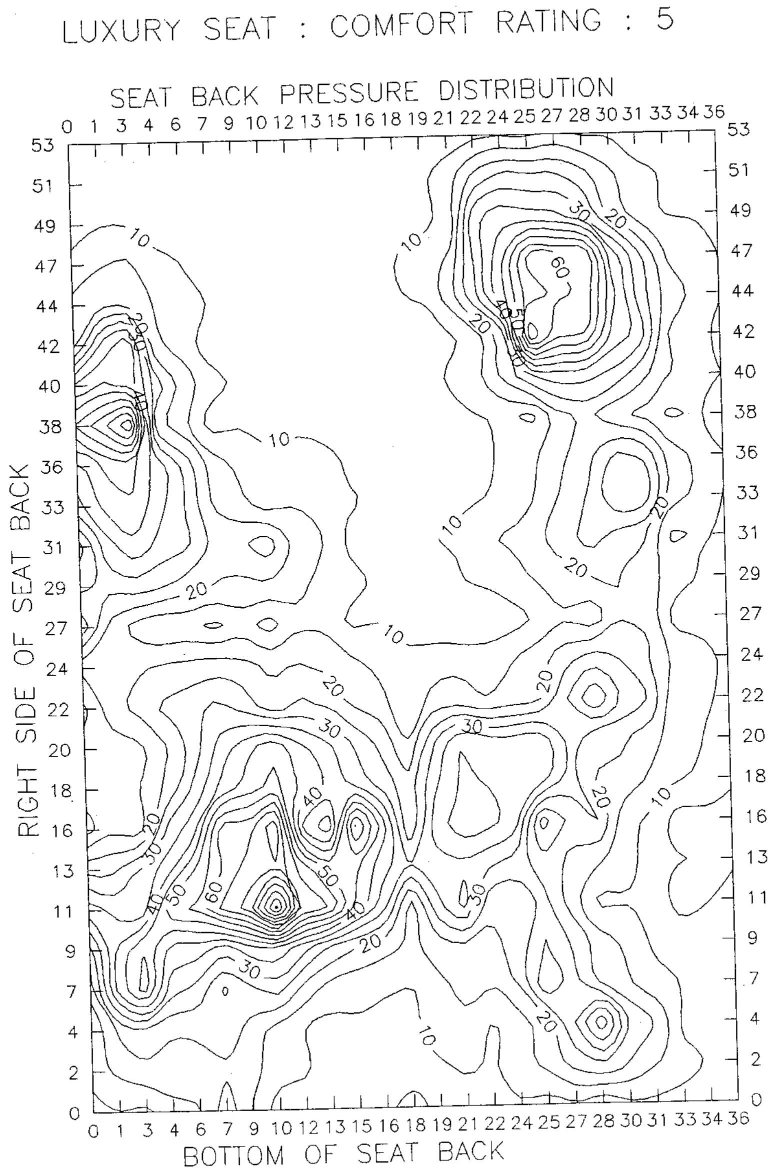

Figure 18.11 Sample pressure contours for different automotive seat classes (comfort rating is on a scale from 1 to 5). Data are normalized to peak pressure

(Table 18.3 shows sample results from 5 seats). Perceived comfort (PC) was calculated as follows:

$$PC = \sum a_i x_i \qquad \text{for all } i$$

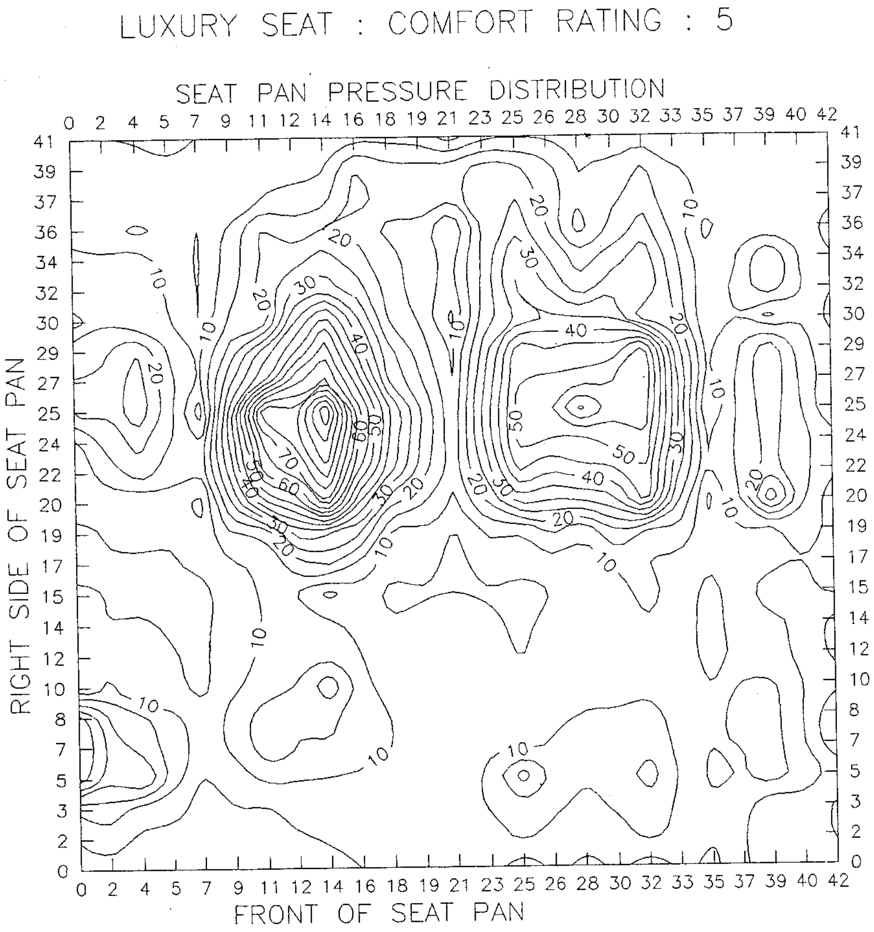

Figure 18.12 Sample pressure contours for different automotive seat classes (comfort rating is on a scale from 1 to 5). Data are normalized to peak pressure

where

a_i = regression coefficient associated with variable x_i

x_i = dependent variable of pressure.

Anthropometry and seat geometry interact in complex ways to produce seat pressures. However, statistics related to the pressure distribution were shown to predict the perceived comfort of a seat. Optimizing the comfort of prototype seats with respect to the magnitude and the pattern of the pressure distribution can significantly reduce product development time.

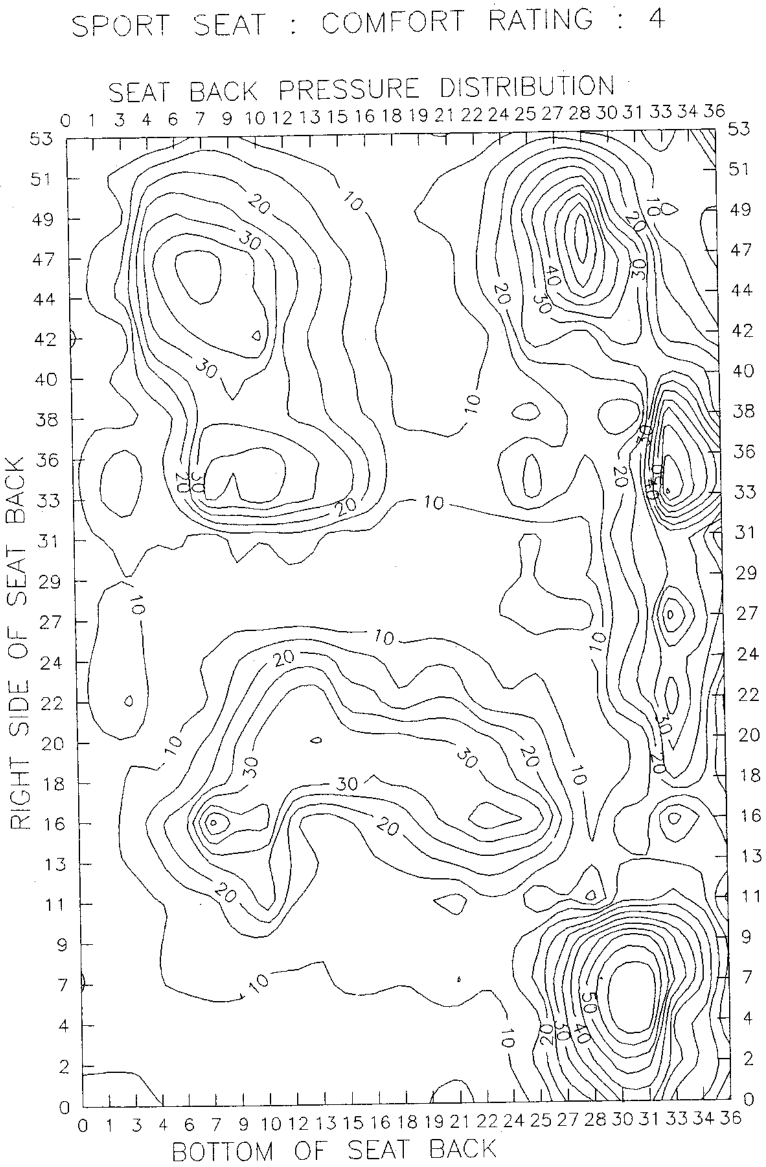

Figure 18.13 Sample pressure contours for different automotive seat classes (comfort rating is on a scale from 1 to 5). Data are normalized to peak pressure

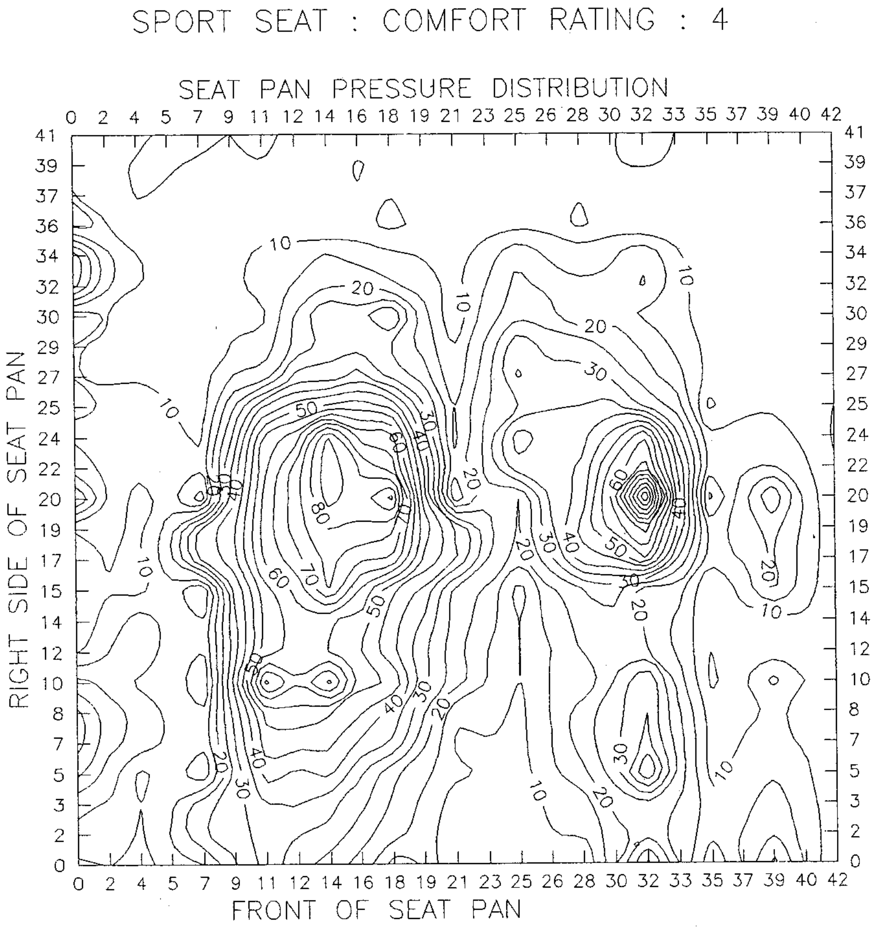

Figure 18.14 Sample pressure contours for different automotive seat classes (comfort rating is on a scale from 1 to 5). Data are normalized to peak pressure

Conclusions

The contours and firmness of seat cushions have been used in the past to redistribute pressures under the ischial tuberosities. However, in most circumstances the pressures were in excess of the capillary pressures, and not sufficiently or easily adjustable, leading to discomfort during prolonged periods of sitting.

Our research was used to develop an 'Intelligent Seat' (Figure 18.18) which avoids this by using an automatic system that can shift the pressures and reduce the pressure gradients. This device senses the pressures at the body-seat interface using sensors placed under the upholstery. Based on the pressure-comfort developed the seat will automatically adjust the elements (e.g., upper

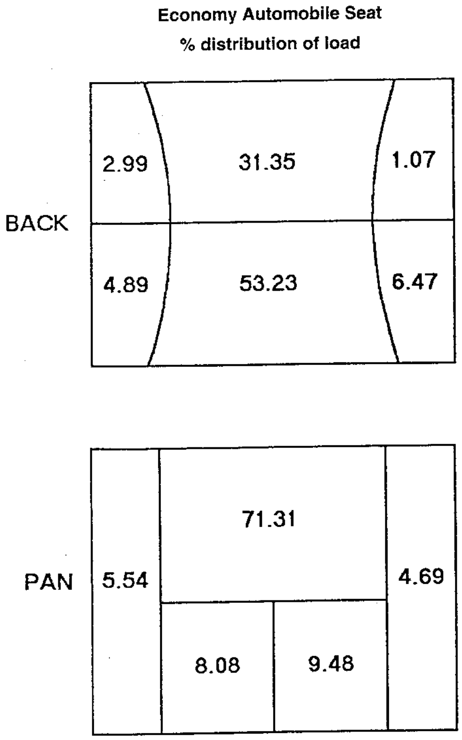

Figure 18.15

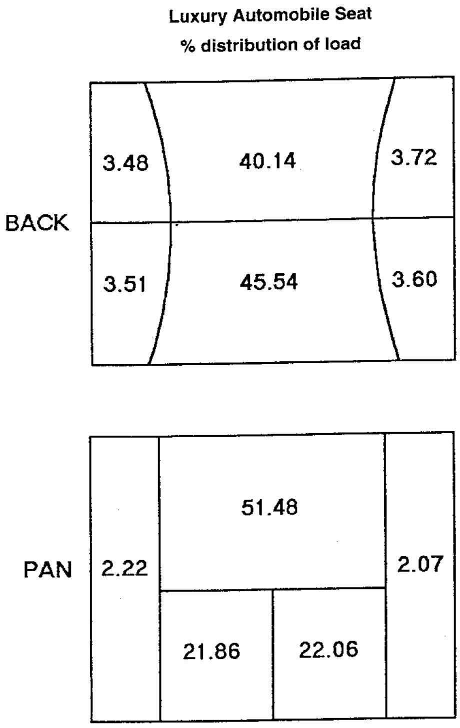

Figure 18.16

Figure 18.17

Percent distribution of loads for different classes of seats

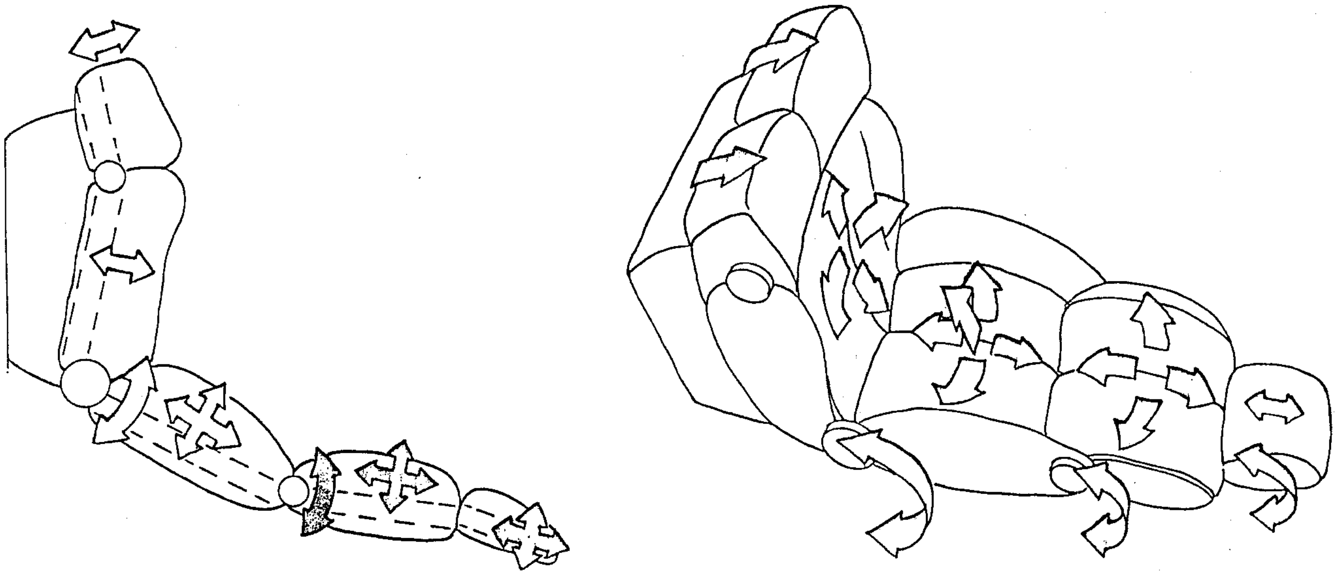

Figure 18.18 Schematic for Intelligent Seat: (a) isometric view; (b) side view

lumbar, mid lumbar, side bolster etc.) to pressure profiles of a person of any size and weight that have been found comfortable. This effectively optimizes comfort and user fit. This new seat measures the seat pressures profile of its occupants and responds to their specific 'comfort' characteristics. By bundling biomechanical 'knowledge' into the seat it can respond accordingly to its occupant.

References

Andersson, G. B. J., (1974), On myo-electric back muscle activity and lumbar disc pressure in sitting postures. Doctoral dissertation, Gotab, University of Goteborg, Goteborg, Sweden.

Arrowsmith, M. J., (1986), The design and development of the XJ40 seating system, *Proc. Instn. Mech. Engrs.*, **200**, D5, s79–s85.

Brand, P. W., (1979), Management of the insensitive limb, *Physical Therapy*, **59**, 8–12.

Branton, P., (1969), Behaviour, body mechanics and discomfort, *Ergonomics*, **12**, 316–27.

Corlett, E. N., (1990), Static muscle loading and the evaluation of posture, in *Evaluation of Human Work*. J. R. Wilson and E. N. Corlett (eds) London: Taylor & Francis.

Corlett, E. N. and Bishop, R. P., (1976), A technique for assessing postural discomfort, *Ergonomics*, **19**, 175–82.

Dainoff, M. J. and Dainoff, M. H., (1986), *People and Productivity: A Manager's Guide to Ergonomics in the Electronic Office*. Canada: Holt, Rinehart and Winston.

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, *The Journal of Bone and Joint Surgery*, **64**-A(7), 1034–9.

Eklund, J. A. E. and Corlett, E. N., (1984), Shrinkage as a measure of the effect of load on the spine, *Spine*, **9**, 189–94.

Eklund, J. A. E., (1986), Industrial Seating and Spinal Loading. PhD thesis. University of Nottingham. Distributed by Department of Industrial Ergonomics. University of Technology, Linkoping, Sweden.

Elftman, H., (1934), Cinematic study of distribution of pressure in human foot, *Anat Rec.*, **59**, 481–91.

Ferguson-Pell, M. W., (1976), Interface pressure sensors: Existing devices, their suitability and limitations, in *Bedsore Biomechanics*. R. M. Kenedi (ed) Baltimore: University Park Press.

Fleischer, A. G., Rademacher, U. and Windberg, H. J., (1987), Individual characteristics of sitting behaviour, *Ergonomics*, **30**(4), 703–9.

Floyd, W. F. and Roberts, D. F., (1958), Anatomical and physiological principles in chair and table design, *Ergonomics*, **2**, 1–16.

Frisnia, Warren and Lehneis, H. R., (1970), Pressure mapping: A preliminary report, *Journal of Biomechanics*, **3**, 526.

Grandjean, E., Hunting, W. and Pidermann, M., (1983), VDT work station design: Preferred settings and their effects, *Human Factors*, **25**, 161–75.

Habsburg, S. and Mittendorf, L., (1980), Calibrating comfort: Systematic studies on human responses to seating, in *Human Factors in Transport Research*. D. J. Oborne and T. A. Levis (eds) NY: Academic Press.

Hertzberg, H. T. E., (1958), Annotated bibliography of applied physical anthropology in human engineering (Report No. WADC-TR-56-30). Wright-Patterson Air Force Base, OH.

Hertzberg, H. T. E., (1972), Human buttocks in sitting: Pressure patterns and palliatives, New York Publication 72005, Society of Automotive Engineers Inc.

Houle, R. J., (1969), Evaluation of seat devices designed to prevent ischemic ulcers in paraplegic patients, *Arch. Phys. Med.*, **50**, 587–94.

Hubbard, R. P. and Reynolds, H. M., (1984), Anatomical geometry and seating, *SAE Technical Paper Series*, 840506.

Kosiak, M., (1959), Etiology and pathology of ischemic ulcers, *Arch. Phys. Med.*, **40**, 62–9.

Kosiak, M. A., (1976), Mechanical resting surface: Its effect on pressure distribution, *Arch. Phys. Med.*, **57**, 481–4.

Landis, E. M., (1930), Micro-injection studies of capillary blood pressure in humans skin, *Heart*, **15**, 209–28.

Lueder, R. K., (1983), Seat comfort: A review of the construct in the office environment, *Human Factors*, **25**(6), 701–11.

Lindan Olgierd, Greenway, R. M. and Piazza, J. M., (1965), Pressure distribution on the surface of the human body: 1. Evaluation in lying and sitting positions using a 'Bed of Springs and Nails', *Arch. Phys. Med.*, **46**, 378–85.

Mandal, A. C., (1981), The seated man (Homo Sedens), the seated work position, theory and practice, *Applied Ergonomics*, **12**, 19–26.

Mayo-Smith, W. and Cochran, G. V. B., (1981), Wheelchair cushion modification: Device for locating high-pressure regions, *Arch. Phys. Med.*, **62**, 135–6.

Mooney, V., Einbund, J. J., Rogers, J. E. and Stauffer, E. S., (1971), Comparison of pressure qualities in seat cushions, *Bull. Pros. Res.*, **10–15**, 129–43.

Peterson, M. J. and Adkins, H. V., (1982), Measurement and redistribution of excessive pressures during wheelchair sitting, *Physical Therapy*, **62**(7), 990–4.

Rebiffe, P. R., (1969), Le siège du conducteur: Son adaptation aux exigences fonctionnelles et anthropometriques, *Ergonomics*, **12**(2), 246–61.

Sanders, M. S. and McCormick, E. J., (1987), *Human Factors in Engineering Design*, NY: McGraw Hill.

Society of Automotive Engineers, (1990), *Society of Automotive Engineers Handbook*, **4**, On-Highway Vehicles and Off-Highway Machinery, Warrendale, PA.

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

Souther, S. G., Carr, S. D. and Vistness, L., (1974), Wheelchair cushions to reduce pressure under bony prominences, *Arch. Phys. Med.*, **55**, 460–4.

Trandel, R. S., Lewis, D. W. and Verhonick, P. J., (1975), Thermographical investigation of decubitus ulcers, *Bull. Pros. Res.*, **10–24**, 137–55.

Treaster, D. and Marras, W. M., (1987), Measurement of seat pressure distributions, *Human Factors*, **29**(5), 563–75.

Van Cott, H. P. and Kincade, R. G., (1972), *Human Engineering Guide to Equipment Design*, NY: John Wiley.

Viano, D. C., Patel, M. and Ciccione, M. A., (1989), Patterns of arm position during normal driving, *Human Factors*, **31**(6), 715–20.

Wachsler, R. A. and Learner, D. B., (1960), An analysis of some factors influencing seat comfort, *Ergonomics*, **3**, 315–20.

Weichenrieder, A. and Haldenwanger, H., (1986), The best function for the seat of a passenger car, *SAE Technical Paper Series*, 850484.