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A methodology to determine the optimum seat depth

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Abstract

Even though the seat pan carries most of the weight during sitting, the number of studies investigating the different aspects of the sitting area are limited. Seat depth has been based on anthropometry or the so-called industry practice. The relevance of the widely used seat depth measure is thus questionable. A methodology has been developed to evaluate the useful seat depth for a target population. The methodology is found to be reliable and valid based on both objective and subjective measurements. A chair with an "adjustable" seat depth was designed and developed for this purpose. A total of 30 Chinese students were tested. The objective measure was the seat edge protrusion when seated. Eight seat features were rated using a 5-point scale. The results show that the seat depth's of 30.4 and 38 cm are significantly different, with the seat depth of 38 cm being on the "long side". In addition, the objective measure of seat edge protrusion indicated that a seat depth of 31–33 cm is adequate for the South China region Chinese population. Based on the subjective ratings and the objective measure developed, it may be concluded that a seat depth of 31–33 cm is appropriate for the same population.

Relevance to industry

Anthropometry alone is not sufficient for the design of seats. The differing sensitivity in the buttock and thigh areas is an indication that chairs should be designed and selected depending on the population under consideration. The need for having chairs of variable depth has to be recognized especially during long periods of sitting.

Keywords: Anthropometry; Chairs; Chinese; Comfort; Discomfort; Seat depth; Seats; Sitting

1. Introduction

The numerous publications related to sitting and seats demonstrate the importance of the various components of a seat. A majority of these publications have concentrated on the backrest and its effects on the human spine. During sitting, 65% of body weight is carried by the seat pan (Branton, 1969). Hence the seat pan is an important variable in seat design. However, the aspects of a seat pan that have been researched in the past have been somewhat limited to contouring or cushioning in relation to interface pressures and comfort (Gross et al., 1994) and seat pan slope (Bendix and Biering-Sorenson, 1983; Drury and

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Francher, 1985; Mandal, 1976; Michel and Helander, 1994). Thus, it is not surprising that Renae et al. (1995) found that the seat pan ranked as the number one aspect needing improvement.

Vegesack (1997) in his introduction to the book *50 chairs* by Byars (1997), gives the designer perspective of chairs:

'Chairs are objects with a soul, not only because they correspond to our physiology with their legs, seats and backs or because they nurture us with their form and comfort but also because they possess an inner, well-conceived technology. However, we rarely recognize the fact that this technical construction is also a component conspicuously related to the design itself' (p. 7).

This quote is a suggestion to match the dimensions of the seat pan to those of the buttock–thigh area. Even though the book by Byars illustrates the work of designers worldwide, the dimensions portrayed are limited to the overall size rather than the individual entities comprising a seat. For example, none of the designs have any mention of the seat depth dimension.

Recommendations for seat pan depth have been based on empirical reasoning and the so-called common industry practice (ANSI/HFS 100-1988; Floyd and Roberts, 1959; Grandjean et al., 1973; JIS S 1011, 1978; Sanders and McCormick, 1992; Shao and Zhou, 1990). Hence it is natural for dimensions such as seat depth to vary among standards and countries (Table 1). For example, the ANSI/HFS 100-1988 specifies a seat depth between 38 and 43 cm, "*based on common industry practice*". The standard further states that the establishment of a strict criterion for maximum seat depth is difficult due to the large variation in buttock–popliteal length of the large male and the small female. Seat-pan dimensions have been primary candidates for anthropometry based recommendations (e.g., Lee et al., 1998, Courtney and Wong, 1985). Hong Kong population anthropometry is outdated but available from two

Table 1
Seat depth recommendations

Source	Criterion	Recommended seat depth (cm)
ANSI/HFS 100-1988	Standard industry practice	38–43
BS 5940 Part 1 (1980)/BS 3044 (1990)	Smallest person in design range (38–43 cm with fixed back)	40.5[a]
BellCore (1985)		40.6–43.2
CEN[b]		38–47
DIN[b]		38–42
Swedish standard[b]		38–43
Bennett (1928)	Less than 6–8 in. between popliteal part and the front edge of seat	more than 20–25[a]
Diffrient et al. (1974)		33–41
Kroemer et al. (1994)	Do not press into sensitive tissues near knee	38–42
Ayoub et al. (1987)	10 cm clearance between popliteal part and the front edge of seat	30.5[a]
Grandjean (1986)		38–42
Courtney and Wong (1985)		40
Pheasant (1991)	Not exceed 5th %ile BPL	<40.5[a]
Shao and Zhou (1990)	Three-quarters of the thigh length	30.4[a]
Lee et al. (1998)	5th% ile BPL-2 cm (for leisure clothing)	38.5[a]
Keegan and Radke (1964)		40.64 (16 in.)
Floyd and Roberts (1959)	Distance between popliteal area and seat edge of 6–8 in. (15.2–20.3 cm) for large adults; 3 or 4 in. for small children	

[a] Based on 5th %ile BPL of 40.5 cm as given in Pheasant (1994).
[b] Adapted from Chaffin and Andersson (1991).

sources (Pheasant, 1994; Lee, 1981). The differences between the two are somewhat small. Using a buttock–popliteal length (BPL) of 40.6 cm reported in Lee (1981), Courtney and Wong (1985) proposed a seat depth of 40 cm for the driver seat of buses in Hong Kong. Stainless-steel bars of 80 mm in diameter are quite common in Singapore to encourage people to sit in a more relaxed sitting posture (Howe and Yong, 1997). The design criteria for supporting the buttocks seem to be quite extreme. Even for a given population, there is no consistent criterion for determining seat depth (Table 1). This problem gets exacerbated when designing airplane seats for people from all over the world. Any particular country standard would not be applicable and the anthropometry variations are so great that anthropometry-based dimensions may also not be applicable (Roebuck, 1995). The variations among different aircraft seats in economy class are shown in Table 2. Even though all the airlines shown serve similar international destinations, the variations in dimensions among the airlines are quite striking. Table 2 does not indicate the exact positioning of the measurements. Our measurements on an Ansett airline seat show that the seat depth varies from 48 cm at the center to 40 cm at the edge of the seat. Hence it may be inferred that the seat-depth measurement corresponds to a dimension between the center and the edge of the seat. The effective seat depth then seems to depend on thigh width. Nevertheless, the comparatively large depth of aircraft seats could be a dominant contributor towards discomfort during air travel.

Goonetilleke (1998) has shown the effect of contact area on perceived sensations. Hence we cannot neglect the seat pan support area if a seat is to be ergonomically designed for maximum positive sensation or even minimum negative sensation. However, Table 1 shows that the dimension corresponding to seat depth is variable and the criteria determining seat depth are also not consistent amongst researchers. The primary reason for such variations may be attributed to the lack of a methodology or a "vehicle" to determine seat depth.

Even though Pheasant (1994) has stated that the lower limit of seat depth is less easy to define, most standards and recommendations seem to point towards a seat depth of 38 cm. Hooton (1945) contended that "the depth of the seat should be selected to provide for the fact that most individuals do not put their buttocks against the back". If this is true, the extensive research related to backrest is in vain. However, Akerblom (1948) was quick to point out that the posture suggested by Hooton is due to the unsatisfactory dimensions or other features of ill-constructed chairs – another pointer towards the inappropriateness of seat depth.

2. Study objectives

The primary aim of this study is to propose a methodology to determine the optimal seat depth for a given population. In this paper, we report an experimental investigation to determine the

Table 2
Aircraft seat information (Rutherford, 1998)

	Cathay Pacific	Virgin Atlantic	Northwest	British Airways	Qantas	Singapore Airlines	Air Canada	Ansett
Aircraft	747–400	Airbus A340–300	747–400	747–400	747	Megatop 747–400	Airbus A340	747–300
Seat width (cm)	43.5	44	43	43	43.8	44.25	44	43.4 (45)[a]
Seat depth (cm)	48.2	50	45	45	[b]	42.5	[b]	45.7 (40–48)[a]
Seat recline (from upright) (cm)	20.3	12.7	12	15.2	19.1	15.5	15	15.2
Gap between seats (cm)	21.5	39	30	[b]	[b]	42.5	[b]	[b]

[a] Values in parenthesis were our measurements on the same type of aircraft. The seat depth on Ansett Airline varied from 40 cm at the two corners to 48 cm at the center of the seat.

[b] Were not available.

acceptable seat depth for the South China region population.

3. Methodology

3.1. Subjects

A total of 30 subjects (22 male and 8 female) participated in the experiment. All subjects were Chinese (from Peoples Republic of China and Hong Kong) students at the Hong Kong University of Science and Technology (HKUST). Each participant was paid HK$ 40 for his/her time. None of the subjects had any musculoskeletal injury.

3.2. Equipment

A special seat with a sitting surface made of cane but without backrest was made (Fig. 1a). The seat was designed to accommodate six cane units. Each cane unit (Fig. 1b) was 45.8 cm wide and 7.6 cm deep giving an "adjustable" depth from 7.6 cm for one cane unit to 45.6 cm for six cane units. A pilot study showed that a maximum seat depth of 38 cm is sufficient for Chinese. The other aspects of the experimental seat were designed according to recommendations (Tougas and Nordin, 1987) that have been proposed for chairs: seat swivel, five-point base, height and tilt adjustability, and so forth.

3.3. Subjective evaluation

Seat evaluations have been mostly subjective (Bishu et al., 1991; Motavalli and Ahmad, 1993). Corlett (1995) has recommended the use of the chair feature check list (CFCL), first proposed by Shackel et al. (1969) and later modified by Drury and Coury (1982), to obtain the mean and distribution effects of the various aspects of a seat. A modified form of the CFCL was used to obtain the subjective responses for a given configuration of the seat. Features such as Cushioning, Stability, Personal Acceptability and Overall Discomfort were added to the Drury and Coury scale. The subjects had to rate eight aspects related to the seat using the five-point semantic differential scale (Fig. 2).

3.4. Experimental design

To avoid any order effects, a completely counterbalanced Latin-Square-like design was used. Hence, there were 10 possible sequences for testing subjects on the five different seat depths. To increase experimental reliability, each subject performed two trials for each seat depth.

The sample size was selected as a multiple of 10 so that counterbalancing was possible. A 3-factor experiment with repeated measurements was carried out and analyzed. The independent variables (treatments) were Gender (males and females), Trials (1 and 2), and number of cane units (1, 2, 3, 4, and 5 corresponding to seat depths of 7.6, 15.2, 22.8, 30.4, and 38 cm).

Fig. 1. (a) Test seat made of removable cane units, (b) Enlarged view of each cane unit.

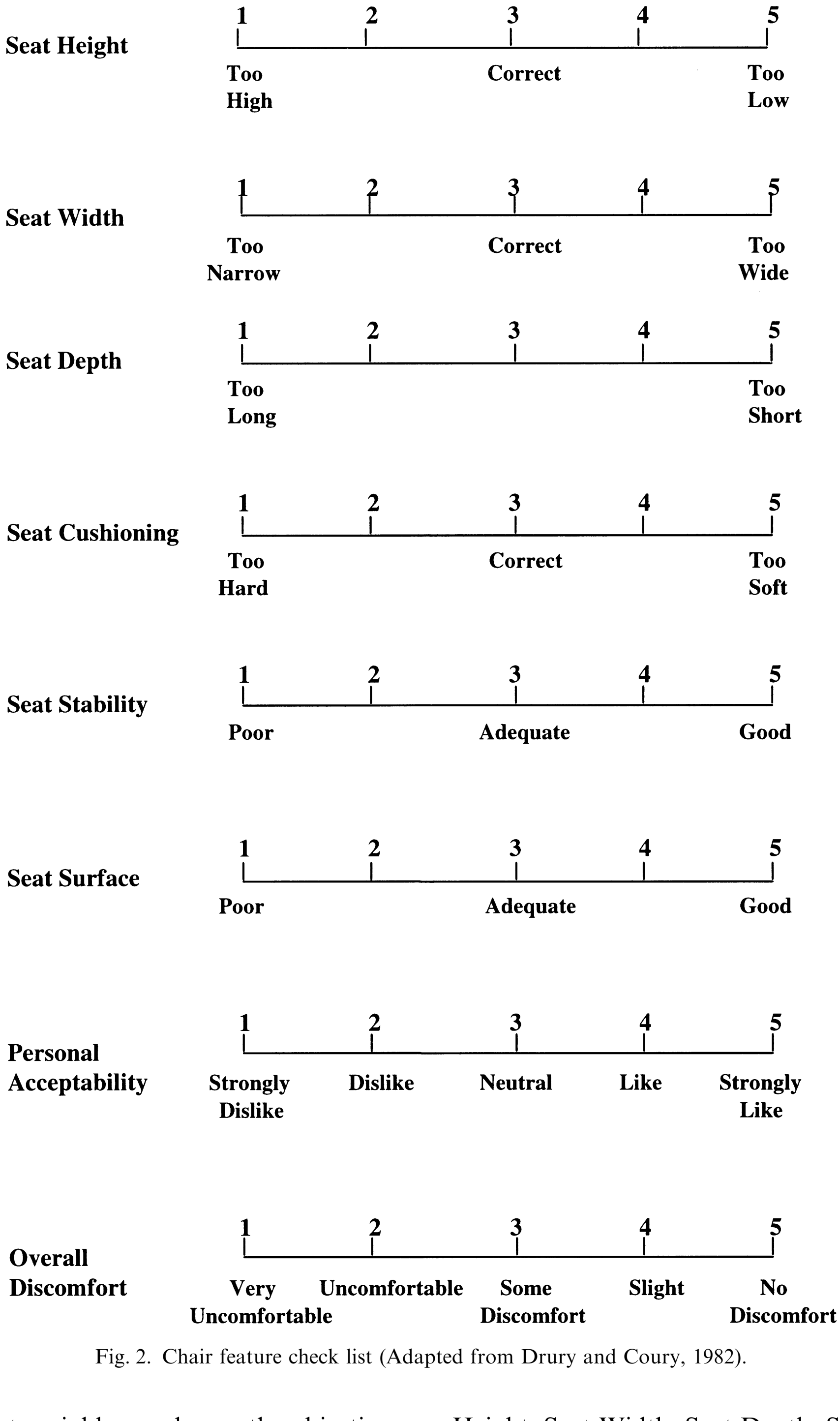

Fig. 2. Chair feature check list (Adapted from Drury and Coury, 1982).

The dependent variables used were the objective measure given by the buttock-seat edge projection "*a*" (Fig. 3) and the subjective ratings of Seat Height, Seat Width, Seat Depth, Seat Cushioning, Seat Surface, Seat Stability, Personal Acceptability, and Overall Discomfort.

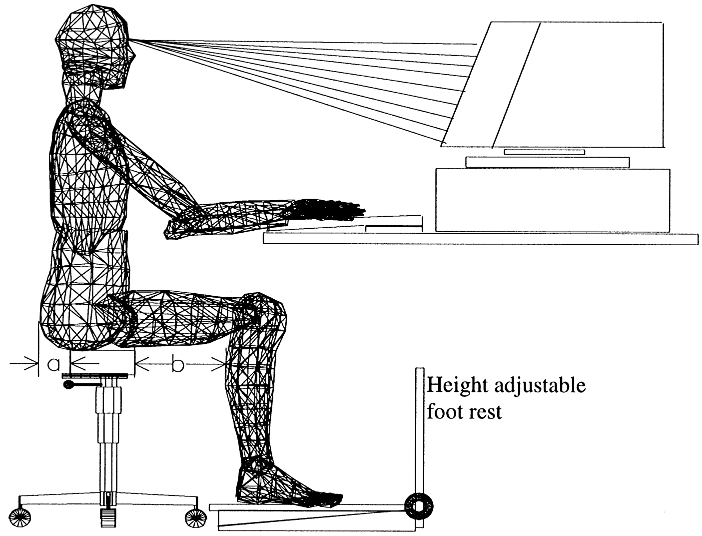

Fig. 3. Experimental setup and dimensions "*a*" and "*b*" measured during sitting. ($a+b+$seat depth = BPL).

3.5. Procedure

The experiment was performed in the Human Performance Laboratory of the Industrial Engineering and Engineering Management (IEEM) department at HKUST. The subjects, upon recruitment, were randomly assigned to one of the 10 possible sequences discussed in Section 3.4. The experiment was performed over a period of two weeks.

Prior to experimentation, the objective of the study and the experimental procedure was explained to the subjects in detail. Then he/she was asked to sign a consent form. The subjects provided certain demographic information such as age and health. The subjects removed all items in their pockets prior to testing. The height and weight were measured using a TANITA electronic weighing scale with a Seca Model 220 height measuring attachment. Popliteal height (PH) and buttock–popliteal length (BPL) were then measured using a Martin-type anthropometer according to Evans et al. (1988).

The seat, height-adjustable footrest, and a table comprised a computer "workstation" (Fig. 3). The subject was instructed to sit on the experimental chair facing the computer screen. The height of the seat was adjusted so that the top of the computer monitor was at eye level (Pheasant, 1994). A footrest was placed under the feet and adjusted so that the knee angle was 90° (Pheasant, 1991). Then the subject was asked to sit in the most comfortable sitting position on the seat pan corresponding to one of five possible seat depths (7.6, 15.2, 22.8, 30.4, 38 cm). The order of presentation was counterbalanced between subjects with an ordering similar to a Latin-square design. After the subject was comfortable, the experimenter recorded the distance from the buttock to the seat-edge distance (dimension '*a*' in Fig. 3). When all the aforementioned measurements were taken, the subject rated the chair characteristics of Seat Height, Seat Width, Seat Depth, Seat Cushioning, Seat Stability, Seat Surface, Personal Acceptability of the seat, and Overall Discomfort on a 5-point scale (Fig. 2) after sitting for about 5 min. Each of the scales was shown on the computer monitor. At the end of all ratings, the subject was asked to stand and relax until the chair was set to perform the second trial. When the chair was repositioned, the subject sat down again and the above procedure was repeated for the other 4 seat depths. The total experimental time for each subject varied between 1 and 1.5 h.

Table 3
Descriptive statistics of subjects

Variable	N	Mean	Median	S.D.	Min	Max
Age (Years)	30	28.9	28	4.38	21	38
Height (cm)	30	169.09	168.25	6.64	154.0	181.70
Weight (kg)	30	64.4	64.82	10.85	45.75	81.05
Popliteal height (PH), cm	30	39.999	39.755	1.917	36.1	45.20
BPL (cm)	30	44.47	44.2	2.21	41.5	49

4. Results and analysis

The descriptive statistics of the subjects are shown in Table 3. They ranged in age from 21 to 38 years with a mean of 28.9 years. Their mean height was 169.09 cm (range: 154–181.7 cm) and mean weight was 64.4 kg (range: 45.75–81.05 kg).

The projection '*a*' (Fig. 3) was the objective measure of seat depth. From Fig. 3, it should be clear that there are three possibilities for the measure '*a*':

1. Buttock protrudes over the back edge of the chair, and $a > 0$;
2. Buttock does not reach the back edge of the chair, and thus $a < 0$;
3. Buttock meets the back edge of chair, and thus $a = 0$.

Since the subjects had varying buttock–popliteal lengths (BPL), the dimension '*a*' was normalized with respect to the BPL of each subject. The plot of these normalized values expressed as a percentage against seat depth (cane depth or number of canes) is shown in Fig. 4. The figure shows that the crossover point (that is where the graph crosses the *x*-axis, i.e., $a = 0$) occurs at a seat depth of approximately 31.26 cm. An '*a*' value of zero indicates the effective seat depth. At the greater seat depth of 38 cm, the mean $(a/\text{BPL})\%$ value is -11.69. The mean observed BPL in this experiment was 44.47 cm which was almost identical to the 44.25 cm (mean of 45 cm for males and 43.5 cm for females) reported by Pheasant (1994). Using a BPL of 44.47 cm at a seat depth of 38 cm, dimension '*a*' would equal $(-11.69)(44.47)/100 = -5.20$ cm. In other words, the effective support depth in this case would equal $(38-5.2) = 32.8$ cm[1]. The *x*-axis crossover point and the '*a*' value at the higher seat depth of 38 cm suggest that a seat depth of approximately 31–33 cm is suitable for the South China region Chinese population.

From Fig. 4, it is clear that '*a*' drops rapidly after a seat depth of 22.8 cm, indicating a general trend of subjects trying to load parts of the thigh area as the seat depth increases. The drop in '*a*' above a seat depth of 22.8 cm is not proportional when compared to the seat depths of those between 7.6 and 22.8 cm. A 3-point regression of $(a/\text{BPL})\%$ was performed at the three seat depths of 7.6, 15.2, and 22.8 cm. The least-squares fit ($R^2 = 0.9998$) for these three points is as follows:

$$(a/\text{BPL})\% = 22.7164 - (0.6035)(\text{seatdepth}), \quad (1)$$

The regression line is also shown in Fig. 4. Extrapolating Eq. (1) till $a = 0$ gives a seat depth value of 37.6 cm which is very close to the generally recommended minimum value in ergonomic standards.

For short seat depths, the '*a*' value is likely to be determined by subject balance rather than "comfort" and it is unlikely that '*a*' would be zero. As seat depth increases, the factor related to balance will gradually decrease and sitting "comfort" or interface pressure becomes more and more important. If the subject maintains complete contact with the seat at the higher seat depths (e.g., 37.6 cm), it would result in a higher contact area and potentially more discomfort (Goonetilleke, 1998). The sudden drop in the '*a*' value seems to explain why people avoid using the backrest when the seat is deep. It is not solely as a result of people not been able to reach the backrest, but also because people have a differing sensitivity in the buttock and thigh areas and thus

[1] A BPL of 44.25 cm would also give a support depth 32.8 cm.

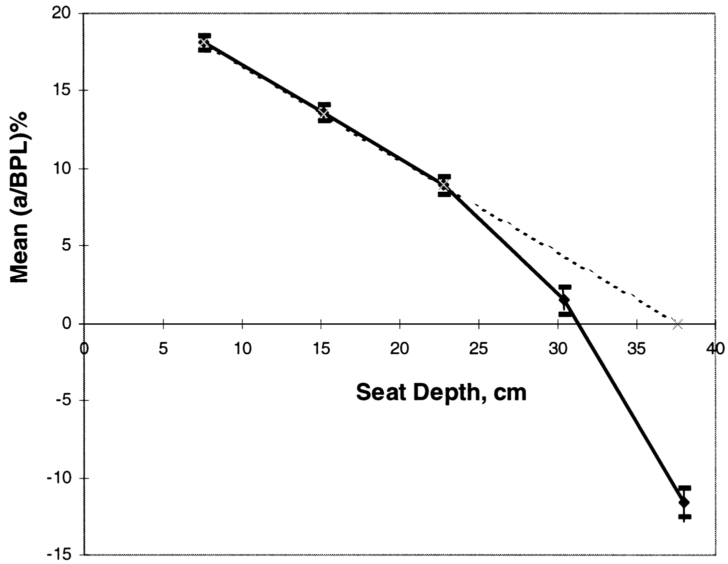

Fig. 4. Dimension "a" as a percentage of buttock–popliteal length (BPL). The vertical lines correspond to the standard error. The dotted line corresponds to the regression line ($R^2 = 0.9998$) based on the (a/BPL)% values for seat depths of 7.6, 15.2, and 22.8 cm.

attempt to obtain an "optimal" contact area during sitting.

The subjective ratings corresponding to each seat depth are shown in Fig. 5. The ANOVA on the subjective ratings (Fig. 2) showed no significant ($p < 0.05$) effects for the dependent variables of seat width (Table 4). The seat width was kept constant throughout the experiment and thus significant differences were not expected. However, significant effects were found among the number of cane units for the dependent variables of Seat Depth, Cushioning, Seat Surface, Stability, Personal Acceptability, and Overall Discomfort ratings. A *post-hoc* Student–Newman–Keuls (SNK) test showed no significant difference between 4 canes (30.4 cm seat depth) and 5 canes (38 cm seat depth) for the subjective ratings of Seat Stability, Seat Surface, Personal Acceptability and Overall Discomfort. The post-hoc SNK for seat depth showed obvious differences among all seat depths. However, Fig. 5 shows that a mean value of 3 (or "correct") is achieved with a total of four cane units (i.e., seat depth of 30.4 cm). In addition, Fig. 5 also shows that Seat Height and Seat Width were considered "correct" (value close to 3).

The subjective ratings for Seat Stability, Seat Surface, Personal Acceptability and Overall Discomfort show that there were no significant differences between the seat depths of 30.4 and 38 cm. However, the most critical rating of seat depth pinpoints towards an optimal depth of 30.4 cm. This is because the seat depth of 38 cm is considered 'too long' (Fig. 5) and because there is significant difference between the seat depth of 30.4 and 38 cm in the post-hoc SNK test.

5. Discussion and conclusions

The objective measure of seat edge protrusion indicates that a seat depth of 31–33 cm is suitable for the South China region population. On the other hand, the seat depth rating indicates a "correct" rating around 30.4 cm even though the other subjective ratings indicate that there is no significant difference between the seat depths of 30.4 and 38 cm. Since the use of five cane units (corresponding to a seat depth of 38 cm) results in a negative value for 'a' (Fig. 4), it may be inferred that a seat depth closer to 30.4 cm is a better

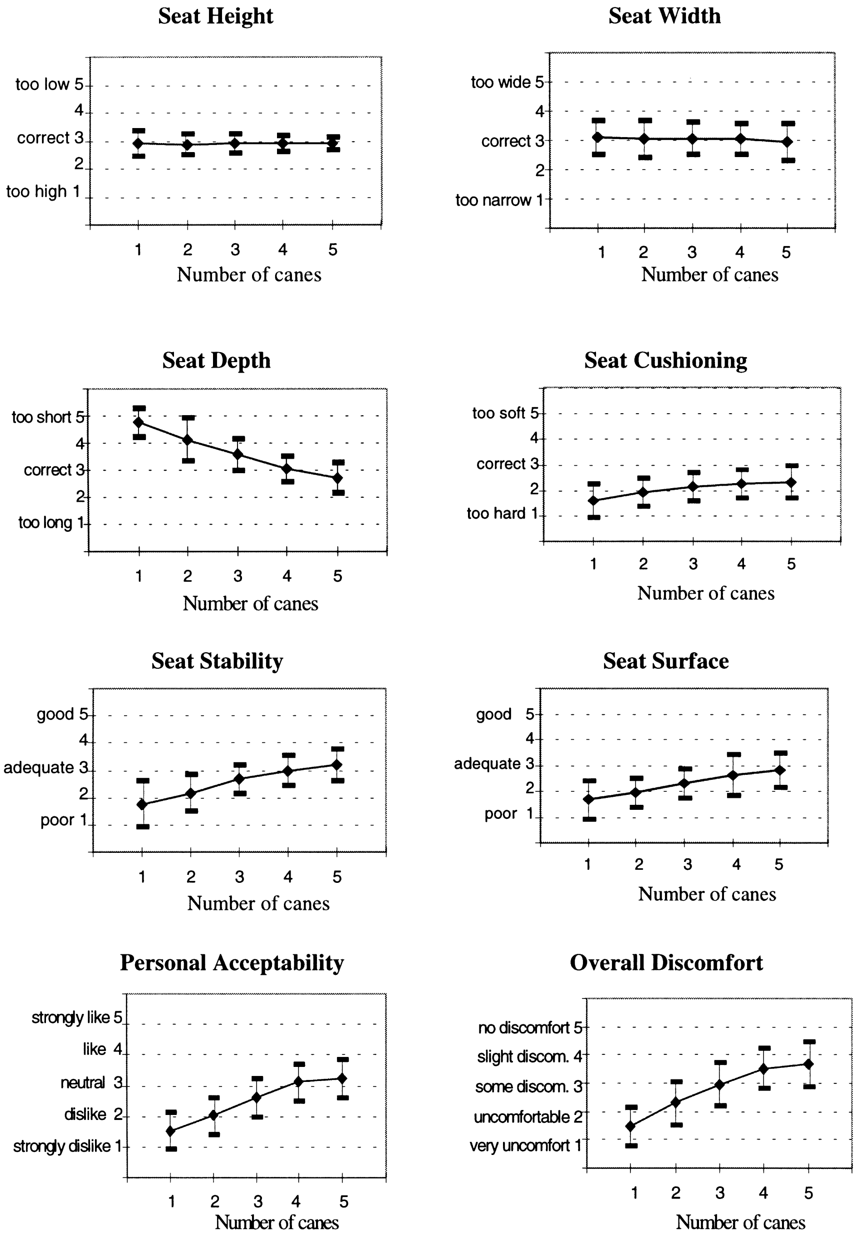

Fig. 5. Mean subjective rating and standard deviation for seat features. Each cane unit corresponds to a seat depth of 7.6 cm.

choice. In addition, the ratings for Seat Surface, Stability, Personal Acceptability and Overall Discomfort may be altered using parameters related to cushioning, chair support, aesthetics and so forth rather than with an increase in seat depth.

Thus it is reasonable to say that a seat depth of approximately 31–33 cm is suitable for the South China region Chinese population in contrast to the ANSI standard of 38–43 cm for the US population. The results we obtained are consistent and

Table 4
ANOVA results of subjective ratings. The *F*-value and the corresponding probability (in parenthesis) for $p<0.05$ are shown below

Source(df)	S. height	S. width	S. depth	Cushion.	S. surface	Stability	Acceptab.	Overall
Gender (1)								
Trial (1)								
Gender*trial				5.23 (0.03)				
Cane (4)			80 (0.0001)	16.2 (0.0001)	28.6 (0.0001)	50.8 (0.0001)	74.96 (0.0001)	99.2 (0.0001)
Gender*cane	2.58 (0.04)					3.11 (0.0182)		
Trial*cane					3.11 (0.018)			
Gender*trial*cane								

are statistically reliable. Hence the methodology that has been developed and used is suitable for determining the optimum seat depth for a target population. Seat depth has been governed, primarily, by anthropometry in the past. Even though seat usability studies have been performed by many, no study has systematically explored the subjective and objective effects of increasing and/or decreasing seat depth. The special seat that was fabricated has helped to develop an objective measure related to sitting. The use of the seat is not restricted to a particular population since the seat depth can be varied between 7.6 cm and any desired upper limit even though a maximum of only 38 cm was used in this study.

In light of the study reported here, it is not surprising that airplane seats, which have a comparatively large seat depth, are uncomfortable over long periods of time. It loads a relatively large area thereby increases negative sensation making a person more uncomfortable (Goonetilleke, 1998). Pheasant's (1991) comments on seat depth are also appropriate: "a seat which is too deep inevitably deprives you of the full benefit of the backrest. Either you must lean back in a flexed position with the lumbar region essentially unsupported, or you must sit forward and lose contact with the backrest altogether. Neither is satisfactory" (p. 216). It is best that the backrest in chairs be designed such that the seat depth is variable to obtain a somewhat "optimum" contact area. This would allow a person to adjust the seat and posture, such that the loading on the buttock, thighs, and the back are below the uncomfortable threshold.

Lastly, Vegesack's (1997) words (p. 7), "Experiments continue to this day. …the optimal armchair, office chair, or car seat is again and again reinvented following the needs and possibilities of its time" should not be forgotten or ignored to determine the seat characteristics and seat dimensions in order to obtain the best "fit" between person and seat.

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