International Journal of Industrial Ergonomics 76 (2020) 102900

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

journal homepage: http://www.elsevier.com/locate/ergon

Effects of aircraft seat pitch on interface pressure and passenger discomfort

Chuan Zhao [a,b,*], Sui-huai Yu [c], Carisa Harris Adamson [b], Sarfraz Ali [c], Wen-hua Li [c], Qian-qian Li [a]

[a] *School of Electromechanic Engineering, Qingdao University China, China*
[b] *School of Public Health, University of California, Berkeley, USA*
[c] *School of Mechanical Engineering, Northwestern Polytechnical University, China*

ARTICLE INFO

Keywords:
Pressure mat
Passenger discomfort
Seat pitch
Aircraft seat

ABSTRACT

Seat pitch, defined as the distance from a point on the back of one seat to the same point on the seat in front, is one of the most important factors influencing aircraft seating comfort. This study assessed the influence of different airline seat pitches on subjective ratings of discomfort and body-seat interface contact pressures. This was a laboratory within-subjects study using an aircraft interior mock up to vary seat pitch. Twelve participants completed 1 h of sitting in each of five different seat pitches (28inches, 30inches, 32inches, 34inches, and 36inches). Interface pressure mats measured seat and backrest pressure distribution, subjective rating scales were used to measure overall and local body region discomfort. The results showed that overall body and local body region discomfort ratings tend to be lower when the seat pitch increased from 28 inches to 36 inches ($p < 0.05$). For pressure variables, the upper back average contact area, upper/lower back average contact pressure, upper/lower back average peak contact pressure, right buttock average contact area, left/right thigh buttock average peak contact pressure, and left buttock average peak contact pressure were significantly affected by seat pitch($p < 0.05$). Separate analyses support that seat pitch was more strongly correlated with backrest interface pressure than with seat pan pressure. In conclusion, seat pitch was found to be an important factor associated with body-seat contact pressure and discomfort ratings.

1. Introduction

Over the last 40 years, commercial air traffic and the number of passengers have been consistently increasing (Kremser et al., 2012). This leading to an increased number of passenger airlines and competition to have the lowest fares. Therefore, maximizing the number of passengers on a plane by reducing seat pitch is one strategy used to lower ticket costs. Although passenger comfort is the main concern of both designers and engineers of aircraft, it is a constant challenge to balance passenger comfort with the financial need to maximize the airplane occupancy (Vink et al., 2012). It has long been known that seat comfort is related to passenger' satisfaction and willingness to use the airline again (RICHARDS and JACOBSON, 1975). Therefore, it is critical for airlines to optimize airplane occupancy with passenger comfort to ensure its viability.

The airline industry uses aircraft seats to distinguish their product from those of their competitors (IATA, 2009). Seat pitch, defined as the distance from a point on the back of one seat to the same point on the seat in front, is one of the primary variables that has been associated with the physical comfort of airline passengers. Seat pitch is influenced by leg space, the depth of the seat back structure and the tray table. In fact, the available legroom and personal space for passengers are primarily influenced by seat pitch which may be highly associated with passenger comfort and satisfaction (Bouwens et al., 2017). A questionnaire found that 70% of surveyed passengers rated the importance of seating design, particularly as it relates to adopting a good posture and being able to change ones posture, as “very important” (Quigley et al., 2001). For example, providing enough space to allow passengers to extend their legs can reduce the onset of leg stiffness or cramps (Li et al., 2017). Vink (2011) found that seat pitch was highly correlated with passenger comfort ($r^2 = 0.72$). Furthermore, a survey conducted at 36 large Brazilian airports (350 passengers) found that the majority of discomfort experienced during air travel was related to seat and cabin space (Greghi et al., 2013). Numerous studies have documented the important relationship between seat pitch and comfort (Naseem et al., 2016; RICHARDS and JACOBSON, 1977); thus it has been a major focus

---

* Corresponding author. School of Public Health, University of California, Berkeley, USA.
E-mail addresses: zhaochuancow@gmail.com, zhaochuancow@qq.com (C. Zhao).

https://doi.org/10.1016/j.ergon.2019.102900
Received 9 October 2018; Received in revised form 30 November 2019; Accepted 17 December 2019

Fig. 1. Aircraft cabin mock-up and example of one participant in this study.

in the design of interior aircrafts. Kremser et al. (2012) investigated the influence of seat pitch on airplane passengers' well-being using a five point Likert Scale. However, the majority of research has utilized subjective measures of comfort without any objective ways to assess the factors of the seat that are leading to the discomfort. For example, Vink et al. (2012) collected more than 10,000 retrospective trip reports to obtain a general rating of overall comfort (on a scale of 0–10) and subjective feedback of passengers' experiences. This study showed that passengers were aware of the legroom, hygiene, crew attention and seat, which were all associated with their comfort and flight experience. Although aforementioned studies provided important information about the passengers' flight experience, they exclusively employed retrospective subjective assessments that may be prone to bias and differ from real-time impressions. Therefore, studies that also include measures of objective seat comfort are needed.

An accurate method for assessing the quality of commercial aircraft seats would have a major advantage of providing rapid and accurate information which could be used early in the design process. Pressure distribution measurements of the body-seat interface is one of the most common objective methods to analyze or compare different chairs or sitting positions. Pressure distribution measurements of the seat pan and back rest have been used in the evaluation of car seats (Franz et al., 2012; Porter et al., 2003; Gyi and Porter, 1999) and office chairs (Groenesteijn et al., 2009). Kyung and Nussbaum (2008) supported that body–seat interface pressure was strongly related to overall comfort ratings during 27 participants involved in six separate driving sessions. Cascioli et al. (2011) compared the limited and unlimited legroom groups for differences in subjective and objective measures over 4 h. It appeared that limited legroom did not, on its own, result in significant changes in discomfort and flexibility nor was it the "driving mechanism" involved in the development of stiffness or the perception of discomfort by the chair users. Li et al. (2017) analyzed the effect of long duration sitting on a seat with the limited leg space on discomfort rating scale, body flexibility and surface pressure with the sitting time. However, the chairs used in these two studies were all office chairs which is dissimilar to an aircraft seat regarding the space underneath the seat, the distance between the seat and the structure in front, and the minimum vertically projected distance between seat rows. Thus, there are few studies of body-seat pressure distribution and its relationship to passenger comfort/discomfort in airplane seats.

Therefore, the objective of this study was to assess the relationship of seat pitches on overall discomfort rating, local body region discomfort ratings, body-seat interface contact pressures and the associations between interface pressures and subjective ratings. The specific study objectives were: (1) to quantify the association between varying seat pitch, whole body and local body region discomfort ratings (2) to analyze the impact of different seat pitches on body-seat interface surface pressure, (3) to investigate the relationship between body-seat interface surface pressure and subjective assessment of discomfort. Understanding the relationship between seat pitch and objective and subjective measures are important for assessing, predicting and improving flight experiences.

Table 1
Seat pitches and legroom of the test scenarios.

Scenario	Seat pitch(inch)	Legroom(inch)
A	28	26
B	30	28
C	32	30
D	34	32
E	36	34

Table 2
Anthropometric dimensions of the volunteers (N = 12) included in the study.

Gender	Variable	Mean	Minimum	Maximum	Std. dev.
Male (n = 7)	Stature(mm)	176.2	167	185	7.34
	Mass(kg)	77.5	72.5	99	13.1
	BMI	24.8	21.2	28.9	2.9
Famle (n = 5)	Stature(mm)	163.8	155	169	4.9
	Mass(kg)	55	47	65	5.9
	BMI	21	18.4	24.5	2.1

2. Methods

2.1. Seat conditions

The research was conducted at Northwestern Polytechnical University using a simulated Boeing 737–800 used to train cabin crews (Fig. 1). It consisted of five rows with six seats per row (30 seats total). The first row was fixed but the second through fifth row seats had adjustable seat pitch. Seat pitch is defined as the distance between the seat cushion and the back of the next seat and varies based on the depth and the contour of the backrest. The seat pitch in the simulated environment varied between 28 (Quigley et al., 2001) and 36 inches (Kremser et al., 2012) which corresponded to legroom distances between 26 and 34 inches (Table 1).

2.2. Participants and procedure

Twelve participants with no history of low back pain took part in this experiment, including 7 males and 5 females. The participants included members of the local university student population as well as members of the general population. Anthropometric measurements including stature and mass were measured and used to calculate BMI (Table 2).

Fig. 2. Photo of the pressure mats positioned on the seat.

Based on an anthropometric table (GB 10000-1988), the male heights ranged between the 20th to 99th percentile and the female heights ranged between the 50th to 95th percentile. In terms of body mass, the males ranged between the 50th to 99th percentile while, the females ranged between the 20th to 90th percentile. Thus, the study participants represented a broad range of the population.

Subjects were tested individually, before the experiment started, each participant was permitted to get familiar with the simulated environment for 5 min. Next, the subjects were advised to sit in the aisle seat and to fasten their seatbelts low and tight across their waist with their backrest in an upright position, similar to the requirements when preparing for a flight. Each simulated flight procedure took about 1 h during which participants were permitted to take a nap, read a book, play on their cell phones and talk to experimenters. Participants were not allowed to leave their seat. Each participant completed this protocol five times to evaluate 5 simulated seat pitch and legroom conditions (Table 1). To avoid muscle fatigue and carryover effects, there was approximately 1 week between conditions. The sequence of the conditions was randomized. Subjects wore comfortable clothes without heavy seams, buttons or pockets to minimize the impact of clothing on the pressure readings.

2.3. Data collection procedures and processing

Body-seat interface pressure were collected continuously during each experiment, using two Tekscan (South Boston, MA, USA) pressure mats. Each mat had an active area of 471.4 mm*471.4 mm, and sensor pitch was 14.73 mm (0.5 sensor/cm^2). Pressures were recorded at 0.5 Hz, the maximum possible due to hardware limitations. This sampling rate, however, was considered sufficient, as the frequency of postural changes and resultant pressure changes were not observed to occur within an order of magnitude of the sampling rate (Kyung and Nussbaum, 2008). The mats were securely attached to the seat and backrest using strips of masking tape (Fig. 2).

Pressure data from the two mats were divided into six body regions (Fig. 3). Contact area, contact pressure, and contact peak pressure were calculated using data from sensors that were pressed at least once. The acquired data were exported to ASCII format using the Body Pressure Measurement System software (Version 7.20c, South Boston, MA, USA) for analysis in SPSS system software (Version 22). Values of interest were average (average of all sensor values) contact pressure, average contact area and average peak contact pressure for the same body regions per condition. A total of 18 pressure variables were derived: the first 6 variables were related to backrest interface pressure; the second 12 variables described seat pan interface pressure (Table 3).

Two subjective rating scales were used to assess physical discomfort at the end of each 1 h test condition. Regional body discomfort of the upper back, lower back, and bilateral buttocks and thighs were rated

Table 3
Subjective and objective variables.

Type	Variable name and description	
Subjective	Overall discomfort rating scale	Whole body (ORS)
	Local body region discomfort rating scale	Left/right thighs (THL/THR) Left/right buttocks (BTL/BTR) Upper/lower back (UB/LB)
Objective	Average contact area (cm^2)	Left/right thigh (aTHL/aTHR) Left/right buttock (aBTL/aBTR) Lower/upper back (aLB/aUB)
	Average contact pressure (mmHg)	Left/right thigh (pTHL/pTHR) Left/right buttock (pBTL/pBTR) Lower/upper back (pLB/pUB)
	Average peak contact pressure (mmHg)	Left/right thigh (pkTHL/pkTHR) Left/right buttock (pkBTL/pkBTR) Lower/upper back (pkLB/pkUB)

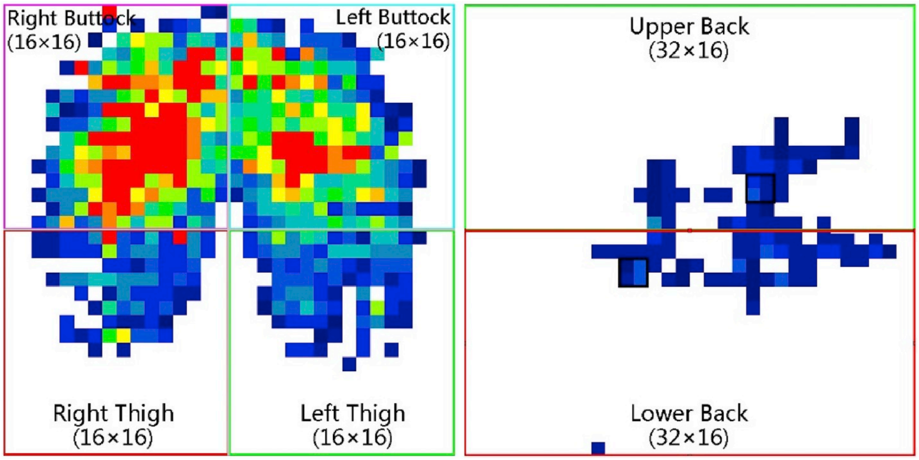
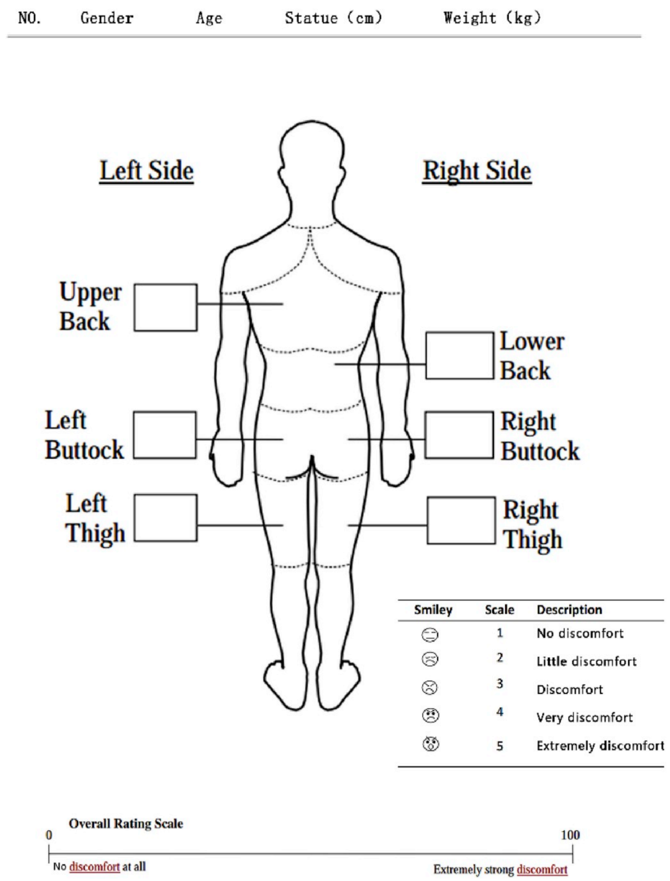


Fig. 3. Division of two pressure mats for six local body regions and exemplar pressure distribution (left, seat cushion pressure; right, back cushion pressure).



Smiley	Scale	Description
☺	1	No discomfort
☹	2	Little discomfort
☹	3	Discomfort
☹	4	Very discomfort
☹	5	Extremely discomfort

Fig. 4. Local body region (top) and overall discomfort rating scale (bottom).

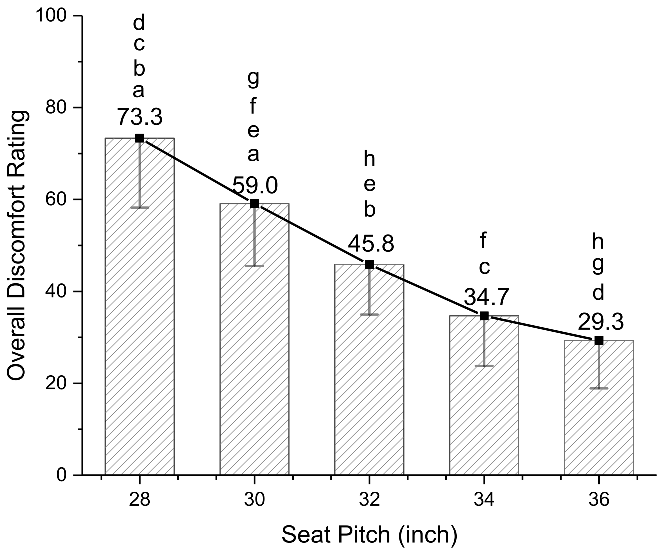


Fig. 5. The overall discomfort rating score for five seat pitches averaged over 12 participants (0 = no discomfort at all, 100 = extremely strong discomfort), bars with same letter superscript represent significant difference ($p < 0.05$).

using a five-point Likert Scale, ranging from 1 (no discomfort) to 5 (extremely discomfort). Additionally, a visual analog scale (VAS) ranging from 0 (no discomfort at all) to100 (extremely strong discomfort) was used to assess overall body discomfort (Fig. 4). Therefore, seven subjective values were obtained after each condition (Table 3).

2.4. Data analysis

A one-way ANOVA with repeated measures was used to determine the differences in subjective discomfort and body-seat interface pressure across seat pitches (five levels). The Tukey's honestly significant different (HSD) test for post hoc pairwise comparisons. In addition, the Pearson product moment correlation coefficient was used to examine the relationship between pressure parameters and subjective discomfort rating parameters. In all statistical tests, $p < 0.05$ was considered to be statistically significant. SPSS system software (Version 22) was used to perform all statistical analyses.

3. Results

3.1. Subjective evaluation

3.1.1. Overall discomfort rating scale

The one-way ANOVA test demonstrated that the seat pitch significantly affected the overall discomfort rating scale ($p < 0.05$). The Tukey's Post Hoc test showed that overall discomfort rating scale were generally lower (indicating less discomfort) with higher seat pitch. (Fig. 5).

3.1.2. Local body region discomfort rating scale

The one-way ANOVA test showed there was a significant ($p < 0.05$) effect of seat pitches on left thigh rating (THL), right thigh rating (THR), right thigh rating (BTL), right thigh rating (BTR), upper back rating (UB), and lower back rating (LB). All the local body region discomfort ratings except upper back (UB) were generally lower (indicating less discomfort) with higher seat pitch (Table 4).

3.2. Backrest and seat pan pressure variables

3.2.1. Backrest pressure variables

The results of the one-way ANOVA test showed that there was a significant effect of seat pitches on the upper back average contact area (aUB) ($F = 3.14$, $p < 0.05$), upper back average contact pressure (pUB) ($F = 14.3$, $p < 0.05$), lower back average contact pressure (pLB) ($F = 8.71$, $p < 0.05$), upper back average peak contact pressure (pkUB) ($F = 10.63$, $p < 0.05$), and lower back average peak contact pressure (pkLB) ($F = 5.23$, $p < 0.05$). All the significant backrest pressure variables were generally higher with larger seat pitch (Fig. 6).

3.2.2. Seat pan pressure variables

Analysis of the right buttock average contact area (aBTR) revealed a significant effect of different seat pitches ($F = 2.64$, $p < 0.05$). The left thigh, right thigh and left buttock average peak contact pressure (pkTHL, pkTHR, pkBTL) were significantly affected by the seat condition ($F = 3.80$, $p < 0.05$; $F = 2.89$, $p < 0.05$; $F = 2.78$, $p < 0.05$). But the results showed that there was no significant effect of seat pitches on the four seat parts average contact pressure (Fig. 7).

3.3. Correlations among ratings of subjective and objective

There were multiple significant correlations between the subjective ratings and pressure variables. The largest correlation ($|R| = 0.673$, $p < 0.05$) was found between lower back average contact pressure and overall discomfort rating. For left/right thighs and left/right buttocks, there were 3 pressure variables moderately correlated either with overall or local body region discomfort ratings ($0.256 \leq |R| \leq 0.307$, $p < 0.05$) (Table 5).

4. Discussion

This study has provided new insights into the effects of different seat pitches on seat pan pressure, backrest pressure, whole body and local

Table 4
Local body region discomfort rating variables (values in parentheses indicate standard error).

Variable	Seat pitch					One-way ANOVA F values (p level)
	28 inches	30 inches	32 inches	34 inches	36 inches	
Left thigh	2.9 (1.0) ^{abc}	2.2 (0.7)^{d}	1.8 (0.7)^{a}	1.4 (0.5)^{b}	1.3 (0.5) ^{cd}	F = 9.8 (P < 0.05)
Right thigh	2.8 (1.0) ^{abc}	2.1 (0.7) ^{de}	1.7 (0.5)^{a}	1.4 (0.5) ^{bd}	1.3 (0.5) ^{ce}	F = 12.3 (P < 0.05)
Left buttocks	3.6 (0.9) ^{abc}	3.3 (0.6)^{d}	2.6 (0.7)^{a}	2.4 (0.5) ^{bd}	2.2 (0.4)^{c}	F = 10.3 (P < 0.05)
Right buttocks	3.7 (1.0) ^{abc}	3.3 (0.6) ^{de}	2.6 (0.7)^{a}	2.3 (0.5) ^{bd}	2.2 (0.4) ^{ce}	F = 11.8 (P < 0.05)
Upper back	2.5 (0.5) ^{abcd}	1.9 (0.3)^{a}	1.4 (0.5)^{b}	1.4 (0.5)^{c}	1.4 (0.5)^{d}	F = 12.0 (P < 0.05)
Lower back	3.3 (0.7) ^{ab}	2.9 (0.9)^{c}	2.5 (0.8)	2.1 (0.7)^{a}	1.8 (0.6) ^{bc}	F = 8.9 (P < 0.05)

Notes: Statistically significant difference (P < 0.05) indicated by same letter superscript; NS means no significant difference (p > 0.05).

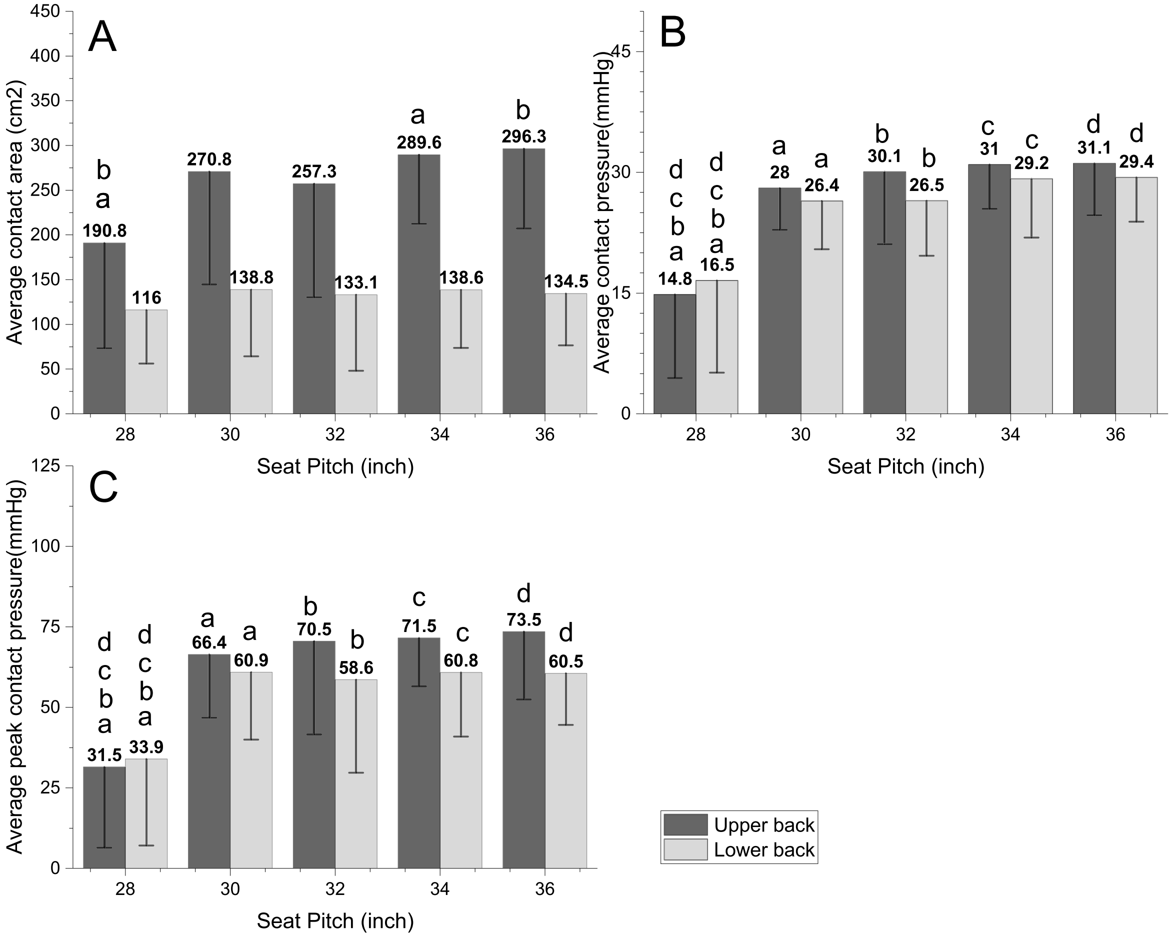


Fig. 6. The backrest pressure variables for five seat pitches averaged over 12 participants. (A) average contact area, (B) average contact pressure, (C) average peak contact pressure.Statistically significant difference (P < 0.05) indicated by same letter superscript.

body region discomfort ratings when sitting in aircraft seats.

For overall discomfort rating scale (ORS), the score tended to be lower when the seat pitch enlarged from 28 inches to 36 inches. The Tukey's Post Hoc test showed that 28 inches and 30 inches had a significant difference with the other seat pitches (p < 0.05), but further seat pitch enlargement didn't induce significant difference (from 32 to 34inches, from 34 to 36 inches). A possible reason is that the small seat pitches (28 inches and 30 inches) restricted the subjects' leg movement, so that their low back and buttocks had a high discomfort rating. In other similar situations, comfort is not simply growing with a larger seat pitch, but there is a turning point where larger seat pitches lead to less well-being (Kremser et al., 2012). However, a case study reported that limited legroom (26 inches) does not significantly contribute to the subject's perception of comfort or discomfort and does not result in significantly reduced neck, lower back or hamstring range of motion or flexibility compared to the unlimited legroom group over 4 h of sitting on stacking chairs (Cascioli et al., 2011). A possible suggestion is that there is a difference between stacking chair and aircraft seat, and the primary source of the discomfort experienced by the subjects was likely due to other factors unrelated to constraining the space. Physiological, biomechanical or fatigue factors might also have influenced the result. Bartels (2003) showed that the physiological seat comfort of aircraft seats can be considerably changed by different seat. Moreover feelings of discomfort were imposed by physical constrains, and mediated by factors such as joint angles, blood pooling and circulation blockage (HELANDER and ZHANG, 1997). It would be easy to change their posture and reduce stiffness as seat pitch increased. This is in agreement with the findings of Vergara and Page (2002) who reported the mobility of postures, reclined on the backrest and contact with the backrest help to decrease lumbar pain. Therefore, the overall discomfort rating scale

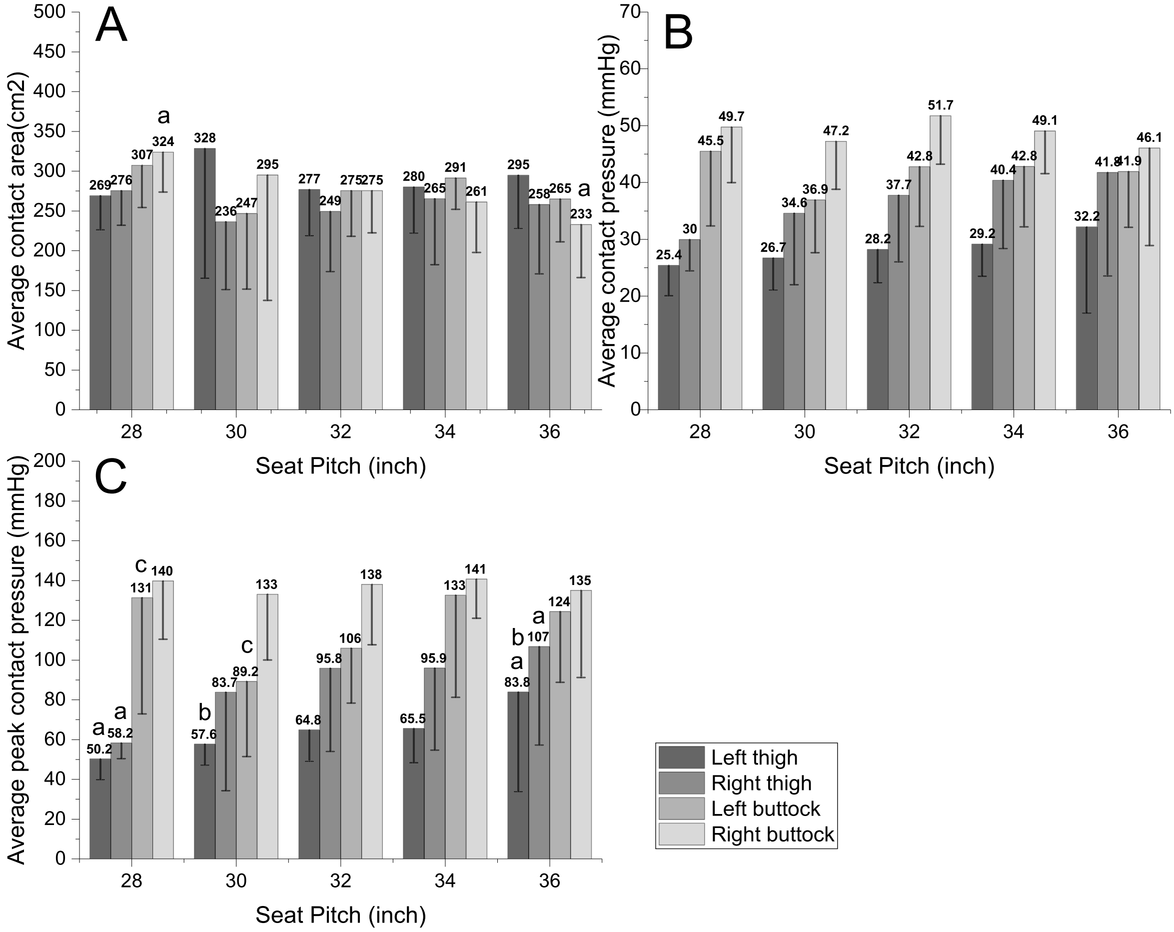


Fig. 7. The seat pan pressure variables for five seat pitches averaged over 12 participants. (A) seat pan average contact area, (B) seat pan average contact pressure, (C) seat pan average peak contact pressure. Statistically significant difference ($P < 0.05$) indicated by same letter superscript.

(ORS) tended to be lower when the seat pitch enlarged from 28 inches to 36 inches in this study. Goonetilleke and Feizhou (2001) found significant effects on the overall discomfort rating of different seat depths (from 7.6 to 38 cm) and indicated that a seat depth of 31–33 cm is appropriate for the South China region Chinese population.

For pressure variables we found that all the backrest variables except lower back average contact area (aLB) were significantly affected by the seat condition. Interesting to see is the upper and lower back average contact pressure (pUB, pLB) and upper back average peak contact pressure (pkUB) tended to be higher when the seat pitch increased from 28 inches to 32 inches (Fig. 6). Furthermore, left and right thigh average contact pressure (pTHL, pTHR), left thigh and right average peak contact pressure (pkTHL, pkTHR), was increased as seat pitch increased. In contrast, the right buttock average contact area (aBTR) was reduced with larger seat pitch (Fig. 7). It may be that the subjects can change their posture easily, and make their back region contact with the seatback (backward position) when the seat pitch enlarged. In other words, when the subjects shifted the lower part of their body forward, they could increase the pressure on their back rest as also observed by Bendix et al.(1985) that the pressure on the backrest was higher with backward posture than forward and erect posture. Furthermore, Graf et al. (1993) found that the body weight was transferred more to the feet when on backward posture. In other similar situations, Li et al. (2017) analyzed the effects of three different seat pitches (32inches,30 inches, and 28 inches) on various seat pan pressure variables. Their result shows that only seat pan average contact pressure was significantly affected by seat pitch. The authors suggest that they should examine the preferred pressure values required for different seat classes in future research. From the pressure data, our results suggest that the larger seat pitch allows for more lean back position and back support. Corlett and Eklund (1984) suggested backrests should promote desirable lumbar curvatures and support the back when users lean back. Vergara and Page (2002) found that postural changes of the back are a good indicator for discomfort, and that mobility and lumbar support of backrest use can reduce discomfort and pain. It is best that the backrest in chairs be designed such that the seat depth is variable to obtain "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. (Goonetilleke and Feizhou, 2001). Therefore, backrest is more important than seat pan when seat pitch changed.

Based on the correlation analyses of the backrest pressure distribution, all of the backrest pressure variables were correlated with overall or local body region discomfort ratings except LB vs. aLB ($p > 0.05$) and ORS vs. aUB ($p > 0.05$). Recent literature shows that interface contact pressure is a useful tool for investigating discomfort during working tasks that require prolonged sitting (Zemp et al., 2015). This result is opposite to a previous expectation that regression analyses indicated that pressure was not a good predictor of preference or discomfort (Gyi and Porter, 1999; Stinson et al., 2003). Carcone and Keir (2007) found that the backrest configuration had a significant correlation with backrest average pressure, average peak pressure and average contact area during word processing. However, in terms of seat pan pressure variables, only 3 pressure variables significantly correlated with subjective ratings. In other situations, the results show that cushion peak pressure was statistically related to the overall discomfort rating scales, but the experiment evaluated five different front driver bucket seats and didn't

Table 5

Pearson correlation coefficients of the subjective ratings and pressure variables.

Variables	Average contact area						Average contact pressure						Average peak contact pressure					
	UB	LB	THL	BTL	THR	BTR	UB	LB	THL	BTL	THR	BTR	UB	LB	THL	BTL	THR	BTR
Subjective variables																		
UB	-.345*	\	\	\	\	\	-.590*	\	\	\	\	\	-.503*	\	\	\	\	\
LB	\	.026	\	\	\	\	\	-.288*	\	\	\	\	\	-.122*	\	\	\	\
THL	\	\	-.159	\	\	\	\	\	.094	\	\	\	\	\	-.060	\	\	\
BTL	\		\	.065	\	\	\	\	\	.169	\	\	\	\	\	.129	\	\
THR	\	\	\	\	.210	\	\	\	\	\	-.174	\	\	\	\	\	-.200	\
BTR	\		\	\	\	.256*	\	\	\	\	\	.187	\	\	\	\	\	.073
ORS	.209	.375*	.261*	-.115	.163	-.163	.588*	.673*	.155	-.071	.085	-.244	.450*	.504*	.307*	.093	.096	-.031

Notes: UB, upper back; LB, lower back; THL, left thigh; THR, right thigh; BTL, left buttock; BTR, right buttock; ORS, overall discomfort rating scale; N = 60. *$p < 0.05$(2-tailed).

change the seat pitch (Kolich et al., 2004; Kolich, 2004). While our data indicate that backrest pressure variables may be stronger correlated with subjective rating variables than seat pan pressure variables for different seat pitches evaluation. Further research is necessary to identify if there are any consistent relationships between these pressure variables and subjective measures during airline traveling.

There are several limitations in this study. The number of subjects in the experiment was limited to 12, it can be even more accurate if the number of participants increases. The assessment period was short (1 h of cruising flight). Existing literature showed that changes in sitting time could increase discomfort of the back (Porter et al., 2003). While Sammonds et al. (2017) describes that as subjects' subjective discomfort increases, the frequency of subjects' seat fidgets and movements increases congruently. Therefore, time-related differences in pressure variables and subjective ratings would be of interest in the future research. Further studies should monitor all posture and movement as a function of time.

5. Conclusion

This study shows that seat pitch has a significant impact on discomfort ratings and backrest/seat pan pressure variables after 1 h sitting. It appears that the seat pitch of 28 inches yielded the highest subjective rating of discomfort. As the seat pitch increased, the discomfort ratings decreased. For pressure variables, the backrest variables are more sensitive than seat pan pressure variables when seat pitch changed. We proposed that this result should be taken into account when designing planes.

CRediT authorship contribution statement

Chuan Zhao: Conceptualization, Methodology, Software, Writing - original draft. **Sui-huai Yu:** Writing - review & editing, Supervision. **Carisa Harris Adamson:** Writing - review & editing, Supervision. **Sarfraz Ali:** Writing - review & editing, Data curation. **Wen-hua Li:** Visualization, Investigation. **Qian-qian Li:** Investigation, Software, Data curation.

Acknowledgments

The authors express their thanks to the participating individuals for their time and effort. The authors would like to acknowledge support for this work from National Key Technology R&D Program, China, Grant No. 2015BAH21F01. The study is partly supported by the Commercial Aircraft Project, Grant No. MJ-2015-F-018.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ergon.2019.102900.

References

Bartels, V.T., 2003. Thermal comfort of aeroplane seats: influence of different seat materials and the use of laboratory test methods. Appl. Ergon. 34, 393–399. https://doi.org/10.1016/S0003-6870(03)00058-9.

Bendix, T., Winkel, Jø, Jessen, F., 1985. Comparison of office chairs with fixed forwards or backwards inclining, or tiltable seats. Eur. J. Appl. Physiol. Occup. Physiol. 54, 378–385.

Bouwens, J.M.A., Tsay, W.-J.J., Vink, P., 2017. The high and low comfort peaks in passengers' flight. Work 58, 579–584. https://doi.org/10.3233/WOR-172637.

Carcone, S.M., Keir, P.J., 2007. Effects of backrest design on biomechanics and comfort during seated work. Appl. Ergon. 38, 755–764. https://doi.org/10.1016/j.apergo.2006.11.001.

Cascioli, V., Heusch, A.I., Mccarthy, P.W., 2011. International Journal of Industrial Ergonomics Does prolonged sitting with limited legroom affect the fl exibility of a healthy subject and their perception of discomfort ? Int. J. Ind. Ergon. 41, 471–480. https://doi.org/10.1016/j.ergon.2011.06.003.

Corlett, E.N., Eklund, J.A.E., 1984. How does a backrest work? Appl. Ergon. 15, 111–114. https://doi.org/10.1016/0003-6870(84)90282-5.

Franz, M., Durt, A., Zenk, R., Desmet, P.M.A., 2012. Comfort Effects of a New Car Headrest with Neck Support, vol. 43, pp. 336–343. https://doi.org/10.1016/j.apergo.2011.06.009.

Goonetilleke, R.S., Feizhou, S., 2001. A methodology to determine the optimum seat depth. Int. J. Ind. Ergon. 27, 207–217. https://doi.org/10.1016/S0169-8141(00)00051-2.

Graf, M., Guggenbühl, U., Krueger, H., 1993. Investigations on the effects of seat shape and slope on posture, comfort and back muscle activity. Int. J. Ind. Ergon. 12, 91–103. https://doi.org/10.1016/0169-8141(93)90041-B.

Greghi, M.F., Rossi, T.N., de Souza, J.B.G., Menegon, N.L., 2013. Brazilian passengers' perceptions of air travel: evidences from a survey. J. Air Transp. Manag. 31, 27–31. https://doi.org/10.1016/j.jairtraman.2012.11.008.

Groenesteijn, L., Vink, P., de Looze, M., Krause, F., 2009. Effects of differences in office chair controls, seat and backrest angle design in relation to tasks. Appl. Ergon. 40, 362–370. https://doi.org/10.1016/j.apergo.2008.11.011.

Gyi, D.E., Porter, J.M., 1999. Interface pressure and the prediction of car seat discomfort. Appl. Ergon. 30, 99–107. https://doi.org/10.1016/S0003-6870(98)00018-0.

HELANDER, M.G., ZHANG, L., 1997. Field studies of comfort and discomfort in sitting. Ergonomics 40, 895–915. https://doi.org/10.1080/001401397187739.

IATA- International Air Transport Association, 2009. Corporate Air Travel Survey. Montreal. Available in. http://www.eurokiosks.org/pdf/iata_cats2009.pdf.

Kolich, M., 2004. Predicting automobile seat comfort using a neural network. Int. J. Ind. Ergon. 33, 285–293. https://doi.org/10.1016/j.ergon.2003.10.004.

Kolich, M., Seal, N., Taboun, S., 2004. Automobile seat comfort prediction: statistical model vs. artificial neural network. Appl. Ergon. 35, 275–284. https://doi.org/10.1016/j.apergo.2004.01.007.

Kremser, F., Guenzkofer, F., Sedlmeier, C., Sabbah, O., Bengler, K., 2012. Aircraft seating comfort: the influence of seat pitch on passengers' well-being. Work 41, 4936–4942. https://doi.org/10.3233/WOR-2012-0789-4936.

Kyung, G., Nussbaum, M.A., 2008. Driver sitting comfort and discomfort (part II): relationships with and prediction from interface pressure. Int. J. Ind. Ergon. 38, 526–538. https://doi.org/10.1016/j.ergon.2007.08.011.

Li, W., Yu, S., Yang, H., Pei, H., Zhao, C., 2017. Effects of long-duration sitting with limited space on discomfort, body flexibility, and surface pressure. Int. J. Ind. Ergon. 58, 12–24. https://doi.org/10.1016/j.ergon.2017.01.002.

Naseem, A., Jean Marc, R., Gitte, L., 2016. Applied Ergonomics 53, 301–308. https://doi.org/10.1016/j.apergo.2015.07.029.

Porter, J.M., Gyi, D.E., Tait, H.A., 2003. Interface pressure data and the prediction of driver discomfort in road trials. Appl. Ergon. 34, 207–214. https://doi.org/10.1016/S0003-6870(03)00009-7.

Quigley, C., Southall, D., Freer, M., Moody, A., P, M., 2001. Anthropometric study to update minimum aircraft seating standards. Report Prepared for Joint Aviation Authorities 1–142.

RICHARDS, L.G., JACOBSON, I.D., 1975. Ride quality evaluation 1. Questionnaire studies of airline passenger comfort. Ergonomics 18, 129–150. https://doi.org/10.1080/00140137508931447.

RICHARDS, L.G., JACOBSON, I.D., 1977. Ride quality assessment III: questionnaire results of a second flight programme. Ergonomics 20, 499–519. https://doi.org/10.1080/00140137708931659.

Sammonds, G.M., Fray, M., Mansfield, N.J., 2017. Effect of long term driving on driver discomfort and its relationship with seat fidgets and movements (SFMs). Appl. Ergon. 58, 119–127. https://doi.org/10.1016/j.apergo.2016.05.009.

Stinson, M.D., Porter-Armstrong, A., Eakin, P., 2003. Seat-interface pressure: a pilot study of the relationship to gender, body mass index, and seating position. Arch. Phys. Med. Rehabil. 84, 405–409. https://doi.org/10.1053/apmr.2003.50011.

V, P., 2011. Aircraft Interior Comfort and Design. CRC press, Boca Raton, FL.

Vergara, M., Page, Á., 2002. Relationship between comfort and back posture and mobility in sitting-posture. Appl. Ergon. 33, 1–8. https://doi.org/10.1016/S0003-6870(01)00056-4.

Vink, P., Bazley, C., Kamp, I., Blok, M., 2012. Possibilities to improve the aircraft interior comfort experience. Appl. Ergon. 43, 354–359. https://doi.org/10.1016/j.apergo.2011.06.011.

Zemp, R., Taylor, W.R., Lorenzetti, S., 2015. Are pressure measurements effective in the assessment of office chair comfort/discomfort? A review. Appl. Ergon. 48, 273–282. https://doi.org/10.1016/j.apergo.2014.12.010.