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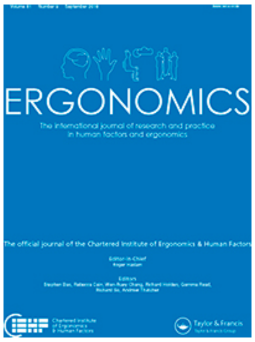

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Measuring pressure distribution under the seat cushion and dividing the pressure map in six regions might be beneficial for comfort studies of aircraft seats

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ABSTRACT
Seat pressure maps are often used to evaluate comfort of the users. In this study, we explored the relationships between pressure maps and comfort/discomfort of users in aircraft seats with a focus on a new 6-division method on the pressure maps collected at the bottom of the cushions. An experiment was designed where three cushions with identical shapes but different stiffnesses were prepared. 33 subjects joined the experiment and after sitting on each cushion in 4 postures, they completed comfort questionnaires. Pressure maps on the top as well as the bottom of cushions were collected and analysed. Results indicated that measures on the proposed 6 divisions, especially on the distal posterior thigh regions and regions close to ischial tuberosity of the bottom pressure maps, had larger correlation values to comfort scores compared to other division methods.

Practitioner summary: The relations between comfort/discomfort and seat pressure maps collected from the top/bottom of three cushions were studied with 33 subjects in four postures. The distal posterior thigh and ischial tuberosity regions in the proposed 6-division of the bottom pressure maps had larger correlation values to comfort/discomfort compared to other methods.

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KEYWORDS
Pressure maps; measures; division; aircraft seat

Introduction

During a flight, train ride or bus ride passengers spend most of their time sitting. Previous research indicated that the perceived sitting comfort and discomfort are of significant importance for passengers when choosing an airline (Hiemstra-van Mastrigt, Meyenborg, and Hoogenhout 2016), and a well-designed seat plays a vital role in enhancing comfort experience of passengers (Ahmadpour, Robert, and Lindgaard 2016).

While sitting, the human body is in direct contact with the seat (cushion) and the interface pressure profile between the body and the seat (cushion), which can be captured by a pressure sensing mat as a pressure map (XSensor 2022; Song and Vink 2021), has relations with the perceived discomfort (De Looze, Kuijt-Evers, and Van Dieën 2003). As the hip joints are often fixed during sitting and the weight is mainly sustained by the bony structure (Floyd and Roberts 1958), distribution of pressure values or pressure distribution in the pressure map is not uniform and a large pressure concentrated area can always be found in the region around the ischial tuberosity (Lay and Fisher 1940), followed by the proximal posterior thigh.

Pressure distributions of people sitting in car seats were studied often to improve comfort of drivers/passengers and reduce potential health risks (Hartung 2005; Zenk et al. 2012; Kilincsoy 2019). Though the backrest recline angle, the posture, and the armrest might influence the supporting forces of a person regarding different seat components while sitting, the seat cushion usually takes 55–95% of the weight (Shen et al. 1999). In the study of Ebe and Griffin (2001), it was found that the 'bottoming feeling' and the 'foam hardness feeling' were two main factors influencing comfort of a seat, which were affirmed by other studies (Vos et al. 2006; Wegner et al. 2019). Zemp, Taylor, and Lorenzetti (2015) showed that less discomfort and higher comfort are related to a lower mean pressure, a lower peak pressure, and a larger contact area(s) of the pressure map. Akgunduz, Rakheja, and Tarczay (2014) also found correlations

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between perceived comfort and the peak and mean pressures on the seat pan.

To highlight the importance of different regions of the seat cushion regarding comfort/discomfort for possible improvements, researchers tried to divide the pressure map into different regions following different criteria. For instance, Kilincsoy (2019) uniformly divided the bounding box of the contact area by a 3×2 grid following the fore-aft and lateral directions, respectively. He found that in the back seat of an SUV, the ideal pressure distribution for comfort can be $<55.8\%$, $<20.0\%$, $<9\%$ reagrding the buttock, the proximal posterior thigh and the distal posterior thigh, respectively. Lantoine et al. (2022) introduced the crotch point as a landmark to divide the bounding box into four regions and they found that the values of contact pressure in the left buttock region were significantly higher than other areas. Table 1 listed the divisions that proposed in previous studies, their application contexts, and the main findings.

Researchers paid extensive effort in using the pressure map measures to explain the perceived comfort/discomfort of users. However, many division methods are subjected to the shape of contact areas regarding different seats, e.g. only a few studies investigated the pressure distribution of aircraft seat regarding comfort (Dangal, Smulders, and Vink 2021); there is no consensus on the use of pressure map measures regarding the perceived comfort/discomfort; and the pressure mat, which uses different materials compared to the upholstery of the seat, is often positioned on the top of the cushion (Moon et al. 2020; Wegner et al. 2020). This limits the comparison of different comfort and discomfort evaluations and it is the question which is most valuable, especially for long-term evaluation.

In this study, we tried to explore the relationships between comfort/discomfort and measures in different regions of pressure maps captured on the top as well as the bottom of the cushion in the context of aircraft seats. The research questions were set as (1) Which division methods and pressure map measures are more suitable for evaluating comfort/discomfort experience of passengers and (2) Can the relationships between comfort/discomfort and the pressure map captured from the bottom of the cushion be established?

Methods

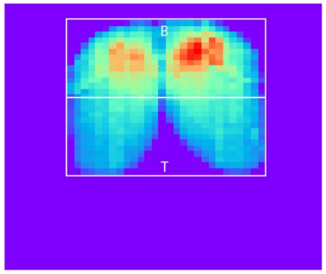
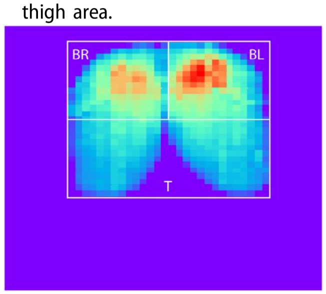
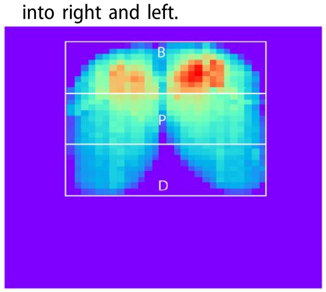
Postures

Passengers experience differences in comfort and discomfort in different postures in an aircraft seat. In the study conducted by Liu et al. (Liu, Yu, and Chu 2019), the different postures and the frequency of occurrences in aircraft cabins were summarised. Four postures were selected for this study (Figure 1): (1) sit with two feet on the ground, hands on lap, both head and back against the backrest; (2) sit with two feet on the ground, back against the backrest, head down to look at the phones/books in hands on lap; (3) sit straight with feet on ground and hands on lap; and (4) sit with feet on the ground, back against the backrest, holding phones in front of the chest and look into the phones. These four postures account for 29.7%, 12.9%, 4.2% and 3.2% of the occurrences, respectively (Liu, Yu, and Chu 2019).

Participants and protocols

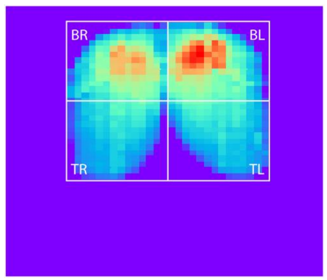
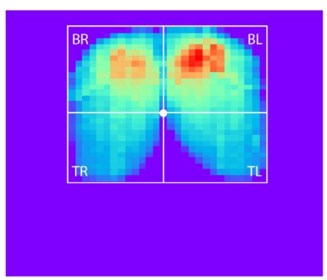
To collect the pressure maps on the top as well as at the bottom of the cushions with these 4 postures, 33 subjects, 18 males and 15 females ageing from 23 to 37 (BMI between 17.6 and 41.3), were invited to a within-subject experiment. Two rows of aircraft seats were used in this experiment to simulate the flying environment. In the 2nd row three self-designed NEVEON® cushions with the same shape but different stiffnesses were evaluated on an economy class seat frame (see Figure 1). The cushions were designed with a depth of 50 cm and a width of 44 cm (17.3 inch). The thicknesses of all cushions were 6 cm. To ensure the fit of the cushions and the frame of a 17-inch-wide seat, two triangular parts (8 and 10 cm for two sides adjacent to the right angle of the orthogonal triangle) were cut off from the upper edges (see Figure 2). All cushions are being used in aircraft seats and cushion A is the softest while cushion C is the hardest. Compression tests were done with Zwick Z010 on three points of each cushion and five times each point. The average displacements under 125 N on the compression platen (Φ 30 mm) are 48.6 mm, 38.1 mm and 31.6 mm. Subjects sat on each cushion for about 12 min. The pressure map of each posture was recorded on the top and at the bottom of the seat cushion using two XSensor LX210:48.48.02 pressure sensing mats (resolution: 48×48 cells, each 1.27 cm $\times$ 1.27 cm). The sequence of the cushions for each participant was altered using the Latin Square method. After experiencing a cushion, participants were asked to complete an overall comfort and discomfort questionnaire (Anjani et al. 2021).

Table 1. Different divisions of the pressure distribution used in past studies.

No. regions (name of the method)	Division methods	Application context	Information of participants	Main outcomes	Literature
2 (2A)	 The pressure map is divided into two equal parts: buttock area and thigh area.	Driver seat	16 Healthy males Age 25.5 ± 2.6 years Height 172.8 ± 5.4 cm Weight 72.3 ± 9.8 kg Driving experience 2.38 ± 2.4 years	It is possible to use the dynamic pressure data as a tool for the assessment of driver discomfort. The pressure measures in different regions change in different driving period.	(Na et al. 2005)
3 (3A)	 The pressure map is divided equally into buttock area and thigh area. The buttock area is divided equally into right and left.	Office chair	18 Participants (9 males, 9 females) Mean age 22.4 (males), 23.8 (females) Height 159–183 cm (males), 158–173 cm (females) Weight 45–82 kg (males), 41–104 kg (females)	The type of sitting posture has significant influence on the pressure distributions in different regions, thus postures in seat can be detected.	(Braun, Frank, and Wichert 2015)
3 (3B)	 The pressure map is equally divided into three parts with two horizontal lines.	Car seat	48 Participants (24 males, 24 females) Age 18–29 years Male height 178–182 cm, weight 72–76 kg Female height 165–169 cm, weight 58–62 kg	Ideal pressure distribution should have 56 ± 7% load at buttock, 30 ± 3.5 at upper thigh, 8 ± 4.4% at lower thigh.	(Hartung 2005)
		School chair	27 Participants (15 males, 12 females) Age 24.37 ± 2.35 years Height 170.19 ± 8.68 cm Weight 69.56 ± 13.9 kg BMI 23.77 ± 2.95	The study investigated the relationships between comfort, human body postures, pressure at interface, and load distribution on the contact area. Measures with the largest correlation is in region D.	(Naddeo, Califano, and Vink 2018)

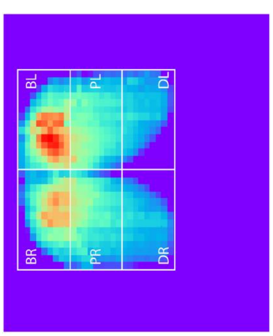
(*continued*)

Table 1. Continued.

No. regions (name of the method)	Division methods	Application context	Information of participants	Main outcomes	Literature
		Aircraft seat	22 Participants (13 males, 9 females) Age 19–29 years BMI P4-P78	The study recorded the pressure map with different cushions and compared the load in each regions. Significant differences were found between pressure measures within the same regions of different cushions.	(Dangal, Smulders, and Vink 2021)
4 (4A)	 The pressure map is divided into 2 × 2 regions equally.	Driver seat	27 Participants (12 males,15 females) Age 20–35 years Weight 69.1 ± 13.1 kg Height 170.7 ± 11.7 cm	The largest correlation between pressure map measures and overall rating was found in region BL.	(Kyung and Nussbaum 2008)
		Office chair	27 Participants (15 males and 12 females) Age 24.37 ± 2.35 years BMI 23.77 ± 2.95	Contributions of different regions are not clear but the study confirmed that the pressure measures are different with different sit pitches.	(Li et al. 2017)
		Aircraft seat	12 Participants (7 males, 5 females) Height 176.2 ± 7.34 cm (males), 163.8 ± 4.9 cm (females) Weight 77.5 ± 13.1 kg (males), 55 ± 5.9 kg (females) BMI 24.8 ± 2.9 (males), 21 ± 2.1 (females)	Seat pitch can significantly influence the contact area of BR region while seat conditions can change the peak pressure in BL,TL and TR regions.	(Zhao et al. 2020)
4 (4B)	 The pressure map is divided into four parts by a vertical and a horizontal line through the crotch point.	Driver seat	20 Participants (10 males, 10 females) Age 27.8 ± 5.6 years Height 1.73 ± 0.1 m Weight 69.9 ± 14.4 kg	The study proposed a division based on the location of crotch. The highest pressure shown in BL region and the largest contact area shown in TR region.	(Lantoine et al. 2022)

(*continued*)

Table 1. Continued.

No. regions (name of the method)	Division methods	Application context	Information of participants	Main outcomes	Literature
6 (6A)	 The pressure map is divided into six parts equally with two horizontal lines and a vertical line.	Car seat	50 Participants (30 males, 20 females) Age 21–53 years Height percentiles 0.1–99.5	Ideally, the load on each region should be 29.5% at buttock, 9.7% at upper thigh and 3.1% at lower thigh on each side of the body.	(Kilincsoy 2019)

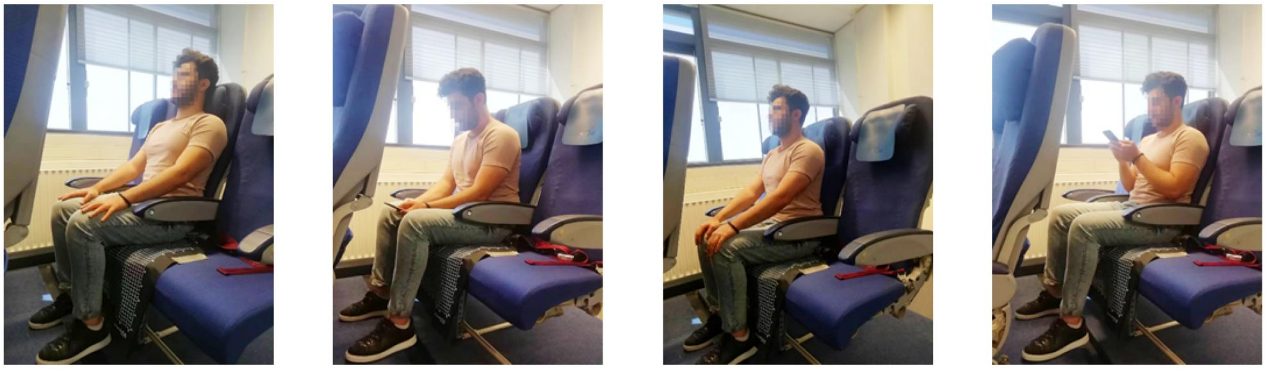
B/T: buttock/thigh region; D/P: distal/proximal posterior thigh region; BL/BR: buttock left/right region; TL/TR: thigh left/right region; DL/DR/PL/RL: distal/proximal posterior thigh left/right.

Data analysis methods

The comfort/discomfort scores of the questionnaires were normalised using the min-max scaling (Gopal, Patro, and Kumar Sahu 2015). To divide the pressure map to different regions, besides the six division methods (2A, 3A, 3B, 4A, 4B, 6A) summarised in Table 1, we proposed a new division (6B, as Figure 3) by combining the six-region division used by Kilincsoy (2019) and the four-region division used by Lantoine et al. (2022). Similar to the work of Lantoine et al. (2022), the highest point on the edge of buttock between two thighs on the pressure map was used as the approximation of the crotch on the upper layer (round dots in Figure 3). The location of crotch on the lower pressure map was defined as the projection of the crotch point on the upper layer. In the bounding box of the contact area, we divided the pressure map to 4 regions using the crotch point. The two posterior thigh regions were further divided by a line in the middle to roughly outline the distal and proximal posterior thigh regions, as Kilincsoy (2019) concluded that the distal posterior thigh might be more sensitive to the proximal side regarding the same pressure.

In Table 2, literature regarding pressure map measures and perceived sitting comfort/discomfort in different contexts is listed. Based on these studies, eight measures were selected for this study: mean pressure, peak pressure, contact area (CA), variance (VA), coefficient of variation (CV), force, load and seat pressure distribution percentage (SPD%). The mean pressure was the mean of all pressure values in the contact area, the peak pressure was calculated as the mean of the five largest pressure values in the contact area. Variance was calculated as the square of standard deviation of pressure values of the valid cells. Coefficient of Variation (CV) was the square root of the variance, i.e. the standard deviation, divided by the mean pressure. The total force applied on the pressure mat can be calculated as the sum of forces applied on all cells (pressure $\times$ area). Load is the ratio between force in each region and the total force. $SPD\% = \sum_1^n (p - \overline{p})^2 / 4n\overline{p}^2 \times 100\%$ (Campos and Xi 2017), where $\overline{p}$ stands for the mean pressure, p stands for the pressure in each valid cell and n is the number of cells in the contact area.

For each subject regarding each cushion, eight pressure recordings (four postures $\times$ the upper and lower) were collected. Using the seven division methods (six in Table 1 and the proposed new method in Figure 3), we computed eight measures of each region of the pressure map. According to Liu, Yu, and Chu



(1) (2) (3) (4)

Figure 1. Four postures selected in this study.

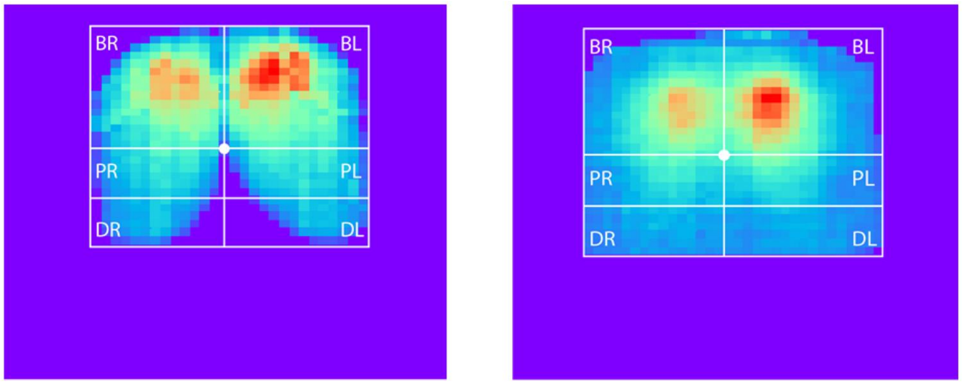
Figure 2. Three cushions with different stiffnesses used in this study (A,B,C from left to right).

(2019), the occurrence of the four postures in a 2-h flight journey account for 29.7%, 12.9%, 4.2% and 3.2% of the total. These percentages were used as weights for the calculation. For each cell in the pressure map regarding four postures, the weighted average pressure value fv was computed as $\mathrm{fv} = \sum_{i=1}^{4} w_i \mathrm{fv}_i / \sum_{i=1}^{4} w_i$. Here $w = [29.7\%,\ 12.6\%,\ 4.2\%,\ 3.2\%]$ and fv_i stands for the pressure values of each posture. For the scores of comfort discomfort questionnaires, Min–Max normalisation (Gopal, Patro, and Kumar Sahu 2015) has been processed with subjective data to show the changes in comfort and discomfort, as compared to use the absolute scores of subjective ratings on comfort/discomfort, using the relative changes of the comfort/discomfort might be less influenced by the background the expectations of subjects (Song and Vink 2021). Pearson correlation coefficients between measured values in different regions and normalised comfort/discomfort scores were calculated regarding all subjects and 3 cushions. Measures with the largest three correlations were highlighted regarding this region.

Results

In Table 3, the mean pressure and its standard deviation (SD) of each posture regarding each cushion are listed. In general, the mean pressure and its SD on the top layer were both larger than that of the bottom layer, whereas for the softest cushion (A), both were the smallest. With the hardest cushion (C), the largest mean pressure was observed both on the top and the bottom pressure maps.

Tables 4–10 present measures with the 3 highest correlations to comfort/discomfort for each division method. The absolute values of correlations (AVC) under 0.1 are not included in these tables. The AVC $\geq$ 0.3 measures are highlighted. Table 4 shows that more AVCs $\geq$ 0.3 were found in the thigh region than the buttock region using method 2A. Compared to discomfort, more AVCs between comfort and pressure parameters are over 0.3. Twelve AVCs are highlighted in Table 5 (method 3A), where the pressure map was divided into right buttock region, left buttock region and thigh region. The highest correlation is 0.447, which was found in the left buttock region. More AVCs $\geq$ 0.3 were found between pressure and comfort both on upper layer and lower layer with division Method 3B (Table 6). For using method 4A (Table 7), results in the buttock regions are similar to that of using the division method 3A (Table 5). The division of the thigh regions suggested that the pressure measures of right thigh might be more correlated to comfort. Results of using the other 2 by 2 division method (4B) are shown in Table 8, in which the division is based on the crotch point. Compare to the uniform division methods, e.g. method 4A in Table 7, more correlations with AVC $\geq$ 0.3 were found. Both the buttock region and the thigh region on the right side show better performance than those of the left. The results of dividing the pressure map into 6 regions equally are shown in Table 9. Most of correlations over 0.3 are in the buttock regions and distal posterior thigh regions. Only 3 out of 22 of them are in proximal posterior thigh regions. The results



(a) Top (b) Bottom

Figure 3. Proposed division (Method 6B) on the top as well as the bottom pressure map.

Table 2. Pressure measures regarding sitting comfort.

context	Pressure measures	Subjective measures	Number of participants	Main outcomes	Literature
Wheelchair	Contact area Mean pressure Peak pressure Peak pressure index Dispersion index	Self-designed questionnaire with questions covering comfort, adaptability and thermal sensation.	22	No clear recommendations regarding measures were given but these measures were used as indicators for evaluating seat cushions and satisfaction.	(García-Molina et al. 2021)
Office chair	Mean pressure Peak pressure Contact area Max pressure gradient	Seat cushion comfort ratings regarding support of the cushion and skin pressure.	16	**Mean pressure** and **peak pressure** are significantly correlated to perceived comfort.	(Li et al. 2020)
School chair	Peak pressure Mean pressure Contact area Load	Local Postural Discomfort in buttock and thigh areas.	27	A positive correlation between perceived discomfort and **contact area** was found.	(Naddeo, Califano, and Vink 2018)
Aircraft seat	SPD%	NA	–	**SPD%** was used as a parameter to indicate sitting comfort and guide seat design.	(Campos and Xi 2017)
Driver seat	Contact force Contact force ratio Peak pressure Mean pressure Contact area	Local Postural Discomfort, stiffness rating and wrapping rating.	8	A strong correlation was found between comfort and **peak pressure** as well as **mean pressure.**	(Akgunduz, Rakheja, and Tarczay 2014)
Surgery seat	Mean pressure Peak pressure Median pressure Standard error Mode Standard deviation variance Contact area	Comfort, Local Postural Discomfort and preference of conditions.	11	Comfort is related to **low peak pressure** and high **contact areas** of the seat pan.	(Noro et al. 2012)
Driver seat	Contact area Contact area ratio Mean pressure Peak pressure Contact pressure ratio	Overall rating, overall comfort, overall discomfort, body region comfort and Local Postural Discomfort.	27	**Contact area** and **contact pressure ratio** could be used for evaluating sitting comfort/discomfort.	(Kyung and Nussbaum 2008)

Table 3. Mean pressure of each posture for each cushion at the top and the bottom (unit: N/cm^2).

	Cushion A top	Cushion A bottom	Cushion B top	Cushion B bottom	Cushion C top	Cushion C bottom
Posture1	0.59 ± 0.08	0.45 ± 0.04	0.65 ± 0.11	0.56 ± 0.05	0.69 ± 0.12	0.57 ± 0.06
Posture2	0.56 ± 0.06	0.42 ± 0.02	0.60 ± 0.09	0.52 ± 0.04	0.63 ± 0.08	0.52 ± 0.04
Posture3	0.55 ± 0.06	0.41 ± 0.02	0.61 ± 0.10	0.52 ± 0.04	0.64 ± 0.09	0.53 ± 0.04
Posture4	0.55 ± 0.06	0.41 ± 0.02	0.60 ± 0.10	0.52 ± 0.04	0.64 ± 0.08	0.52 ± 0.04

of proposed 6-division method (Method 6B) are shown in Table 10. The correlations between pressure measures and (dis)comfort in buttock regions are the same with the results of division method 4B (Table 8). Compared to method 6A (Table 9), more correlations over 0.3 were found in proximal posterior thigh regions, mostly on the right side. In total, 24 correlations were highlighted with the proposed method. Among the 7 division methods, method 6B (Fig.3), had the most measures that had AVCs ≥ 0.3, which were mostly centred on the bottom layer.

Table 4. Highest correlations (5 AVCs ≥ 0.3, in bold) in buttock and thigh regions (Method 2A) on different layers of three cushions.

Buttock region (B)	Upper layer comfort	A: CA	0.208
		B: CA	0.164
		C: CV	0.204
	Upper layer discomfort	A: CV	0.219
		B: CA	−0.164
		C: CA	−0.264
	Lower layer comfort	A: CA	**0.345**
		B: Force	0.197
		C: –	–
	Lower layer discomfort	A: Load	0.163
		B: CA	−0.22
		C: CA	−0.253
Thigh region (T)	Upper layer comfort	A: CA	**0.363**
		B: CA	0.193
		C: CA	0.191
	Upper layer discomfort	A: CA	−0.154
		B: VA	**0.335**
		C: SPD%	0.267
	Lower layer comfort	A: Force	**0.34**
		B: CA	**0.318**
		C: Peak	0.104
	Lower layer discomfort	A: Force	−0.185
		B: Load	0.17
		C: CA	−0.195

CA: contact area, VA: variance, CV: coefficient of variance, SPD%: seat pressure distribution percentage.

Discussion

In this study, we tried to explore the relationships between the perceived comfort/discomfort and different measures in different divisions of the pressure maps, which were collected on the top as well as at the bottom of three different cushions. We synthesised 4 postures in comfort evaluation and calculating pressure map measures. And a new division method (6B) was proposed based on landmarks as well as the knowledge that the proximal and distal posterior thigh has different sensitivity regarding the same load (Kilincsoy 2019; Hirao, Naito, and Yamazaki 2022).

The proposed division method

Comparing method 4B and 6B, in which the only difference is whether the distal posterior thigh is separated, the number of measures with AVCs ≥ 0.3 in the thigh area and the distal posterior area are the same on the bottom layer. The high correlation values in the distal posterior thigh (Region 5, 6 in division 6A and 6B) also affirmed the findings. This is also in accordance with the work of Vink and Lips (2017) who

Table 5. Highest correlations (12 AVCs ≥ 0.3, in bold) in buttock right, buttock left and thigh regions (Method 3A) on different layers of three cushions.

Buttock right region (BR)	Upper layer comfort	A: Load	**−0.441**	Upper layer comfort	A: Force	0.285	Buttock left region (BL)
		B: Load	−0.243		B: Force	**0.447**	
		C: CV	0.19		C: Load	−0.227	
	Upper layer discomfort	A: Load	**0.351**	Upper layer discomfort	A: CV	0.234	
		B: CA	−0.212		B: Force	**−0.342**	
		C: CA	−0.289		C: CA	−0.229	
	Lower layer comfort	A: Mean	0.254	Lower layer comfort	A: CA	**0.431**	
		B: CA	0.204		B: Force	0.295	
		C: –	–		C: –	–	
	Lower layer discomfort	A: CA	−0.112	Lower layer discomfort	A: Force	−0.122	
		B: CA	**−0.319**		B: CV	**−0.399**	
		C: Mean	**0.345**		C: CA	−0.218	
Thigh region (T)	Upper layer comfort	A: CA		**0.363**			
		B: CA		0.193			
		C: CA		0.191			
	Upper layer discomfort	A: CA		−0.154			
		B: VA		**0.335**			
		C: SPD%		0.267			
	Lower layer comfort	A: Force		**0.34**			
		B: CA		**0.318**			
		C: Peak		0.104			
	Lower layer discomfort	A: Force		−0.185			
		B: Load		0.17			
		C: CA		−0.195			

CA: contact area, VA: variance, CV: coefficient of variance, SPD%: seat pressure distribution percentage.

Table 6. Highest correlations (9 AVCs $\geq$ 0.3, in bold) in buttock, proximal posterior thigh and distal posterior regions (Method 3B) on different layers of three cushions.

Buttock region (B)	Upper layer comfort	A: Load	**−0.305**
		B: CA	0.162
		C: CV	0.272
	Upper layer discomfort	A: CA	−0.242
		B: CA	−0.148
		C: CA	−0.273
	Lower layer comfort	A: CA	**0.425**
		B: Load	−0.178
		C: Load	−0.122
	Lower layer discomfort	A: CA	−0.244
		B: CA	−0.223
		C: CA	**−0.306**
Proximal posterior thigh(P)	Upper layer comfort	A: CA	**0.351**
		B: CA	0.205
		C: Peak	0.213
	Upper layer discomfort	A: CV	0.296
		B: Mean	0.136
		C: CA	−0.203
	Lower layer comfort	A: Mean	**0.305**
		B: CA	0.246
		C: Force	0.134
	Lower layer discomfort	A: SPD%	0.199
		B: CA	−0.155
		C: CA	−0.142
Distal posterior thigh(D)	Upper layer comfort	A: CA	**0.347**
		B: CA	0.168
		C: CA	0.209
	Upper layer discomfort	A: CA	−0.138
		B: VA	**0.375**
		C: CA	−0.234
	Lower layer comfort	A: VA	**0.312**
		B: CA	**0.327**
		C: Peak	0.11
	Lower layer discomfort	A: VA	−0.213
		B: Mean	0.156
		C: CA	−0.206

CA: contact area, VA: variance, CV: coefficient of variance, SPD%: seat pressure distribution percentage.

concluded the feeling in the distal posterior thigh of both legs are essential as the sensitivity of the lower thigh parts are significantly higher than other parts touching the seat pan, most probably due to that in this area the blood vessels and nerves are 'unprotected' and soft tissue can be easily deformed.

In this study, the highest value of correlation showed up in the left buttock area of 4B and 6B methods. This is in accordance with Kyung and Nussbaum(2008). In their study, the pressure map of a driver seat cushion was divided using method 4A. The correlations between 39 pressure measures (including different regions on seat pan and backrest) of the driver seat cushion and whole-body comfort rating were calculated. The ratio between average regional pressure of left buttock and average total pressure had the largest correlations with comfort. Zhao et al.(2020) also used the method 4A in their study and the highest correlation they achieved in their study is 0.307, which is between the peak pressure of left thigh region and the subjective ratings. Both works from Kyung and Nussbaum(2008) and Zhao et al.(2020) found the highest correlations in regions on the left. Similarly, more correlations with AVCs $\geq$0.3 were found on the left in this study with methods 4A, 4B, 6A and 6B. The consistency may indicate that maybe because of 90% of population are right hand dominant, humans tend to put more weight on the left part of the seat. This could explain more correlations with discomfort. Another research studied the correlations between global pressure measures and regional comfort (Fang, Gao, and Xie 2015), in which the driver seat pan pressure map was divided equally into three regions (3B). Values of the correlations varied from −0.426 to 0.253, which is comparable to our study.

Top and bottom pressure maps

Comparing the pressure map of the top to the bottom, the regions with high correlation values differ. The foam cushion dissipates the weight of the user towards the seat pan (Lam et al. 2018), resulting in a larger contact area, less mean pressure values and less noise at the bottom pressure map. The force applied by the distal posterior thigh is not large, therefore not prominent in the pressure map at the bottom. For instance, with the 6A division method, 7 AVCs $\geq$ 0.3 measures in the distal posterior thigh area were found on the top layer while only 3 AVCs $\geq$ 0.3 were found in the same area on the bottom layer. When the pressure map is divided uniformly, the performance on the bottom layer decreased as the number of regions grow. Dividing the pressure map base on the location of the crotch can solve this problem since the anatomy of human being can still be reflected on the map. For instance, using the 6B division, there are 2 AVCs $\geq$ 0.3 measures in the distal posterior thigh area, 3 in the proximal posterior thigh on the top map, for the bottom, the numbers are 6 and 4. Also, the measures of bottom pressure map had larger correlation values to comfort than discomfort. This finding indicates the potential of using pressure maps collected from the bottom of a cushion for long-term comfort studies, as in this spatial configuration, the materials of the pressure sensing mats will probably not influence the comfort experience of users as users will 'feel' the normal upholstery and the foam might allow moisture to pass through. Additionally, it might be that the bottom pressure mat had smaller

Table 7. Highest correlations (17 AVCs ≥ 0.3, in bold) in buttock right, buttock left, thigh right and thigh left regions (Method 4A) on different layers of three cushions.

Buttock right region (BR)	Upper layer comfort	A: Load	**−0.441**	Upper layer comfort	A: Force	0.285	Buttock left region (BL)
		B: Load	−0.243		B: Force	**0.447**	
		C: CV	0.19		C: Load	−0.227	
	Upper layer discomfort	A: Load	**0.351**	Upper layer discomfort	A: CV	0.234	
		B: CA	−0.212		B: Force	**−0.342**	
		C: CA	−0.251		C: CA	−0.123	
	Lower layer comfort	A: Mean	0.254	Lower layer comfort	A: CA	**0.431**	
		B: CA	0.204		B: Force	0.295	
		C: –	–		C: –	–	
	Lower layer discomfort	A: CA	−0.118	Lower layer discomfort	A: Force	−0.122	
		B: CA	**−0.319**		B: CV	**−0.399**	
		C: Mean	**0.345**		C: CA	−0.218	
Thigh right region (TR)	Upper layer comfort	A: CA	**0.352**	Upper layer comfort	A: CA	**0.364**	Thigh left region (TL)
		B: SPD%	**0.318**		B: CA	0.194	
		C: SPD%	**0.33**		C: CA	0.147	
	Upper layer discomfort	A: CA	−0.169	Upper layer discomfort	A: CA	−0.136	
		B: VA	**0.302**		B: VA	**0.318**	
		C: SPD%	0.29		C: CA	−0.129	
	Lower layer comfort	A: VA	**0.308**	Lower layer comfort	A: Force	**0.384**	
		B: CA	**0.354**		B: CA	0.267	
		C: Load	0.158		C: Force	0.121	
	Lower layer discomfort	A: Mean	−0.185	Lower layer discomfort	A: Force	−0.194	
		B: CA	−0.219		B: Load	0.26	
		C: CA	−0.231		C: SPD%	−0.239	

CA: contact area, VA: variance, CV: coefficient of variance, SPD%: seat pressure distribution percentage.

Table 8. Highest correlations (21 AVCs ≥ 0.3, in bold) in buttock right, buttock left, thigh right and thigh left regions (Method 4B) divided based on crotch location on different layers of three cushions.

Buttock right region (BR)	Upper layer comfort	A: Mean	**0.376**	Upper layer comfort	A: SPD%	0.264	Buttock left region (BL)
		B: Mean	−0.229		B: Force	**0.453**	
		C: CV	0.251		C: Peak	0.13	
	Upper layer discomfort	A: Load	0.234	Upper layer discomfort	A: Load	**0.471**	
		B: Mean	0.161		B: Force	−0.144	
		C: Load	0.278		C: Mean	−0.138	
	Lower layer comfort	A: Force	**0.403**	Lower layer comfort	A: Peak	0.181	
		B: CA	**0.328**		B: CA	**0.398**	
		C: Force	**0.422**		C: CA	**0.31**	
	Lower layer discomfort	A: Force	−0.102	Lower layer discomfort	A: CV	0.274	
		B: CV	**0.357**		B: CA	−0.135	
		C: Mean	**0.313**		C: Force	−0.127	
Thigh right region (TR)	Upper layer comfort	A: Force	0.166	Upper layer comfort	A: VA	0.176	Thigh left region (TL)
		B: Load	−0.174		B: Load	−0.174	
		C: SPD%	**0.373**		C: –	–	
	Upper layer discomfort	A: Force	**−0.3**	Upper layer discomfort	A: CV	0.12	
		B: VA	**0.388**		B: Mean	**0.359**	
		C: VA	0.236		C: CV	**0.323**	
	Lower layer comfort	A: Mean	0.254	Lower layer comfort	A: Mean	**0.301**	
		B: Load	**−0.345**		B: Mean	**0.431**	
		C: VA	**0.322**		C: Mean	**0.367**	
	Lower layer discomfort	A: Force	**−0.353**	Lower layer discomfort	A: Mean	−0.187	
		B: SPD%	0.123		B: Peak	−0.194	
		C: Peak	−0.154		C: Mean	−0.292	

CA: contact area, VA: variance, CV: coefficient of variance, SPD%: seat pressure distribution percentage.

peak pressure values and is less sensitive to unexpected damages.

Measures of the pressure maps

The largest correlation between pressure map measures and comfort/discomfort is the load with a value of 0.471, which show up in the left buttock area in 4B and 6B. The absolute value is comparable to the study of Fang, Gao, and Xie (2015), in which 28 correlations with values between −0.426 to 0.253 were found between pressure parameters and comfort (overall and regional) in a driver seat. In general, CA (31 time > 0.3), Force (23 times > 0.3), and Mean (17 times >

Table 9. Highest correlations (21 AVCs ≥ 0.3, in bold) in buttock right, buttock left, proximal posterior thigh right, proximal posterior thigh left, distal posterior thigh right and distal posterior thigh left regions (Method 6A) on different layers of three cushions.

Buttock right region (BR)	Upper layer comfort	A: Load	**−0.441**	Upper layer comfort	A: Force	0.285	Buttock left region (BL)
		B: Load	−0.243		B: Force	**0.447**	
		C: CV	0.189		C: Load	−0.214	
	Upper layer discomfort	A: Load	**0.351**	Upper layer discomfort	A: CV	0.234	
		B: CA	−0.212		B: Force	**−0.342**	
		C: Mean	0.271		C: CA	−0.17	
	Lower layer comfort	A: Mean	0.254	Lower layer comfort	A: CA	**0.431**	
		B: CA	0.204		B: Force	0.295	
		C: –	–		C: –	–	
	Lower layer discomfort	A: CA	−0.118	Lower layer discomfort	A: Force	−0.122	
		B: CA	**−0.319**		B: CV	**−0.399**	
		C: Mean	**0.345**		C: CA	−0.218	
Proximal posterior thigh right region (PR)	Upper layer comfort	A: CA	**0.325**	Upper layer comfort	A: CA	**0.365**	Proximal posterior thigh left region (PL)
		B: CA	0.202		B: Peak	0.212	
		C: VA	0.24		C: CV	0.154	
	Upper layer discomfort	A: CV	0.268	Upper layer discomfort	A: CV	0.299	
		B: Mean	0.173		B: –	–	
		C: CA	−0.2		C: Load	0.193	
	Lower layer comfort	A: Mean	0.264	Lower layer comfort	A: Force	**0.334**	
		B: CA	0.273		B: Peak	0.275	
		C: Mean	0.174		C: Force	0.12	
	Lower layer discomfort	A: SPD%	0.148	Lower layer discomfort	A: CV	0.192	
		B: CA	−0.253		B: CV	−0.265	
		C: SPD%	0.222		C: Load	0.116	
Distal posterior thigh right region (DR)	Upper layer comfort	A: CA	**0.352**	Upper layer comfort	A: CA	**0.364**	Distal posterior thigh left region (DL)
		B: SPD%	**0.318**		B: CA	0.194	
		C: SPD%	**0.327**		C: CA	0.139	
	Upper layer discomfort	A: Force	−0.161	Upper layer discomfort	A: CA	−0.136	
		B: VA	**0.302**		B: VA	**0.318**	
		C: Load	0.236		C: SPD%	**0.364**	
	Lower layer comfort	A: VA	**0.308**	Lower layer comfort	A: Force	**0.384**	
		B: CA	**0.354**		B: CA	0.267	
		C: Load	0.158		C: Force	0.121	
	Lower layer discomfort	A: Mean	−0.185	Lower layer discomfort	A: Force	−0.194	
		B: CA	−0.219		B: Load	0.26	
		C: CA	−0.231		C: SPD%	−0.239	

CA: contact area, VA: variance, CV: coefficient of variance, SPD%: seat pressure distribution percentage.

0.3) are the most prominent measures. This is in accordance with findings of Naddeo, Califano, and Vink (2018) and Li et al. (2020). However, in study done by Zhao et al. (2020), the highest correlation was found between the peak pressure of left thigh and overall discomfort. This could be an indication that using single pressure parameter for comfort and discomfort evaluation might not be sufficient. The fluctuating performance of individual measures regarding different stiffnesses of the cushions implies that synthesising multiple measures in predicting comfort/discomfort can be an important topic to study in future research.

Pressure measurement vs (dis)comfort

The pressure distribution is essential for studying both comfort and discomfort of the aircraft seats. Many AVCs ≥ 0.3 measures were found between the recordings and discomfort, which is accordance with the literature (Na et al. 2005; Kyung and Nussbaum 2008; Zhao et al. 2020). However, more AVCs ≥ 0.3 measures between the recordings and comfort, especially on the bottom layer, were found which is in accordance with the work of Vink and Hallbeck (2012) that physical aspects are still an important construct of comfort. Moderate correlations were found between (dis)comfort and pressure parameters, which is in accordance with previous studies (Fang, Gao, and Xie 2015; Li et al. 2020; Zhao et al. 2020). These findings highlight the importance of pressure distribution in studying comfort. On the other side, comfort has a multifactorial construct (Mansfield et al. 2020) and objective measurements on other factors such as anthropometry, heart rate variability, electromyography and skin temperature can also reflect comfort of the subjects (Song & Vink, 2021). A proper integration of different measurements is recommended for a better understanding of sitting (dis)comfort.

Table 10. Highest correlations (25 AVCs ≥ 0.3 , in bold) in buttock right, buttock left, proximal posterior thigh right, proximal posterior thigh left, distal posterior thigh right and distal posterior thigh left regions (6B) divided based on crotch location on different layers of three cushions.

Buttock right region (BR)	Upper layer comfort	A: Force	**0.376**	Upper layer comfort	A: SPD%	0.264	Buttock left region (BL)
		B: Mean	−0.229		B: Force	**0.453**	
		C: CV	0.251		C: Peak	0.13	
	Upper layer discomfort	A: Load	0.234	Upper layer discomfort	A: Load	**0.471**	
		B: Mean	0.161		B: Force	−0.144	
		C: Load	0.278		C: Mean	−0.138	
	Lower layer comfort	A: Force	**0.403**	Lower layer comfort	A: Mean	0.196	
		B: CA	**0.328**		B: CA	**0.398**	
		C: Force	**0.422**		C: CA	**0.309**	
	Lower layer discomfort	A: Force	−0.102	Lower layer discomfort	A: CV	0.274	
		B: CV	**0.357**		B: CA	−0.135	
		C: Mean	**0.313**		C: Force	−0.127	
Proximal posterior thigh right region (PR)	Upper layer comfort	A: Force	0.158	Upper layer comfort	A:–	–	Proximal posterior thigh left region (PL)
		B: Load	−0.249		B: Load	−0.131	
		C: Force	0.115		C: –	–	
	Upper layer discomfort	A: Force	**−0.327**	Upper layer discomfort	A: Force	−0.113	
		B: Mean	**0.36**		B: Mean	**0.307**	
		C: SPD%	0.289		C: VA	0.269	
	Lower layer comfort	A: Mean	0.255	Lower layer comfort	A: Mean	0.283	
		B: CV	**−0.321**		B: Mean	**0.349**	
		C: Load	−0.286		C: CA	−0.273	
	Lower layer discomfort	A: Force	**−0.358**	Lower layer discomfort	A: Mean	−0.168	
		B: VA	0.266		B: –	–	
		C: CV	**0.34**		C: Mean	−0.161	
Distal posterior thigh right region (DR)	Upper layer comfort	A: Mean	−0.235	Upper layer comfort	A: CV	0.26	Distal posterior thigh left region (DL)
		B: Load	−0.232		B: Force	−0.204	
		C: Mean	−0.235		C: CV	0.26	
	Upper layer discomfort	A: CA	−0.286	Upper layer discomfort	A: CV	0.227	
		B: VA	**0.402**		B: VA	**0.352**	
		C: CA	−0.222		C: CA	−0.14	
	Lower layer comfort	A: Mean	0.213	Lower layer comfort	A: Mean	**0.302**	
		B: CA	**−0.35**		B: Mean	**0.419**	
		C: VA	**0.435**		C: Mean	**0.353**	
	Lower layer discomfort	A: Force	**−0.338**	Lower layer discomfort	A: VA	−0.209	
		B: Peak	−0.151		B: Peak	−0.231	
		C: VA	−0.296		C: Mean	−0.285	

CA: contact area, VA: variance, CV: coefficient of variance, SPD%: seat pressure distribution percentage.

Limitations

The population age of this study is between 23 and 37. Children, young persons and older adults were not included. Also, the sitting time was short and it is known that sitting longer increases discomfort (e.g. Smulders et al. 2016) and higher correlations over time might have been found. However, it is difficult to evaluate the long-term comfort of a cushion with a pressure mat on the top, which is also a support for using pressure mats under the cushion. The thickness of cushions used in this study were 6 cm. The results might change if cushions with different thickness and hardness are used. Also, the seat pan that was used was relatively flat, which was needed because of the bottom pressure mat. A pressure mat can also not be curved that much as it creates a pressure value just by bending the material, which we wanted to avoid. A curved seat pan might have different comfort experiences, but was not used, which might be a limitation as well. Besides, the study focussed on aircraft seats which limited the possibility of movement and made generalisation to other areas limited.

Conclusion

In this study, we explored the comfort/discomfort experience regarding different divisions and measures of pressure maps collected on both the top and bottom of three different cushions. Based on literature, a new division method based on the location of the crotch point to divide buttock, proximal and distal posterior thigh on both sides was explored. This six-region division of the pressure map gives more information, especially on the bottom layer which shows a potential for further use in comfort studies. Among all the regions, pressure measures under the distal posterior thigh area have strong relationships with comfort and discomfort, especially the relationship with comfort on the bottom layer. For the area around the ischial tuberosity, pressure maps collected under the cushion seem to give more information related to comfort/discomfort, which highlights the potential of using this spatial configuration for long-term comfort studies.

Ethics statement

The experiment setup and the protocol were approved by the Human Research Ethical Committee (HREC) of Delft University of Technology under file number 1228. Consent forms were signed by all subjects.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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