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Implementing spring-foam technology to design a lightweight and comfortable aircraft seat-pan

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Abstract

This paper investigates whether spring-foam technology in an aircraft seat-pan can reduce weight and at the same time provide equal or better comfort. Firstly, through literature studies and using an iterative design process a prototype seat-pan was designed and developed using spring-foam technology. The (dis)comfort of this seat was compared with a standard aircraft seat-pan. Twenty-two participants were asked to sit in each seat for 90 min, completing a questionnaire every 15 min. At the end of each seating session pressure map recordings were made of the seat-pans. The results showed that the prototype seat-pan has on average a significantly higher comfort for the first 30 min and at a 60 min recording than the standard seat-pan. The discomfort and long-term comfort were not significantly influenced. The pressure distribution on the prototype seat-pan was significantly closer to an ideal pressure distribution than a conventional seat-pan. In addition, the prototype seat-pan had a significantly larger contact area and lower average pressure. The seat-cushion weighs 20% less than the conventional seat-cushion. The study indicates that a seat-pan design using spring-foam technology can be lighter and more comfortable than conventional foam cushion materials. It is recommended to optimize the prototype seat further and conduct long term (dis)comfort studies with a broader variation in subjects' age.

Keywords: Pressure distribution, Comfort, Aircraft seat, Ideal seat contour

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1. Introduction

Air travel demand is estimated to double over 20 years (IATA, 2016). Even with such an increment, as a measure to mitigate global warming, the International Civil Aviation Organization aims to reduce 50% of the aviation emissions by 2050 (Maurice and Lee, 2009). One way to reduce emissions would be to decrease the overall weight of an airplane (Ordoukhanian and Madni, 2014), which decreases fuel burn and associated emissions, and additionally saves fuel costs for airlines. Especially for long haul flights the impact of weight saving is high and therefore interesting (Filippone, 2012). Apart from weight savings, passenger comfort is important as well to airlines, as it is one of the decisive factors for passengers to "fly again with same airline" (Vink et al., 2012). Vink et al. (2012) and Amirpour et al. (2014) showed that seat comfort is one of the most influencing factors in overall passenger comfort, especially on long-haul flights (Vink and Brauer, 2011). Therefore, increasing the seat-pan comfort is valuable for airline companies. For comfort, the second most important element of the seat is the seat cushion of seat-pan (after legroom) (Nijholt et al., in press) and there are opportunities to increase comfort and reduce weight by using spring foam technology. Spring foam technology is a relatively new range of specially fabricated foams. Octaspring is first described in a patent by Poppe (1980). It is a type of spring foam manufactured in eight ("octa") sided tubes with lattice holes throughout the structure (see Fig. 1). These can then be close-packed to create a layer that can be encased to form a structure such as a seat cushion. This type of spring foam is readily used in bed mattresses and is easily available. Due to its availability and being already used in other products, Octaspring spring foam is used for this study. This tubular spring foam is lighter than traditional foam structures with similar firmness. By using different foam densities in the foam springs, it is possible to create different firmnesses of springs and the modular nature of spring-foams allows firmness to vary across the seat. The literature indicates that the firmness should differ for the various contact areas between the seat and human body to have an optimal comfort experience (Goossens et al., 2005; Vink and Lips, 2017; Zenk et al., 2006). In addition, due to its "hollow" design, spring foams could be more efficient at moisture transport (i.e. have better breathability) than standard foam. This "breathability" quality in seats has a positive correlation with thermal comfort (Bartels, 2003). These properties mean spring foam technology provides a potential replacement for current moulded foams, which could increase comfort as well as reduce weight. However, no scientific study has been conducted to determine its effect on comfort and the weight savings when compared with traditional foams.

The first research question of this paper is: can a spring-foam technology in an aircraft seat-pan reduce weight and at the same time provide equal or better comfort? Therefore, a new seat-pan was designed and tested against a traditional seat-pan. In order to design the new seat-pan, firstly, literature is studied on pressure distribution, contour and firmness to determine the parameters for spring-foam cushion.

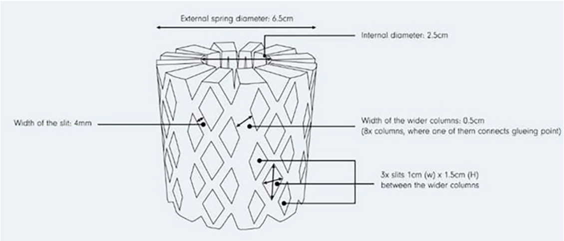


Fig. 1. Spring foam unit.

1.1. *Ideal pressure distribution*

The correlation between the pressure distribution and comfort in car seats has been indicated by various papers (Mergl, 2006; Zenk et al., 2006; Fang et al., 2016). Fig. 2 shows an ideal pressure distribution for a car seat by Mergl (2006). An aircraft seat providing this ideal pressure distribution could result in higher passenger comfort and lower discomfort. The study was conducted with seats in which foam elements of different densities were placed to develop a pressure distribution close to the ideal one.

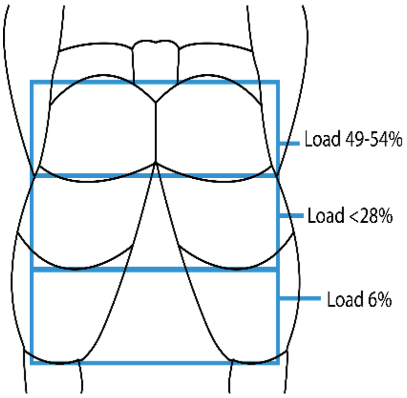


Fig. 2. Ideal pressure distribution for car seat according to Mergl (2006).

1.2. *Ideal contour*

There are indications that a seat contour resulting in a large contact area is correlated to more comfort (Fang et al., 2016; Zemp et al., 2015; Looze et al., 2003; Franz et al., 2011). One way to achieve this would be to use soft foam in the cushion to let the foam follow the entire contour shape of the user's buttocks. However, this means using large volumes of foams; resulting in increased weight. Another option would be to use a shaped contour shell derived from the human body and use inflatable cushions to fill gaps between P5 female to P95 male (Franz et al., 2011). Similarly, Smulders et al. (2016) showed that lower mean pressure between human and seat-pan could be achieved by using a human contour shaped aircraft seat. It can be assumed that spring-foam can also act as cushioning material to produce a similar effect.

Hiemstra-van Mastrigt (2015) described seat contours based on participants with a large variety in anthropometric dimensions (see Fig. 3). Wang et al. (2018) used cylinder pistons to create a contour profile based on an optimal pressure distribution. These profile models where used as qualitative guidance for the prototype seat-pan contour.

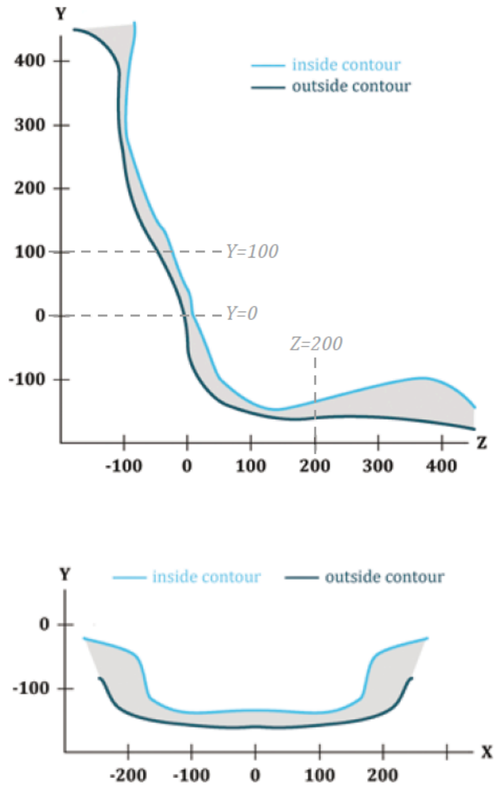


Fig. 3. Contour profile side view (top) and front view (bottom) (from Hiemstra-van Mastrigt, 2015) (n = 12).

1.3. Firmness

In general, a softer cushion (lower stiffness) is often considered more comfortable than a firmer cushion (Ebe and Griffin, 2001; Fang et al., 2016). A soft cushion also increases contact area (Fang et al., 2016) and increases tolerable sitting time (Wang et al., 2014). However, a very soft cushion which is not thick may not be able to support heavy loads and has an increased chance of bottoming (buttocks "feeling" the hard bottom plate of the seat), leading to discomfort (Ebe and Griffin, 2001). In addition to the overall firmness of the cushion, the sensitivities of the buttocks and the upper leg differ, with the front thigh being more sensitive than the middle and back (Vink and Lips, 2017). This might mean that, the firmness should differ for the various contact areas between the seat and the human body to give the occupant an optimal comfort experience with a firmer cushion in less sensitive areas and softer in more sensitive areas (Smulders et al., 2016).

1.4. Spring foam seat-cushion

The decisions on design parameters such as the number of layers (see Fig. 5), exact firmness distribution (see Fig. 4) and exact contour (see Fig. 6) are guided by the literature from §1.1 to §1.3. The form of the seat shell follows the 'outer contour' described by Hiemstra-van Mastrigt (2015). Various foam configurations were made and adapted based on user feedback and pressure distribution recordings. It is recognised that these parameters may not yet be optimal. However, if a prototype seat pan results in an increase in comfort, it opens possibilities to improve the seat further to make it more lightweight and more comfortable.

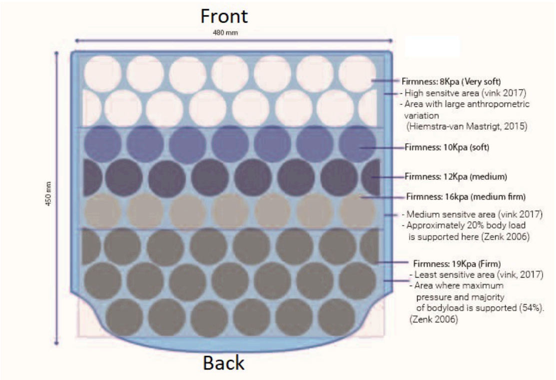


Fig. 4. Top-view representing the firmness distribution of spring-foam in the prototype seat-pan. Please note that the given firmness value (kPa) is taken before the foam is manufactured into a spring-foam. The actual firmness of a spring-foam is half of the stated firmness.

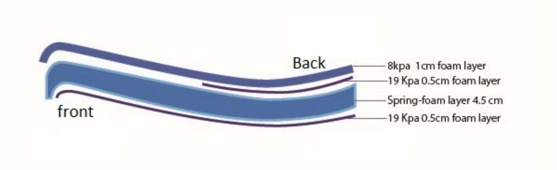


Fig. 5. Side-view of the prototype seat-pan showing the layer composition of different foams.

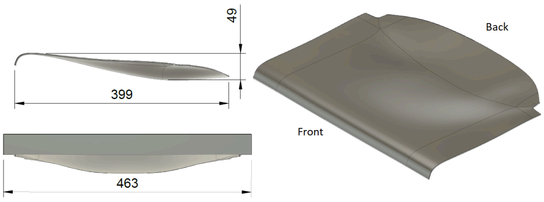


Fig. 6. Seat-pan contour for baseplate underneath the cushioning, side view (bottom left), back view (top left), orthographic view (right).

2. Method and materials

2.1. Study setup

Two prototype seat-pans (see Fig. 7) were developed using the specifications mentioned in §1.4 and covered with a thin white fabric. Hard foam was machined to the contour in Fig. 6 to form the base of the seat-pan. This was attached firmly to the seat frame (Recaro 3510 A) and the prototype seat cushion was firmly attached to the seat-pan base. Both attachments were done with double sided foam tapes (Tesa 4952). Additionally, the upholstery of two Recaro economy class seat-pans (Recaro F2RE0134) was replaced with the thin white upholstery in order to minimize visual influence during the study. These seat-pans were used as a reference condition in the study.

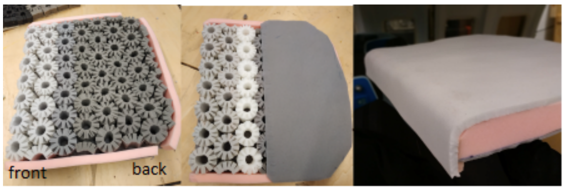


Fig. 7. Seat prototype. Spring-foam distribution (left), firm layer addition (centre), final cushion without upholstery (right).

The study was conducted in a Boeing 737-500 airplane cabin at the campus of the Delft University of Technology to simulate a realistic inflight sitting experience. Temperature and humidity were kept at a typical aircraft cabin temperature between 19-23◦ (Space et al., 2000) and a humidity of 40–50% respectively. This was done by setting the temperature of on-board heaters to 22 ◦C and (de)humidifier to 45%. The temperature and humidity was crosschecked every 15 min next to each participant during the study using a Roline A1 temperature and humidity sensor.

The seat pitch was set to 74 cm (29") and the seat pan height to 51 cm. All the seat backrests were fixed in the Taxi, Take-off and Landing (TTL) position (the most upright position in the seat). The four seats were placed at the window sides to keep the environmental variable constant for all subjects in each seat (see Fig. 8). Two XSENSOR LX100 pressure mats were calibrated and used for measuring the pressure distribution in each seat for each participant. The questionnaire document and pen were placed in the seat pocket and the subjects were allowed to take either a phone or a book with them. Subjects were requested to conduct the same activity in both seats (e.g. use the phone or book in both seats).

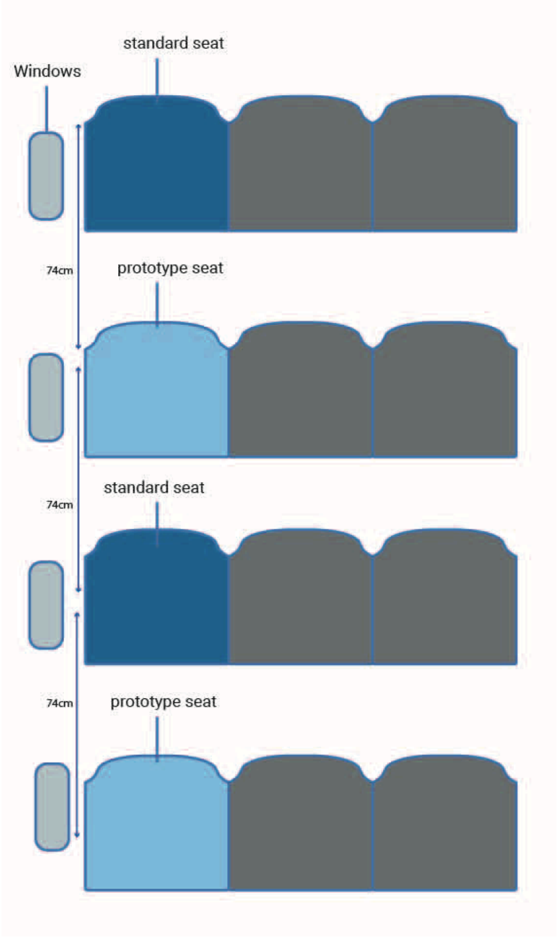


Fig. 8. Seating setup in the Boeing 737-500 fuselage.

2.2. *Participants*

During the recruitment process, any interested participant was asked to report their weight, stature and gender. Using this information, 22 participants (13 male, 9 female) aged between 19 and 29 years were selectively chosen to have a large distribution of stature and Body Mass Index (BMI), ranging from P4 female to P78 male (see Table 1) (percentiles based on DINED Dutch adults, 2014 (Molenbroek, 2004)).

Table 1 Anthropometric measurements of subjects.

	N		Mean	SD	Range
Male	13	Weight [kg]	75.3	8.5	28.2
		Stature [cm]	179.68	9.34	32.3
		BMI	23.45	3.15	10.6
Female	9	Weight [kg]	62.20	10.16	32.3
		Stature [cm]	165.31	7.39	25
		BMI	23.00	5.01	14.51
All	22	Weight [kg]	69.95	11/13	50
		Stature [cm]	173.80	10/84	40
		BMI	23.26	3.91	14.51

2.3. *Procedure*

The study was conducted with up to four participants per session, each seated on either a standard or prototyped seat-pan. The order was systematically changed among participants. Before the study, subjects were informed on the procedure and were asked to sign a consent form. After signing, participants' anthropometric measurements were determined following the DINED procedure (Molenbroek, 2004).

Each participant was seated in both the standard and prototype seat-pan for 1.5 hours. Drinks and snacks were provided around the 45-min mark by an actor playing a Flight Attendant (see Fig. 9). During the study, the participants were not allowed to talk or stand, change the backrest position or use the tray table, but were allowed to read a book, or use a cell phone, or rest during the study. After the end of first round, there was a 10 min break before the second round was conducted. At the end of each round, a recording of the pressure distribution on the seat-pan was made of each participant with the XSENSOR LX100 pressure mat.

Fig. 9. An actor playing a flight attendant serving drinks and snacks.

2.4. *Measurements*

2.4.1. *Local perceived discomfort measurement*

Discomfort was recorded using a modified version of the local perceived discomfort (LPD) method (Van der Grinten and Smitt, 1992). A body map consisting of 7 regions (see Fig. 10) was presented in the questionnaire in which participants were asked to give a score on a LIKERT scale ranging from 1 to 7 (1 = ‘no discomfort’; 7 = ‘severe discomfort’). Participants were asked to complete the LPD questionnaire at the first contact (t = 0 min) and after every 15 min during the 1.5 h (t = 0, t = 15, t = 30, t = 45, t = 60, t = 75, t = 90 min). The difference in discomfort of each body part was tested between the two seats using a Wilcoxon signed rank test ($p < 0.05$) for paired observations (IBM SPSS Statistics 25); this analysis was conducted at each time interval.

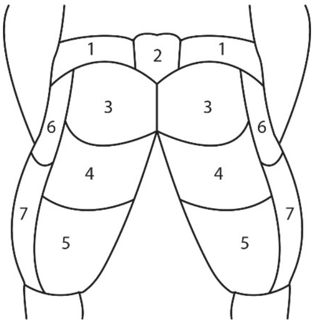


Fig. 10. Body Map to measure LPD.

2.4.2. *Comfort and discomfort measurement*

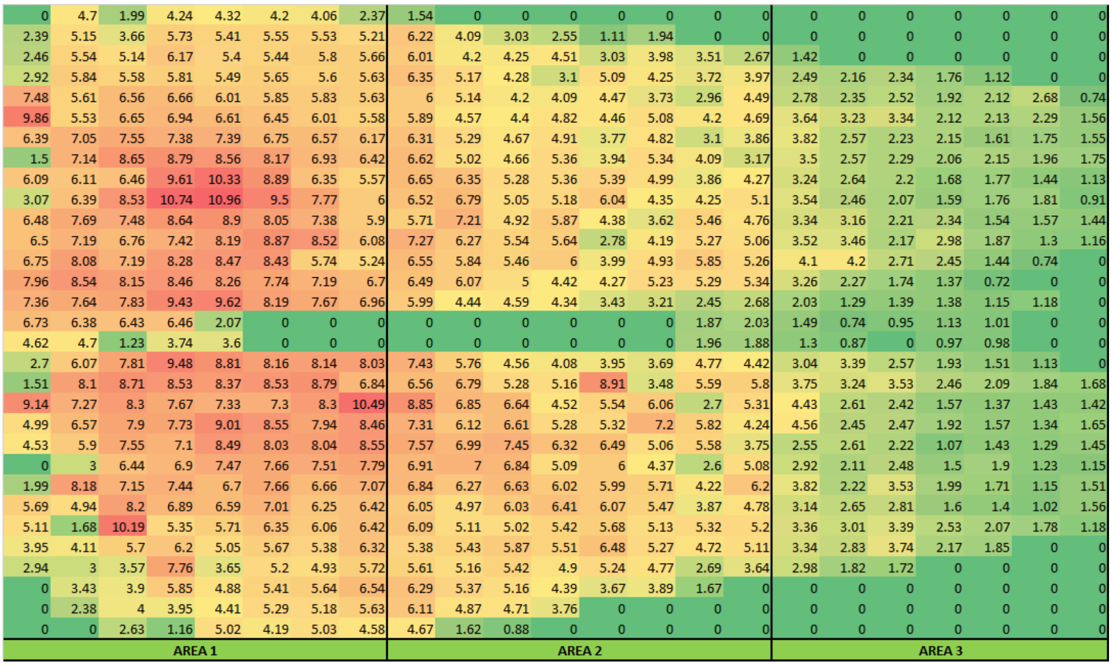
As Helander and Zhang (1997) made a distinction between sitting discomfort and sitting comfort, both aspects are studied. At 15 min intervals (t = 0, t = 15, t = 30, t = 45, t = 60, t = 75, t = 90), the participants were asked to rate their overall comfort using a LIKERT scale rating from 1 to 9 (1 = very uncomfortable; 9 = very comfortable), and overall discomfort using a LIKERT scale rating from 1 to 9 (1 = no discomfort; 9 = very severe discomfort). Additionally, at the same time interval, participants had to complete scores on comfort related statements; “I find the firmness of the seat (too soft –too firm)”, “I feel sweaty between my buttocks and the seat”, “I feel uneasy”, “I like the chair”. A space was provided for participants to make any additional remarks. At the end of the study having experienced both seats, the participants were asked to give a preference for one of the two seats imagining that they would sit long-term (>4 h) during a flight and add a reason for that. For this question, the participants were first allowed to sit on the previous seat before answering this question.

Internal consistency was determined using Cronbach’s alpha test. The ratings of statements were tested for significance ($p < 0.05$) between the prototype seat and the standard seat using the Wilcoxon signed rank test for paired observations.

2.4.3. *Pressure mapping*

At the end of each 90-min sitting session, recordings of the pressure distribution were made of each participant. The pressure map values were taken after 30 seconds sitting. During this process, participants were asked to sit in a comfortable position with their feet flat on the ground and their back rested against the backrest, which was kept in the TTL position.

The pressure map data were exported to MS Excel and a single rectangular box was drawn covering all the non-zero pressure values. During this process, any abnormal pressure reading outside potential seating areas was ignored. This box was then segmented into three equal areas (see Fig. 11) and the total force in each area was calculated. This force (Fn) at each area was converted into a percentage of total body weight on the seat (Fn/body-weight), this gave the pressure distribution across the seat-pan. This pressure distribution of each area of the prototype seat-pan was tested for significance against standard seat-pan using a t-test. This was then compared to the ideal pressure distribution (Mergl, 2006). In addition, the average pressure in each area, contact area and peak pressure were calculated and tested for significant differences between the standard seat-pan and prototype seat-pan.



0	4.7	1.99	4.24	4.32	4.2	4.06	2.37	1.54	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2.39	5.15	3.66	5.73	5.41	5.55	5.53	5.21	6.22	4.09	3.03	2.55	1.11	1.94	0	0	0	0	0	0	0	0	0
2.46	5.54	5.14	6.17	5.4	5.44	5.8	5.66	6.01	4.2	4.25	4.51	3.03	3.98	3.51	2.67	1.42	0	0	0	0	0	0
2.92	5.84	5.58	5.81	5.49	5.65	5.6	5.63	6.35	5.17	4.28	3.1	5.09	4.25	3.72	3.97	2.49	2.16	2.34	1.76	1.12	0	0
7.48	5.61	6.56	6.66	6.01	5.85	5.83	5.63	6	5.14	4.2	4.09	4.47	3.73	2.96	4.49	2.78	2.35	2.52	1.92	2.12	2.68	0.74
9.86	5.53	6.65	6.94	6.61	6.45	6.01	5.58	5.89	4.57	4.4	4.82	4.46	5.08	4.2	4.69	3.64	3.23	3.34	2.12	2.13	2.29	1.56
6.39	7.05	7.55	7.38	7.39	6.75	6.57	6.17	6.31	5.29	4.67	4.91	3.77	4.82	3.1	3.86	3.82	2.57	2.23	2.15	1.61	1.75	1.55
1.5	7.14	8.65	8.79	8.56	8.17	6.93	6.42	6.62	5.02	4.66	5.36	3.94	5.34	4.09	3.17	3.5	2.57	2.29	2.06	2.15	1.96	1.75
6.09	6.11	6.46	9.61	10.33	8.89	6.35	5.57	6.65	6.35	5.28	5.36	5.39	4.99	3.86	4.27	3.24	2.64	2.2	1.68	1.77	1.44	1.13
3.07	6.39	8.53	10.74	10.96	9.5	7.77	6	6.52	6.79	5.05	5.18	6.04	4.35	4.25	5.1	3.54	2.46	2.07	1.59	1.76	1.81	0.91
6.48	7.69	7.48	8.64	8.9	8.05	7.38	5.9	5.71	7.21	4.92	5.87	4.38	3.62	5.46	4.76	3.34	3.16	2.21	2.34	1.54	1.57	1.44
6.5	7.19	6.76	7.42	8.19	8.87	8.52	6.08	7.27	6.27	5.54	5.64	2.78	4.19	5.27	5.06	3.52	3.46	2.17	2.98	1.87	1.3	1.16
6.75	8.08	7.19	8.28	8.47	8.43	5.74	5.24	6.55	5.84	5.46	6	3.99	4.93	5.85	5.26	4.1	4.2	2.71	2.45	1.44	0.74	0
7.96	8.54	8.15	8.46	8.26	7.74	7.19	6.7	6.49	6.07	5	4.42	4.27	5.23	5.29	5.34	3.26	2.27	1.74	1.37	0.72	0	0
7.36	7.64	7.83	9.43	9.62	8.19	7.67	6.96	5.99	4.44	4.59	4.34	3.43	3.21	2.45	2.68	2.03	1.29	1.39	1.38	1.15	1.18	0
6.73	6.38	6.43	6.46	2.07	0	0	0	0	0	0	0	0	0	1.87	2.03	1.49	0.74	0.95	1.13	1.01	0	0
4.62	4.7	1.23	3.74	3.6	0	0	0	0	0	0	0	0	0	1.96	1.88	1.3	0.87	0	0.97	0.98	0	0
2.7	6.07	7.81	9.48	8.81	8.16	8.14	8.03	7.43	5.76	4.56	4.08	3.95	3.69	4.77	4.42	3.04	3.39	2.57	1.93	1.51	1.13	0
1.51	8.1	8.71	8.53	8.37	8.53	8.79	6.84	6.56	6.79	5.28	5.16	8.91	3.48	5.59	5.8	3.75	3.24	3.53	2.46	2.09	1.84	1.68
9.14	7.27	8.3	7.67	7.33	7.3	8.3	10.49	8.85	6.85	6.64	4.52	5.54	6.06	2.7	5.31	4.43	2.61	2.42	1.57	1.37	1.43	1.42
4.99	6.57	7.9	7.73	9.01	8.55	7.94	8.46	7.31	6.12	6.61	5.28	5.32	7.2	5.82	4.24	4.56	2.45	2.47	1.92	1.57	1.34	1.65
4.53	5.9	7.55	7.1	8.49	8.03	8.04	8.55	7.57	6.99	7.45	6.32	6.49	5.06	5.58	3.75	2.55	2.61	2.22	1.07	1.43	1.29	1.45
0	3	6.44	6.9	7.47	7.66	7.51	7.79	6.91	7	6.84	5.09	6	4.37	2.6	5.08	2.92	2.11	2.48	1.5	1.9	1.23	1.15
1.99	8.18	7.15	7.44	6.7	7.66	6.66	7.07	6.84	6.27	6.63	6.02	5.99	5.71	4.22	6.2	3.82	2.22	3.53	1.99	1.71	1.15	1.51
5.69	4.94	8.2	6.89	6.59	7.01	6.25	6.42	6.05	4.97	6.03	6.41	6.07	5.47	3.87	4.78	3.14	2.65	2.81	1.6	1.4	1.02	1.56
5.11	1.68	10.19	5.35	5.71	6.35	6.06	6.42	6.09	5.11	5.02	5.42	5.68	5.13	5.32	5.2	3.36	3.01	3.39	2.53	2.07	1.78	1.18
3.95	4.11	5.7	6.2	5.05	5.67	5.38	6.32	5.38	5.43	5.87	5.51	6.48	5.27	4.72	5.11	3.34	2.83	3.74	2.17	1.85	0	0
2.94	3	3.57	7.76	3.65	5.2	4.93	5.72	5.61	5.16	5.42	4.9	5.24	4.77	2.69	3.64	2.98	1.82	1.72	0	0	0	0
0	3.43	3.9	5.85	4.88	5.41	5.64	6.54	6.29	5.37	5.16	4.39	3.67	3.89	1.67	0	0	0	0	0	0	0	0
0	2.38	4	3.95	4.41	5.29	5.18	5.63	6.11	4.87	4.71	3.76	0	0	0	0	0	0	0	0	0	0	0
0	0	2.63	1.16	5.02	4.19	5.03	4.58	4.67	1.62	0.88	0	0	0	0	0	0	0	0	0	0	0	0
AREA 1								AREA 2								AREA 3						

Fig. 11. Pressure map data segmentation in excel. Area 1 (A1): Buttocks area, Area 2 (A2): Mid thigh area, Area 3 (A3): Front thigh area.

3. Results & discussion

3.1. *Local perceived discomfort*

The results of Local Perceived Discomfort of the different areas showed a general trend of increasing discomfort in all areas through time for both the standard and the prototype seat-pan. There was no significant difference in discomfort at any time (t = 0 to t = 90) at any area between the standard and prototype seat-pan.

3.2. *Overall perceived discomfort*

The overall perceived discomfort of the prototype and standard seat-pan is shown in Fig. 12, Although the graph shows the overall perceived discomfort of the prototype is lower than that of the standard seat-pan, a significant difference is only found at 60 min from the start (P = 0.035) (see Table 2).

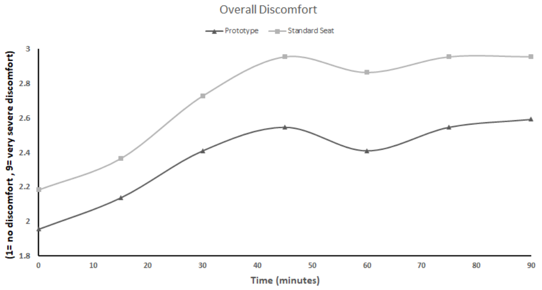


Fig. 12. Mean discomfort rating of standard and prototype seat-pan against time (n = 22).

Table 2 Wilcoxon signed-rank test for overall perceived discomfort (standard seat vs prototype) (n = 22). Null hypothesis rejected at significance <0.05. Significant results are marked by asterisk.

Time (min.)	0	15	30	45	60	75	90
Z	-1.165	-.929	-1.064	-1.263	-1.812	-.915	-.615
Asymp. Sig. (one-tailed)	0.122	0.1765	0.143	0.103	0.035*	0.18	0.269

3.3. *Overall perceived comfort*

The overall perceived comfort of the prototype and standard seat-pan is shown in Fig. 13. From the graph, it can be observed that on average, comfort of the prototype seat-pan tends to be rated higher than the standard seat. A significant difference was found between the standard seat and prototype seat-pan during the first 30 min (T = 0, T = 15, T = 30) and at T = 60 (Table 3).

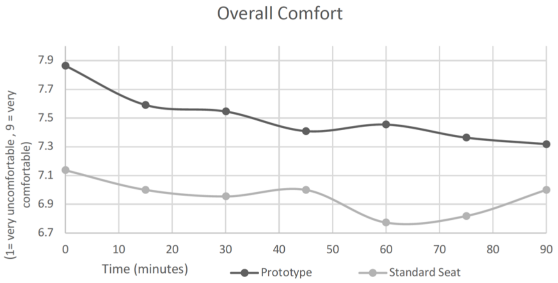


Fig. 13. Mean comfort rating of standard and prototype seat-pan against time (n = 22).

Table 3 Wilcoxon signed-rank test for overall perceived Comfort (standard seat vs prototype) (n = 22). Null hypothesis rejected at significance <0.05. Significant results are marked by asterisk.

Time (min.)	0	15	30	45	60	75	90
Z	-1.830	-1.789	-1.941	-1.135	-2.040	-1.363	-.534
Asymp. Sig. (one-tailed)	0.002*	0.037*	0.026*	0.127	0.021*	0.087	0.298

3.4. *Firmness*

The overall perceived firmness's of the prototype and the standard seat-pan are shown in Fig. 14 where on average, the firmness of the prototype tends to be rated lower than the standard cushion. Participants scored a significant difference in firmness between the standard cushion and the prototype at all times (see Table 4).

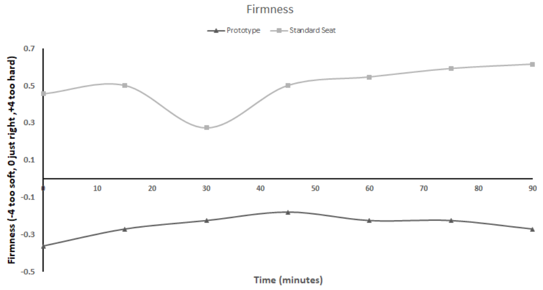


Fig. 14. Mean perceived firmness rating of standard and prototype seat against time (n = 22).

Table 4 Wilcoxon signed-rank test for perceived firmness of the cushion (standard seat vs prototype) (n = 22). Null hypothesis rejected at significance <0.05. Significant results are marked by asterisk.

Time (min.)	0	15	30	45	60	75	90
Z	-2.794	-2.896	-2.215	-2.627	-3.039	-2.951	-2.959
Asymp. Sig. (one-tailed)	0.003*	0.002*	0.013*	0.004*	0.001*	0.002*	0.002*

3.5. *Seat preference and user remarks*

The overall seat preference for >4 hours of seating was equal (11 preferred the prototype vs 11 preferred the standard) (see Fig. 15). Three participants with history of back problems preferred the standard seat and mentioned that they felt that their back was more "supported" with a firmer seat than a softer one. Two participants choosing the standard seat mentioned that whilst they felt more comfortable in the prototype seat, they may like a firmer one (standard seat) for >4 hours seating. Two participants preferring the standard seat mentioned that the seat may be "too soft" for longer flights.

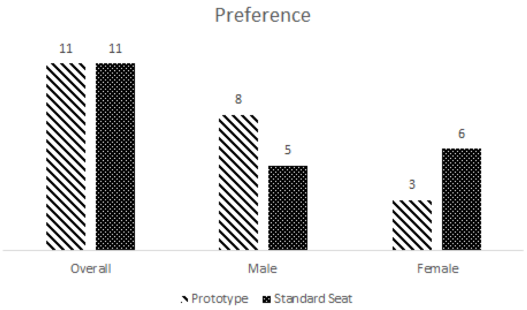


Fig. 15. Seat preference between standard and prototype seat-pan for >4 h seating (n = 22).

Participant choosing the prototype seat used key words like "very comfortable", "gave warm feeling", "makes me feel relaxed", "Wraps around body nicely", "good support from all sides" and "easier to sleep in", "slight element of sinking which was comfortable and helped me maintain a good posture", "found it thicker but also more comfortable on long term". Three participants found the seat "more softer", therefore "more comfortable". 8 out of 12 male participants preferred the prototype seat whilst 3 out of 9 female participants preferred the prototype seat. Why the males preferred the prototype seat and the females the standard might be a coincidence, but would be interesting to study further.

3.6. Pressure map

The pressure distribution is compared with the Ideal pressure distribution (Mergl, 2006) in Fig. 16. Table 5 shows that significant differences were found in the pressure distributions under the buttocks (p = 0.008) and the front thighs (p = 0.01) favouring the prototype seat-pan as it is closer to the ideal pressure distribution. This supports the general tendency of higher comfort in the prototype seat-pan than in the standard seat-pan.

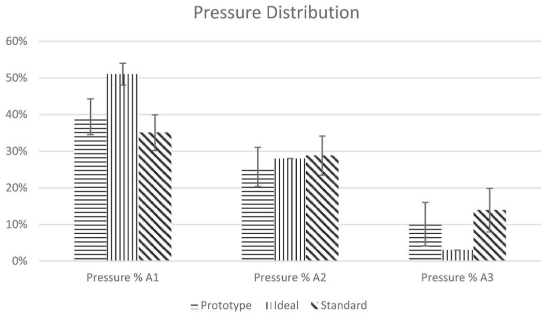


Fig. 16. Comparison of pressure distribution of 3 areas in standard (old) vs prototype (new) seat-pan, (Buttocks:A1, mid-thigh:A2, front-thigh:A3, see Fig. 11) vs ideal pressure distribution (Mergl, 2006).

Table 5 Two tailed T-test for pressure distribution (PD), peak pressure and contact area of standard seat vs prototype seat-pan (n=22). Null hypothesis rejected at significance <0.05. Significant results are marked by asterisk.

	P-Value
PD of A1 (Buttocks)	0.008*
PD of A2 (Mid Thigh)	0.058
PD of A3 (Front Thigh)	0.016*
Contact Area	0.014*
Average Pressure	0.003*
Peak Pressure	0.35
Average P of A1	0.054
Average P of A2	0.002*
Average P of A3	0.011*

However, the pressure distribution of the prototype seat is still not close to the ideal pressure distribution. This may be due to several factors. Firstly, this is an aircraft seat and the position is more upright than in a car seat of the study of Mergl (2006). The maximum pressure might be more shifted to the front as in a more upright position the centre of gravity of the occupant moves forward. This may explain higher pressure in the front and middle thigh, and lower in buttock area.

There was also a significant difference in contact area (p = 0.014) and average pressure (p = 0.0025) favouring the larger contact area and the lower average pressure for the prototype seat (Table 5). This supports the relation indicated by Fang et al. (2016), where a higher contact area is suggested to be linked to higher comfort and a lower average pressure.

There was no significant difference between the peak pressure of the standard and the prototype seat-pan (see Fig. 17 & Table 5). A possible explanation is that in both cases no bottoming is found.

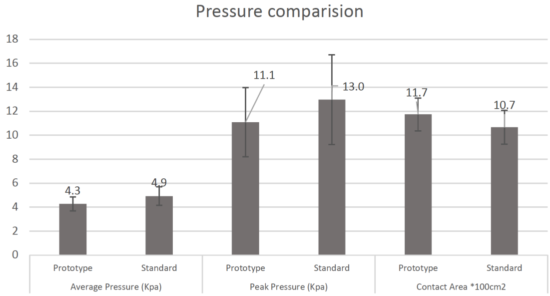


Fig. 17. Average pressure, peak pressure and contact area comparison between standard and prototype seat.

3.7. Weight

The prototype seat-cushion weighs 530 g without fire-blocker. It can be assumed that 60–70 g will be added to this due to fire blocker, weighing 600 (±10 g) grams in total. The current available seat-cushion for this seat weighs 750 g, which means reduction of 150 g (20%) in weight. In an Airbus A330-300 with 259 economy seats, this results in a total reduction of 39 kg per aircraft. This is comparable to a typical total baggage allowance of 30 kg per person (23 kg luggage + 7 kg hand luggage), which at a glance do not seem very significant. However, considering every kg of weight reduction reduces the carbon emission by about 400 kg yearly (Schäfer et al., 2016), this sums up to 15.6 tonnes of CO2 emissions reduction yearly per aircraft. In addition, this reduction in weight and improvement in comfort opens a possibility for spring-foam technology to be implemented in seats of not just for aircrafts, but the entire transportation industry.

3.8. Limitations

There are several limitations of this study: the prototype seat was made manually by the researcher and may not have the professional level of finishing (e.g. gluing, cutting and trimming), this may influence the overall comfort as well as the weight of the seat. Furthermore, the prototype seat was not covered with a fire-blocker whilst the standard cushion had a fire-blocker, this may also have influenced the result. In addition, the study was conducted in 1.5 h seating sessions and this may not be representative for the comfort/discomfort experience during a long-haul flight (>4 h). Furthermore, the study was conducted in seats in a TTL position and the influence of the seat-pan at the fully reclined position has not been studied. Moreover, the participants, age range was between 19 and 29 years, therefore results of the study may only apply to this specific demographic group.

There may also be inconsistency in pressure map reading due to variation in “comfortable” posture by the user. In addition, data processing of the pressure matrix into area segments (A1, A2 & A3, see Fig. 12) was done manually and could be prone to human errors. Nevertheless, the experiment was a within subject design and significant differences were found between the seats, which indicates a promising direction of development. Studying the effects on the long term with other ages of passengers is recommended.

3.9. Future design improvement & research

Considering the survey and user feedback in §3.1 and §3.2 it is recommended to develop a seat with a slightly increased firmness of the front area of seat-pan (from 8 to 12 kPa) and the top layer (from 8 kPa to 10 kPa) during the next iteration of the design (see Fig. 18). In addition, the next iteration should be made professionally and include a fire blocker layer.

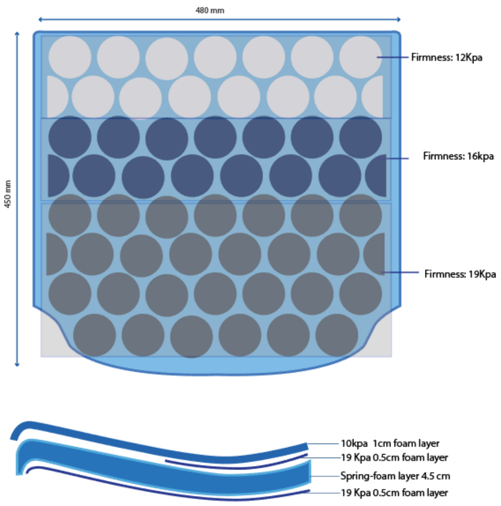


Fig. 18. Design for final iteration.

It was found that there was no significant change in discomfort but a significant improvement in comfort, so it is important to use comfort and discomfort questions or questions linked to these aspects. Hiemstra-van Mastrigt et al. (2015) also found no significant differences in discomfort between passive and active sitting, while significant differences were found in the score ‘I feel refreshed’, which is linked to comfort. Probably for a good seat the discomfort scale is not sensitive enough. Another issue to take care of is the distraction. From Fig. 12, it can be seen that serving drinks (at t = 45) decreased the discomfort slightly on both seats. The influence of this distraction (Ie. serving drinks) to the comfort experience has been shown before (e.g. Lewis et al., 2016; Hiemstra-van Mastrigt, 2015).

It is also suggested to have a 5-min general interview session after the user-test for their overall seating experience as in our case the participants were enthusiastic talking about their experience, and they may give crucial feedback that may have not been written on the questionnaire. In addition to subjective rating and pressure mapping, in-seat movement during the user-test seems a promising measurement method as it is related to discomfort (Cascioli et al., 2016; Sammonds et al., 2017). It is recommended to consider also recording fidgeting in future studies. Finally, dynamic testing (U.S. Dept. of Transportation, Federal Aviation Administration, 1989) and flammability testing (U.S. Dept. of Transportation, Federal Aviation Administration, 1986) should be conducted in the prototype in accordance to the regulations for their implementation in aircraft.

4. Conclusion

This study indicates that a seat-pan design using spring-foam technology can be lighter and more comfortable than conventional foam cushion materials. The prototype seat-pan provides higher comfort than a conventional seat-pan in first the 30 min and at the 60 min mark. This experience was supported by pressure mapping as the pressure distribution of the prototype seat-pan was found to be significantly closer to an ideal pressure distribution than compared with the conventional seat-pan. In addition, the prototype seat had a larger contact area and a lower average pressure, which by some authors is seen as linked to higher comfort. Furthermore, the seat-pan cushion has a reduction of 20% in weight over a standard cushion.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

This study was financially supported by Vanema Storitve d.o.o., Slovenia. The sponsor advised on the design of the seat-pan. The sponsor had no influence on the study design, data collection, analysis, data interpretation, writing and publication.

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