

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

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1 Abstract

This paper investigates whether spring-foam technology in an aircraft seatpan can reduce weight and at the same time provides equal or better comfort. Firstly, through literature studies and iterative design process a prototype seatpan was designed and developed using spring-foam technology. This was then tested against standard aircraft seat pan for comfort and discomfort; 22 participants were asked to sit in each seat for 90 minutes while filling out comfort and discomfort questionnaire every 15 minutes. At the end of each seating session, pressure map was taken of the seatpan. The results showed prototype seatpan having significantly higher initial comfort (~0 min.), and at the 35 and 50-minute mark than standard seatpan. Pressure map data showed pressure distribution of the prototype seatpan was found to be significantly closer to an ideal pressure distribution opposed to the conventional seatpan. In addition, the prototype seatpan had a significantly bigger contact area and lower average pressure suggesting a higher comfort. The seat-cushion weighs 20% lower than 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

2 Introduction

Air travel demand is estimated to double in 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 & Lee, 2009). One way to reduce emissions would be to decrease the overall weight of an airplane (Ordoukhanian & Madni, 2014), which in turn 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 to do (Filippone, 2012). Apart from weight savings, airlines 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, 2012; Ahmadpour et al. , 2014) showed that seat comfort is one of the most influencing factors in overall passenger comfort, especially in long haul flights (Brauer, 2004). Therefore increasing the seatpan comfort is valuable for airline companies.

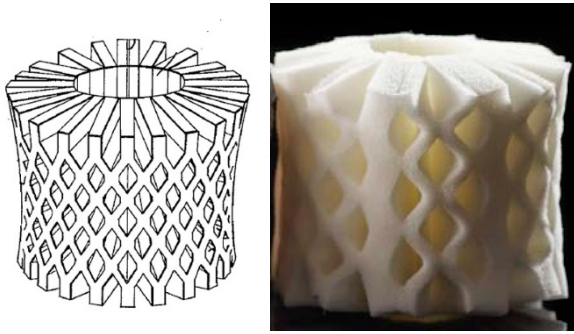


Figure 1 Spring foam unit

For comfort the second most important element of the seat is the seat cushion of seat-pan (after leg-room) (Nijholt et al., 2018) 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. These tubular foam springs (Figure 1) are lighter than traditional foam structures with similar firmness. By using different foam densities in the foam springs, it is possible to create different firmness's of springs and the modular nature of spring-foams allows to vary firmness per area in the seat. It is assumed that the firmness should differ for the

various contact areas between seat and human body to have an optimal comfort experience (Goossens et al., 2015; Vink and Lips, 2017; Zenk, 2006). In addition, due to its "hollow" design, spring foams are more efficient at moisture transport (i.e. better breathability) than standard foam (Poppe, 1980). This "breathability" quality in seats has a positive correlation with thermal comfort (Volkmar, 2003). These properties of 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 validity on comfort and weight savings against traditional foams

As spring foam technology offers possibilities to vary the density in various parts of the seats, literature is studied on requirements regarding pressure distribution, contour and firmness.

2.1 Ideal Pressure Distribution

Pressure distribution recorded between the human and the seat pan shows the distribution of body load over the different areas of the seat. Zenk (2006) indicated a correlation between pressure distribution and discomfort and was able to determine an ideal pressure distribution (Figure 2) for low discomfort in a car seat. Fang (2016) found similar correlations in pressure distribution. Therefore a seat providing close to ideal pressure distribution would possibly result in higher comfort and lower discomfort. Various densities in different areas was tested to develop a pressure distribution close to the ideal one.

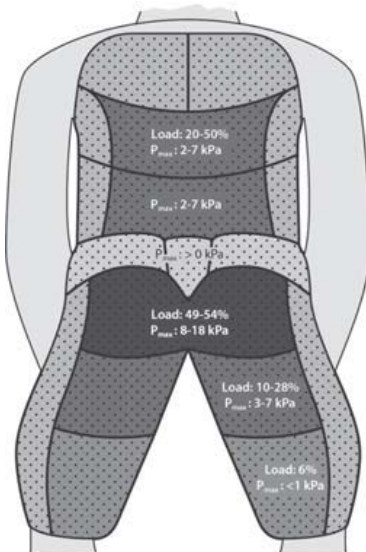


Figure 2. Pressure distribution according to Zenk (2006). Figure from Smulders et al (2016), based on Zenk (2006).

2.2 Ideal Contour

There are indications that a seat contour resulting in a large contact area is correlated to more comfort (Fang, 2016; Zemp, 2015; Looze, 2003; Franz, 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 users 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). It can be assumed that any form of cushioning material can be used to produce a similar effect. 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.

Hiemstra-van Mastrigt (2015) shows seat contours based on participants with carefully selected dimensions (Figure 3). Wang et. al (2018) used cylinder pistons to create a contour profile based on an optimal pressure distribution (Figure 2, Figure 3). These profile models were used as qualitative guidance for the seat pan contour.

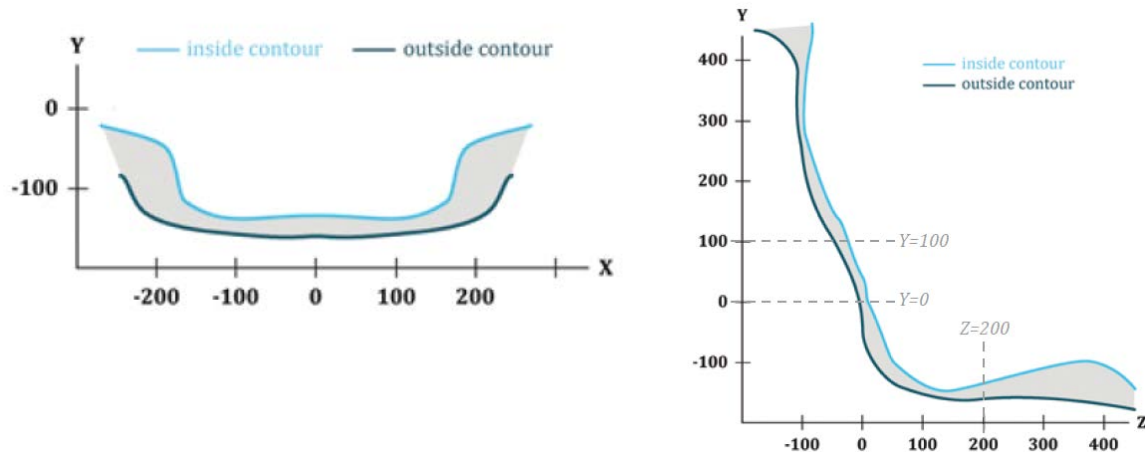


Figure 3. Contour profile front view (left) side view (right) (Hiemstra-van Mastrigt, 2015) (n=12)

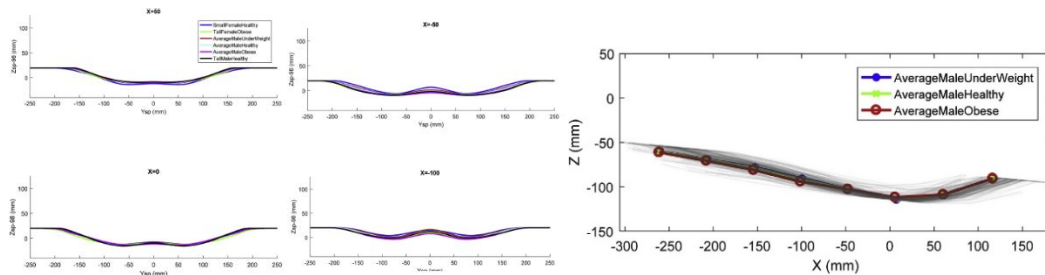


Figure 4 Contour profile at various segments of seat (left) side view profile (right) (Wang, 2018) (n=5)

2.3 Firmness

In general, a softer cushion (low stiffness) is often considered more comfortable than a firmer one (Ebe, 2001; Fang, 2016). A soft cushion also increases contact area (Fang, 2016) and is able to increase tolerable sitting time (Wang et al, 2015). However, a very soft cushion may not be able to support heavy loads and has an increased chance of bottoming, leading to discomfort (Ebe, 2001).

In addition to the overall firmness of the cushion, the sensitivity of buttocks differ at different areas with part of body contacting front of the seat pan becoming more sensitive than the rows in the middle and back (Vink, 2017; Lips, 2017). This might mean that, as mentioned previously the firmness should differ for the various contact areas between seat and human body to have an optimal comfort experience with firmer cushion in less sensitive areas and softer in higher ones. This is in alignment with the paper from Smulders (2016) and provides a direction towards ideal firmness distribution in the seat-pan.

2.4 Spring foam seat-cushion

Partly arbitrary decisions had to be made as not everything followed directly from the literature (e.g. number of layers, exact firmness distribution, exact contour etc.). Guided by the literature from 2.1 to 2.3, and after several iterative testing, the following design was determined.

2.4.1 Firmness distribution

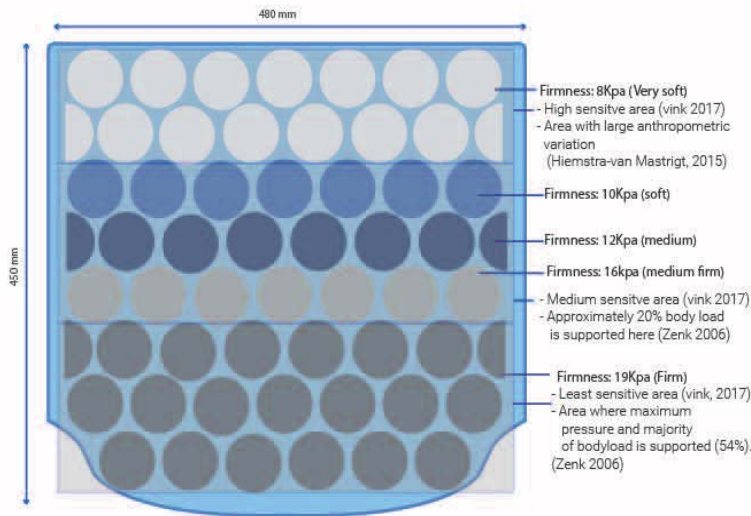


Figure 5: top view representing the firmness distribution of spring-foam.

2.4.2 Layer composition`



Figure 6: Side view of seat-foam showing layer composition

2.4.3 Seat-pan contour

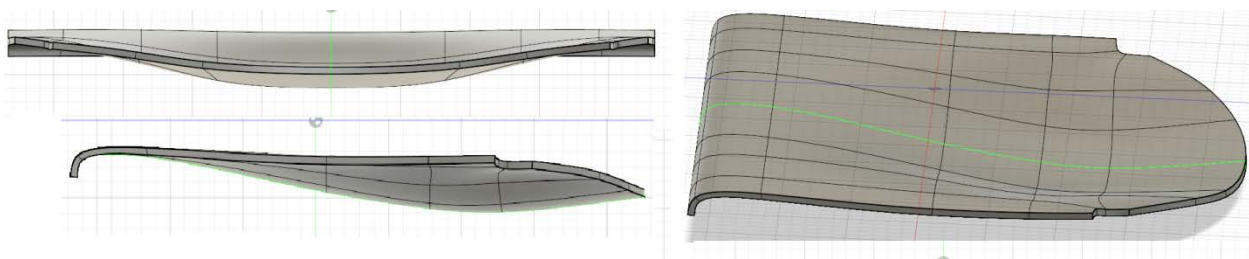


Figure 7. Seat pan contour, side view (bottom left), back view (top left), orthographic view (right).

The first question is whether a spring-foam technology in an aircraft seat pan can reduce weight and at the same time provides equal or better comfort while being lighter. However, in general this question is hard to answer. Therefore, a new seat pan was designed and in designing this seat pan it might be that not yet the optimal structure is found. However, if an increase in comfort could be observed by the new designed seat pan, it opens possibilities to improve the seat further and optimize a seat which is lighter and more comfortable.

3 Method and Materials

3.1 Study setup

Two prototype seatpans were developed using specifications mentioned in 3.1(Figure 8) and a thin white upholstery was used in order to cover the prototypes. Hard-foam was CNC machined according to the contour design mentioned on §3.1.7 to form the base of seat pan. The prototype seat pan base was attached firmly to the seat frame (Recaro 3510A). Double-sided tapes were used to firmly attach the prototype seat cushion to the seat pan base (Figure 9).

Additionally, upholstery of two Recaroeconomy class seatpan(Recaro F2RE0134) was changed to the thin white upholstery in order to minimize visual influence during the test. These seatpan were used as a reference condition for the test.



Figure 8 seat prototype. Spring-foam distribution (left), firm layer addition (centre), final cushion without upholstery



Figure 9: Hard-foam CNC made bottom plate attached to seat frame (left,) prototype, cushion attached to bottom plate (right)

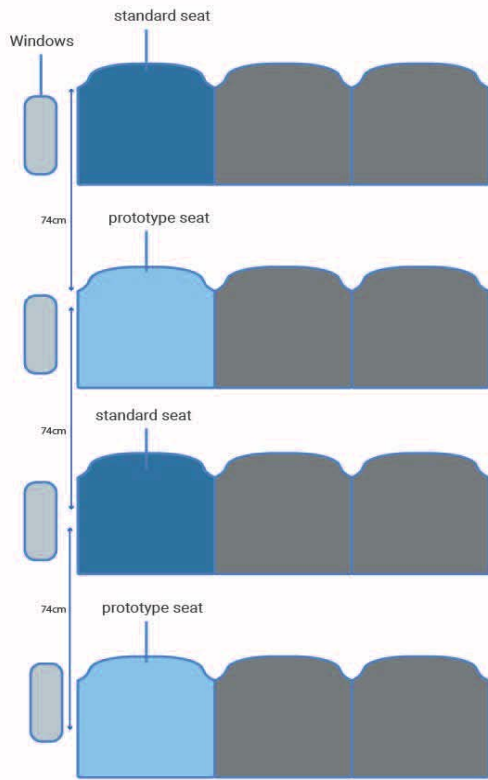


Figure 10 Seating setup in TU Delft fuselage.



Figure 11: Aircraft Fuselage

The experiment was conducted in a Boeing 737-500 airplane cabin at the campus of the TU-Delft to simulate a realistic in-flight sitting experience (Figure 11). Temperature and humidity were kept between 19*- 23* (standard aircraft cabin temperature) (Space, Johnson, Rankin, & Nagda, 2000) and humidity to 40-50% respectively.

The pitch was set to 74.5cm and total seat height to 51cm. All the seat backs were fixed in (TTL) position. The four seats were placed at the window sides to keep the environmental variable constant.

Two X-sensor LX100 pressure mats were calibrated and made ready to take in readings.

Questionnaire forum and pen was placed at the back pocket of the seat and the subjects were allowed to take either a phone or a book with them.

3.2 Participants

During the recruitment process, any interested candidate was asked to fill out their weight, stature and gender. Using the information, twenty two candidate (13 male, 9 female) aged from 19-29 were selectively chosen to have a large distribution of stature and BMI (Table 1), ranging from P4.21 female to P 78.5 male.

Table 1 - Anthropometric measurements of subjects

N		Mean	SD	Range
Male	Weight [kg]	75.3	8.5	28.2
	13 Stature [cm]	179.68	9.34	32.3
	BMI	23.45	3.15	10.6
Female	Weight [kg]	62.20	10.16	32.3
	9 Stature [cm]	165.31	7.39	25
	BMI	23.00	5.01	14.51
All	Weight [kg]	69.95	11.13	50
	22 Stature [cm]	173.80	10.84	40
	BMI	23.26	3.91	14.51

3.3 Procedure

The test was conducted with four participants per session with each seated on either standard or prototyped seat pans. The order was systematically changed among participants. Before the test, subjects were informed on the procedure and were asked to sign a consent form before participation. After signage, anthropomorphic measurements were taken of the participants following the DINED procedure (Molenbroek, 2004).

Each participant was seated on the two seats for 1.5 hours each. Drinks and Snacks were provided at 45-minutes by a flight actor (figure 12). During the test, the participants were not allowed to talk or stand, change the backrest position or use the tray table, but were either allowed to read a book, use cell phone, or rest during the test. After the end of first round, there was 10 minutes break before the second round was conducted. At the end of each round, a seat recording of the pressure distribution on the seat pan was made of each participant.



Figure 12: In-flight attendant actor serving drinks and snacks

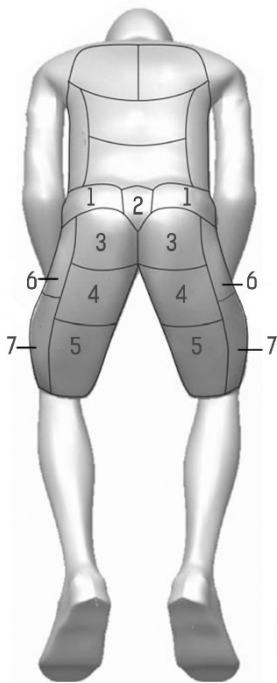


Figure 13 : Body Map to measure LPD

3.4 Measurements

3.4.1 Local perceived discomfort measurement

Discomfort was measured 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 Figure 9) was presented in the questionnaire in which participants were asked to give a score on a LIKERT scale ranging from 1-7 (1 being ‘no discomfort’ and 7 being ‘severe discomfort’). Participants were asked to complete the LPD questionnaire at the first contact ($t=0$ min.) and after every 15 minutes during the 1.5 hours ($t=0$, $t=15$, $t=30$, $t=45$, $t=60$, $t=75$, $t=90$ min.). The discomfort of each body part was tested between prototype seat and standard seat using a Wilcoxon signed rank test ($p<.05$) for paired observations (IBM SPSS Statistics 25), this analysis was conducted at each time intervals.

3.4.2 Comfort and discomfort measurement

Similarly, at ($t=0$, $t=15$, $t=30$, $t=45$, $t=60$, $t=75$, $t=90$), participants were asked to rate their overall comfort and overall discomfort using a LIKERT scale rating from 1-9 (1 being very uncomfortable and 9 being very comfortable). Additionally at the same time interval, participants had to fill out 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 fill in if they had any additional remarks.

At the end of the test having experienced both seats, the participants were asked to give preference between the two seats on which they would prefer sitting during long term (4+ hours) flight and their reason to do so. For this question, the participants were first allowed to sit on the previous seat before answering this question.

4 Results & Discussion

4.1 Local Perceived Discomfort

The results of Local Perceived Discomfort is show in Figure 15. Whilst there is a general trend of increment of discomfort in all areas through time for both standard and prototype seatpan, there was no significant difference in discomfort at any time (t=0 to t=90) at any area between the standard and prototype seatpan.

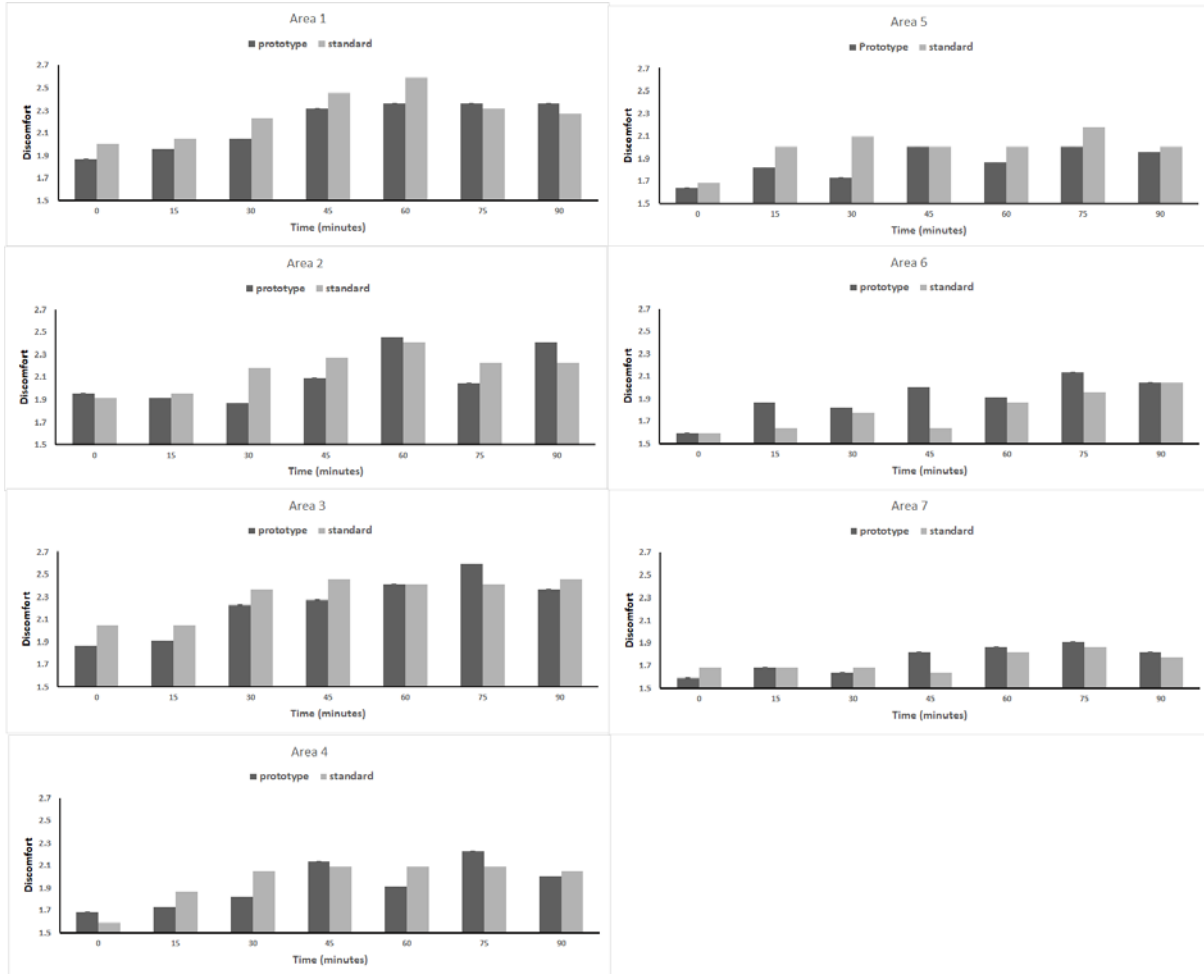


Figure 15: Mean LPD measurements graph at different time intervals comparing standard vs prototype seatpan per body area (see figure 10). (n=22)

4.2 Overall Perceived discomfort

The overall perceived discomfort of prototype seatpan and standard seatpan is shown in Figure 15, Although observation from the graph shows the overall perceived discomfort of the prototype seat pan tend to be lower than that of the standard seatpan, no significant difference was found between them (table 2).

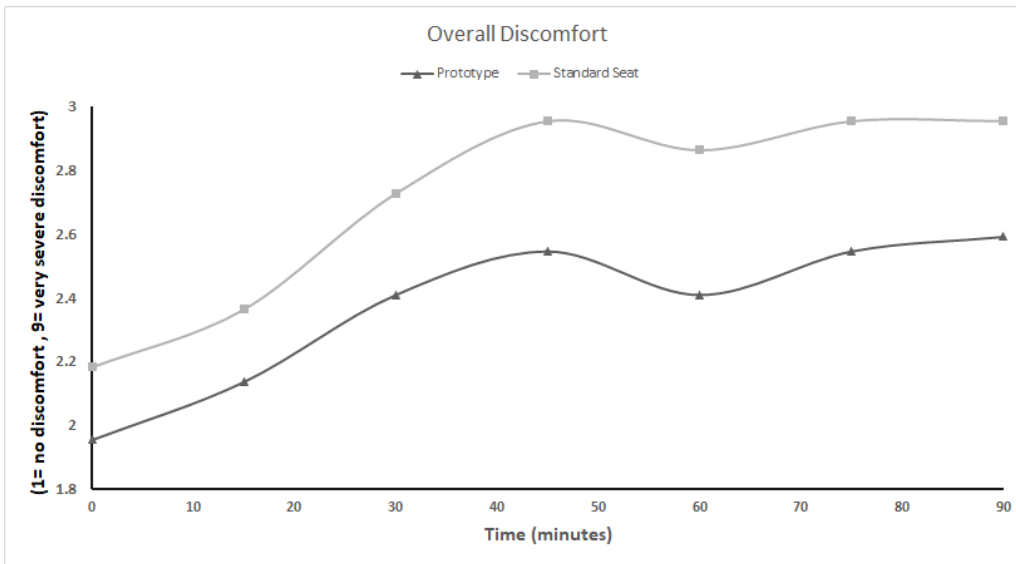


Figure 16: Mean discomfort rating of standard and prototype seatpan against time (n=22)

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

	T=0	T=15	T=30	T=45	T=60	T=75	T=90
Z	-1.165	-.929	-1.064	-1.263	-1.812	-.915	-.615
Asymp. Sig. (2-tailed)	.244	.353	.287	.206	.070	.360	.538

4.3 Overall Perceived Comfort

The overall perceived comfort of the prototype and standard seatpan is shown in Figure 18 From the graph, it can be observed that on average, comfort of prototype seat pan tend to be rated higher than the standard seat. A significance difference was found between the standard seat and prototype seatpan at time interval T=0, T=30 and T=60 (Table3)

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

	T=0	T=15	T=30	T=45	T=60	T=75	T=90
Z	-2.944	-1.838	-2.049	-1.178	-2.095	-1.382	-.548
Asymp. Sig. (2-tailed)	.003*	.066	.040*	.239	.036*	.167	.584

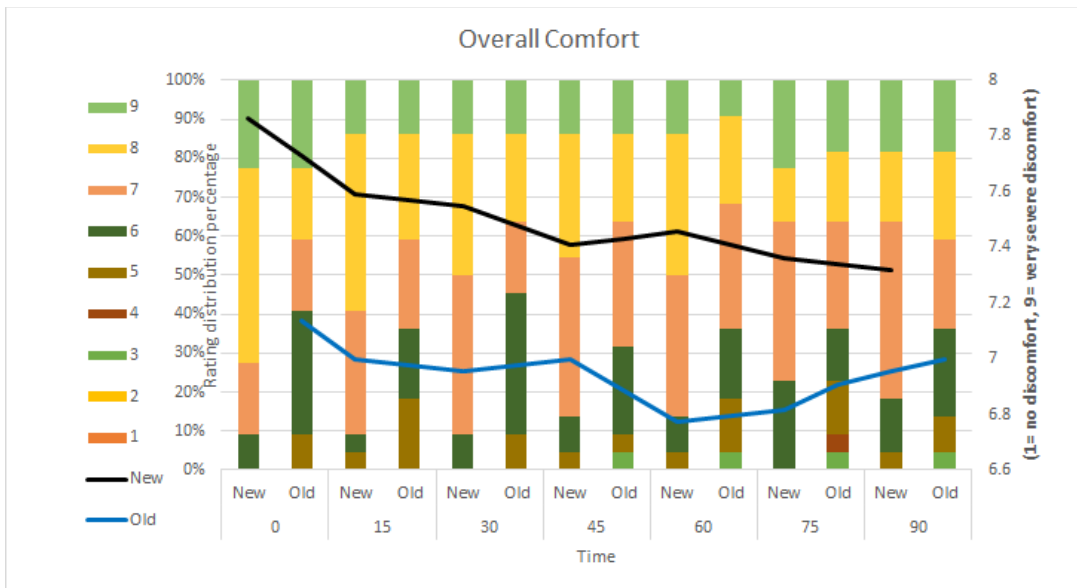


Figure 17 Mean comfort rating of standard (old) and prototype seat (new) against time (n=22). The percentage rating distribution is shown in Likert graph in background.

4.4 Firmness

The overall perceived firmness of prototype and standard seatpan is shown in Figure 18 where on average, the firmness of prototype tend to be rated lower than of the standard cushion. Participants felt significantly different firmness between the standard cushion and the prototype at all times (table 4).

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

	T=0	T=15	T=30	T=45	T=60	T=75	T=90
Z	-2.858	-3.019	-2.399	-2.777	-3.231	-3.082	-3.123
Asymp. Sig. (2-tailed)	.004*	.003*	.016*	.005*	.001*	.002*	.002*

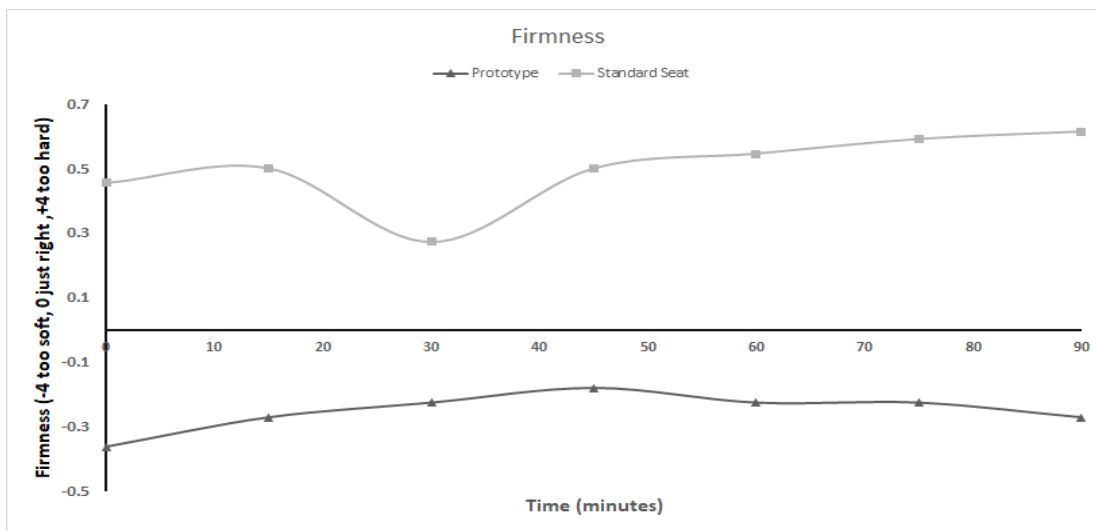


Figure 18: Mean perceived firmness rating of standard and prototype seat against time (n=22).

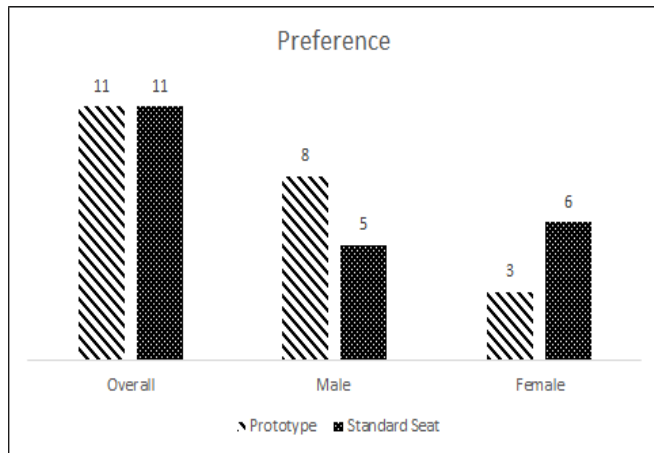


Figure 19: Seat preference between standard and prototype seatpan for 4+hour seating (n=22).

4.5 Seat Preference and user remarks

The overall seat preference for 4+ hour of seating was equal (11 preferred prototype vs 11 preferred standard) (Figure 18). Three candidates with history of back problem preferred the standard seat and mentioned that they felt that their back was more “supported” with a firmer seat than a softer one. Two candidates choosing standard seat mentioned that whilst they felt more comfortable in the prototype seat, they may like firmer one (standard seat) for 4+ hour seating. Two subjects preferring standard seat mentioned that the seat may be “too soft” for longer flights.

Subjects choosing 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”.

8 out of 12 male candidates preferred the prototype seat whilst only 3 out of 9 female candidates preferred the prototype seat. The reason behind majority of male preferring the prototype seat and female choosing the standard could be interesting. It might be interesting to check whether this pattern also applies to a larger sample.

4.6 Pressure Map

The pressure distribution of the study results compared to Ideal pressure distribution (Zenk, 2012) are displayed in Figure 20. The conducted significance test and comparing pressure distribution, contact area and peak pressure is shown in table 4. Significant difference was found in Pressure distribution of buttocks ($p=0.008$) and front thigh ($p=0.01$) 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 seatpan than in standard seatpan.

However, the pressure distribution of prototype seat is still different from that of Ideal seat distribution (Figure 19), 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 Zenk (2006). The maximum pressure might be more shifted to the middle of the back and buttock tend to slip towards front of the seat pan (Zenk, 2006). This may explain higher than ideal pressure distribution in the front thigh (Area 3) and middle thigh (Area 2) and a lower in buttock area (Area 1) (Figure 13).

There was also a significant difference in contact area ($p=0.014$) and average pressure ($p=0.0025$) favouring higher contact area and lower average pressure for prototype seat (Figure 17, Table 4). This supports the relation indicated by Fang et al (2012). where a higher contact area suggested a higher comfort and lower average pressure.

No significant difference between peak pressure of standard and prototype seat pan indicates no bottoming has taken place in the prototype seat cushion.

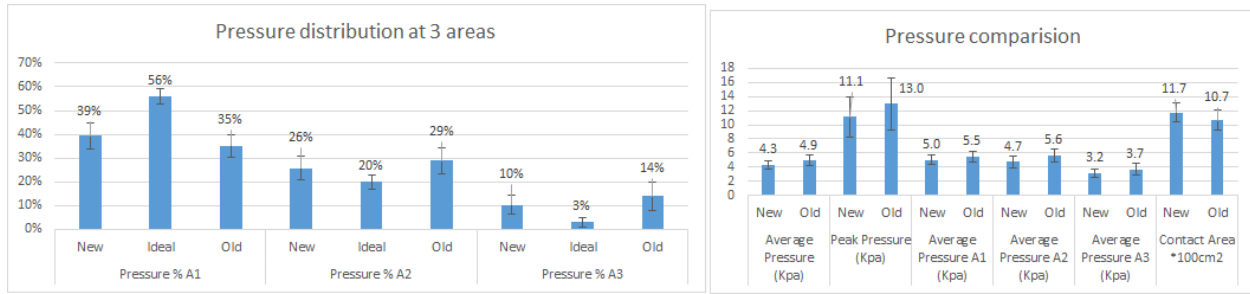


Figure 20: (left) Comparison of pressure distribution of 3 areas in standard (old) vs prototype (new) seat pan, (Buttocks:A1, mid-thigh:A2, front-thigh:A3) vs ideal pressure distribution (Zenk, 2012). (right) Average pressure, peak pressure and contact area comparison between standard (old) and prototype seat (new).

Table 4: Two tailed T-test for pressure distribution, peak pressure and contact area of standard seat vs prototype seatpan. (Null hypothesis rejected at significance <0.05). (n=22)

	A1 (Buttocks)	A2 (Mid Thigh)	A3 (front Thigh)	Contact Area	Average Pressure	Peak Pressure	Average P A1	Average P A2	Average P A3
P-Value	0.0080	0.0575	0.0163	0.01374	0.0025	0.350	0.0537	0.00153	0.011
Result	Significant	Not Significant	Significant	Significant	Significant	Not Significant	Not Significant	Significant	Significant

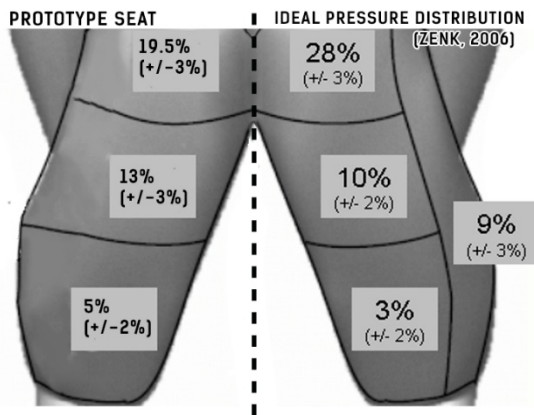


Figure 21: Comparison of prototype seat pressure distribution vs Ideal pressure distribution (Zenk, 2012)

4.7 Weight

The prototype seat-cushion weighs 530 grams without fire-blocker. It can be assumed that 60-70 grams will be added to this due to fire blocker, weighing 600 (+/- 10 grams) grams in total. The standard seat-cushion weighs 750 grams, which means reduction of 150g (20%) in weight has been achieved. In a Boeing 737 with a standard 140 seats configuration (seat-guru, 2017), this results in a total reduction of 21Kg of weight in the aircraft from seat cushion alone.

4.8 Limitations

There are several limitations to this study; the prototype seat was made manually by the researcher and may not have a acquired 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 fire-blocker whilst the standard cushion had fire-blocker, this may also have an influence on the result. In addition, the test was conducted in 1.5 hours seating sessions and this may not conclusively indicate the comfort/discomfort experience during a long-haul flight (4+ hours). Furthermore, the study was conducted in seats in a TTL position and the influence of the seat-pan at fully reclined position have not been studied. Moreover, the user test participants aged between 19-29, therefore results of the study may only apply to users within the age range.

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 § figure 11) was done manually and would be prone to human errors.

4.9 Future design improvement & research

Considering the survey and user feedback in §3.1 and §3.2 it is recommended to slightly increase the firmness of front area of seat-pan (from 8 to 12 Kpa) and the top layer (from 8Kpa to12Kpa) during the next iteration of the design. In addition, next iteration of design should be made by a professional with fire-

blocker included. The influence of these changes should then be tested for comfort and discomfort in 2+ hours seating session with both TTL and fully reclined position.

From the result we found that there was no significant change in discomfort but had significant improvement in comfort, so it is important to get as much feedback as possible through questionnaire using various quantitative measurements.

It can also be suggested to have a 5-minute general interview session after the user-test for their overall seating experience as participants seem to be very enthusiastic talking about it, and they may give crucial feedbacks that may have not been written in questionnaire.

In addition to subjective rating and pressure mapping, In-seat movement of the user test could be recorded to provide additional objective measure for discomfort (Cascioli, Liu, Heusch, & McCarthy, 2016; Sammonds, Fray, & Mansfield, 2017).

Finally, dynamic and flammability test should be conducted in the prototype as according to FAR 25.853 (1986) & FAR 23.562 (1989) regulation for its implementation in aircraft.

5 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 tend towards providing higher comfort than a conventional seat-pan, with significant difference in initial comfort (~0 min.), and at the 35 and 50-minute mark. This subjective result was supported by pressure mapping where, pressure distribution of the prototype seat pan was found to be significantly closer to an ideal pressure distribution opposed to the conventional seat pan. In addition, the prototype seat had a significantly bigger contact area and lower average pressure, suggesting higher comfort (Fang, 2016). Furthermore the seat pan cushion has a reduction of 20% in weight over a standard cushion.

The reduction in weight and improvement in comfort opens a possibility of spring-foam technology to be implemented in seats of not just for aircrafts, but entire automotive industry.

6 Conflict of interests

This study was financially supported by Dormeo UK Ltd. The sponsor had influence on the design of the seat pan in this study. The sponsor had no influence on the study design, data collection, analysis, data interpretation, writing and publication.

7 Acknowledgements

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