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DOI
10.3233/WOR-162363

Publication date
2016

Document Version
Final published version

Published in
Work

Citation (APA)
Smulders, M., Berghman, K., Koenraads, M., Kane, J. A., Krishna, K., Carter, T. K., & Schultheis, U. (2016). Comfort and pressure distribution in a human contour shaped aircraft seat (developed with 3D scans of the human body). *Work*, *54*(4), 925-940. https://doi.org/10.3233/WOR-162363

Work 54 (2016) 925–940
DOI:10.3233/WOR-162363
IOS Press

Comfort and pressure distribution in a human contour shaped aircraft seat (developed with 3D scans of the human body)

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Received 3 May 2015
Accepted 24 July 2015

Abstract.
BACKGROUND: The concept of comfort is one way for the growing airline market to differentiate and build customer loyalty. This work follows the idea that increasing the contact area between human and seat can have a positive effect on comfort [5, 6, 7].
OBJECTIVE: To improve comfort, reduce weight and optimise space used, a human contour shaped seat shell and cushioning was developed.
METHODS: First the most common activities, the corresponding postures and seat inclination angles were defined. The imprints of these postures on a rescue mat were 3D scanned and an average human contour curve was defined. The outcome was transferred to a prototype seat that was used to test the effect on perceived comfort/discomfort and pressure distribution.
RESULTS: The resulting human contour based prototype seat has comfort and discomfort scores comparable to a traditional seat. The prototype seat had a significantly lower average pressure between subjects' buttocks and the seat pan over a traditional seat.
CONCLUSIONS: This study shows that it is possible to design a seat pan and backrest based on the different contours of study subjects using 3D scan technology. However, translating the 3D scans into a prototype seat also showed that this can only be seen as a first step; additionally biomechanical information and calculations are needed to create ergonomic seats. Furthermore, it is not possible to capture all different human shapes and postures and translate these into one human contour shape that fits all activities and all human sizes.

Keywords: Lightweight, 3D scanning, aircraft seat, comfort, pressure distribution

1. Introduction

The average 5.6% growth of passenger demand (Passenger Revenue Kilometers) over the last 10 years, as estimated by IATA [1], creates opportunities for airlines. By understanding the passengers' flight selection behaviour and developing products and services fitting the selection behavior, airlines can increase passenger revenue [2].

Brauer [2] showed that in order of priority, passengers select their flights on point-to-point transport, time, price, and subsequently on aspects such as fre-

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quent flyer programs, comfort, past experiences and delays. Comfort is considered a higher priority on long haul flights.

Already in the 80s, passenger comfort was a key variable for passenger satisfaction and willingness to use the airline again [3]. Therefore, passenger comfort might be a way for airlines to differentiate, attract new customers and build customer loyalty.

The comfort of air travel is influenced by several factors. One of the main factors is the seat [4], as it represents the largest contact area during a flight between the passenger and the airplane. Improving this contact area can potentially increase a positive experience of a flight. Several studies about the subject of the contact area and its relation to comfort have been conducted [5,6] and showed that pressure distribution of the human mass in the seat is one of the best objective methods of getting information about the perceived comfort/discomfort of subjects. Additionally, Franz et al. [8] showed a method for developing a contour based seat in order to increase and subsequently improve the contact area.

These studies [5,6,8] indicate that a large contact area between the seat and the human decreases the effect of discomfort perception. Therefore, the assumption is that developing an aircraft seat based on human contour could improve pressure distribution and accordingly increase comfort and decrease discomfort perception. However, these studies are all focused on car seats. The question is whether a contour based seat design is also valuable in the field of aircraft seats. Applying the human contour as a base for aircraft seat design is therefore the topic of this study.

Apart from increasing the airlines revenue by attracting more passengers, revenue could also increased by reducing fuel consumption, which has a positive effect on the environment too [9]. Making a seat which better fits the human contour could result in the reduction of required seat materials and thereby weight [8], which contributes to the reduction of the aircraft's fuel consumption. However, the question is: what is the effect of this lightweight human contour based seat on comfort.

The two main research questions of the study are:

- Is it possible to design a seat pan and backrest based on the human contour using 3D scan technology?
- How does a lightweight human contour shaped aircraft seat affect comfort, discomfort and pressure distribution compared to a traditional aircraft seat?

The research and development of the test seat were focused on long haul flights, since long haul flights are most challenging in terms of comfort.

2. Materials and methods

In order to design a seat pan and backrest of an aircraft seat based on the human contour, first the most frequently performed activities in aircraft seats were determined by interviewing three experienced long-haul frequent flyers (age 58–64, flying for both business and leisure). These activities were compared and confirmed by literature [10, 11]. Second, the preferred inclination angles corresponding with the determined activities were established. Third, the human contours in the corresponding inclination angles were captured using 3D scanning. This input was used to develop the shell of the seat and pressure distribution data completed the cushioning. A prototype was developed with the designed cushioning and shell for testing the effects on comfort, discomfort and pressure distribution. In this study a distinction was made between measuring comfort and discomfort, as Helander and Zhang [12] showed that these could be different entities when studying a seat.

2.1. Inclination for different activities in Business Class aircraft seats

2.1.1. Subjects

In the first study ten Dutch adults participated. Care was taken to select subjects with a variety of height and weight. Five female and five male subjects participated (Table 1). All subjects frequently flew by plane and two were accustomed to travelling business class.

2.1.2. Stimuli

A realistic setting was created by using business class seats placed in a partial airplane cabin

Table 1
Anthropometric measurements of subjects

		Mean	SD
Male ($n=5$)	Age [years]	21	1.2
	Stature [cm]	184	10.6
	Body weight [Kg]	74.8	7.9
Female ($n=5$)	Age [years]	21.8	1.6
	Stature [cm]	170.4	8.2
	Body weight [Kg]	62.4	5.3

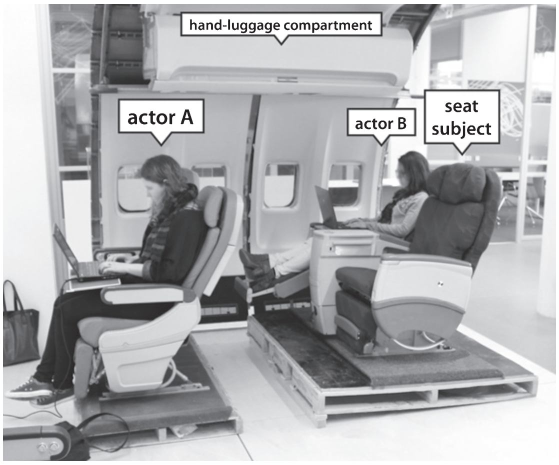

Fig. 1. Partial airplane cabin with two actors.

Fig. 2. Inclination angle and pitch length.

with two actors (Fig. 1). The actors were seated in the nearby seats to simulate realistic movement and social boundaries. The floor of the business class seats was positioned at a 3 degree angle to simulate the standard inclination of an airplane during flight at cruising altitude (angle of attack). The pitch was set at 60 inches (∼1.52 metres) (Fig. 2), as is standard in business class. Furthermore, subjects were provided with hand luggage containing a questionnaire, laptop, magazines, one book, a pen, a sleeping mask and headphones. These objects were used to simulate different activities in a realistic manner. Subjects were also provided with food and drinks during the simulated flight by an actor (the flight attendant).

2.1.3. Apparatus

Two cameras were used to capture every posture (Fig. 3). One camera was fixed and positioned laterally to the passenger; one camera was used to capture interesting details during the test. The lateral pictures were used to trace the position of the backrest, seat pan, leg rest, and determine the angles.

2.1.4. Procedure

Subjects were first asked to experience the adaptability of the seat for a couple of minutes. During this activity, the subjects were told to pretend to travel by plane and to adjust the seat in the most comfortable position for every activity performed in the seat.

When the subjects found a comfortable position and inclination, they mentioned this to the researcher and a picture was taken with both cameras. The subjects were asked to confirm the most comfortable position for the activity. When the position was confirmed, the next task was given. This step was repeated for each of the tasks.

The first task was removing hand luggage from the overhead compartment, and filling out a questionnaire about age, gender, height, weight, and previous flight experiences. Writing served as the first activity in the seat.

Next, drinks and food were offered to provoke an eat/drink posture. While drinking and eating, the subjects were asked about their commercial air travel experience and what tasks they performed most during flights. In addition to writing, eating and drinking, and their own mentioned activities, subjects were asked to perform the following activities: sleeping, watching. In Flight Entertainment (IFE), listening to music, playing on a smartphone (or tablet), reading a book and working on a laptop.

2.1.5. Measures

The pictures taken with the fixed camera were analysed using Adobe Illustrator. The angles of the leg rest, seat pan and backrest were established. These measures were compared and confirmed by literature [13, 14].

2.2. 3D scanning the human contour in pre-determined inclinations

2.2.1. Subjects

In the second study twelve Dutch adults participated. Care was taken to select subjects with a large variety in stature height, weight and age. Six female and six male subjects participated (Table 2).

2.2.2. Apparatus

A test seat was built with an adjustable leg rest and backrest inclination angles. A rescue mat (further referred to as mat) was positioned on the test seat

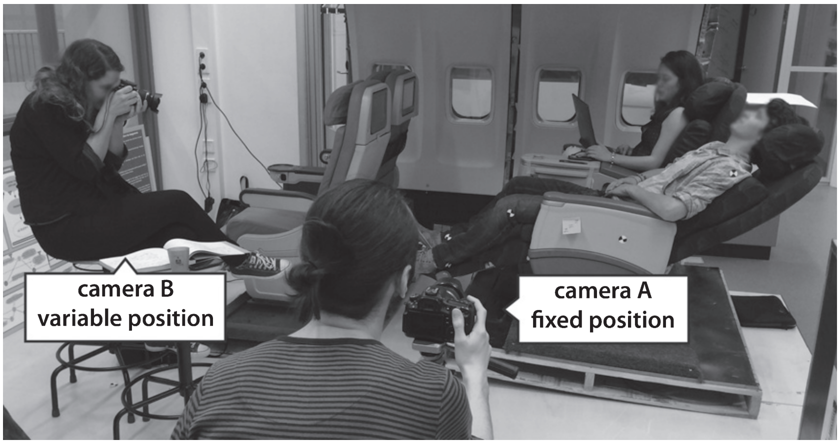

Fig. 3. Camera positions.

Table 2
Anthropometric measurements of subjects

		Mean	SD
Male ($n = 6$)	Age [years]	34.3	19.6
	Stature [cm]	183.2	11.3
	Body weight [Kg]	90.7	12.7
Female ($n = 6$)	Age [years]	26.8	12.3
	Stature [cm]	167.8	8.8
	Body weight [Kg]	65.2	13.2

Fig. 4. Rescue mat in test seat.

(Fig. 4). The mat deformed to the human imprint and held the form after a vacuum was created in the mat using a vacuum cleaner. A 3D laser scanner (Artec L scanner) scanned the human imprint. The CAD software (Artec Studio) was used to mesh the data. The meshes were processed in Rhinoceros 3D to form a 3D representation of the average human contour.

2.2.3. Procedure

At first subjects laid down upon the mat, which was positioned horizontally. Then the leg rest and backrest were inclined by two researchers (Fig. 5) to a predetermined inclination (Table 3), based on the findings of the study described in §2.1 (results can be found in §3.1).

Subjects were asked to sit in a comfortable posture and wiggle their body to get a better imprint. The mat was vacuumed to fixate this imprint. The subject left the seat and the imprint was 3D scanned.

Fig. 5. Backrest being inclined by two researchers.

Table 3
Inclinations defined based on measurements

	Active	Passive	Sleeping
Backrest	23°	31°	56°
Leg rest	20°	48°	63°
Seat pan	8°	8°	8°

After the scanning, the air nozzle of the mat was opened and the seat was reclined back into a flat position. Then the mat was massaged to create an even surface again.

This process was repeated for each subject, in the three set postures; active, passive and sleeping.

2.2.4. Measures

All imprints were individually 3D scanned and meshed. In Rhinoceros 3D a grid with fixed dimensions (seatpan 11x9, backrest 11x9 points) was placed over each mesh. The grid was limited in detail on purpose to avoid minor errors (such as irregular surfaces), – to enhance processing time and to have sufficient detail to get a representative shape. Points on this grid were projected on the mesh, resulting in height maps (Z-coordinate for each XY-coordinate on the grid). The height maps were made for the leg rest, seat pan and backrest individually (see Fig. 6). To ensure each grid was projected from the same origin, vertical metal pins on the seat (Fig. 7) were reference points, for alignment of all scans.

2.3. Pressure distribution calculations and testing for cushioning

Since postural change is important for decreasing discomfort during prolonged sitting [15], it is important the cushioning does not limit movement while at the same time providing a large contact area. Thick soft cushioning for example will have a large contact are, but it impedes movement.

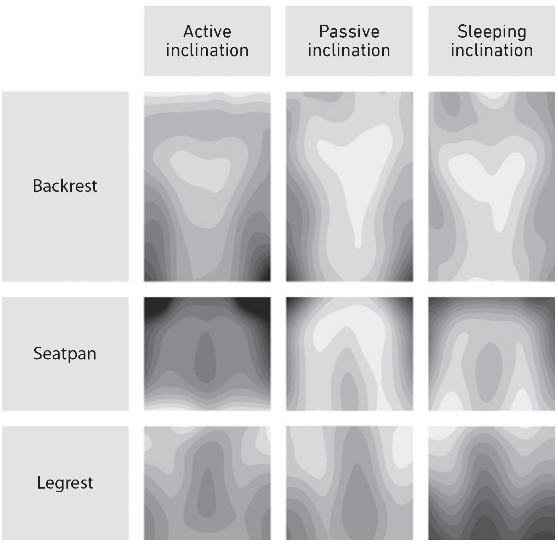

Fig. 6. Height map projection of the backrest, seat pan and leg rest of one subject.

Fig. 7. Reference pins on test seat, covered by socks for safety.

Since the seat's shell (in this design) is a single curved 2D shape (see §2.4), the 3D human contour is achieved by varying the firmness of the cushioning.

The thickness of the cushioning was set to 30 mm, for the purpose of weight and space reduction. The new cushioning is relatively thin compared to the traditional cushioning of 85-139 mm. The firmness needed for the cushioning to create the average human 3D curve was calculated with the help of the ideal pressure distribution [7] and validated using a theory for calculating cushion indentation [16]. The ideal pressure distribution avoids pressure peaks on softer tissues of the body since this is more healthy [16]. For calculation purposes, the unit IFD was used. IFD represents the Indentation Force Deflection, which is the force needed to indent the material a certain percentage of its original thickness.

The input for calculating the IFD is the force on the cushioning and the desired indentation of the cushioning. The force was calculated [17] based on the pressure distribution as represented by Zenk et al. [8] (Fig. 8). The pressure distribution was translated into the maximum pressure and subsequently into maximum load per body area as sectioned in the pressure distribution figure. These sections were chosen to simplify the pressure distribution in 3 equally sized areas: the buttocks, the thighs and the knee cavities. The seat pan and backrest were divided into a grid and afterwards the maximum force per grid square was calculated. The desired indentation per grid square was derived from the average human 3D shape as a result from §2.2. The IFD was calculated with the maximum force per grid square and the desired indentation per grid square. The data was checked using the percentage of the body mass from different body parts [18]. The different masses per body area were

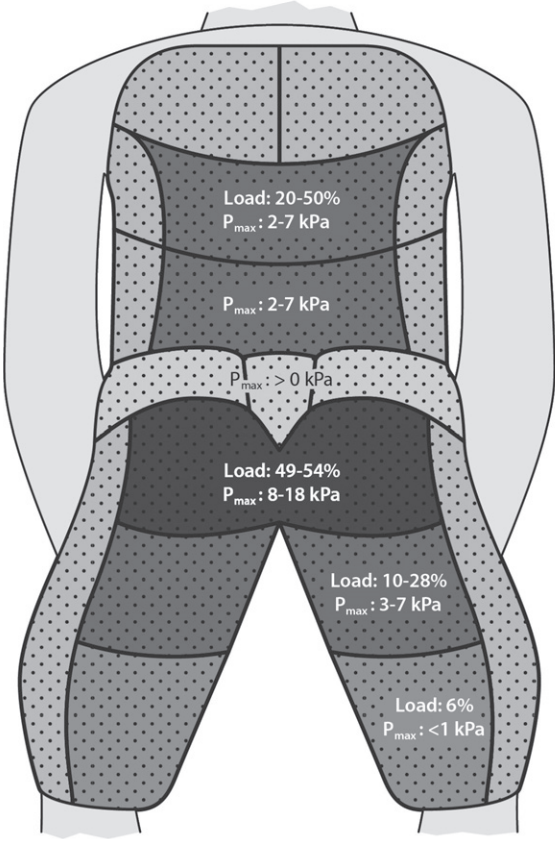

Fig. 8. Pressure distribution as described by Vink and Brauer [18].

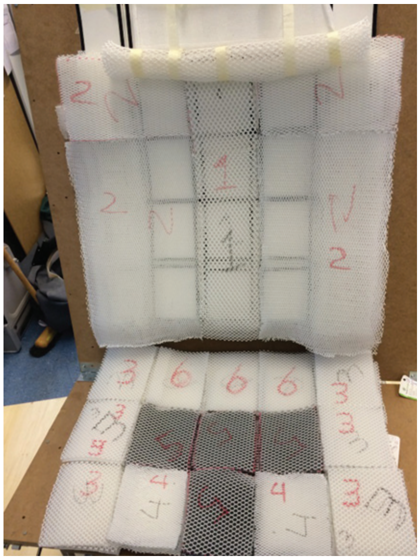

Fig. 9. Prototyped cushioning.

Fig. 10. Trial and error test.

translated into the resulting force per grid square to check the calculations.

Based on the calculated firmnesses, cushioning was prototyped by using different firmnesses of AMES DISTO® Spacer Fabric (Fig. 9). The comfort of the cushioning on the shell was optimised using a trial and error validation test. Twelve subjects sat on the seat for five minutes (Fig. 10) and subsequently completed a Local Postural Discomfort (LPD) form, indicating discomfort per body area. The form provided an indication whether the cushioning per body area felt too soft, too firm or just right (Fig. 11). The cushioning was adjusted and the test repeated until the subjects rated the cushioning as satisfactory.

2.4. *Prototyping business aircraft seat based on the human contour*

The 3D representation of the average human contour was used to develop the business class aircraft seat. The seat consisted of a hard shell, padded with cushioning. To develop the shell, the average 3D surface was simplified into a 2D line. The line represented the (average) curve of the spline, which was also the deepest part of the surface. The 2D line was translated into a shell, which forms the structural shape of the seat. Aluminium sheets were bent into the shape to form a mould. A sheet of TenCate Cetex® TC925 FST Polycarbonate Thermoplastic Resin System was then thermoformed onto the aluminium mould. The TenCate Cetex sheets were considered suitable since the sheets are currently used in aircraft

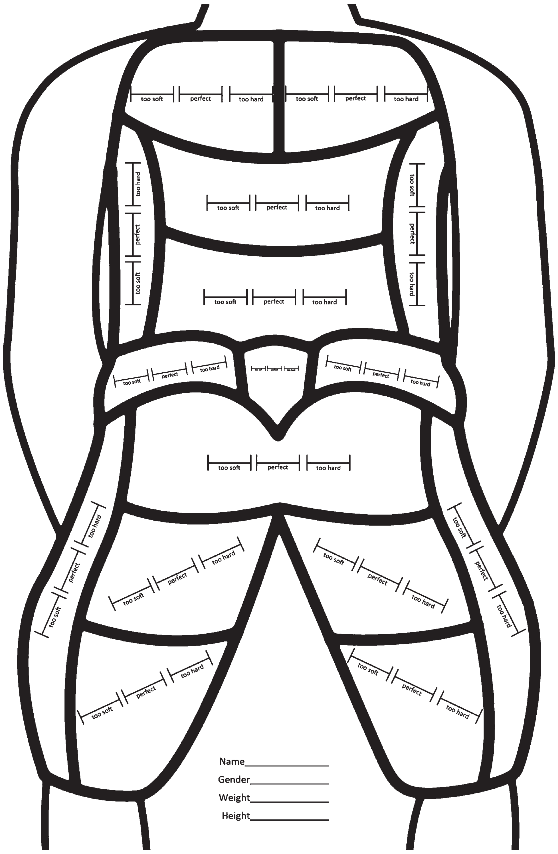

Fig. 11. LPD like form.

interiors for its properties related to flame retardent qualities, density and strength. Because the cushioning was more firm on the lateral sides of the seat, a 3D human contour was recreated. The cushion parts with different firmness were sewn together as one seat pan and one backrest cushion. The cushioning was mounted onto the hard shell and covered with fabric. During the study as described in §2.5, the shell was supported by a wooden frame. In the final prototype the common aluminium frame of traditional business class seats was replaced by a new designed carbon fibre frame with CNC milled foam core, to reduce the weight of the seat.

The reduction in weight of this new seat (compared with the traditional one) was estimated at 10.25 kg per seat, thanks to the use of lower density and less materials (–9.9 kg), lighter cushioning (–1.1 kg) and the change to thicker breathing fabric (+0.75 kg). However, extra weight can be expected since the prototype does not meet the strict aviation safety and crash regulations.

Table 4
Anthropometric measurements of subjects

		Mean	SD
Male ($n = 5$)	Age [years]	31.6	21.2
	Stature [cm]	182.4	10.9
	Body weight [Kg]	83.6	17.0
Female ($n = 5$)	Age [years]	31.6	13.2
	Stature [cm]	172.7	8.6
	Body weight [Kg]	78.0	14.5

2.5. Comfort and discomfort effects of the prototype and traditional seat

2.5.1. Subjects

Twenty people participated in the third study. Care was taken to select subjects with a variety in stature height, weight and age. Ten female and ten male subjects participated (Table 4).

2.5.2. Apparatus

A prototype seat was built with the 2D curved shell and the cushioning, as described in §2.4. The prototype seat was positioned in an existing framework of two business class seats with one seat removed. As a result the test setting consisted of an existing business class seat and the prototype seat. The seats were covered with a white sheet to prevent prejudice by appearance. Both of the seats had a 20 degree inclined backrest, an 8 degree inclined seat pan, a 20 degree inclined leg rest and a footrest perpendicular to the leg rest (all including a 3 degree inflight inclination). The inclination resembled the active position as determined in §2.1. This posture was selected since it causes the highest pressure points on the seat and is therefore the most interesting to investigate. A wooden wall simulated the pitch size of 1.5 meter which is common for long-haul business class and contained two 20” screens as IFE (Fig. 12). Two small tables, headphones, food and drinks were provided. Furthermore human measures were taken using an anthropometer, an adjustable measuring seat and a digital scale.

2.5.3. Procedure

Prior to the study, subjects received a letter with instructions not to wear clothing with solid components on their buttocks and back (e.g. buttons, buckles and zippers) to prevent influencing perceived comfort, discomfort and measured pressure.

Subjects were seated in pairs (to prevent order effects) and experienced each seat for 90 minutes. Each pair of subjects sat in the existing seat (seat A) and the prototype seat (seat B). After 90 minutes

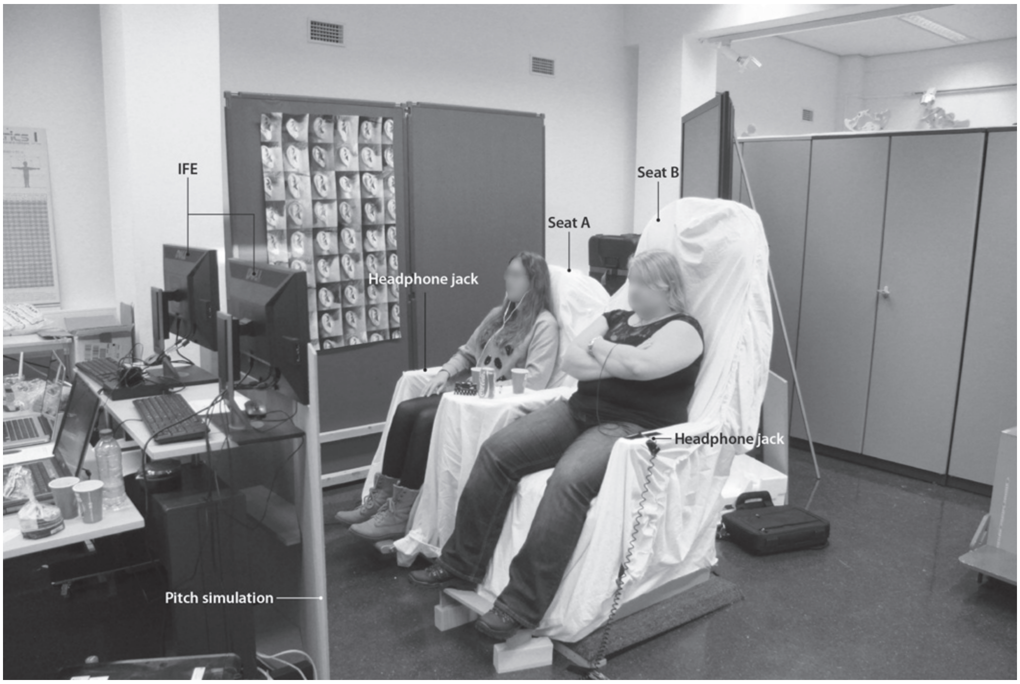

Fig. 12. Test set up.

the participants took a break. The break was used to conduct the research described in §2.6 and take anthropometric measurements of the subjects, such as weight, stature length and hip width. Furthermore the subjects had a chance to walk and use the toilet before switching seats for the other 90 minutes of sitting. The subjects were asked to choose one activity to conduct during the entire experiment; working on a laptop, reading or watching IFE. Only one activity was permitted as large postural change would influence perceived comfort and discomfort too much over time, making a time dependent comparison impossible. Every 15 minutes the subjects described their overall comfort on a 0–5 Likert scale and every 30 minutes the subjects completed a LPD form (see Fig. 13). Subjects were requested not to leave the seat during the 90 minutes. Drinks and snacks were offered.

2.5.4. Measures

All comfort and discomfort ratings per seat were compared over time and per seat using Microsoft Excel and SPSS. Because comfort values are not normally distributed, the Wilcoxon test was used in addition to a *t* test, to look for differences between the prototype and the traditional seat. The significant differences between total comfort and discomfort score were calculated ($p < 0.05$), and also between regions in the body (buttock and low back).

2.6. Pressure distribution effects of the prototype and traditional seat

2.6.1. Subjects

Pressure distribution of the prototype and traditional seat was recorded using the same subjects from §2.5.1.

2.6.2. Apparatus

The same test set up with two seats as mentioned in §2.5.2 was used. A mFLEX 4.0 UT4010-7000 pressure mat (sensor matrix of 32x16) and a laptop with FSA software were used to measure the pressure distribution in both the existing and the prototype seat.

2.6.3. Procedure

During the break described in §2.5.3, the pressure mat was subsequently placed in both the test seat and the existing seat, covering the seating area from the knee cavities up to and including the lower back. The focus was on measuring the sitting area, since it, has the most influence on comfort. The subjects sat in the seat on the mat for 5 minutes for posture settlement [19]. Then the pressure distribution was recorded.

2.6.4. Measures

With the FSA software the pressure in kiloPascals (kPa) per cell was determined. Coloured images were

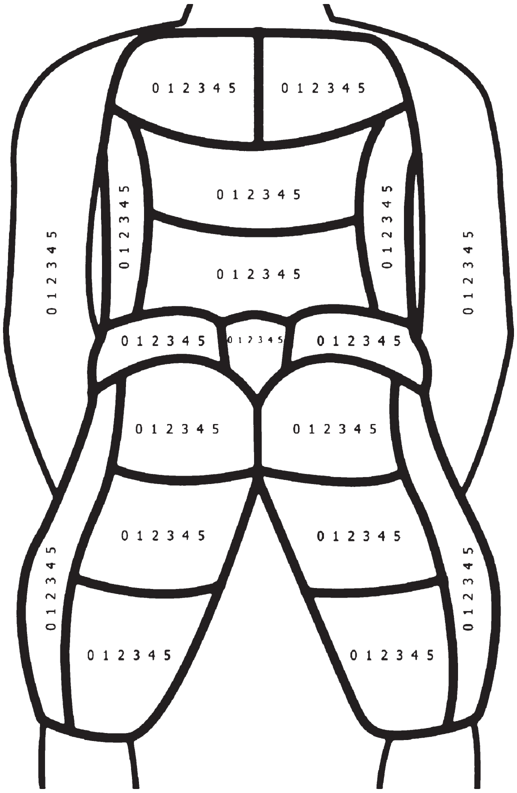

Fig. 13. LPD form.

saved as a reference to check the calculated pressure distribution, to help determine the position of body parts and to detect inaccuracies in the measurement (e.g. folds and pressure points caused by other body parts than buttocks and back).

Measurements of the average pressure were calculated for the seat pan and the back for both seats, by summing the measured pressures and dividing the total pressure by the number of cells that were activated. Additionally, the contact area in the seat pan and backrest were calculated by counting the number of cells that were activated. A t-test for paired comparison was used to check on significant differences between the prototype and traditional seat ($p < 0.05$).

3. Results

3.1. Inclination for different activities in Business Class aircraft seats

The results of the mean angles and standard deviation (SD) of the backrest inclination of the experiment described in §2.1 are shown in Table 5 and of the leg rest inclination in Table 6.

Plotting the results graphically (see Fig. 14) showed that the inclinations of different activities can be clustered into roughly three positions; active, passive and sleeping. Active activities used a relative upright backrest inclination and downward leg rest inclination. More ‘passive’ activities, such as watching IFE, had a relatively downward backrest inclination and upward leg rest inclination. Sleeping had an ‘as flat as possible’ inclination.

When combining all measures, three main business class inclinations were determined (backrest mean ± SD, leg rest ± SD): Cluster #1 (active) with 22.8° ± 6.8, 20.3° ± 20.3, Cluster #2 (passive) 31.0° ± 7.7, 48.1° ± 17.5 and Cluster #3 (sleeping) 55.5° ± 0.6, 63.1° ± 2.3. These three inclination clusters were used in the ‘3D scanning the human

Table 5
Backrest angles in degrees ($n = 10$, except ‘Listening to music’) with respect to the vertical

	Angles backrest in degrees (incl. 3 deg. airplane angle)							
	Write	Eat and drink	Sleep	Watch Flight Entertainment System	Listen to music ($n = 6$)	Play/work on mobile phone/tablet	Read book	Work on notebook
Mean	20,5°	20,4°	55,5°	31,7°	36,3°	31,3°	30,2°	27,5°
SD	5,5°	5,0°	0,6°	5,6°	11,3°	7,6°	6,4°	7,6°

Table 6
Leg-rest angles in degrees ($n = 10$, except ‘Listening to music’) with respect to the vertical

	Angles leg-rests in degrees (incl. 3 deg. airplane angle)							
	Write	Eat and drink	Sleep	Watch Flight Entertainment System	Listen to music ($n = 6$)	Play/work on mobile phone/tablet	Read book	Work on notebook
Mean	28,5°	37,9°	63,1°	50,0°	51,0°	43,4°	49,0°	42,1°
SD	19,1°	22,1°	2,3°	20,2°	14,7°	20,3°	14,9°	19,2°

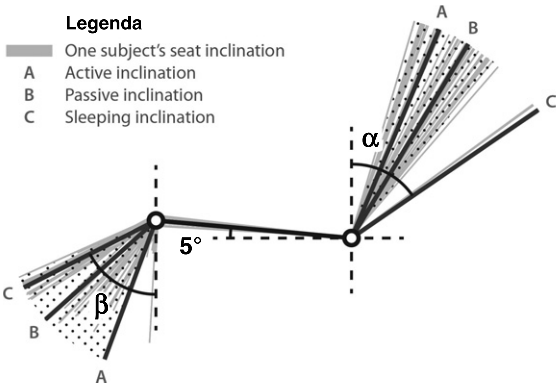

Fig. 14. Plotted inclination angles.

contour in pre-determined inclinations' study, as described in §2.2. Comparing the results with literature [12, 13] showed similarities. Kilincsoy et al. [13] described an active posture with a 105° trunk thigh angle, confirming this studies active inclination angle. Park et al. [14] describe a 117° trunk thigh angle, similar to this studies passive inclination angle.

3.2. 3D scanning the human contour in pre-determined inclinations

The results of the measures (the grid projections) were positioned in the same plane to determine an average of all scans. For each cluster of points on each XY coordinate a mean could be determined by averaging the Z-coordinates of the grids.

The result was an averaged point grid, converted into a non uniform rational B-spline (NURBS) surface. The surface was a smooth 3D representation of the average human contour of the scanned participants in all the three sitting positions (Fig. 15). These surfaces were used in §2.4.

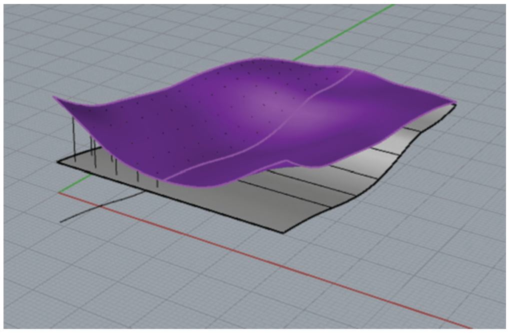

Fig. 15. Average point grid of the seat pan.

3.3. Pressure distribution calculations and testing

The calculations for the ideal pressure distribution cushioning developed for the human contour based shape resulted in IFD values. The IFD values per body region, divided in blocks of 50 × 50 mm, can be found in Tables 7 and 8. The IFD values and the recorded average human contour shape formed the base for the trial and error testing. By putting pieces of cushioning with different firmnesses on top of the contoured shell, an attempt was made to arrive as close as possible to the calculated IFD values. This process resulted in the final cushioning design made out of separate pieces of different thicknesses and firmnesses (Fig. 16), which were sewn together into one layered cushion. To limit the influence of the seams on the cushion properties, but at the same be small enough to create the ideal pressure distribution based cushioning, block sizes of 140 × 165 mm were used.

3.4. Prototyping business aircraft seat based on the human contour

The shape of the seat was based on a hard shell and cushioning design. All previously stated findings are combined in the prototype.

Table 7
IFD values backrest in Newton per mm

	Head									
Backrest	3,33	1,37	–1,29	–2,73	–3,06	–3,06	–2,73	–1,29	1,37	3,33
	0,82	–0,82	–2,34	–3,02	–3,08	–3,08	–3,02	–2,34	–0,82	0,82
	–0,61	–2,06	–2,96	–3,14	–2,98	–2,98	–3,14	–2,96	–2,06	–0,61
	–0,40	–0,88	–1,11	–1,09	–0,97	–0,97	–1,09	–1,11	–0,88	–0,40
	–0,48	–0,95	–1,12	–1,04	–0,88	–0,88	–1,04	–1,12	–0,95	–0,48
	–0,51	–0,96	–1,11	–0,99	–0,80	–0,80	–0,99	–1,11	–0,96	–0,51
	–0,08	–0,13	–0,16	–0,14	–0,11	–0,11	–0,14	–0,16	–0,13	–0,08
	–0,09	–0,13	–0,15	–0,14	–0,11	–0,11	–0,14	–0,15	–0,13	–0,09
	–0,11	–0,13	–0,15	–0,14	–0,12	–0,12	–0,14	–0,15	–0,13	–0,11
	Tailbone									

Table 8
IFD values seat pan in Newton per mm

	Tailbone									
Seat pan	0,42	0,13	–0,33	–0,64	–0,72	–0,72	–0,64	–0,33	0,13	0,42
	0,58	0,28	–0,22	–0,58	–0,71	–0,71	–0,58	–0,22	0,28	0,58
	0,68	0,39	–0,12	–0,53	–0,70	–0,70	–0,53	–0,12	0,39	0,68
	0,42	0,25	–0,05	–0,31	–0,42	–0,42	–0,31	–0,05	0,25	0,42
	0,39	0,22	–0,07	–0,32	–0,42	–0,42	–0,32	–0,07	0,22	0,39
	0,38	0,20	–0,10	–0,34	–0,43	–0,43	–0,34	–0,10	0,20	0,38
	0,18	0,08	–0,04	–0,12	–0,15	–0,15	–0,12	–0,04	0,08	0,18
	0,25	0,11	–0,03	–0,12	–0,15	–0,15	–0,12	–0,03	0,11	0,25
	Knee cavity									

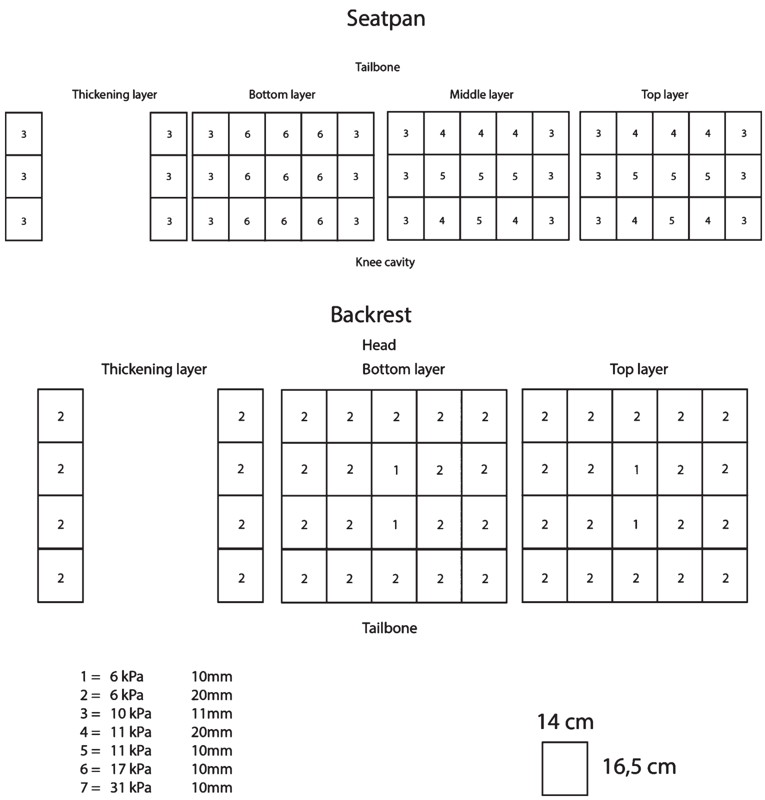

Fig. 16. Final firmnesses cushioning.

3.5. *Comfort and discomfort effects of the prototype and traditional seat*

The goal of this study was to find out if there was a difference in comfort and discomfort in the existing seat (seat A) and the prototype (seat B).

Regarding the discomfort calculated with the LPD forms, there was a significant difference in discomfort between seat A and seat B (see Table 9). Seat B shows significantly more overall discomfort than seat A after 30 minutes of sitting ($p = 0.007$). This effect diminished after 60 and 90 minutes, thus there was no significant discomfort after 60 and 90 minutes in seat A or B. Studying the discomfort of seat A and B in the different body areas, lower back and the buttock, the only significant difference found was the lower back after 30 minutes. Seat B caused significantly higher discomfort than seat A in the lower back after 30 minutes ($p = 0.04$). There was no significant difference in seat A and B for the discomfort in the buttocks.

The significance in change of overall discomfort over time is found in Table 10. There was a significant

Table 9
Values of discomfort within the seat compared ($n = 20$)

	Time	30 minutes		60 minutes		90 minutes	
	Seat type	A	B	A	B	A	B
Average overall discomfort	Mean	3.9	6.2	8.1	6.55	7.9	9.65
	Standard deviation	2.31	4.74	6.27	4.41	8.40	5.84
	p-value	0.073		0.383		0.361	
Lower back discomfort	Mean	1	1.7	3.15	3.4	2.45	3.65
	Standard deviation	1.03	1.63	2.83	3.93	2.28	2.81
	p-value	0.044		0.783		0.114	
Seat discomfort	Mean	1.5	2.35	3.3	2	3.6	4.05
	Standard deviation	1.88	2.96	5.32	2.20	5.76	5.35
	p-value	0.204		0.265		0.640	

Table 10
Difference in discomfort at different times within same seat ($n = 20$)

Seat A		Seat B	
Values compared (minutes)	*p*-value	Values compared	*p*-value
30–60	0.004	30–60	0.817
60–90	0.913	60–90	0.054
30–90	0.025	30–90	0.0007

increase in discomfort in seat A during the period of 30 to 60 minutes in the seat ($p = 0.04$). Furthermore the discomfort significantly increased in the period after 30 minutes of sitting until 90 minutes of sitting in seat A ($p = 0.03$). The discomfort in seat B significantly increased in the period from 30 until 90 minutes of sitting ($p = 0.0007$). Thus the discomfort in seat A and in seat B significantly increased over the period of 30 to 90 minutes of sitting. Only in seat A was there a significant increase of discomfort in the period between 30 and 60 minutes of sitting.

The difference in comfort in seat A and seat B are found in Table 11. There was no significant difference of comfort in seat A or B at anytime. The comfort in seat A decreased significantly over time (see Table 12) in the period from 45–60 minutes ($p = 0.015$) and in the seat and during the overall period from 15 to 90 minutes in the seat ($p = 0.009$). The comfort in seat B decreased significantly over time in the period from 30–45 minutes ($p = 0.010$) in the seat and during the overall period from 15 to 90 minutes in the seat ($p = 0.012$). Thus the comfort in both seat A and seat B significantly decreased in the period from 15 to 90 minutes of sitting. In seat A there was a significant decrease in comfort in the period from 45–60 minutes of sitting, in seat B this decrease occured in the period from 30–45 minutes of sitting.

3.6. *Pressure distribution effects of the prototype and traditional seat*

The mean pressure of the seat pan of seat A mean ± SD was 6.0 ± 1.4 [kPa/cell] and seat B mean ± SD of 4.8 ± 1.5 [kPa/cell], which was significantly different ($p < 0.001$). This means there was a lower average pressure in the prototype seat's seat pan.

The mean pressure of the lower backrest of seat A was 1.2 ± 0.4 [kPa/cell] and seat B mean ± SD of 2.5 ± 0.8 [kPa/cell], which was significantly different ($p < 0.001$). This means there was higher average pressure in the prototype seat's backrest.

The number of recorded contacts of the seat pan for seat A was 144.3 ± 23.5 [cells] and for seat B 123.0 ± 18.5 [cells], was also significant ($p < 0.001$).

The number of recorded contacts of the backrest for seat A was 73.8 ± 25.9 [cells] and for seat B 50.6 ± 14.4 [cells], was also significant ($p < 0.001$). This means that the contact area in seat A was larger than in seat B for both the seat pan and the backrest.

Table 11
Values of comfort within the seat compared ($n = 20$)

	Time in seat in minutes	15	30	45	60	75	90
Seat A	Mean comfort score	4.25	4.15	4	3.65	3.6	3.5
	Standard deviation	0.55	0.59	0.46	0.75	0.68	0.83
Seat B	Mean comfort score	4.00	3.90	3.60	3.50	3.35	3.45
	Standard deviation	1.17	1.10	1.16	1.11	1.08	1.15
	p-value difference A and B (Wilcoxon)	0.344	0.291	0.130	0.570	0.344	0.787

Table 12
Difference in comfort at different times within same seat ($n = 20$)

Values compared	p value	Values compared	p value
A 15–A 30	0.428	B 15–B 30	0.428
A 30–A 45	0.083	B 30–B 45	0.010
A 45–A 60	0.015	B 45–B 60	0.428
A 60–A 75	0.716	B 60–B 75	0.186
A 75–A 90	0.330	B 75–B 90	0.330
A 15–A 90	0.009	B 15–B 90	0.012

4. Discussion

4.1. Inclination for different activities in Business Class aircraft seats

During the inclination study, it was noted that subjects did not always change their inclination when conducting another activity. As subjects were asked to move from one activity to another, without the request to adjust the seat to the initial inclination first, the inclination of one activity could influence the inclination of the next activity as described by Helander et al. [20]. The effect of this on the resulting inclination preferences was not further investigated, but it could have disturbed the results. Subjects may judge their current inclination as sufficiently comfortable to conduct their new activity and therefore will not feel the urge to adjust their inclination for a better one. It is therefore recommended to incline the test seat back into a standard position after each performed activity in further research.

4.2. 3D scanning the human contour in pre-determined inclinations

The first research question considered the link between 3D scanned human contours and defining the shape of the seat. This study showed that it is possible to use the form as a base. However, due to the variation of body anthropometrics a creative step was needed. By using a grid and condensing the data, a 2D form could be defined and by adding variation in foam firmness a translation to a seat could be made.

As stated in §2.2.4 vertical metal pins on the seat (Fig. 7) were used as reference points, to align all 3D scans. This however was not ideal, because subjects never sat in the exact centre of the rescue mat. A better method would be to use a software algorithm to superimpose the scans into an average curve, as Hiemstra-van Mastrigt [21] did in the YZ-plane.

Franz et al. [8] used a similar technique. They arranged the scanning data in a position, approaching the scatter plots of the scans as close as possible to each other, using a best-fit algorithm. They also used a creative solution to combine the scans by prioritizing areas which are most important to comfort.

Apparently a one-to-one translation from scan to seat is not possible for groups of users. A one-to-one translation often results in a more or less even pressure on the body, while some parts of the body are more sensitive to pressure and others can handle more pressure. Franz et al. [8] showed that in the neck less pressure was acceptable than on the back of the head. Zenk et al. [7] showed that more pressure was preferred on the buttocks than under the front of the legs. A comfortable posture in the rescue mat does not guarantee an ergonomically correct posture. Additional creative steps and testing are therefore recommended to encourage people to adopt a better posture, which will lead to more comfort in the long term. Therefore biomechanical models and mathematical steps need to be taken in order to develop an ergonomic seat.

Another factor which makes the interpretation complex is that different activities are performed in the same seat [10]. Scans of different persons performing different activities should be combined. This study clearly shows that the angles of backrest and leg rest differ per activity, which was also described previously by Groenesteijn [22]. This means that a 3D scan is helpful for the design, but a creative step to translate it into a product is still needed. At this time it is unclear what the best procedure would be to make this step.

The approach used in this study is effective, but Franz et al. [8] show another possibility of measurement. Franz et al. suggested using inflatable cushioning, which is made out of inflatable compartments. By pumping air in or out, the firmness per region can be adjusted, which allows the seat to match every individual's contour.

Lastly it is important to note that the resulting average curve of the human contour in this study is based on Dutch subjects only, who are rather tall compared to an international audience [24]. It is therefore recommended to take the audience (e.g. international, children) into account when selecting subjects for gaining a representative average or ideal curve.

4.3. Pressure distribution calculations and testing

By adding the cushioning with different firmnesses to the shell, the 2D shaped shell was translated to the

3D human contour based shape. Postural differences between different people were adressed. As the cushioning on the sides of the seat are more firm, larger and heavier people will cause the cushioning on the sides of the seat to indent as well. Smaller and lighter people will not cause the cushioning on the sides of the seat to indent. Therefore the seat supports different contours for larger and smaller people.

Whilst calculating the firmnesses of the cushioning, some assumptions were made. First of all, the ideal pressure distribution as described by Vink and Brauer [18] was projected onto the seat. As the exact sizes of the pressure distribution, supports on the size of the subject, the pressure distribution was simplified in 3 equally sized area's; the buttocks, the thighs and the knee cavities. Secondly the seat pan and backrest were divided into a 50 × 50 mm grid to calculate the different forces. The size of the grid may have influenced the IFD values. A smaller grid would have given more exact values, although the ideal pressure distribution as described by Vink and Brauer [18] was not detailed enough to make more precise calculations. Additionally, the used cushioning did not allow for smaller squares.

4.4. Prototyping business aircraft seat based on the human contour

The prototype used during the study as described in §2.5 was supported by a wooden frame, which was not adjustable and the foot rest was not attached to the seat. Therefore the prototype was different from the traditional seat, as the traditional seat had an adjustable foot rest attached to the leg rest. Although one subject assumed the traditional seat was the newly developed seat, it can be questioned whether subjects were prejudiced by the test setup and the difference of the two seats was visible. As a recommendation for future research, both seats should look the same in all aspects to prevent subjects' visual interpretation having an influence on their perceived comfort and discomfort.

4.5. Comfort and discomfort effects of the prototype and traditional seat

The study to answer the second research question concerning the difference in comfort and discomfort between both seats showed no statistical results, only interpretations. There is no significant difference, which might lead to the conclusion that reducing the weight is possible without large effects on comfort.

The cushioning of the prototype was 30 mm thick and the cushioning of the traditional seat was to 85-139 mm thick in the seat pan and 133 mm thick in the backrest. Thus the contour based seat was 65-79% thinner in the seat pan and 73% thinner in the backrest than in the traditional seat. The thickness of the backrest has a direct effect on the pitch length; the new backrest design is 83 mm thinner. Valuable space was saved whilst the same level of comfort was obtained. This has also been described for car seats [8,9]. However, there is more discomfort at the beginning of the test (after 30 minutes) in the lower back, which was so large that it influenced the total discomfort. Later, the difference between the two seats was not significant anymore. Ahmadpour et al. [4] showed that the first 30 minutes of the flight are crucial, since it has major influence on the experience of the total flight. It is therefore recommended to further optimize the seat form or cushioning, to improve the experience in the first 30 minutes.

4.6. Pressure distribution effects of the prototype and traditional seat

The pressure distribution showed (see §3.6) the pressure was better distributed in the seat pan, but less in the back in the prototype seat. Literature shows that a lower average pressure is accompanied by less discomfort (e.g. Noro et al. [23]). However, this is not affirmed in this paper, because there was no significant difference in discomfort between the prototype and traditional seat. The results show that the contact area in the traditional seat is larger than in the prototype seat. This was due to the soft thick cushioning, which however impaired movement.

The higher pressure in the backrest of the prototype seat may have caused the discomfort in the lower back, compared with the traditional seat. Further research and redesign of the backrest are recommended to improve pressure distribution.

5. Conclusion

This study showed that it is possible to design a seat pan and backrest based on the human contour using 3D scan technology, however a creative and/or mathematical process is needed to transform it to curvature and cushioning. It is not possible to capture all different human shapes and postures and translate these to one average human contour shape that fits all activities and all humans; design choices and compromises are necessary.

The lightweight human contour shaped business class aircraft seat did not affect the comfort, discomfort and pressure distribution when compared with a traditional business class aircraft seat. However, small differences could be distinguished especially in the lower back. Furthermore the mean pressure between the human and seat pan was lower in the new seat compared to the traditional seat. Due to discomfort and higher than average pressure, it is advised to adjust the lower part of the backrest and further study the effects. This study shows that the lightweight human contour based seat has a potential to achieve the same comfort and discomfort effects as a traditional business class seat.

Acknowledgments

We want to thank our colleagues who helped with 3D scanning the human contour and processing the results; A. Vogel, J.A. Stewart, A.J. Weiss, L.J. Lam, A.L.E. de Vries, S.H.F. van Gils. Staff of the Delft University of Technology, for their help, advice and/or guidance in this project; Prof.dr. P. Vink, B.J. Naagen, Prof.dr.ir. R.H.M. Goossens and Dr. H.F. Broekhuizen. For facilitating prototyping; Delft Aerospace Structures and Materials Laboratory of the faculty Aerospace Engineering of the Delft University of Technology, Model Making and Machine Lab (PMB) of the faculty Industrial Design Engineering of the Delft University of Technology and I.J. Berghman. Special thanks to F. Lee, S. Does and Zodiac Seats US LLC, for supporting this research and design project. H. Albers and Royal TenCate NV for supplying fiber materials and J. Berning and Ames Europe BV for supplying cushioning. R. Könemann and TNO (Netherlands Organisation for Applied Scientific Research) for lending the rescue mat. And lastly, thank you to all the participants who took part in this study.

Conflict of interest

The authors have no conflict of interest to report.

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