Seat-Human Interaction and Perception
A Multi-factorial-Problem

Wegner, M.; Reuter, C.; Fitzen, F.; Anjani, S.; Vink, P.

DOI
10.1007/978-3-030-51044-2_1

Publication date
2021

Document Version
Final published version

Published in
Future Inetrior Concepts

Seat-Human Interaction and Perception: A Multi-factorial-Problem

M. Wegner, C. Reuter, F. Fitzen, S. Anjani, and P. Vink

Abstract This study investigates the tactile perceived seat-human interaction of four types of BMW 5-series seats with the same foam properties and contours but different seat cover and seat suspension properties; 38 healthy subjects participated in an experiment rating and ranking the tactile perceived properties of the seats while blindfolded. A discomfort test, a seat characterizing rating on a scale of word pairs, and the overall experience of the seats were examined in four different sitting positions. The results of the experiment were related with the outcome of an objective measurement method: a pressure measurement mat and the measurement tool of Wegner et al. [19]. The study showed that the perception of the surface while interacting with the seat is independent from the sitting position. In contrast, the perception of the hardness and the elasticity of the seat is position-dependent. The results of the seat characterization are in line with the results of the measurement tool of Wegner et al. [19]. Further research is needed to investigate the mutual interdependence of the various measurement points of the measurement tool and to improve the prediction accuracy of the seat characteristics.

Keywords Pressure measurements · Shear force · Discomfort · Seat perception

1 Introduction

Most individuals, and particularly those with sedentary jobs, sit for nearly ten hours each work day and eight hours during their own, independent leisure time [14]. Typically, as long as the individual feels comfortable and supported, the seat on which an individual is seated is of little importance. Regardless of what seat and

M. Wegner (✉) · P. Vink
Faculty of Industrial Design Engineering, Delft University of Technology, Landbergstraat 15, 2628 CE Delft, The Netherlands
e-mail: Maximilian.Wegner@bmw.de

M. Wegner · C. Reuter · F. Fitzen · S. Anjani
BMW GROUP Research and Innovation Centre (FIZ), BMW Group, Knorrstraße 147, 80937 Munich, Germany

A. Fuchs and B. Brandstätter (eds.), *Future Interior Concepts*,
Automotive Engineering : Simulation and Validation Methods,
https://doi.org/10.1007/978-3-030-51044-2_1

what position a person takes, the seat or chair should allow to vary and shift the posture easily. In this context Sammonds et al. [16] showed that movements and seat fidgets correlate with the discomfort rating of a seat. The micro and macro movements rise over the duration of time as well as the poor subjective discomfort ratings.

The development of seats for automobiles that allow passengers to move and switch to various positions from sitting through to lying is crucial to the automotive industry. This could become even more important in autonomous driving cars as more seat positions will be possible when there is no driving task. For an individual to be comfortable in the car, a car seat must support the passenger in a dynamic driving situation but moreover provide enough space for postural changes in various loading situations. Hence, it should be considered to change loading of the area of the seat being in contact with the passenger as well as the interaction area including various sensitivity areas. A study by Vink and Lips [18] proved that the pressure sensitivity of the area touching the shoulder and the area touching the front of the cushion close to the knees is significantly higher than all other body areas in contact with the seat. Furthermore, some parts of the body need more support than others. Biedermann and Guttmann [1] claimed, inter alia, that the natural physiological curve of the spine should be supported in the lumbar area. There are more influencing factors [20] making the discomfort and comfort perception of an automotive seat a multi-factorial problem with contributions occurring from effects of the seat layout including the foam properties, the contour, the cover properties, and the dynamic environment as well as effects on the human senses including the sitting, position, the sitting duration, pressure, shear force, and blood flow.

Most studies focus on the driver position and on the discomfort ratings of seat contours and seat foams relating the findings to pressure parameters (e.g. [9, 12, 21]). However, the multi-factorial problem is often reduced to a mono-problem, not taking the seat cover and other seat components into account. Most studies neglect to address other interactions parameters of the human senses than pressure. Mansfield et al. [13] investigated the extent of which foam properties affect the discomfort rating. For his study he removed the seat cover in order to enable the foam being in direct contact with the subject's clothing. Also, Hiemstra-van Mastrigt [11] compare the foam hardness of two train seats and checked the effect on comfort experience. Zenk et al. [21] used various foams to evoke different pressure distributions and thus different discomfort ratings. In reference to this approach an ideal pressure distribution was developed and after validated in a long-term rating. The results represent that there is a link between the cushion, the discomfort rating, and the pressure distribution of the cushion. Notably, the correlation between the backrest was not significant. Both, Mansfield et al. [13] and Zenk et al. [21] excluded the surface, cover properties of the seat, and the interaction of the seat components.

In contrast, Zuo et al. [22] revealed that the sensory properties of materials are relevant for the interaction between users and should be considered in the course of the material selection process. Regarding the gathered information he developed a method for an intelligent choice of materials based on holistic perceptional information of different materials. Likewise, Wegner et al. [20] showed that the seat cover material has fundamental influence on the perception and the characterization of a seat. The study compares two seats with the same contour and the same foam properties but with different cover materials.

With reference to the human mechanoreceptors explained by Schmidt and Thews [17], not only the pressure is an important tactile sensor but also the shear and the elongation have to be taken into account. Chow and Odell [2] linked the pressure to shear stress stating that interface shear force significantly affects the pressure distribution. Based on simulative results Grujicic et al. [6] correlated a higher cover friction to higher shear forces. Also, Goossens and Snijders [5] showed that the shear force could be reduced by changing the seat position and seat angles on the one hand. On the other hand, Goossens [7] presented that the shear force can be reduced by using the right cushion material, a LiquiCell cushion. Thus, not only the ideal seat angle [10], seat pan angle of 10° and backrest angle of 120° is important but additionally the angle position in combination with the applied seat components.

In this study the seat perception is considered as a multi-factorial problem including various seat components as well as the seat-human interaction parameters: pressure, elongation and shear force [17]. The aim for this study is to investigate how occupants rate and perceive seat characteristics and discomfort of car seats with equal foam properties and contours but different cover properties and seat suspensions in various loading states. Next, the study investigates whether the objective measurement methods with the pressure measurement mat and the measurement tool of Wegner et al. [19] sufficiently explain the seat ratings.

2 Methods

In this section the study approach: the scope of participants, the seats used for the study, the procedure of the study, and the statistical analysis are presented. The description of the procedure also includes the presentation of two objective seat measurement methods: first, the pressure measurement mat and second the seat measurement with the measurement tool of Wegner et al. [19].

2.1 Participants

38 subjects, 17 males and 21 females, participated in the experiment. The mean body height of the participants was 1.69 m (1.53–1.86 m) with a mean body weight of 66.2 kg (48–98 kg). On the torso, the participants either whore t-shirts (60%), pullovers (16%), long sleeve t-shirts (11%), polo shirts (8%), or dresses (5%); on the bottom either jeans (55%), cloth pants (40%), or leggings (5%).

2.2 Seats

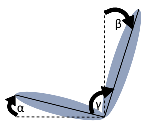
Four BMW 5-series seats are used in this study. The standard contour of the seats was used, which is not distinctive. The seat layout was kept simple, consisting of a seat frame, foam, heating mat, and cover. All seats are produced and assembled in the same factory on the same day, and during a similar period fulfilling all specified requirements of the manufacturer, especially the foam hardness which is measured in kPa. One seat, defined as the reference seat, is without any modification (*seat 1*). *Seat 1* is a leather seat with a specified foam hardness of 6 kPa in the main surface of the cushion and 10 kPa in the bolsters. The backrest has a foam hardness specification of 5 kPa in the main surface and 8 kPa in the bolsters. Compared to the reference seat, each seat differs in one parameter: One seat has an Alcantara cover instead of leather (*seat 2*), another seat (*seat 3*) has a looser cover tension, and the last seat has a metal plate installed instead of the original seat suspension (*seat 4*).

2.3 Setup

The four seats are mounted next to each other on a base plate (Fig. 1). The plate has a footrest following the geometric specifications of the BMW 5-series. All seats have an electrical seat adjustment which allows to adjust all seats equally to four different positions (Table 1). Position 1 is the driving position, containing the required seat angles for development of the seat and safety requirements. Position 2 and 3 have a flat cushion angle with the difference that the backrest angle in Position 3 is more horizontal than in Position 2. Position 3 and 4 have the same γ-angle but Position

Fig. 1 The figure illustrates the setup of the study with all four seats in a row from left to right: reference seat (*seat 1*); Alcantara seat (*seat 2*); loose cover tension (*seat 3*), and the seat with the metal plate instead of the seat suspension (*seat 4*)

Table 1 Illustration of the four adjusted seat angles for the cushion and the backrest



	α	β	γ
Position 1	14°	20°	96°
Position 2	3°	40°	127°
Position 3	3°	55°	142°
Position 4	18°	70	142°

4 has a higher cushion (α) and backrest (β) angle. The reason for these position changes was to create changes in comfort perception and pressure distribution as by the variation of the angles the weight of the body loads the cushion and backrest differently.

2.4 Procedure

2.4.1 Seat Evaluation

For gathering anthropometrics data, an anthropometric chair was used. Data regarding sitting height, hip width, buttock-popliteal length etc. were recorded using the procedure described by Molenbroek et al. [15]. During the recording, which took several minutes, each participant was informed about the procedure and the questionnaire but did not get any information regarding the setup and the differences of the seats. The participants were blindfolded wearing an eye mask during the entire experiment in order to exclude visual impressions. Only one participant at a time was going through the procedure. Once all tests were completed the next participant started. This way the participants could not exchange any information prior to the test. The study began with the participants discomfort rating of all four seats in Position 1. The order in which the participants rated the seats was changed for all tests systematically. The participants were not allowed to touch the seat surface. After sitting three minutes in each seat, the participants rated the discomfort of the seats through a Local Postural Discomfort (LPD) body map and a discomfort score from zero (no discomfort) to six (very heavy discomfort). Afterwards, for each seat and each participant a pressure measurement was conducted in Position 1. Regarding the pressure analysis the cushion is divided in three groups shown in Fig. 2: *buttock Group*, *front Group* and *side Group*. The backrest is cumulated into another group, called *back Group*. For every participant the recorded frames per each group were merged and the *average pressure*, *peak pressure*, and *contact area* calculated. The mean value and the standard deviation for the *average pressure*, *peak pressure*, and *contact area* over all 38 participants and for each seat were determined.

Next, the participants had to rate with words each seat in all of the four positions (Table 1). Three pairs of words given for them to describe the cushion and the backrest: *soft-hard*, *elastic-stiff*, and *slippery-abrasive*. The word pairs are shown

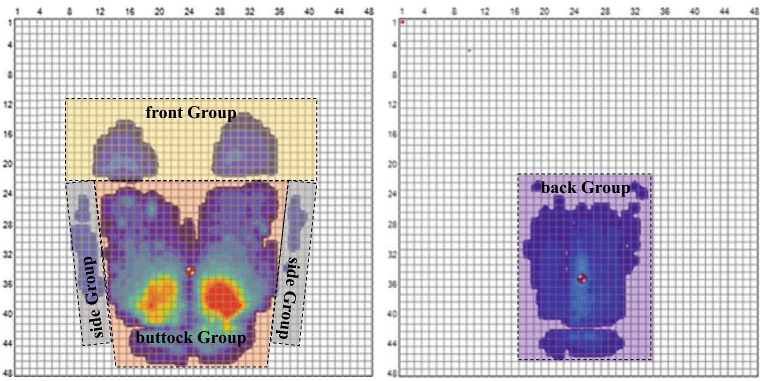


Fig. 2 Considered areas of pressure defined in three groups for the cushion and one group for the backrest

on a Likert Scale (1–7). Ratings of 1, 2, or 3 represent a tendency to a soft, elastic, and slippery characterization whereas ratings of 5, 6, or 7 have a tendency to a hard, stiff, or abrasive characterization. A rating of 4 demonstrates a neutral rating without any tendency to one of the extremes. After rating all four seats the participants were asked to rank the seats from their favorite to their least favorite seat.

2.4.2 Measuring the Seats with a Measurement Tool

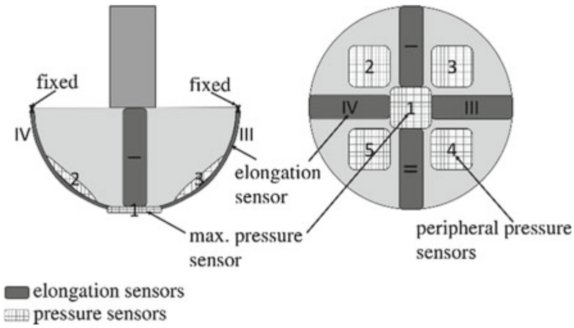
After the test was conducted the seats were analyzed with the measurement tool of Wegner et al. [19]. The measurement points (Fig. 3) for the backrest are the shoulder (1), the lumbar area (2), and the bolster of the backrest (3). The measurement points for the cushion are at the area of the ischial tuberosity (4), the front of the cushion (5), and the bolster of the cushion (6).

The measurement procedure for each measurement point includes four cycles, three pre-cycles, and one measurement cycle (following the guidelines in DIN 53579 [3] and DIN EN ISO 3386-1 [4]. The measurement cycle has four phases (see Fig. 5). During the first phase (①) the stamp loads the seat with a velocity of 100 mm/min until 100 N is reached. During the second phase (②) the stamp remains in the position for 30 s. Hereafter, the machine adjusts during the third phase (③) the force again up to 100 N and moves the Seat 5 mm in lateral direction relative to the stamp and remains 15 s in this position. The fourth phase (④) is the relief phase (300 mm/min).

During this measurement procedure the sensors of the stamp (five pressure sensors and fore elongations sensors, Fig. 4) record constantly the properties of the seats in each measurement point. The stamp has a silicon surface simulating the human skin. Figure 5 shows an example of the recorded data for a seat in one of the six measurement points. The first plot shows the recordings of the force and indentation. This plot includes the division into the four measurement phases (①–④). The second plot shows the recordings of the five pressure sensors (1–5). Last, the third plot

Fig. 3 Illustration of the measurement points

Fig. 4 Detailed illustration of the stamp. Pressure sensor are named from 1 to 5 and elongations sensors from I to IV



exposes the recording of the elongation sensors (I–IV). Based on these plots the following parameters for pressure and elongation are calculated.

Pressure: The (1) *first touch pressure* is defined as the pressure information of pressure sensor 1 after 5 mm indentation (empirical defined value of BMW internal Comfort Experts). The (2) *maximum pressure* has been defined as the value of pressure sensor 1 when a force of 100 N is reached. The (3) *linear pressure* identifies the shift from a linear rise of the pressure to an exponential rise of pressure based on the values of sensor 1 (first phase ①). The (4) *pressure distribution* is defined as the average pressure of the peripheral pressure sensors (sensor 2–4, Fig. 4) in phase two (②). The *maximum pressure* and the *linear pressure* are linked to the indentation information ((7) *linear indentation*, (8) *maximum indentation*).

Elongation: While loading (first phase ①), the elongation of each of the four sensors is recorded. The information of sensor I, II, III, and IV is summed to an

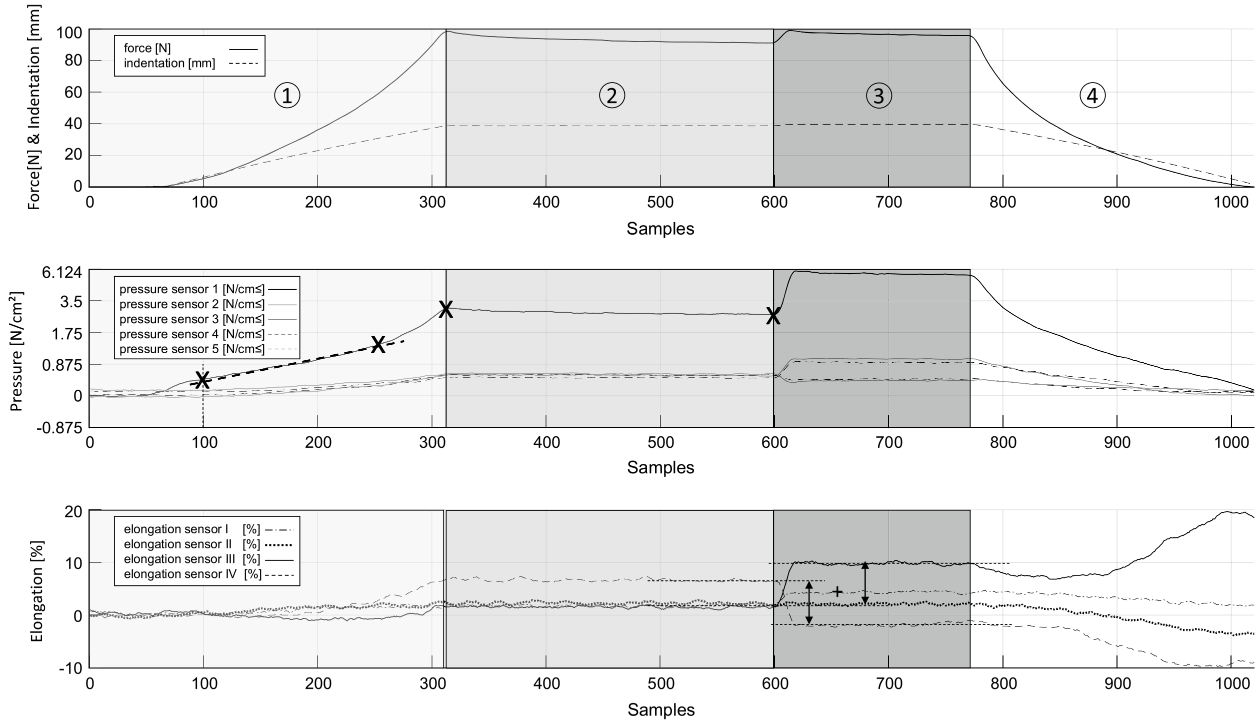


Fig. 5 The top diagram illustrates the force and indentation, the middle diagram presents the sensor data of the five pressure sensors, and diagram at the bottom presents the four elnongations sensor data

overall elongation (5) *elongation while loading the seat.* The information of the elongation sensor III and IV in phase three (③) enables to calculate the change of the elongation while applying a shear stress (moving the seat relative to the stamp in the direction of sensor III and IV). The change of elongation sensor III and IV is identified by calculating the difference between phase two (②) and phase three (③) of each sensor. Both values of sensor III and IV are summed up to an overall (6) *elongation due to the lateral movement*.

For a better comparability of the seats the (2) *maximum pressure* is normalized with the (8) *maximum indentation* and the (3) *linear pressure* is normalized with the (7) *linear indentation.* The (5) *elongation while loading the seat* and the (6) *elongation due to the lateral movement* are both normalized with a factor consisting the multiplication of the (2) *maximum pressure* and the *friction coefficient*. The (1) *first touch pressure* and the (4) *pressure distribution* are not normalized.

2.4.3 Determination of the Friction Coefficients

For an adequate comparison of both seat cover materials (leather and Alcantara) static and dynamic friction coefficient tests are conducted. The following material pairs are tested: *leather–silicon*, *Alcantara–silicon*, *leather–jeans*, *Alcantara–jeans*. By testing the friction coefficients of leather and Alcantara in combination with silicon and jeans a conclusion on the differences between silicon and jeans material could be made.

2.5 Statistical Analysis

The data of the word pair ratings were analyzed using a statistical analysis software program (IBM SPSS Statistics 25). The Friedman's Test was used to determine whether the participants detect differences in the perception of the four seats. The analysis was separately done for the cushions and the backrests ($\alpha < 0.05$) regarding their sitting position. If the results of the Friedman's Test are significant a post hoc analysis with a Wilcoxon signed-rank test is conducted for all six seat combinations (e.g., *seat 1–seat 2* or *seat 2–seat 4*). The six seat combinations are treated as six separate and unrelated observations, therefore, the Bonferroni correction is not applied, and the statistical significance is set to $\alpha < 0.05$.

3 Results

In the following section the results of the discomfort ratings are presented first. After this the descriptive results of the word pair ratings in each of the four positions is presented. Furthermore, the results of the Friedman's Test and the Wilcoxon signed-rank test are presented. Eventually, the last part illustrates the results of the pressure measurements and the analysis of the four seats with the measurement tool of Wegner et al. [20] as well as the results of the friction coefficient measurements.

3.1 Subjective Perception of the Seats

3.1.1 Discomfort Rating

Table 2 shows the results of the discomfort rating of the four seats. Ratings higher than 0 indicate discomfort. Regions with more than two complaints (N > 2) are bold. Regarding the cushion most participants have discomfort complaints in the second seat, the Alcantara seat. Discomfort appears to be large for the rear bolster region (H1 and H2) and in the front of the main surface (G1 and G2).

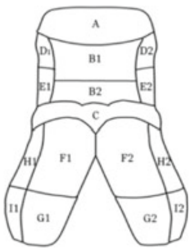
Regarding the backrest the reference seat (*seat 1*) has only one noticeable complaint; four participants mentioned discomfort in the upper back. The modified seats have all discomfort in the outer shoulder area (D1, D2), whereas *seat 3* has the most noticeable discomfort. For the same seat also in the backrest bolsters (E1, E2) noticeable discomfort complaints were issued. *Seat 4* (seat without seat suspension) has also noticeable discomfort complaint in the lumbar area (B2).

Participants who mentioned discomfort it was predominantly high in more than two areas for one seat. Nevertheless, the Alcantara seat (*seat 2*) has most discomfort in the cushion area and the seat with the loose cover tension (*seat 3*) as well as the seat with a plate instead of the seat suspension (*seat 4*) have high discomfort in the backrest areas.

3.1.2 Word Pair Rating

Descriptive: Figure 6 gives a descriptive overview of the seat and position characteristics. The orange circle represents the neutral rating (Likert Scale rating of 4). Every characteristic which is rated hard, stiff, or abrasive lies outside the circle and the characteristics soft, elastic, and slippery lie inside the circle. Figure 6 illustrates that *seat 3* in Position 1, the driving position, is rated as the softest and the most elastic seat. In contrast, all other seats are rated stiffer for the backrest as well as for the cushion. *Seat 2* is rated as the most abrasive seat especially for the backrest. The seat rated the hardest regarding the cushion and the backrest is *seat 4*. As for Position 2 the abrasive surface of *seat 2* appears dominant for the participants. Furthermore, the hardness of the backrest of *seat 4* is dominant. Overall, in Position 2 all other ratings of the characteristics move closer to the neutral rating. In Position 3 the abrasive surface of *seat 2* is still dominant to the participants. Other than that, all seats in Positions 3 are rated harder and stiffer for the backrest than in Position 1 and 2. As opposed to Position 2 and 3, in which most characteristics for the four seats were

Table 2 Results of the discomfort rating with a local postural discomfort (LPD) body map for all four seats



			Seat 1 reference (leather)		Seat 2 Alcantara		Seat 3 loose cover (leather)		Seat 4 plate (leather)	
			N	Ø-rating	N	Ø-rating	N	Ø-rating	N	Ø-rating
	Backrest	A	0	0	0	0	2	2	2	1.5
		B1	**4**	**2.5**	1	1	2	1.5	2	3
		B2	2	2	1	1	3	3	**4**	**2.25**
		C	0	0	0	0	0	0	0	0
		D1	2	1	**3**	**1.33**	**5**	**2.8**	**3**	**1.33**
		D2	2	1	**3**	**1.33**	**5**	**2.8**	**3**	**1.33**
		E1	1	4	1	3	**3**	**2.67**	1	4
		E2	1	4	1	3	**3**	**2.67**	1	4
	Cushion	F1	2	1	0	0	0	0	1	3
		F2	2	1	0	0	0	0	1	3
		G1	2	1.5	**3**	**1.33**	1	2	2	2
		G2	2	1.5	**3**	**1.33**	1	2	2	2
		H1	1	1	**5**	**2**	1	1	1	1
		H2	1	1	**5**	**2**	1	1	1	1
		I1	0	0	0	0	1	1	1	1
		I2	0	0	0	0	1	1	1	1

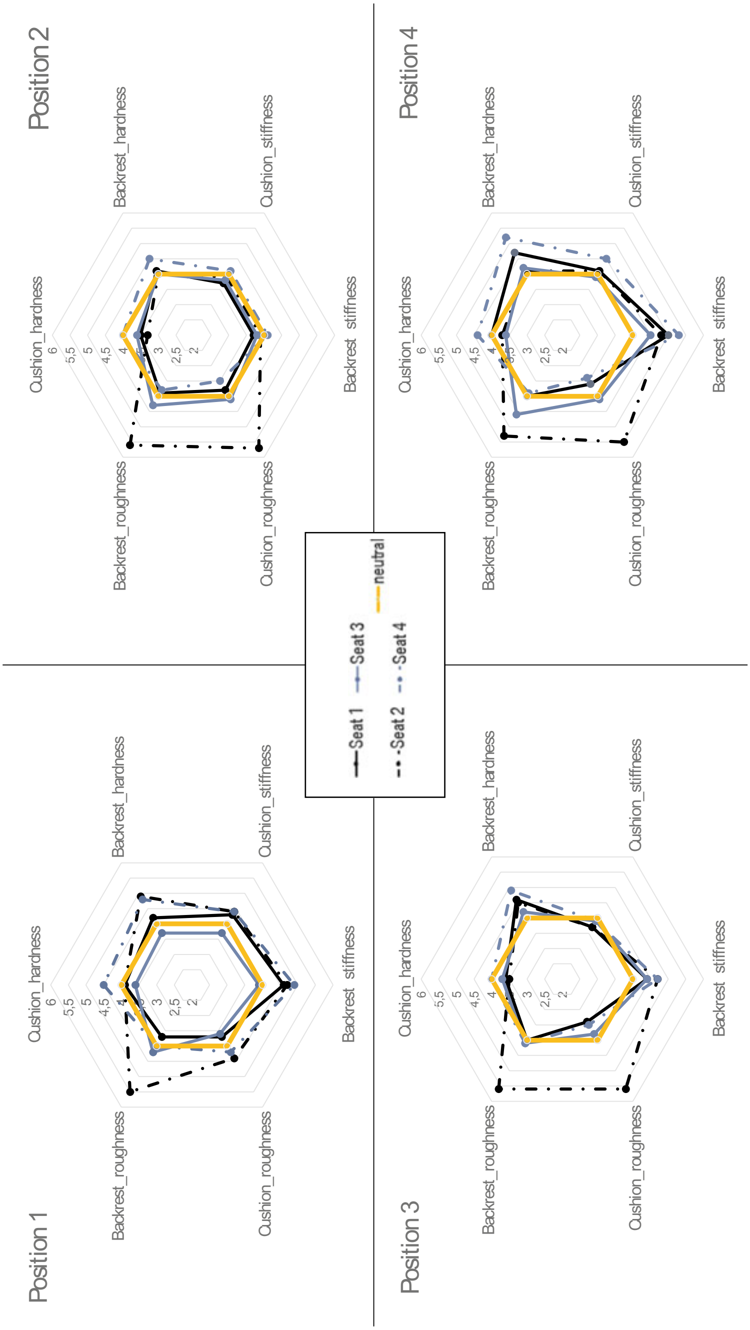


Fig. 6 Illustration of the rated seat characteristics for the Position 1, Position 2, Position 3, Position 4

rated similarly, the ratings and the characterizations in Position 4 are different for all four seat. For Position 4 *seat 1* is rated slippery in the cushion and hard and stiff in the backrest. *Seat 2* is rated abrasive in cushion and backrest and stiff in backrest. *Seat 3* is rated abrasive and stiff in backrest and *seat 4* is rated hard and stiff in the cushion and backrest.

A detailed listing of the means and the standard deviations for each seat in each position is presented in the appendix. All in all, *seat 1* received a rather neutral rating but has in some positions (Position 1 and Position 3) slippery characteristics. *Seat 2* is according to the ratings in each position the most abrasive seat regarding the cushion and the backrest and is also rated the softest either for the cushion or the backrest in each position except for Position 1. *Seat 3* is rated as the softest seat in Position 1 for the backrest and cushion and for Position 2, 3, and 4 as the softest either for cushion or the backrest. *Seat 3* is moreover rated the most elastic seat. *Seat 4* is rated the hardest seat regarding cushion and the backrest and also the most stiff and most slippery for the cushion and the backrest.

Statistical analysis:

Position 1: For the cushion the results of the Friedman's Test indicated a significance for all three word pairs: *soft–hard* ($\chi 2(3) = 12.77, p = 0.005$), *elastic–stiff* ($\chi 2(3) = 8.21, p = 0.042$) and *slippery–abrasive* ($\chi 2(3) = 32.55, p = 0.001$). Each word pair is used to differentiate between the four seats. Also for the backrest the differentiation of the four seats is for all three word pairs significant: *soft–hard* ($\chi 2(3) = 20.61, p = 0.001$), *elastic–stiff* ($\chi 2(3) = 19.22, p = 0.001$) and *slippery–abrasive* ($\chi 2(3) = 30.68, p = 0.001$).

Table 3 illustrates the results of the post hoc analysis using the Wilcoxon signed-rank test ($\alpha < 0.05$). The Wilcoxon test presents for the word pair *soft–hard* significances in the cushion for the following seat pairings: *seat 1–seat 4*, *seat 2–seat 4*, *seat 3–seat 4*. Thus, it is clear that *seat 4* (metal plate instead of a seat suspension) has the highest load on the cushion in Position 1, because *seat 4* is present in each word pair that shows significance. The backrest shows significances for the same set of seat parings and furthermore for seat pairing: *seat 1–seat 3* (reference seat and the seat with a loose cover tension). For the word pair *elastic–stiff* the results of the Wilcoxon signed-rank test present the same significant seat pairings for cushion and backrest: *seat 1–seat 3*, *seat 2–seat 3*, and *seat 4–seat 3*. In this case each seat pairing contains *seat 3* with the loose cover tension. For the word pair *slippery–abrasive* the significant seat pairings of the Wilcoxon signed-rank test are the same also for the cushion and backrest: *seat 1–seat 2*, *seat 2–seat 3*, *seat 2–seat 4*. In this case the *seat 2* with the Alcantara cover is in each of the pairings present.

Position 2: For Position 2 the Friedman's Test indicates significant differences of the seat cushion for the word pairs *soft–hard* ($\chi 2(3) = 8.80, p = 0.032$) and *slippery–abrasive* ($\chi 2(3) = 36.14, p = 0.001$). For the backrest the word pair *slippery–abrasive* ($\chi 2(3) = 41.34, p = 0.001$) indicates significance in differentiation.

Table 4 demonstrates the results of the Wilcoxon signed-rank test for the cushion and the backrest in each seat pairing combination. Concerning the word pair *soft–hard* the Wilcoxon singed-rank test points out that there are significant differences

Table 3 Results of the Wilcoxon sign-rank test for Position 1

Position 1		Seat 1–seat 2	Seat 1–seat 3	Seat 1–seat 4	Seat 2–seat 3	Seat 2–seat 4	Seat 3–seat 4
Soft–hard	*Cushion*						
	Z	−0.365	−1.222	−2.129	−0.802	−2.196	−3.412
	P	0.715	0.222	**0.033**	0.423	**0.028**	**0.001**
	Backrest						
	Z	−1.232	−2.202	−2.623	−1.020	−2.437	−3.868
	P	0.218	**0.028**	**0.008**	0.308	**0.015**	**0.000**
Elastic–stiff	*Cushion*						
	Z	−0.440	−2.525	−0.243	−2.224	−0.058	−2.239
	P	0.66	**0.012**	0.808	**0.026**	0.954	**0.025**
	Backrest						
	Z	−0.208	−2.967	−0.922	−2.697	−1.111	−3.378
	P	0.835	**0.003**	0.356	**0.007**	0.266	**0.001**
Slippery–abrasive	*Cushion*						
	Z	−4.382	−1.281	−0.037	−3.713	−4.274	−1.251
	P	**0.000**	0.200	0.970	**0.000**	**0.000**	0.211
	Backrest						
	Z	−4.060	−1.457	−0.726	−3.613	−4.030	−0.822
	P	**0.000**	0.145	0.468	**0.000**	**0.000**	0.411

Table 4 Results of the Wilcoxon sign-rank test for Position 2

Position 2		Seat 1–seat 2	Seat 1–seat 3	Seat 1–seat 4	Seat 2–seat 3	Seat 2–seat 4	Seat 3–seat 4
Soft–hard	*Cushion*						
	Z	−0.741	−0.502	−2.210	−1.230	−2.413	−1.749
	P	0.458	0.615	**0.027**	0.219	**0.016**	0.080
Slippery–abrasive	*Cushion*						
	Z	−4.389	−0.962	−1.312	−3.940	−4.455	−2.064
	P	**0.000**	0.336	0.189	**0.000**	**0.000**	**0.039**
	Backrest						
	Z	−4.360	−1.852	−0.030	−4.094	−4.491	−1.715
	P	**0.000**	0.064	0.976	**0.000**	**0.000**	0.086

for the seat pairings: *seat 1–seat 4* and *seat 2–seat 4*. Both seat pairings include *seat 4*. The Wilcoxon signed-rank test results referring to the word pair *slippery–abrasive* have the same significant seat pairings for the cushion and backrest: *seat 1–seat 2*, *seat 2–seat 3*, *seat 2–seat 4*. All seat combinations contain the *seat 2*.

Table 5 Results of the Wilcoxon sign-rank test for Position 3

Position 3		Seat 1–seat 2	Seat 1–seat 3	Seat 1–seat 4	Seat 2–seat 3	Seat 2–seat 4	Seat 3–seat 4
Soft–hard	*Backrest*						
	Z	−0.751	−1.727	−0.931	−1.501	−1.437	−2.213
	P	0.453	0.084	0.352	0.133	0.151	**0.027**
Slippery–abrasive	*Cushion*						
	Z	−5.100	−1.532	−0.787	−4.626	−5.049	−1.207
	P	**0.000**	0.125	0.431	**0.000**	**0.000**	0.228
	Backrest						
	Z	−4.511	−0.546	−0.559	−4.122	−4.448	−0.222
	P	**0.000**	0.585	0.576	**0.000**	**0.000**	0.824

Position 3: The results of the Friedman's Test are significant for the word pair *slippery–abrasive* for the cushion ($\chi 2(3) = 56.01$, $p = 0.001$) as well as for the backrest ($\chi 2(3) = 36.72$, $p = 0.001$). The word pair *soft–hard* ($\chi 2(3) = 10.07$, $p = 0.018$) is only significant for the backrest.

Table 5 exposes for the backrest regarding the word pair *soft–hard* only one significant seat pairing: *seat 3–seat 4*. With reference to the word pair *slippery–abrasive* the cushion as well as the backrest have the same seat pairings with significant results of the Wilcoxon signed-rank test. The significant seat pairings are: *seat 1–seat 2*, *seat 2–seat 3*, *seat 2–seat 4*. In all seat pairings *seat 2* with the Alcantara cover is present.

Position 4: The Friedman's Test is significant for the backrest for all three word pairs: *soft–hard* ($\chi 2(3) = 21.54, p = 0.001$), *elastic–stiff* ($\chi 2(3) = 16.22, p = 0.001$), and *slippery–abrasive* ($\chi 2(3) = 29.25$, $p = 0.001$). As to the cushion the word pairs *soft–hard* ($\chi 2(3) = 13.19$, $p = 0.004$) and *slippery–abrasive* ($\chi 2(3) = 44.64$, $p = 0.001$) are significant (Table 6).

The Wilcoxon singed-rank test lays out, that in respect to the cushion and the word pair *soft–hard* the seat pairings *seat 2–seat 4* and *seat 3–seat 4* are significant for differentiation. *Seat 1* is not included in the differentiation of hardness (word pair *soft–hard*). Thus, for Position 4 the differentiation of the hardness for the cushion is perceived between the *seat 4* with a plate instead of a seat suspension and *seat 3* with loose cover tension or *seat 2* with an Alcantara cover. As for the word pair *slippery–abrasive* all seat pairings are significant for differentiation, except seat pairing *seat 1–seat 4*, which is the reference seat compared to the seat without a seat suspension. The backrests can be differentiated regarding the word pair *soft–hard* with the significant seat pairings: *seat 1–seat 3*, *seat 2–seat 4* and *seat 3–seat 4*; the word pair *elastic–stiff* with the significant word pairings: *seat 1–seat 3* and *seat 3–seat 4*; and the word pair *slippery–abrasive* with the seat pairing: *seat 1–seat 2*, *seat 1–seat 3*, *seat 2–seat 3*, *seat 2–seat 4* and *seat 3–seat 4*. The results for the cushion do not include the seat pairing *seat 1–seat 4*.

Referring to Position 1 and 4 the differentiation of the word pairs and seat pairings are more distinctive compared to the Position 2 and 3. In general, the results of the

Table 6 Wilcoxon sign-rank test for Position 4

Position 4		Seat 1–seat 2	Seat 1–seat 3	Seat 1–seat 4	Seat 2–seat 3	Seat 2–seat 4	Seat 3–seat 4
Soft–hard	*Cushion*						
	Z	−1.255	−1.881	−1.588	−0.076	−2.931	−3.555
	P	0.209	0.060	0.112	0.940	**0.003**	**0.000**
	Backrest						
	Z	−1.807	−2.307	−1.900	−0.513	−3.006	−3.632
	P	0.071	**0.021**	0.057	0.608	**0.003**	**0.000**
Elastic–stiff	*Backrest*						
	Z	−0.867	−2.664	−1.380	−1.066	−1.794	−3.391
	P	0.386	**0.008**	0.168	0.286	0.073	**0.001**
Slippery–abrasive	*Cushion*						
	Z	−4.508	−2.029	−0.485	−3.947	−4.872	−2.895
	P	**0.000**	**0.042**	0.627	**0.000**	**0.000**	**0.004**
	Backrest						
	Z	−4.141	−2.504	−0.062	−2.617	−4.143	−2.617
	P	**0.000**	**0.012**	0.951	**0.008**	**0.000**	**0.008**

Wilcoxon signed-rank test show that the word pair *slippery–abrasive* is a differentiation factor independently from the position and the load. In contrast, the significance for the differentiation of the seats for the word pair *soft-hard* and *elastic-stiff* changes with the position.

3.1.3 Overall Rating

In Position 1 *seat 1* was rated as the best and *seat 4* as the worst seat. In Position 2 *seat 2* was rated as the best and *seat 4* as the worst seat. In Position 3 the best seat was *seat 3* and the worst one *seat 4*. Furthermore, in Position 4 *seat 1* was rated as the best and *seat 4* as the worst seat.

3.2 Objective Characterization of the Seats

3.2.1 Pressure Measurements

Table 7 shows the mean of all participants for each parameter: *average pressure*, *peak pressure*, and *contact area* for all four groups (*buttock Group*, *front Group*, *side Group* and *back Group*). The parameters with the highest values are made bold for each group. *Seat 1* (reference seat) has the highest *average pressure* and the highest

Table 7 Results of the pressure measurements. The highest values are bold for each group and parameter

		Seat 1		Seat 2		Seat 3		Seat 4	
		Mean	Std.	Mean	Std.	Mean	Std.	Mean	Std.
Buttock group	Average pressure [N/cm²]	**0.50**	0.10	0.45	0.11	0.44	0.10	0.47	0.10
	Peak pressure [N/cm²]	**1.20**	0.31	1.04	0.38	1.15	0.40	1.05	0.37
	Contact area [cm²]	579	40	574	72	**643**	89	600	80
Front group	Average pressure [N/cm²]	0.27	0.8	0.26	0.08	0.28	0.09	**0.32**	0.1
	Peak pressure [N/cm²]	0.53	0.17	0.49	0.18	0.55	0.18	**0.63**	0.26
	Contact area [cm²]	238	83	207	79	235	80	**264**	87
Side group	Average pressure [N/cm²]	**0.28**	0.08	0.27	0.09	0.22	0.07	0.27	0.08
	Peak pressure [N/cm²]	0.56	0.18	**0.59**	0.23	0.46	0.18	0.53	0.19
	Contact area [cm²]	240	105	**240**	111	217	119	228	167
Back group	Average pressure [N/cm²]	0.20	0.04	0.19	0.04	0.19	0.03	**0.21**	0.05
	Peak pressure [N/cm²]	0.67	0.38	0.67	0.41	0.67	0.26	**0.69**	0.43
	Contact area [cm²]	**530**	168	521	195	521	199	527	181

peak pressure in the area of the buttock (*buttock Group*). Especially the difference between the *peak pressure* of *seat 1* and *seat 4* is noticeable: even though *seat 1* has a seat suspension and *seat 4* a metal plate instead of the suspension, the *peak pressure* of *seat 1* is 0.15 N/cm^2 higher than for *seat 4*. For the *buttock Group seat 3* has the largest *area* in contact between person and seat. The measurement results for the front of the cushion (*front Group*), illustrate the highest *average pressure*, *peak pressure* and the largest *contact area* in *seat 4*. The lowest *average pressure*, *peak pressure*, and *contact area* has the Alcantara seat (*seat 2*). The values of *seat 1* and *seat 3* are close to the values of *seat 2*. Related to the bolster area of the cushion (*side Group*), the highest *average pressure* was found in *seat 1*, the highest *peak pressure* and contact *area* has the *seat 2*, and the lowest values for all three parameters has *seat 3*. The results regarding the backrest area (*back Group*) point out that the highest *average pressure* and the highest *peak pressure* is reached in *seat 4*. The largest *area* in contact between participant and the seat is found in *seat 1*.

In general, most of the measured differences between the four seats are small. The *peak pressure* reaches in the *buttock Group* the highest, in the *back Group* the second highest and in the *front Group* and *side Group* the lowest values. In addition, the *buttock Group* has the highest values for the *average pressure* and the *back Group* has the lowest values. The values of the *front Group* and *side Group* are in between those values.

3.2.2 Measurement Tool

Table 8 presents the results of the analysis of the four seats with the new developed measurement tool of Wegner et al. [19]. The results are divided into six blocks. Each block which contains the normalized values, compares the four seats through one appropriate measurement point. The detailed table without the normalized values is attached in the appendix. The maximum values are bold, and the minimum values are underlined.

The measurement results present that *seat 3* has the lowest pressure regarding the *first touch pressure* in cushion. As for the backrest, for most measurement points *seat 2* has the lowest *first touch pressure*. The *normalized linear pressure* (rise of pressure [N/cm^2] per cm) appears in most measurement points for the backrest and the cushion the highest in seat 4, except for the lumbar area and the wings. In this measurement point *seat 1* shows the highest *normalized linear pressure* but the highest *linear indentation* at the same time. The *normalized maximum pressure* (pressure rises per cm until the maximum pressure is reached) is in *seat 4* the highest, except for the area of the ischial tuberosity. For this measurement point *seat 3* has the highest values. The lowest *normalized maximum pressure* has *seat 2*, except for the bolster in the backrest. *Seat 2* distributes the pressure (*pressure distribution*) the best for most measurement points. For the bolsters in the backrest and cushion *seat 3* distributes the pressure the most. The *normalized elongation while loading the seat* is for all measurement points for *seat 2* (Alcantara seat) the highest. The lowest *normalized elongation while loading the seat* has *seat 3*, except for the measurement point in the lumbar area and the backrest bolsters. For the lumbar *seat 1* and for the backrest bolster *seat 4* have the lowest *normalized elongation while loading the seat*. Concerning the *elongation due to the lateral movement seat 2* has the highest values in most cases. The highest *elongation due to the lateral movement* for the shoulder is evoked by *seat 4* and for the front of the cushion *seat 3* has the highest values. The *linear indentation* is for

Table 8 The Table illustrates the measurements results of the four seat in six measurement points. The highest values are highlighted bold numbers and the lowest values are highlighted with underlined numbers

	Max. pressure [N/cm^2 * 1/cm]	First touch [N/cm^2]	Lin. pressure [N/cm^2 * 1/cm]	Pressure distribution [N/cm^2]	Elongation loading [%/(N/cm^2)]	Elongation move [%/(N/cm^2)]	Max. indentation [mm]	Lin. indentation [mm]
(1) Shoulder								
Seat 1	3.5	0.60	0.9	0.70	1.07	0.99	31.9	16.1
Seat 2	2.1	**0.80**	1.0	**1.10**	**2.01**	1.05	**34.7**	**26.7**
Seat 3	3.1	0.40	0.7	0.80	0.77	0.83	**34.7**	14.8
Seat 4	**4.2**	0.60	**1.1**	0.80	1.35	**1.48**	31.4	13.2
(2) Lumbar								
Seat 1	2.9	**0.60**	**1.6**	0.50	0.06	**2.19**	33.2	**17.2**
Seat 2	1.2	0.40	0.8	**1.0**	**0.82**	**2.19**	**36**	15.7
Seat 3	1.8	0.50	0.7	0.70	0.59	1.92	35.7	14.4
Seat 4	**3.6**	0.50	0.9	0.50	0.14	1.85	30.1	12.3
(3) Bolster backrest								
Seat 1	7.6	**0.80**	1.7	0.60	0.49	2.69	23.4	12
Seat 2	6.0	0.40	0.9	0.80	**0.55**	**2.81**	26.1	12.7
Seat 3	5.5	0.60	1.1	**0.90**	0.47	2.50	24.7	**14.2**
Seat 4	**7.7**	0.60	**2.2**	0.80	0.24	2.57	24.3	13.0
(4) Ischial tuberosity								
Seat 1	3.3	0.70	1.7	0.50	0.42	1.86	30.1	**22.4**
Seat 2	1.1	0.60	0.8	**0.90**	**1.32**	**2.59**	31.5	19.6
Seat 3	**4.1**	0.60	1.0	0.40	0.36	1.78	30.3	12.7

(continued)

Table 8 (continued)

	Max. pressure [N/cm^2 * 1/cm]	First touch [N/cm^2]	Lin. pressure [N/cm^2 * 1/cm]	Pressure distribution [N/cm^2]	Elongation loading [%/(N/cm^2)]	Elongation move [%/(N/cm^2)]	Max. indentation [mm]	Lin. indentation [mm]
Seat 4	3.8	**0.80**	**1.9**	0.40	0.53	1.58	30.3	18.9
(5) Front of the cushion								
Seat 1	4.1	0.80	**2.7**	0.30	0.30	1.77	28.5	**22.8**
Seat 2	2.1	0.80	1.2	**0.80**	**0.60**	2.23	29.7	16.9
Seat 3	4.8	0.50	1.0	0.40	0.08	**2.25**	28.9	14.3
Seat 4	**8.9**	**0.90**	**2.7**	0.20	0.29	0.55	29	16.2
(6) Bolster cushion								
Seat 1	3.3	0.50	**0.90**	0.60	0.89	3.66	30.4	**16.2**
Seat 2	2.5	**0.60**	0.80	**0.90**	**1.05**	**4.58**	28.8	19
Seat 3	3.7	0.20	0.80	**0.90**	0.59	3.73	28.6	12.5
Seat 4	**4.2**	0.40	0.70	0.80	0.88	4.55	24.3	15.4

Table 9 Overview of the static and dynamic friction coefficient for various material parings

	μ_{static}	$\mu_{dynamic}$
Leather–silicon	–	1.38
Alcantara–silicon	–	1.30
Leather–jeans	0.35	0.34
Alcantara–jeans	1.03	0.70

seat 3 the lowest and for *seat 1* the highest regarding the cushion. The lowest *linear indentation* mostly has seat 4 in reference to the backrest.

In summary, the results show that *seat 4* can be identified as hardest regarding the pressure measurements with the new tool and *seat 2* and *3* the softest. *Seat 1* is in between. While loading the seat, *seat 2* shows the most elongation. *Seat 3* has the least elongation recorded by the stamp sensors (I–IV, Fig. 4) or rather elongate the human skin. *Seat 3* shows also the least linear characteristics (*linear indentation* is the lowest) and *seat 1* has the most. Considering the backrest *seat 4* has the lowest linear properties.

3.2.3 Friction Measurement

Table 9 presents the results of the friction tests. The *leather–silicon* and *Alcantara–silicon* combination showed no static friction even with forces over 100 N (the force used in all test) the combination skips immediately to sliding. The dynamic μ is for the *leather–silicon* combination a bit higher than for *Alcantara–silicon.* For the jeans combinations with leather and Alcantara a static μ could be detected. The μ_{static} is for a leather cover three times lower than for Alcantara, the $\mu_{dynamic}$ is nearly two times lower. The friction coefficient for *leather–jeans* is nearly the same for static and dynamic setups.

3.2.4 The Influence of the Friction Coefficient on the Measurement Data

The *elongation while loading the seat* and the *elongation due to the lateral movement* recorded by the stamp are based on the friction coefficient including silicon (*leather–silicon* and *Alcantara–silicon*). To include also clothing materials like jeans, which are in direct contact with the seat surface, theses parameters were normalized based on the dynamic friction coefficient of silicon (see Sect. 2.4.2 and Table 8) and afterwards multiplied with the dynamic friction coefficient of the jeans pairings. Table 10 presents the results exemplary for the cushion. The highest values are bold and the lowest are underlined.

The calculated parameter *elongation while loading the seat* and *elongation due to the lateral movement* for the jeans pairings (*leather–jeans* and *Alcantara–jeans)* are for each measurement point the highest in *seat 2*. The *elongation while loading*

Table 10 Results of the parameters elongation while loading and elongation due to the lateral movement including the interaction with a jeans material. The highest values are bold and lowest underlined

	Seat 1	Seat 2	Seat 3	Seat 4	Seat 1	Seat 2	Seat 3	Seat 4	Seat 1	Seat 2	Seat 3	Seat 4
	(4) Ischial tuberosity				(5) Front of the cushion				(6) Bolster cushion			
Elongation loading [%/(N/cm^2)]	0.14	**0.93**	0.12	0.18	0.10	**0.42**	0.03	0.10	0.30	**0.75**	0.20	0.20
Elongation move [%/(N/cm^2)]	0.63	**1.81**	0.61	0.54	0.60	**1.56**	0.76	0.19	1.24	**3.21**	1.27	1.06

is for each measurement point of the cushion in *seat 3* the least. For the *elongation due to the lateral movement* the lowest values are found for all measurement points in *seat 4*.

4 Discussion

4.1 Discomfort of the Seats

The discomfort ratings have shown that the seat components (foam, seat cover, seat suspension) of the reference seat (*seat 1*) are more balanced than the manipulated seats (*seat 2*, *seat 3*, *seat 4*). In particular, in the sensitive shoulder area [18] the participants perceived discomfort on the outer edge of the manipulated seats. The reason might be that a disharmony is perceived, meaning that particular parts of the seat do not match with other parts of the seat while sitting. Neither the pressure measurement nor the results of the measurement tool have data that clearly explain the discomfort in these parts. The pressure distribution of the participants, who stated discomfort in those areas, had no pressure peaks or points. The measurement tool did not measure remarkable characteristics in this particular area; therefore, exact predictions and explanation are hard to make.

Seat 2, the Alcantara seat, has noticeable discomfort ratings in the rear bolster of the cushion. The implemented shear force through the higher friction coefficient (*leather–jeans* vs. *Alcantara–jeans*) might cause an additional force which results in a discomfort feeling. This is in line with Chow and Odell [2] who linked the pressure perception to the shear force perception. Furthermore, the measurement tool of Wegner et al. [19] confirms this perception. The measurement results in the bolster show a low pressure, but large elongations and therefore additional tensile strain might be felt, which could also evoke the shear force [8]. The explanation why only a few participants rated this as discomfort could be that some of these participants are shear sensitive or because the hips of the participants were wider. Another reason could be that the combinations of pressure and shear evokes a discomfort feeling [2].

Seat 3 has a noticeable discomfort in the bolsters of the backrest. The loose cover tension might evoke that some of the participants sink more into the backrest of the seat and thus feel the plastic plates of the side adjustments because of the higher compression of the foam. The pressure measurement of the participants does not explain the discomfort ratings, because the values of *seat 3* are not significantly different to the pressure values of *seat 1*, *seat 2* and *seat 4*. The pressure mat itself could influence the measurement by its thickness negatively and therefore might not record the pressure distribution in the right way. The results of the measurement tool illustrate that the bolster of *seat 3* has nearly the same pressure characteristics as the other seats. In combination with a softer lumbar area (higher tendency to sink into the seat) there is more contact with the bolsters and these are more compressed and therefore might be perceived more uncomfortable.

Seat 4 has a noticeable discomfort in the lumbar area. Replacing the seat suspension with a metal plate could influence this lumbar support experience, affecting the sitting posture not supporting the natural S-shape of the spine. This might be the reason why some participants perceived a discomfort in this region of the body. For the lumbar area the pressure measurements correspond to the experience. The *average pressure* and the *peak pressure* are both the highest in this area. The results of the measurement tool show that for higher loading the pressure for *seat 4* rises the most and has the highest value of all four seats.

Overall, with the help of the measurement tool it is possible to explain the discomfort rating better than the results of the pressure measurements alone. The correlation of the pressure mat measurements and discomfort is useful for only some parts (lumbar area) of the seat: in most cases the recordings of the pressure mat are not useful for building a correlation because the pressure mat does not record the influence of the surface or even the tension of the cover leading to elongation and shear force. In contrast, the measurement tool records the influences of the surface and the cover tension but is only capable to measure in discrete points. In future it would be good to study the connection of the measurement points to what is happening in the human seat interface at that point and connected to pressure mat measurements for more precise statements.

4.2 Characterization

Based on the word pair ratings, the results have shown that the Alcantara seat (*seat 2*) is characterized abrasive so that the abrasive surface differentiates *seat 2* in each position from the other seats. The differentiation of the surface might be independent from the position or the loading due to the significant results of the surface differentiation in each position. The pressure measurement does not record this perceived difference of the surface but the results of the measurement tool illustrate the difference presenting the highest *elongation while loading the seat* in each measurement point for the abrasive *seat 2*. In addition, the parameter *normalized elongation due to the lateral movement* is for the material pairing *silicon–Alcantara* for nearly every measurement point the highest. That is in line with the study of Goossens [7] who stated that a LiquiCell cushion material evokes less shear stress (internal shear stress) than a foam cushion. Including the friction coefficient of all jeans-pairings demonstrate the high impact of the external applied shear force provoked by high friction coefficients. Therefore, the adapted parameter of Table 10 *elongation due to the lateral movement* including the friction coefficients of the jeans pairings (*Alcantara–jeans* and *leather–jeans*) have in each measurement point the highest shear force in *seat 2*. These measurement results are in line with the perceived differences of the participants.

The results of the word pair rating for the hardness and elasticity show that the differentiation of both parameters depends on the position. For Position 1 and Position

4 the participants differentiate the hardness and elasticity of the seats most significantly. In both positions the cushion angle is high (15°–18°). Therefore, the sensitive area of the body (front of the cushion) is in contact with the seat [18] and might be the reason for the differentiation. In contrast, Position 2 and 3 with a cushion angle of 3° and hence less sensitive contact area in the front of the cushion the participants notice less differences regarding the hardness and elasticity of the seats. Additional, in Position 1 the backrest is more upright than in Position 4 (but both high cushion angles). Therefore, the differentiation of the cushion is probably more related to the area being in contact than to the load. In Position 2 and 3 the participants were not able to differentiate the elasticity neither for the backrest nor the cushion. *Seat 4* characterized as the hardest seat differs in Position 2 regarding the cushion hardness from the other seat, but in Position 3 with the same cushion angle but a more horizontal backrest angle (less load on cushion) the hardness of the cushion cannot be differentiated anymore. Furthermore, the more horizontal angle in Position 3 than in Position 2 evokes a higher contact area with the sensitive shoulder area (same cushion angle). The results of the word pair rating suggest that in Position 3 the hardness of the backrest can be differentiated, whereas in Position 2 it cannot be differentiated. Therefore, it might be concluded that also the sensitive areas of the backrest evoke a better differentiation of the seats. Position 1 and 4 are the most significant positions regarding the hardness and the elasticity differentiation. *Seat 3* with the loose cover tension and therefore with the best foam properties was rated as the most elastic seat. Unfortunately, the pressure mat measurements do not offer a connection to the seat elasticity but the results of the measurement tool of Wegner et al. [19] demonstrate that the parameter *normalized elongation while loading the seat* is in almost every measurement point (except lumbar and backrest bolster) the lowest. Therefore, *seat 3* might not stress the skin as much as in the other seats. On the one hand, the low cover tension provokes the best foam properties and thus, the best spring/damper properties. On the other hand, it causes a high interaction between the seat suspension and the foam. This fact is illustrated by the results of the measurement tool in the measurement point of the ischial tuberosity. The results present the highest maximum pressure in *seat 3* hence to a high relative movement between the seat suspension and the foam. The foam is pressing through the suspension spring. For all other measurement points the results of stamp measurements show that seats 2 and 3 both have the lowest pressure attributes or rather the best pressure distributions. On the contrary, *seat 4*, characterized as the hardest seat, has the highest maximum pressure in each measurement point and an unequal pressure distribution. The results of the measurement tool are in line with the results of the word pair ratings. Unfortunately, the results of the pressure mat measurements do not correlate with the results of the word pair ratings in most cases.

However, for further studies the different loadings and the connection of the different measurement points of the measurement tool should be taken more into account. The study has shown that the position, the contact area, and the sensitivities of the human body influence the ratings and the characterizations of a seat. This should additionally be included into the measurement procedure of the measurement tool. Moreover, it is pointed out that the optimum position for an occupant in one specific seat is not necessarily the optimum position in another seat with different cover and seat suspension properties.

5 Conclusion

The study has shown that seats with the same contour and foam properties and differ in cover (surface and cover tension) and seat suspension are perceived different. The seat layout has a huge impact on the seat-human interaction and therefore influences the parameters for the seat characterization. Moreover, the positions evoke various significances for the differentiation due to different sensitivity areas in contact with the seat. The results of the objective measurement tool from Wegner et al. [19] could be used to explain the rated characteristics of the seats. The correlations between the discomfort ratings and the stamp measurements could be improved by including the mutual interdependencies of the measurement points. Unfortunately, in most cases the pressure mat measurements neither correlate with the discomfort rating nor with the characterizations of the seats. In order to receive a more precise characterization as well as a more precise discomfort rating the results of the measurement points (measurement tool Wegner et al. [19]) and the interdependencies of the measured parameter have to be correlated and evaluated in further studies with various participants and seats.

Acknowledgments We are thankful to our TU Delft colleagues and Rudolf Rackl, Renato Martic and Mario Buljan who provided expertise that greatly assisted the research. We are also grateful to Erich Zerhoch and Johann Sax for assistance organizing the measuring instruments and for assistance building up the setup.

Appendix

Descriptive Results of the word pair ratings for Position 1–Position 4

Position 1	Seat 1		Seat 2		Seat 3		Seat 4	
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Cushion								
Soft–hard	3.9	1.4	3.9	1.4	3.6	1.4	4.5	1.4
Elastic–stiff	4.3	1.3	4.4	1.2	3.7	1.5	4.4	1.5
Slippery–abrasive	3.7	1.4	4.4	1.4	3.6	1.7	3.2	1.5
Backrest								
Soft–hard	4.2	1.4	4.0	1.4	3.7	1.3	4.8	1.4

(continued)

(continued)

Position 1	Seat 1		Seat 2		Seat 3		Seat 4	
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Elastic–stiff	4.6	1.3	4.7	1.4	3.9	1.5	4.9	1.5
Slippery–abrasive	3.7	1.5	5.5	1.4	4.2	1.5	4.0	1.5

Position 2	Seat 1		Seat 2		Seat 3		Seat 4	
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Cushion								
Soft–hard	3.5	1.3	3.3	1.4	3.6	1.4	4.0	1.4
Elastic–stiff	3.7	1.2	3.9	1.4	3.8	1.3	4.1	1.4
Slippery–abrasive	3.8	1.6	5.7	1.1	4.1	1.4	3.5	1.4
Backrest								
Soft–hard	4.1	1.2	4.0	1.4	4.0	1.2	4.5	1.4
Elastic–stiff	3.7	1.2	3.9	1.3	3.8	1.3	4.1	1.4
Slippery–abrasive	3.9	1.3	5.6	1.0	4.3	1.3	3.8	1.3

Position 3	Seat 1		Seat 2		Seat 3		Seat 4	
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Cushion								
Soft–hard	3.6	1.4	3.5	1.3	3.7	1.3	4.0	1.5
Elastic–stiff	3.7	1.4	3.7	1.4	3.9	1.2	3.9	1.4
Slippery–abrasive	3.4	1.4	5.6	0.9	3.8	1.3	3.5	1.3
Backrest								
Soft–hard	4.6	1.2	4.5	1.3	4.2	1.3	4.9	1.3
Elastic–stiff	4.4	1.3	4.7	1.2	4.4	1.2	4.7	1.3
Slippery-abrasive	4.0	1.4	5.6	0.9	4.1	1.4	4.1	1.3

Position 4	Seat 1		Seat 2		Seat 3		Seat 4	
	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Cushion								
Soft–hard	4.0	1.5	3.7	1.3	3.6	1.5	4.4	1.3
Elastic–stiff	4.1	1.4	4.1	1.2	3.9	1.4	4.5	1.5
Slippery–abrasive	3.6	1.6	5.5	1.2	4.11	1.3	3.4	1.5
Backrest								
Soft–hard	4.7	1.5	4.1	1.4	4.2	1.2	5.2	1.4

Elastic–stiff	5.0	1.1	4.8	1.3	4.5	1.2	5.3	1.3
Slippery–abrasive	4.0	1.4	5.3	1.1	4.6	1.3	3.9	1.3

Overview of the non-normalized measurement results of the four seat in six different measurement positions of the seas.

	Max. pressure [N/cm^2]	First touch [N/cm^2]	Lin. pressure [N/cm^2]	Pressure distribution [N/cm^2]	Elongation loading [%]	Elongation move [%]	Max. indentation [mm]	Lin. indentation [mm]
(1) Shoulder								
Seat 1	11.10	0.60	1.50	0.70	16.40	15.20	31.90	16.10
Seat 2	7.20	0.80	2.80	1.10	18.80	9.80	34.70	26.70
Seat 3	10.60	0.40	1.10	0.80	11.20	12.10	34.70	14.80
Seat 4	13.20	0.60	1.40	0.80	24.60	27.00	31.40	13.20
(2) Lumbar								
Seat 1	9.60	0.60	2.80	0.50	0.80	29.00	33.20	17.20
Seat 2	4.40	0.40	1.20	1.00	4.70	12.50	36.00	15.70
Seat 3	6.40	0.50	1.00	0.70	5.20	17.00	35.70	14.40
Seat 4	10.80	0.50	1.10	0.50	2.10	27.50	30.10	12.30
(3) Bolster backrest								
Seat 1	17.70	0.80	2.00	0.60	12.00	65.80	23.40	12.00
Seat 2	15.70	0.40	1.20	0.80	11.30	57.30	26.10	12.70
Seat 3	13.70	0.60	1.60	0.90	8.80	47.30	24.70	14.20
Seat 4	18.80	0.60	2.90	0.80	6.10	66.60	24.30	13.00
(4) Ischial tuberosity								
Seat 1	10.00	0.70	3.80	0.50	5.80	25.70	30.10	22.40
Seat 2	3.60	0.60	1.60	0.90	6.20	12.10	31.50	19.60
Seat 3	12.40	0.60	1.30	0.40	6.10	30.50	30.30	12.70
Seat 4	11.50	0.80	3.50	0.40	8.40	25.10	30.30	18.90

(continued)

(continued)

	Max. pressure [N/cm^2]	First touch [N/cm^2]	Lin. pressure [N/cm^2]	Pressure distribution [N/cm^2]	Elongation loading [%]	Elongation move [%]	Max. indentation [mm]	Lin. indentation [mm]
(5) Front of the cushion								
Seat 1	11.60	0.80	6.20	0.30	4.80	28.30	28.50	22.80
Seat 2	6.30	0.80	2.00	0.80	4.90	18.30	29.70	16.90
Seat 3	14.00	0.50	1.50	0.40	1.50	43.40	28.90	14.30
Seat 4	25.70	0.90	4.40	0.20	10.40	19.50	29.00	16.20
(6) Bolster cushion								
Seat 1	10.10	0.50	1.40	0.60	12.40	51.00	30.40	16.20
Seat 2	7.30	0.60	1.60	0.90	10.00	43.50	28.80	19.00
Seat 3	10.70	0.20	1.00	0.90	8.70	55.10	28.60	12.50
Seat 4	10.10	0.40	1.10	0.80	8.40	43.30	24.30	15.40

References

1. Biedermann H, Guttmann G (1984) Funktionelle Pathologie und Klinik der Wirbelsäule, Band 1, Teil 2, Elsevier, Munich
2. Chow WW, Odell EI (1978) Deformations and stresses in soft body tissues of a sitting person
3. DIN 53579 (2005) Testing of flexible cellular materials—Indentation test on finished parts. DIN-Normenausschuss Materialprüfung (NMP)
4. DIN EN ISO 3386-1 (2009) Polymeric materials, cellular flexible—Determination of stress-strain characteristics in compression—Part 1: low-density materials. DIN-Normenausschuss Materialprüfung (NMP)
5. Goossens RHM, Snijders CJ (1995) Design cirteria for the reduction of shear forces in beds and seats. J Biomech 28(2):225–230
6. Grujicic M, Pandurangan B, Arakere G, Bell WC, He T, Xie X (2009) Seat-cushion and soft-tissue material modeling and a finite element investigation of the seating comfort for passenger-vehicle occupants. Mater Des 30(10):4273–4285. https://doi.org/10.1016/j.matdes.2009.04.028
7. Goossens RHM (2001) Shear stress measured on three different cushioning materials. Delft University of Technology
8. Goossens RHM, Teeuw R, Snijders CJ (2000) Decubitus risk: is shear more important than pressure? In: Proceedings of the lEA 2000 lHFES 2000 Congress
9. Hartung J (2006) Objektivierung des statischen Sitzkomforts auf Fahrzeugsitzen durch die Kontaktkräfte zwischen Mensch und Sitz. Dissertation, Technischen Universität München

10. Harrison DD, Harrison SO, Croft AC, Harrison DE, Troyanovich SJ (2000) Sitting Biomechanics Part II: optimal car driver's seat and optimal driver's spinal model. J Manipulative Physiol Ther 23(1):37–47
11. Hiemstra-van Mastrigt S (2015) Comfortable passenger seats: recommendations for design and research. PhD dissertation, Delft University of Technology
12. Kilincsoy Ü (2015) Digitalization of posture-based seat design. PhD dissertation, Delft University of Technology
13. Mansfield N, Sammonds G, Nguyen L (2015) Driver discomfort in vehicle seats- Effect of changing road conditions and seat foam compositions. Appl Ergonom 50:153–159
14. McCrady SK, Levine JA (2009) Sedentariness at work: how much do we really sit? Obesity 17(11):2103–2105
15. Molenbroek JFM, Albin TJ, Vink P (2017) Thirty years of anthropometric changes relevant to the width and depth of transportation seating spaces, present and future. Appl Ergonom 65:130–138. https://doi.org/10.1016/j.apergo.2017.06.003
16. Sammonds GM, Fray M, Mansfield NJ (2017) Effect of long term driving on driver discomfort and its relationship with seat fidgets and movements (SFMs). Appl Ergonom 58:119–127
17. Schmidt RF, Thews G (1980) Physiologie des Menschen. Springer Verlag, Berlin
18. Vink P, Lips D (2017) Sensitivity of the human back and buttocks: The missing link in comfort seat design. Appl Ergonom 58:287–292
19. Wegner M, Martic M, Franz M, Vink P (2017) A new approach for measuring the sea comfort. In: 11th international comfort congress, Salerno
20. Wegner M, Anjani S, Li W, Vink P (2019) How does the seat cover influence the seat comfort evaluation? In: Bagnara S, Tartaglia R, Albolino S, Alexander T, Fujita Y (eds) Proceedings of the 20th congress of the international ergonomics association (IEA 2018). IEA 2018. Advances in intelligent systems and computing, vol 824. Springer, Cham
21. Zenk R, Mergl C, Hartung J, Sabbah O, Bubb H (2006) Objectifying the comfort of car seats. SAE International
22. Zuo H, Jones M, Hope T (2004) A matrix of material representation. In: Proceedings of future ground, design research society international conference. Melborne