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Sensitivity of the human back and buttocks: The missing link in comfort seat design

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ABSTRACT

Purpose: The purpose of this study is to examine the differences in pressure sensitivity for areas of the human body in contact with the seat pan and backrest of a vehicle seat. These could provide a theoretical base for adapting the softness of the foam or the flexibility components used in seat design.
Methods: Sensitivity was recorded at 32 points touching the seat pan and backrest by pushing a cylinder with a diameter of 20 mm into the seat until the participant reported that they were no longer comfortable. The force at which discomfort was reported was recorded using an advanced force gauge.
Results and conclusions: The area of the body having contact with the front of the seat pan was more sensitive than the rest of those parts touching the seat pan. The area of the seat touching the shoulders was significantly more sensitive than the area in between the shoulders and lower down the back. Translating these findings directly into seat design should be done with care. Tests are still needed to confirm the assumed relationship between sensitivity and foam softness. Further information is also needed regarding the complete use of a seat, including analysis of vibrations while driving and comfort during ingress and egress.

1. Introduction

The number of vehicle seats in circulation is increasing. In 2013, three billion passengers were carried by the world's airlines (ATAG, 2013), and this figure is anticipated to increase even further. Airbus estimates a 4.7% annual growth between 2013 and 2033 (Airbus, 2014). As well as aircraft, seats are also made for cars, buses, trains, trams and ships. It is important to use ergonomics and human factors in seat design, as comfortable seats can attract passengers and increase sales. Almost 40 years ago, Richards et al. (1978) stated that passenger comfort is a key variable in user acceptance of transportation systems. More recently, Vink and Hallbeck (2012) found a correlation ($r = 0.73$) between the interior comfort of an aircraft and passengers' desire to 'fly again with the same airline'.

There are many scientific studies to assist with the design of vehicle seats. Seat width, backrest height and seat pan length can be based on anthropometric data, which are sometimes incorporated in design software packages such as RAMSIS (Vogt et al., 2005) and Jack (Stefani et al., 2007). The backrest and seat pan angle have also been studied. Harrison et al. (2000) stipulated a backrest inclination of 100°. Park et al. (2000) observed that 117° is the preferred trunk thigh angle for Korean drivers. Kilincsoy et al. (2014) concluded that 119° was the preferred relaxed position for car passengers, and 105° the preferred upright position. The body contour in contact with the seat has also been the subject of scientific research. Franz et al. (2011) and Hiemstra-van Mastrigt (2015) used 3D scans to study contours in both car and aircraft seats. Studies regarding pressure distribution are also available. Zenk et al. (2012) used a previous study by Hartung (2006) to describe the ideal pressure distribution, which can be used to determine the form of the seat. They found that discomfort increases if the pressure between the front of the seat and the part of the thighs just above the knees is higher or lower than 6% of the total weight on the seat. Equally, the pressure in the intervertebral disc increases when the pressure deviates from 6%. Franz et al. (2012) studied the sensitivity of the head and neck, concluding that foam in the neck support should be softer than the foam contacting the head. The term 'sensitivity' is highly relevant to the aims of the current paper. It is a broad term, but this paper treats it in the same way as Goossens et al. (2005) – i.e. sensitivity relating

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to pressure on the skin and underlying tissue. The assumption in the approach of Franz et al. (2012) is that there could be a relationship between the sensitivity of particular body parts and seat design. Fig. 1 offers a schematic elaboration of this claim. It is assumed that both the form of the area contacting the body and the softness of this area influence the contact area between the body and the product. It is also assumed that the pressure sensitivity of the skin and underlying tissue plays a role in the way that less discomfort is experienced. This information could be used to both enhance comfort and, in the case of improved pressure distribution, reduce discomfort.

It is also assumed that knowledge of sensitivity is useful in seat design, as increased softness may be needed for sensitive areas. Various studies demonstrating the relationship between pressure and discomfort offer support for this reasoning (e.g. Ballard, 1997; Buckle and Fernandes, 1998; Goossens et al., 2005).

Strangely, it is hard to find data on the sensitivity for the backrest and the buttocks. Nevertheless, these are important, as both feature prominently in seating design – for instance, in defining the foam characteristics of a seat pan and backrest to create a comfortable seat, or defining the flexibility of the material underlying the foam. Goossens et al. (2005) have studied the pressure sensitivity of the tuberositas ischiadicus area. They applied pressure upwards under the tuberositas ischiadicus with round contact surfaces, and concluded that the buttocks' sensitivity is dependent on the size of the contact area and the speed at which the pressure is exerted. However, this information alone is insufficient to design a seat.

Of course, comfort and discomfort are influenced by many other factors, including service (Vink and Hallbeck, 2012), psychological factors (Ahmadpour et al., 2014) and angles of the joints (Apostolico et al., 2014). Moreover, the main effect of the product in contact with the body relates to discomfort rather than comfort, as discomfort is more closely linked to physical factors (Looze et al., 2003). Knowledge of pressure sensitivity, however, is useful for vehicle seat design (assuming that the model in Fig. 1 is valid). The subject of this study is hence the sensitivity of the human back and buttocks. Of particular interest are whether there are areas with greater or lesser sensitivity to adjustments in the softness, flexibility or curvature of the backrest and the seat pan.

Our research question is: 'Are there differences in sensitivity for areas of the human body that contact the seat pan and backrest, and, if so, what are the relative sensitivities of these areas?'

2. Methods

The sensitivity of the back and buttocks areas in contact with the seat pan and backrest was recorded for 23 participants, who were asked to indicate whether they felt discomfort when a researcher slowly and gradually increased pressure at a specific point on the human body.

2.1. Equipment

An advanced force gauge (AFG) meter (Mecmesin AFG 500N) connected to a round aluminium plate with a diameter of 20 mm was used to apply the pressure. A seat was fabricated with 32 holes (see Fig. 2), into which the AFG's cylindrical plate could be positioned. Care was taken to connect the measurements to landmarks on the body. However, as the research related to seat design, connection was to the product rather than the body. A disadvantage of connecting to body parts is that other areas of the body will be come into contact with the instrument due to variations in anthropometry between individuals. An advantage, conversely, is that the translation to seat design may be easier.

The 12 seat pan holes and 20 backrest holes were made in a wooden plate. The backrest was positioned at an angle of 110° – a position in between the relaxed and upright positions given by Kilincsoy et al. (2014). The seat pan was positioned at 15° – the angle with the least shear force for the corresponding backrest angle, according to Goossens and Snijders' model (1995). The 20 mm diameter of the contact surface was chosen for ease of comparison with a study by Goossens et al. (2005). A specially designed seat was fabricated to enhance the reachability of the holes (see Fig. 3). The seat was positioned at a table to enable researchers to read the forces in question (see Fig. 3).

2.2. Participants and procedure

The study involved 23 participants, of whom 8 were female and 15 male, with ages ranging from 19 to 54 (see Table 1). Following participants' informed consent, data were gathered on weight, body height, shoulder width, hip width, shoulder-buttocks height, and upper and lower leg length, according to Standard NEN-EN-ISO 7250-1 (CEN, 2010). Participants were asked to wear only one layer of clothing (trousers and a T-shirt) and underwear. After their anthropometrical data was recorded, participants were asked to

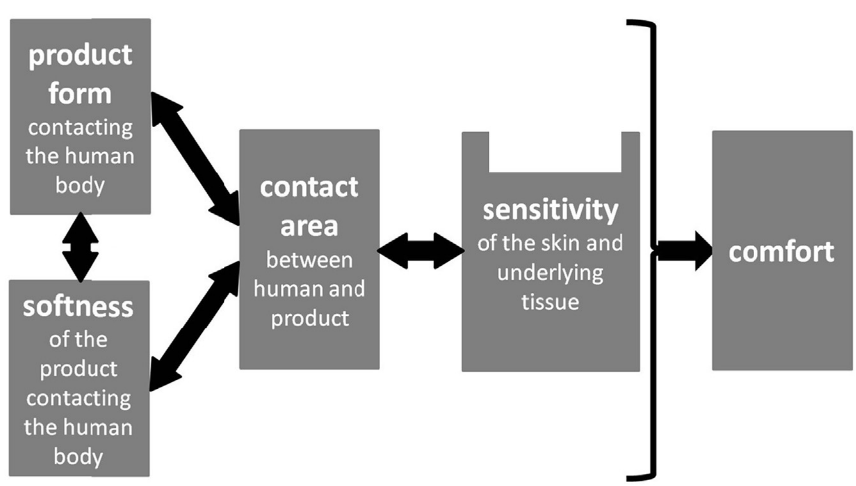

Fig. 1. A model of how both the product of the area contacting the human body and the softness of this area influences the way in which the contact area affects our experience of (dis)comfort.

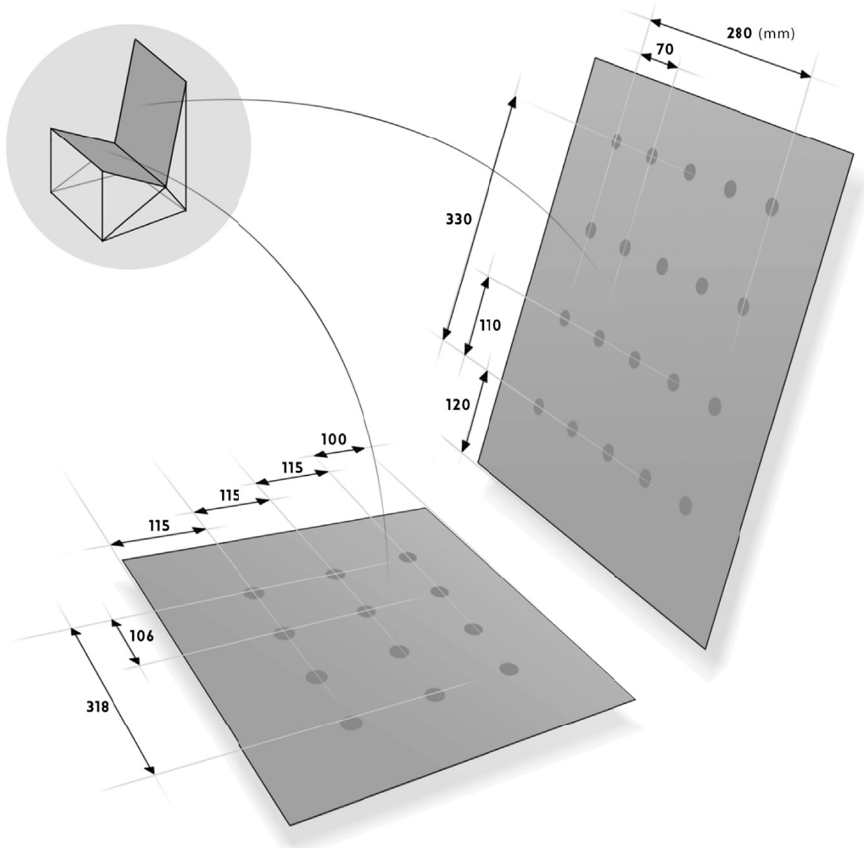

Fig. 2. Points on the seat and backrest where the AFG is positioned to record sensitivity.

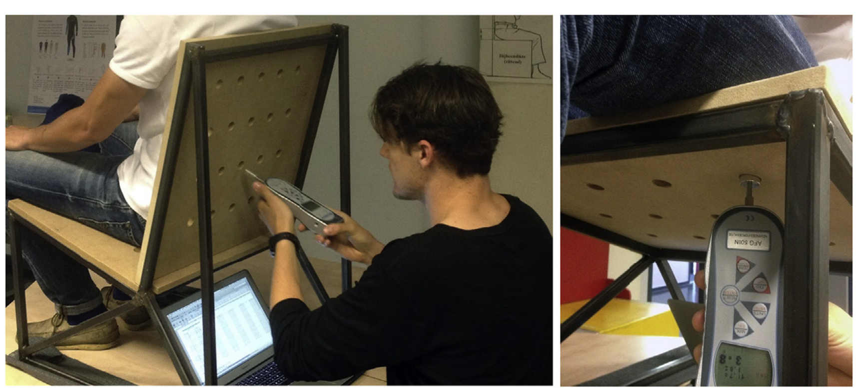

Fig. 3. Recording of sensitivity.

take a seat. The AFG was then positioned through each of the 32 holes. Pressure was slowly increased until the participants stated that their level of discomfort was too high. Each point was measured three times per participant, with the last two recordings taken as the values for the calculation due to the possible habituation effect associated with the first.

2.3. Data analysis

The values of the forces at which the pressure started to create discomfort were recorded in an Excel file. These data were later transferred to SPSS version 20. As the points at which participants reported discomfort differed, the data were made comparable. This was done by dividing all back values for a single participant by the average back value, and dividing all buttocks values by the average buttocks value. Average values and standard deviations were calculated for each point. A formula was developed in which each point was compared with the four neighbouring points (above, below, left and right for the backrest; ahead, behind, left and right for the seat pan) and a *t*-test for paired samples was performed to check whether these differences were statistically significant ($p < 0.05$). Additionally, the mean of all recorded values was taken for each participant, and correlations were calculated. Correlations between BMI and sensitivity were also calculated to check for a link between obesity and lessened sensitivity. Correlations between age and sensitivity were calculated to asses whether older people are

Table 1
Characteristics of the participants.

	Average	sd	Min	Max
Age (years)	28.7	9.8	19	54
Weight (kg)	75.4	10.0	65	102
Length (m)	1.81	0.07	1.72	1.97
Shoulder width (m)	0.44	0.03	0.38	0.49
Waist width (m)	0.27	0.02	0.22	0.31
Hip width (m)	0.38	0.02	0.34	0.42
Shoulder-buttock height (m)	0.61	0.02	0.57	0.65
Upper leg length (m)	0.52	0.02	0.48	0.57
Lower leg length (m)	0.50	0.02	0.46	0.54

more or less sensitive. Correlations between hip and shoulder width and sensitivity were calculated, as broader people spread their mass over a larger area. Additionally, a *t*-test was performed to see whether the averages differed significantly ($p < 0.05$) between males and females.

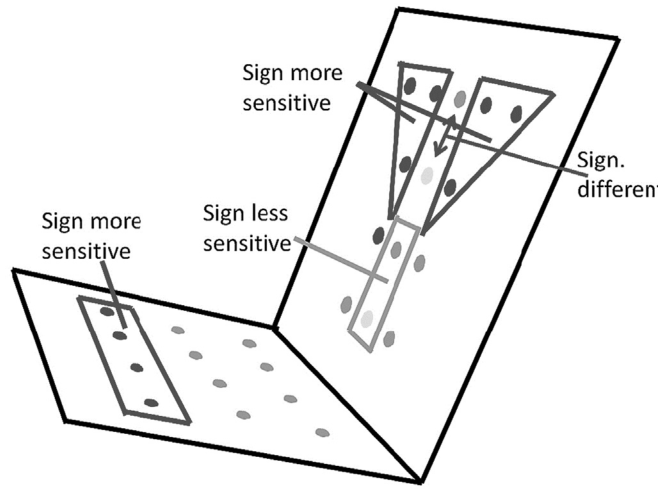

Fig. 4. Areas with significantly different sensitivities.

3. Results

- Large interindividual differences

There were several large differences observed between the participants. For instance, at the second point next to the middle, one participant reported discomfort at a force of 8 N, while another reported discomfort at 34 N for the same point.

- Seat pan pressure sensitivity

Measurements showed that certain areas are significantly more pressure sensitive (see Table 2 and Fig. 4). The parts of the body contacting the front of the seat pan were significantly more sensitive than those contacting the rows in the middle (p values of 0.001 and lower). Sensitivity to the points in the middle row of the seat pan, however, were not significantly different from that of the most posterior row.

- Backrest pressure sensitivity

The three lower points in the middle column of the backrest were not significantly different from one another. The points left and right of the middle were significantly different (p values of 0.011 and lower), while the highest middle point differed significantly from the middle point a row lower ($p = 0.006$). There were some missing values for the most lateral areas of the back, as these could not be reached in 15 out of the 23 participants. However, values for the eight participants where the lateral points could be recorded showed no significant differences. The points in the lateral column were not significantly different from the columns left and right of the middle column (only eight participants were used, as it was a paired *t*-test). However, conclusions regarding these values should be treated with caution as the number of participants was low. At shoulder level, where data were available for all participants, the most lateral column was not significantly different from the columns left and right of the middle column.

- Pressure sensitivity, gender, age, BMI and anthropometrics

There was a significant difference between the female and male sensitivity values, with females significantly more sensitive ($p = 0.021$). The correlation between BMI and sensitivity was low ($r = 0.058$; $p = 0.79$), as was the correlation between shoulder width and sensitivity ($r = 0.22$, $p = 0.31$), hip width and sensitivity ($r = -0.08$, $p = 0.71$), and age and sensitivity ($r = 0.125$, $p = 0.57$).

4. Discussion

Results of the study revealed that there are differences in

Table 2
Average values (in N, not equalized) at which the 23 participants experience the pressure as no longer comfortable, with standard deviations (in brackets).

<table>
<tr><td rowspan="3">Backrest</td><td colspan="2">10.92 (5.30)</td><td colspan="2">12.17 (5.94)</td><td colspan="2">15.17 (7.2)</td><td colspan="2">12.61 (6.86)</td><td colspan="2">10.73 (6.68)</td></tr>
<tr><td colspan="2"></td><td colspan="2">11.81 (8.3)</td><td colspan="2">21.57 (16.02)</td><td colspan="2">13.10 (7.99)</td><td colspan="2"></td></tr>
<tr><td colspan="2"></td><td colspan="2">14.38 (9.44)</td><td colspan="2">19.24 (13.1)</td><td colspan="2">15.36 (9.73)</td><td colspan="2"></td></tr>
<tr><td></td><td colspan="2"></td><td colspan="2">15.29 (6.59)</td><td colspan="2">21.01 (8.67)</td><td colspan="2">17.18 (8.67)</td><td colspan="2"></td></tr>
<tr><td rowspan="3">Seat pan</td><td colspan="2">22.39 (9.33)</td><td colspan="3">23.42 (11.09)</td><td colspan="3">23.21 (7.87)</td><td colspan="2">22.69 (9.40)</td></tr>
<tr><td colspan="2">23.5 (9.33)</td><td colspan="3">22.39 (10.17)</td><td colspan="3">21.35 (8.01)</td><td colspan="2">22.64 (8.88)</td></tr>
<tr><td colspan="2">19.76 (8.63)</td><td colspan="3">15.73 (6.23)</td><td colspan="3">16.61 (6.45)</td><td colspan="2">18.83 (7.28)</td></tr>
</table>

sensitivity between the parts of the human body that contact the seat pan and backrest, with those in contact with the front of the seat pan being more sensitive. According to Zenk et al. (2012) and Hartung (2006) the pressure on this area should be around 6% of the total pressure on the seat. A higher pressure level increases the discomfort. Areas further back in the seat can tolerate greater pressure (>10%), and the area touching the seat around the tuberositas ischiadicus can bear up to 50–65% of the load. This aligns with our finding that the part of the body in contact with the front of the seat pan is more sensitive. Regarding the shoulders, the present study shows that humans are more sensitive at shoulder level than lower down in the body, and that the area lateral from the spine is also more sensitive. The pressure pain thresholds in a study by Binderup et al. (2010) showed similar results. Here, the authors found no differences between left and right side in the cervicothoracic and lumbar regions, but large differences between the subdivisions in the trapezius, with the most sensitive areas in the upper part. The least sensitive areas were found around the lumbar area. Binderup et al. (2010) also found differences in sensitivity between the middle area between the two scapula (close to the spine) and the regions more lateral to the middle. Their method was different to that of the present study, however, as it related to landmarks on the naked body and not to the seat measured with a clothed subject. Also, they studied pain rather than comfort, and they used an algometer (Somedic® Algometer type 2, Sweden) with a 1 cm^2 wide rubber tip, while we used a firmer material (aluminium) and a round plate with a diameter of 20 mm. Despite these differences, results of the two studies are comparable. Both revealed the lateral upper shoulder area to be the most sensitive. Both also reported a significant difference between males and females, with women having slightly lower pressure pain thresholds in both cervicothoracic and lumbar regions. In the present study, women were generally more sensitive for pressure.

Data gathered in this study on the most lateral points in the backrest are difficult to interpret, as the majority of participants had an insufficiently wide back to generate values. Standard deviations were relatively high for the other measurements, as there were large differences between participants. Clothing and variations in anthropometrics could be influential factors here. The fact that the influence of clothing is unknown, and that participants of different sizes were measured in a standard seat, is a disadvantage of this study. However, it is also the case that seats should be suitable for people with a range of different anthropometrics and clothing choices, and that these differences should be accommodated by the design. In this study, rather tall people were used (p41-p98 if we compare the data to the anthropometry of the Dutch population aged 20–60 in DINED) – a factor that must be taken into account. For more luxury seating, this problem can be solved by making the seat pan and backrest (length and width) adjustable. The effects on comfort of an adjustable seat is an area for future research. Equally, research involving a moving car would help give a fuller picture of the data in question. Mansfield et al. (2015) showed a relationship between discomfort, road conditions and seat foam composition. The same authors also concluded that ignoring parts of the relationship between discomfort, vibration magnitude and exposure time compromises the understanding of discomfort in context.

Another complicating factor is that the comfort of the front of the seat is very much influenced by both anthropometry and the activities performed while seated (Hiemstra-van Mastrigt, 2015). Hiemstra-van Mastrigt (2015) recorded 3D scans of people with different anthropometrics performing different activities while seated. Fig. 5 shows that the variation in 3D scans is greatest where the body touches the seat pan. The fact that this is also the area of greatest sensitivity presents a challenge for designers. Additionally, first impressions may influence the perception of comfort – a factor not taken into account by this study. Brosh and Arcan (2000) showed that the stiffness of the seat, the peak contact stresses, and the internal body stresses all substantially decreased during the process of sitting down. Designing a seat based solely on these data could hence have the disadvantage that the complete use of the seat may be ignored. While it is possible to develop a seat based on the data in this study, additional research to check whether the seat is more comfortable while sitting is required. Equally, data regarding use while driving and during ingress and egress would be advantageous for achieving optimal comfort in future seat design.

According to Helander (2003) chair design and biomechanics of sitting are not so important unless the chair user has a bad back, or unless the design of the chair is too small or too large for the user, or unless it violates basic design criteria, like sharp edges. Helander (2003) states that the aesthetics may be of be more importance. This means that the values on pressure sensitivity are not as important. However, research shows (Vink, 2014) that the aesthetics play an important role during the first 40 min of seating as opposed to sitting longer than 40 min where the physical contact is more important. Zenk (2008) also showed during a three hour drive, participants were able to distinguish between the ideal pressure distribution and a self-chosen adjustment. Probably the results of this study on pressure sensitivity for seating are more relevant for seats used more than 40 min.

5. Conclusion

The sensitivity of areas in the back and buttocks touching the seat are significantly different, with those parts of the body having contact with the front of the seat pan being more sensitive. Sensitivity is significantly elevated for the area of the seat touching the shoulders compared with the area touching the spine and the lumbar. This aligns with findings from other studies regarding ideal pressure distribution and pain thresholds. However, further research is needed to determine whether softer foam or more flexible materials could reduce discomfort in these sensitive areas. Additional research into discomfort during driving, as well as

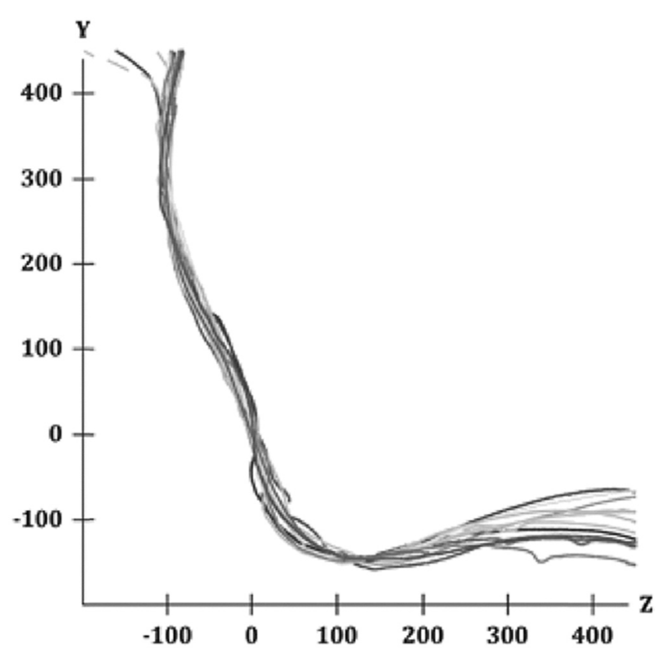

Fig. 5. Body contours (in mm) while seated based on 3D scans by Hiemstra-van Mastrigt (2015) (the largest variation is at the front of the seat pan).

during ingress and egress, would also be of benefit for future seat design.

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