PROCEEDINGS OF THE 5TH INTERNATIONAL COMFORT CONGRESS

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Proceedings of the 5th International Comfort Congress

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Edited by:
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PREFACE

Welcome to the 5th International Comfort Congress!

The International Comfort Congress (ICC) has been a pivotal gathering for researchers and practitioners in the field of comfort since its inception. Our common goal is to share the latest knowledge and stimulate ideas within and across sectors, and between industry and research. This Congress is the perfect opportunity to meet with thought-leaders in comfort research, to discuss comfort state of the art theory, test methods, models, and applications.

The journey began at the University of Salerno, Italy, in 2017, where the inaugural Congress laid the groundwork for international collaboration and knowledge exchange. Building on this success, the second Congress convened at TU-Delft, Netherlands in 2019, further solidifying the ICC's commitment to advancing comfort science. The challenges of the global pandemic led to a successful virtual Congress, hosted online from Nottingham Trent University, UK in 2021, demonstrating the community's adaptability and dedication, even when many were working from home. The fourth installment brought the community together at Grammer, Amberg, Germany in 2023, the first time hosted by industry. Now, in 2025, we look forward to the fifth International Comfort Congress in Delaware, USA. Our hosts are W.L.Gore & Associates, which means that this is our second Congress with an industrial host, and our first outside of Europe.

We encourage interactions, in sessions and breaks, taking opportunity to visit facilities that are usually behind closed doors, and at our congress dinner. Importantly we always award a prize for the best presentation, the prize being free registration as a special guest at the next congress. Please keep this in mind while you enjoy the conference as we will be requesting your votes!

Thank you for joining us!

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About the sponsor and host: W.L. Gore & Associates

W.L. Gore & Associates is a global materials science company founded in 1958 by Bill and Vieve Gore. They are known for their innovative materials, especially GORE-TEX fabric, which revolutionized outerwear with its waterproof and breathable properties. The company also develops solutions for various industries, including electronics, medical devices, and industrial applications.

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Subjective Comfort Analysis of Construction Vehicle Seats

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ABSTRACT

Seating comfort is an important design factor for construction vehicle cabins. However, seating comfort has many characteristics that are difficult to quantify. There are no studies that address the comfort evaluation structure of construction vehicle seats. The purpose of this study is to systematically clarify seating comfort by analyzing its evaluation structure through subjective evaluation and quantifying it with design values. In this study, 67 experienced operators were asked to evaluate 11 seats on a 7-point scale (analytical and preference type evaluations). Factor analysis of the preference type evaluation showed six factors of operator's preference. Multiple regression analysis showed the factor with the largest contribution to the general evaluation was "Backrest Lateral Support Feel" and "Cushion Feel". Principal component analysis of analytical type evaluation showed operators prefer the seat which is soft and well-fitted. These results suggested that the operator's experience in a dynamic environment with vibration and working on lateral slopes reflected in their static evaluations.

KEYWORDS

Construction vehicle seat, Seating comfort, Subjective evaluation, Evaluation structure

Introduction

Cabin comfort is an important design factor for construction vehicles. Kuijt-Evers et al. (2003) found that improving seating comfort in construction vehicles improves cabin comfort, based on operator comments. Spasojević Brkić et al. (2023) extracted seat characteristics as one of the factors to assess cabin ergonomic risk and found that improving seat characteristics leads to improvement of other factors. These previous studies indicated that seating comfort is a principal factor in cabin comfort. In addition, there are some previous studies about seating comfort. Chin-Chuan (2001) reported that seat type did significantly affect mean body part discomfort and mean subjective preference score and that a wide adjustment range and a good adjustment mechanism can satisfy operator requirements, reduce body part discomfort, and improve subjective preferences. Sugano et al. (1997), based on subjective evaluations of four seat and physiological measurements during seating, found that a moderate degree of firmness is necessary to reduce muscle activity and numbness. The evaluation structure of seating comfort is not clarified in these studies.

The purpose of this study is to systematically clarify seating comfort by analyzing the seating comfort evaluation structure through subjective evaluation and quantifying it by design values.

Method

(1) Experiment environment

The experiment was conducted without mounting the seats on a construction vehicle; instead, 11 seats were arranged side by side for testing (Fig.1). In the experiment, the operator's posture during excavation with a hydraulic excavator was replicated with a joystick mounted on the seat (Fig.2). In addition, a laptop computer was placed in front of the seat to replicate the direction of operator's sight. (1.1 meters ahead and 0.86 meters high).

(2) Subjective evaluation

A total of 67 subjects with experience operating construction vehicles took part in the subjective evaluation (height: 170 ± 6.78 cm, weight: 73 ± 18.52 kg, age: 40 ± 10.16 years). Evaluation items and their definitions are shown in table 1. Eleven seats available on the market were used. The subjects were asked to rate 7-points scale. The 24 items, excluding the general evaluation, were evaluated in terms of the strength or weakness of the seating comfort features (analytical type), and all items were evaluated in terms of liking or disliking (preference type).

Fig.1 Eleven seats (A-K)

Fig.2 Evaluation environment

Table.1 Evaluation questionnaires (Miura et al., 2024)

No.	Evaluation Items	Defination
1	Feeling of Seat Firmness	Do you feel Seat firm?
2	Seat Width	How do you feel seat width?
3	Seat Depth	How do you feel seat depth?
4	Seat Side Support Height	How do you feel seat side support height?
5	Feeling of Sinking(a)	Do you feel hips only sink down?
6	Feeling of Sinking(b)	Do you feel seat cushion touch the bottom?
7	Feeling of Spring	Do you feel elasticity or repelling power when you sit down on the seat?
8	Feeling of Seat Fitness(a)	How do you feel seat cushion fit the body? (a)lateral (right to left) direction
9	Feeling of Seat Fitness(b)	How do you feel seat cushion fit the body? (b)front to rear direction
10	Feeling of Seat Holding	Do you feel your body is held by seat when the excavator turns?
11	Tightness of Thigh Lateral	Do you feel thigh lateral tight?
12	Thigh Support Pressure	How is the thigh support strength?
13	Tightness of Hips Lateral	Do you feel hips lateral tight?
14	Feeling of Hips Slide	Do you feel hips slide forward?
15	Feeling of Backrest Firmness	Do you feel Back firm?
16	Backrest Width	How do you feel seat width?
17	Backrest Height	How do you feel seat height?
18	Backrest Side Sapport Height	How do you feel back side sapport height?
19	Lumbar Support Height	How do you feel lumbar support height?
20	Feeling of Backrest Fitness(a)	How do you feel seat cushion fit the body? (a)horizontal direction
21	Feeling of Backrest Fitness(b)	How do you feel seat cushion fit the body? (b)vartical direction
22	Lumbar Support Pressure	How is the lumbar support strength?
23	Abdomen Oppressive Feeling	Do you feel the abdomen oppressed or tight?
24	Feeling of Backrest Holding	Do you feel your body is held by back when the excavator turns?
25	General Evaluation	What is a overall evaluation as a seat?

Evaluation result analysis

(1) Extracting evaluation factors of preference type

Table 2 shows results of the factor analysis of preference type evaluation except general evaluation. The analysis used data from 63 individuals excluding 4 subjects who do not properly evaluate seats. The method used was the maximum likelihood method followed by varimax rotation. Six factors with eigenvalues greater than 1.0 were extracted. The extracted 6 factors were interpreted as factor 1 *"Seat Dimension Feel"*, factor 2 *"Cushion Feel"*, factor 3 *"Backrest Lateral Support Feel"*, factor 4 *"Seat Lateral Support Feel"*, factor 5 *"Lumbar Support Feel"*, and Factor 6 *"Backrest Height Feel"*, based on Table 2. The cumulative contribution rate was 61%.

(2) Contribution to general evaluation

Equation (1) shows results of multiple regression analysis. The response variable was general evaluation. Explanatory variables were factor scores of the factor analysis. x_1 to x_6 are factors 1 to 6. The multiple correlation coefficient is 0.62. The factor with the largest contribution to the general evaluation was *"Backrest Lateral Support Feel"* and *"Cushion Feel"*.

$$Y = 0.460x_1 + 0.477x_2 + 0.566x_3 + 0.323x_4 + 0.317x_5 + 0.139x_6 + 4.063 \qquad (1)$$

For each seat, the factor scores averaged by the 63 subjects were plotted with the axes of the second and third factors that contributed most to the general evaluation in Figure.3. Contour lines of the

Table.2 Factor loading

abs.≧0.4

	Factor1	Factor2	Factor3	Factor4	Factor5	Factor6
Tightness of Hips Lateral	0.563	0.091	0.216	0.067	0.102	0.084
Tightness of Thigh Lateral	0.553	0.073	0.121	0.203	0.136	0.057
Thigh Support Pressure	0.547	0.195	0.032	0.132	0.147	0.112
Seat Depth	0.513	0.252	0.084	0.087	0.057	0.102
Feeling of Seat Fitness(b)	0.489	0.172	0.077	0.226	0.134	0.068
Feeling of Seat Firmness	0.479	0.162	0.188	0.271	0.044	0.076
Feeling of Hips Slide	0.431	0.100	0.116	0.123	0.099	-0.025
Feeling of Spring	0.151	0.767	0.065	0.121	0.082	0.066
Feeling of Seat Firmness	0.213	0.690	0.117	0.140	0.088	0.090
Feeling of Sinking(b)	0.171	0.686	0.070	0.073	0.088	0.035
Feeling of Sinking(a)	0.272	0.564	0.094	0.102	0.111	0.053
Feeling of Backrest Firmness	0.061	0.511	0.221	0.116	0.262	0.097
Feeling of Backrest Fitness(a)	0.167	0.111	0.855	0.185	0.105	0.094
Feeling of Backrest Holding	0.143	0.109	0.697	0.232	0.171	0.052
Backrest Side Sapport Height	0.172	0.120	0.676	0.143	0.197	0.109
Backrest Width	0.214	0.138	0.519	0.021	0.124	0.213
Feeling of Backrest Holding	0.259	0.176	0.190	0.691	0.108	0.081
Feeling of Seat Fitness(a)	0.371	0.159	0.217	0.690	0.047	0.029
Seat Side Support Height	0.301	0.180	0.169	0.614	0.122	0.060
Lumbar Support Pressure	0.199	0.162	0.143	0.149	0.777	0.064
Lumbar Support Height	0.135	0.170	0.241	0.060	0.600	0.102
Abdomen Oppressive Feeling	0.294	0.138	0.157	0.028	0.424	0.098
Backrest Height	0.176	0.119	0.191	0.051	0.089	0.953
Feeling of Backrest Fitness(b)	0.127	0.178	0.298	0.134	0.246	0.479
Eigenvalues	7.591	1.954	1.736	1.330	1.136	1.029
Proportion Explained	31.628	8.143	7.235	5.540	4.733	4.289
Cumulative Contribution	31.628	39.770	47.005	52.545	57.278	61.567

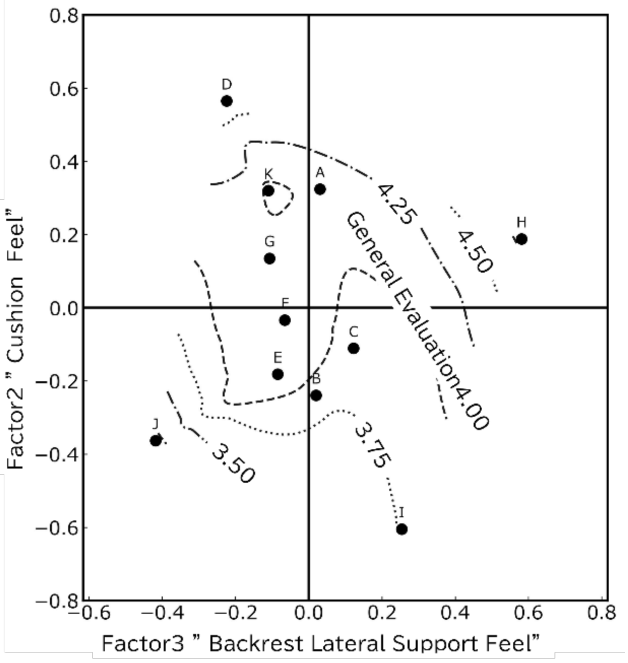

Fig.3 Factor scores of samples

general evaluation are shown as dashed lines. The general evaluation tended to be higher as one went to the upper right. Seat H, which has a highest general evaluation, has highest evaluation for the factor 3 *"Backrest Lateral Support Feel"*. Seat D, which has second highest general evaluation, has highest evaluation for the factor 2 *"Cushion Feel"*.

(3) Seat characteristics from analytical type

Principal component analysis was conducted for each seat and backrest using mean scores of the analytical type. First principal component was interpreted as *"Softness and Fitness"*, and second principal component was interpreted as *"Not Sinking and Thigh Pressure"*. The cumulative contribution was 68.1%. First principal component was interpreted as *"Lateral Support"*, and second principal component was interpreted as *"Hardness and Lumbar Support"*. The cumulative contribution is 72.6%. Principal component scores are plotted the planes of the first and second principal component axes in Figure.4. Seat H has the highest evaluation for the principal component 1 *"Lateral Support"* of backrest. Seat D has high evaluation for the principal component 1 *"Softness and Fitness"* and low evaluation for principal component 2 *"Not Sinking and Thigh Pressure"* of seat.

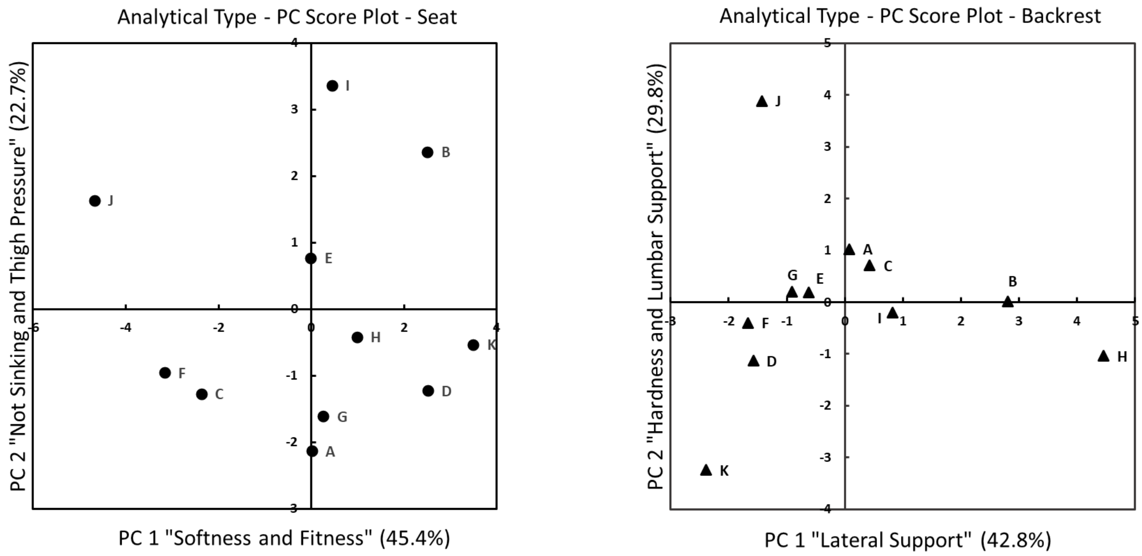

Fig.4 Principal components score of samples

(4) Relationship between preference type and analytical type of important factors

Table.3 is correlations coefficient between preference type and analytical type of some evaluation items composing factor 2 and factor 3. In factor 2, *"Sensation of Seat Firmness"* and *"Sensation of Backrest Firmness"* have negative correlations. This means that operators prefer softer seats. In factor 3, *"Backrest Side Support Height"*, *"Feeling of Backrest Fitness(a)"* and *"Feeling of Backrest Holding"* have positive correlations. This means that operators prefer a well-fitted backrest.

Table.3 Preference type vs analytical type

	Evaluation Items	R	p-value
Factor 2	Feeling of Seat Firmness	-0.80	**
	Feeling of Sinking (a)	0.73	*
	Feeling of Sinking (b)	-0.68	*
	Feeling of Spring	0.88	***
	Feeling of Back Firmness	-0.90	***
Factor 3	Backrest Width	0.67	*
	Backrest Side Sapport Height	0.75	**
	Feeling of Backrest Fitness (a)	0.91	***
	Feeling of Backrest Holding	0.94	***

* : p<0.05, ** : p<0.01, *** : p<0.001

Discussion

These results show backrest lateral support and seat cushions are important for seating comfort and operators prefer well-fitted backrest and soft seat cushions. Backrest lateral support is needed to support operator's backrest when they feel horizontal vibration and are on lateral slopes when excavating. Cushion is needed to reduce shock of vertical vibration in the comments of evaluation. There are some comments that it is better to have high side support and have soft cushion for strong impact. These comments are consistent with the relationship between preference and analytical evaluations presented above. It seems that subjects reflect their experience in a dynamic environment even if in a static experiment.

Conclusion

In this paper, subjective comfort evaluations of construction vehicles were conducted by using 25 evaluation items. It was indicated that operators prefer softer cushions and well-fitted backrest. In the static experiment, it was suggested that the experienced operators also evaluate the dynamic operation.

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Quantitative Analysis of Construction Vehicle Seat Comfort

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ABSTRACT

At construction sites, work with excavators requires operators to sit for a long time, which can place heavy physical loads on them. Despite the high physical loads, designing the seating comfort of excavator seats is still dependent on the knowledge of the designer due to a lack of comfort research. As a result, it is not possible to accumulate and improve the development and stable evaluation of sitting comfort. This study aims to solve these problems by analyzing the evaluation structure of seating comfort and presenting design development indices. Measurements of sitting posture and pressure distribution together with subjective evaluations of seating comfort for 11 different construction vehicle seats were conducted for 67 subjects who had experience operating an excavator. Based on the results of the relationships between subjective evaluations, measured postures, and pressure distributions were analyzed for quantifications of comfort. The clarification of the seating comfort structure in this study will increase its design and development efficiency.

KEYWORDS

Construction vehicle seat, Seating comfort, Sitting posture, Pressure distribution

Introduction

The operator's seat of a construction vehicle is an essential element for comfortably operating the machine. Based on the results of a survey conducted with operators, it was revealed that improving seating comfort in construction machinery leads to improved cabin comfort (Kuijt-Evers et al. 2003). Chin-Chuan (2001) reported that seat type significantly affects discomfort and preferences, and that seats with wide and effective adjustability can better meet operator needs. Therefore, it is considered that improving seat comfort can provide operators with a more comfortable working environment. However, seating comfort is influenced by various seat characteristics and subjective evaluation factors, many of which are difficult to quantify. As a result, improvements in seat design during construction vehicle development are often based on subjective evaluations.

In this study, a method to develop design indicators aimed at seating comfort was investigated as an alternative to conventional trial-and-error methods based on subjective evaluations. Subjective evaluation of 11 different construction vehicle seats was conducted with 67 subjects who had experience operating an excavator. When operators assumed the operating posture used during excavation work, 6 factors significantly contributed to seating comfort: Factor 1: Seat dimension Feel, Factor 2: Cushion Feel, Factor 3: Backrest lateral support Feel, Factor 4: Seat lateral support Feel, Factor 5: Lumber support Feel, and Factor 6: Backrest height Feel. Among the 6 factors, Backrest lateral support Feel contributed the most to the general evaluation of seating comfort (Miura et al. 2025).

In this paper, in addition to subjective evaluations, measurements of seat dimensions and pressure distribution were conducted. The relationship between the subjective evaluations and the measurement results was analyzed to quantify seat comfort.

Experiment Method

The Experiment was conducted without mounting the seats on a construction vehicle; instead, 11 seats were arranged side by side for testing (Figure 1). In the experiment, the operator's posture during excavation with a hydraulic excavator was replicated with a joystick mounted on the seat (Figure 2). In addition, a laptop computer was placed in front of the seat to replicate the direction of operator's sight (1.1 meters ahead and 0.86 meters high). A total of 67 subjects with experience operating construction vehicles took part in the subjective evaluation (height: 170 ± 6.78 cm, weight: 73 ± 18.52 kg, age: 40 ± 10.16 years).

Measurement Method

Subjective evaluation: After sitting in the seat and stabilizing their operating posture, subjects responded to 24 questions using two types of 7-point rating scales (Table 1). Preference type was a preference-based evaluation (1: dislike, 4: moderate, 7: like), referred to as the preference type, and analytical type was an evaluation of the intensity of seating comfort characteristics (1: do not feel at all, 4: moderate, 7: strongly feel), referred to as the analytical type. The average value of each subject's evaluation score was used for the analysis. The analysis used data from 63 individuals excluding 4 subjects who do not properly evaluate seats.

Pressure distribution: The pressure distribution was measured by the SR Soft Vision whole-body version (Sumitomo Riko) installed on the seat. The total body pressure and the total contact area were calculated.

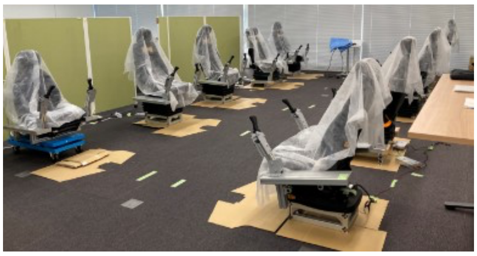

Fig.1 Eleven Seats (A-K)

Fig.2 Evaluation Condition

Table.1 Evaluation questionnaires (Miura et al., 2024)

No.	Evaluation Items	Defination
1	Feeling of Seat Firmness	Do you feel Seat firm ?
2	Seat Width	How do you feel seat width?
3	Seat Depth	How do you feel seat depth?
4	Seat Side Support Height	How do you feel seat side support height?
5	Feeling of Sinking (a)	Do you feel hips only sink down?
6	Feeling of Sinking (b)	Do you feel seat cushion touch the bottom ?
7	Feeling of Spring	Do you feel elasticity or repelling power when you sit down on the seat?
8	Feeling of Seat Fitness (a)	How do you feel seat cushion fit the body? (a) lateral (right to left) direction
9	Feeling of Seat Fitness (b)	How do you feel seat cushion fit the body? (b) front to rear direction
10	Feeling of Seat Holding	Do you feel your body is held by seat when the excavator turns?
11	Tightness of Thigh Lateral	Do you feel thigh lateral tight?
12	Thigh Support Pressure	How is the thigh support strength?
13	Tightness of Hips Lateral	Do you feel hips lateral tight?
14	Feeling of Hips Slide	Do you feel hips slide forward?
15	Feeling of Backrest Firmness	Do you feel Back firm ?
16	Backrest Width	How do you feel seat width?
17	Backrest Height	How do you feel seat height?
18	Backrest Side Sapport Height	How do you feel back side sapport height?
19	Lumbar Support Height	How do you feel lumbar support height?
20	Feeling of Backrest Fitness (a)	How do you feel seat cushion fit the body? (a) horizontal direction
21	Feeling of Backrest Fitness (b)	How do you feel seat cushion fit the body? (b) vartical direction
22	Lumbar Support Pressure	How is the lumbar support strength?
23	Abdomen Oppressive Feeling	Do you feel the abdomen oppressed or tight?
24	Feeling of Backrest Holding	Do you feel your body is held by back when the excavator turns?
25	General Evaluation	What is a overall evaluation as a seat?

Results

This study focuses on two critical factors that significantly influence the general evaluation of seating comfort extracted by subjective comfort analysis (Miura et al. 2025): Backrest lateral support Feel and Cushion Feel.

Backrest lateral support Feel: correlation analysis was conducted between the two types of subjective evaluations for each seat's backrest fit (the width direction). The two types refer to a preference-type and analytical-type (Figure 3). The correlation between the two types of evaluations indicates that a better backrest fit is more favorable. Figure 4 shows the relationship between the backrest fit and the backrest contact area. Figure 5 shows the relationship between the backrest fit and the average pressure. The correlation coefficients for both the backrest contact area and the average pressure were low and not statistically significant.

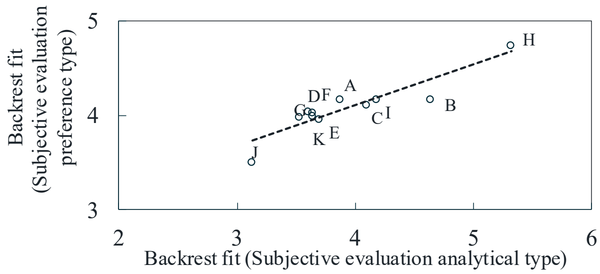

Fig.3 Backrest fit Evaluation Results

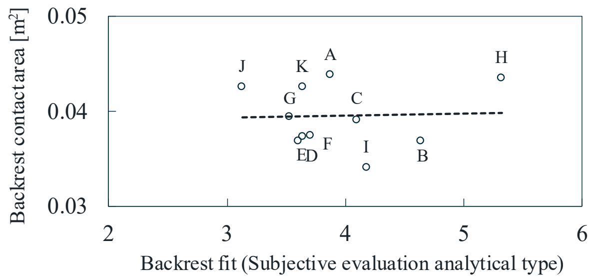

Fig.4 Backrest fit and Contact area

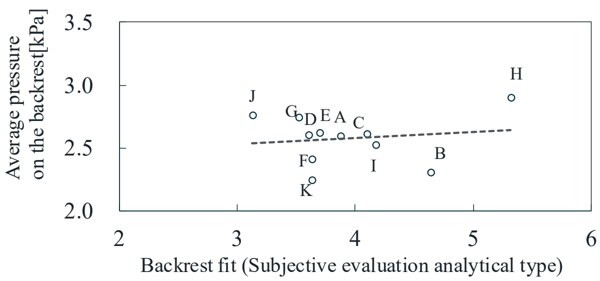

Fig.5 Backrest fit and average pressure

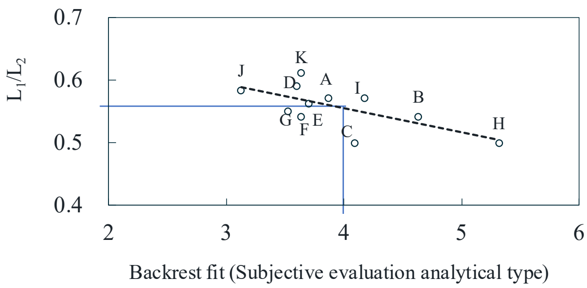

Fig.6 Backrest fit and L_1/L_2

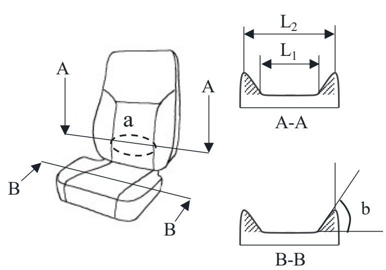

Fig.7 Positions on the seat

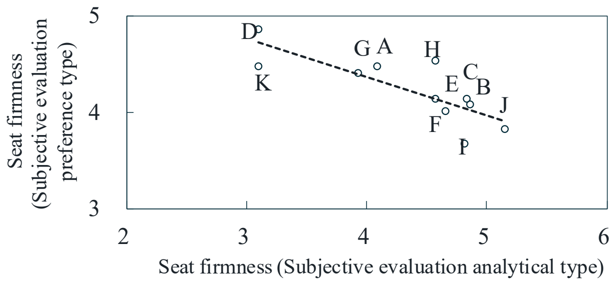

Fig.8 Evaluation results of seat firmness

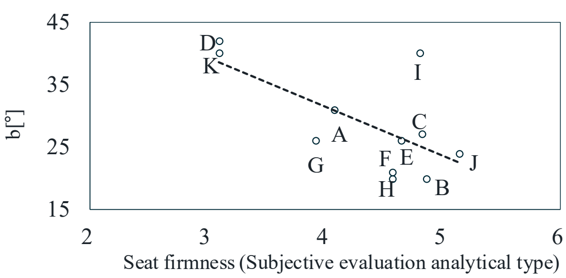

Fig.9 Seat firmness and angle b

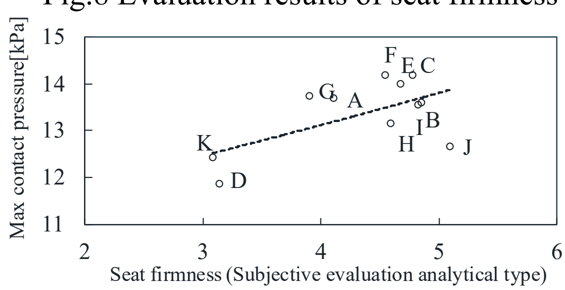

Fig.10 Seat firmness and max pressure

On the other hand, Figure 6 shows the relationship between the evaluation of the intensity of seating comfort characteristics and the ratio of the backrest seat width L_1 to L_2. As the fit improves, the ratio of backrest seat width L_1 to L2 decreases (correlation coefficient: 0.61).

Cushion Feel: Figure 8 shows the relationship between analytical type and preference type evaluations of seat firmness. It was found that softer seat cushions tend to be preferred. Correlation analysis between seat dimensions and perceived firmness indicated a strong negative correlation with the side support angle (Figure 9). As the side support angle of the seat cushion decreases and the seat becomes flatter, it tends to be perceived as firmer.

Discussion

At construction sites, the operator's operating posture in the hydraulic excavator tends to lean forward to excavate the ground in front of the machine. As a result, the operator does not lean their body against the entire backrest of the seat. The pressure distribution is such that the body is supported only by the low area of the backrest labeled "a" in Figure 7. Since the operator's operating posture remained the same for each seat and there were no differences in the contact area, it is considered that there is no correlation with the backrest fit. On the other hand, the correlation was found with the backrest seat width, L_1/L_2. As L_1/L_2 decreases, the hatched area of the seat shown in the A-A section of Figure 7 becomes wider in the width direction. As the hatched area becomes wider, it better conforms to the horizontal shape of back. This likely explains why the correlation between L_1/L_2 and backrest fit was higher than other measured values. However, if L_2 is made too wide, the seat may interfere with the operator's arms during excavator operation, potentially making it more difficult to control the machine. Enhancing backrest fits based on the L_1/L_2 ratio while also considering operability during machine operation should improve excavator seating comfort. Additionally, based on Figure 5 and Figure 6, it is suggested that to design a seat that provides a favorable fit with a positive rating, the seat should be shaped with an L_1/L_2 ratio of 0.56 or less. We will continue with more detailed analysis going forward.

The seat cushion tends to feel firmer as the seat surface becomes flatter. Flat and perceived firm seats tend to show higher maximum pressure (Figure 10), It is considered that there is a correlation between pressure distribution and subjective evaluation (correlation coefficient: 0.60). However, it is considered that the perceived characteristics of the seat cushion are significantly influenced not only by its shape, but also by its deflection and material hardness. Therefore, it will be necessary to examine the correlation between seat cushion deflection under load and subjective evaluations.

In future research, correlation analyses between subjective evaluations and seat characteristics will be further conducted for other factors that affect seating comfort, such as Seat dimension Feel, Seat lateral support Feel, Lumbar support Feel, and Backrest height Feel. It is considered that this will allow for the quantitative establishment of design indicators that influence seating comfort.

Conclusion

The seating comfort of construction vehicle seats was quantified using subjective evaluations, pressure distribution, and seat dimensions, leading to the following findings:

Backrest lateral support feel: The backrest fit, quantifiable through the characteristics of backrest width.

Cushion feel: The perceived cushion firmness is quantifiable using the side support angle of the seat cushion. However, it is necessary to examine correlations with other seat characteristics such as deflection under load.

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Sitting in Motion Evaluation of sitting devices by COP-Extent

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ABSTRACT

Within the context of an inactive lifestyle, prolonged sitting is identified as a primary cause. Sedentary behavior describes a lack of movement in people, which leads to a disruption of natural, physiological body processes due to insufficient physical exposure to gravity. For this reason, wherever activities demand long-term sitting postures, every sitting device should have the functional property of providing the benefit of natural freedom to move to the person sitting on it. In the pursuit of Sitting in Motion, design principles were first operationalized in an objective and reproducible manner within the human-centered design process. This aimed to determine functional properties for Sitting in Motion —conceived as a diametrically opposed solution towards freedom of movement as the optimum. A sitting device representing such a design solution embodies functional properties offering the benefit of movement freedom. Its existence (tertium non datur) and extent can be examined and optimized applying the principle of cause and effect. An evaluation methodology leads towards the possibility of targeted optimization of the functional property during its iterative development process. This research was conducted as a case study applied to the domain of commercial vehicle operation, where the truck driver’s workplace represents a prolonged, fixed sitting position throughout the driving task. This context provided the framework for the methodological examination of the functional properties for Sitting in Motion, evaluated as transferable design principles.

KEYWORDS

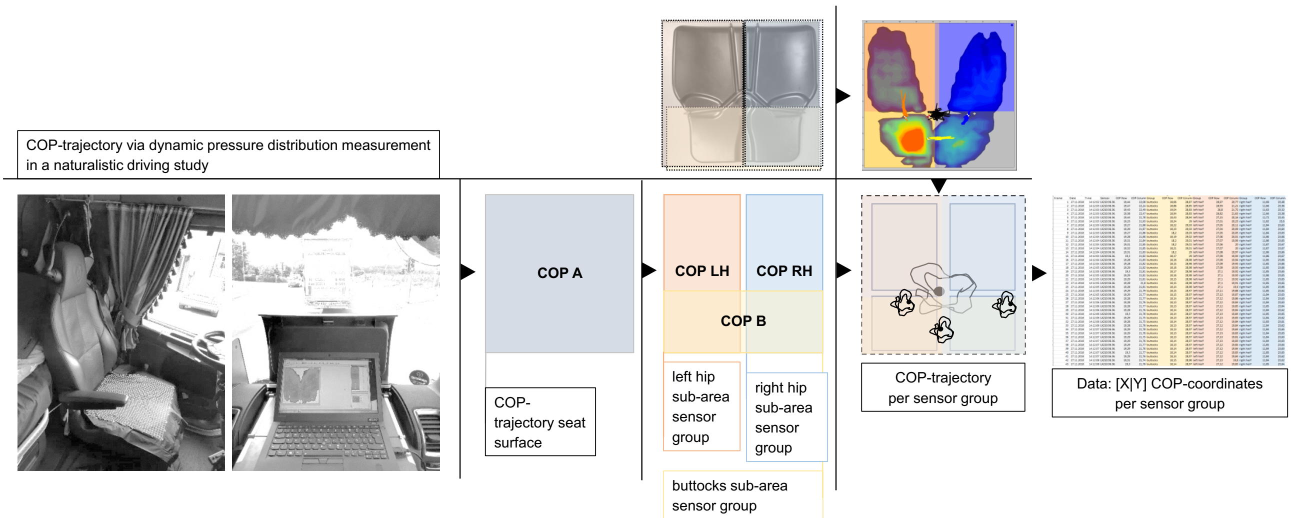
Sitting in Motion, COP-Extent, Truck Seat

Introduction

“Internally, your body is constantly in motion-if it ever stopped, you’d be dead. Indeed, you might say that the human body is designed to be a perpetual motion machine”(Vernikos, 2011). Guided by this perspective a prototype of a kinematic seating module for a truck driver seat was created within the human-centered design process (ISO 9241-210, 2019). The design solution aims to offer the benefit of natural movement within the context of the driving task. According to sensomotoric ability (driver's natural ability to move) the contact surface, support surface and its flexible attachment were defined for the horizontal seating surface with functional constructive freedom of movement based on functional anatomy and anthropometric data (Gordon, 1999; Schünke et al., 2007). The parameters were dimensioned in shape, material and constructive outcome. A seating device with the property of a functionality for Sitting in Motion offers the driver the benefits of natural freedom of movement. Below the waist there are at least four degrees of freedom to move (Branton, 1969). Action is provided by the sitter while a functionality of a sitting device accommodates this active behavior due to criticizable design parameters (Pynt, 2015). The assessment of the functional property of the seating device shall be evaluated by monitoring moving behavior over time with: dynamic pressure distribution measurement (Fenety et al., 2000). Data analysis focuses on typology of recorded center of pressure (COP) -trajectory (Marenzi et al., 2014) interpreted as postural sway fluctuation (Schubert, 2014).

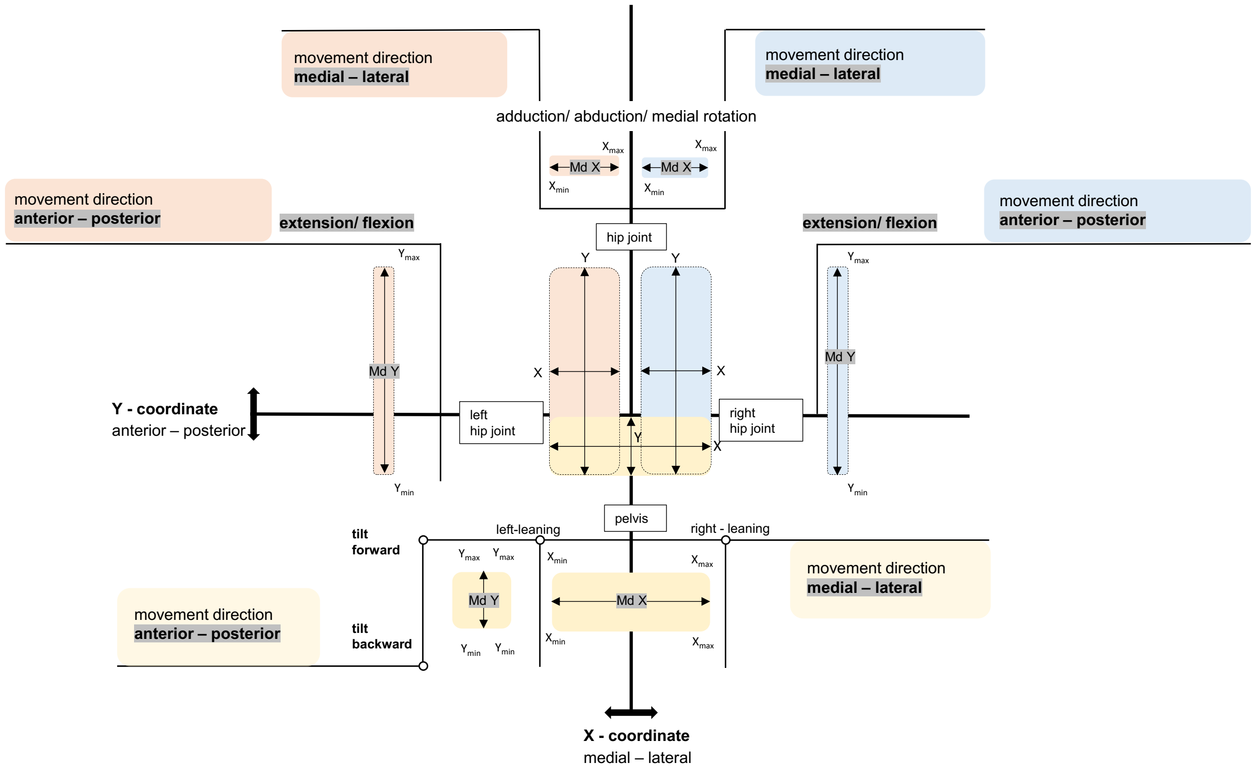
Method

As movement emerges from the interaction between individual, task and environment (Shumway-Cook et al., 2023) the context parameter is proceeded within a naturalistic driving study. Sitting in Motion is observed as a physical parameter recorded as the course of the COP over time using a pressure distribution measuring mat (XSENSOR). The experimental set up involved placing the sensor mat directly on the seating surface. Three participants (n = 3)—one 50th percentile female and two 95th percentile males, selected according to anthropometric distribution—performed the driving task in public traffic over a period ranging from 1.5 to 3 hours. There were no further constraints regarding route or distance. Driving session were performed four times – respectively two sessions on each different seat surface. The experimenter was positioned in the co-driver seat, overseeing the measurement procedure. The seating surface is the independent variable manipulating the driver's movement behavior as dependent variable caused by its functional properties. The COP-trajectory is recorded and represents the seating surface as one area. The COP-trajectory of a dynamic pressure distribution measurement will sum up the range of overall movement performed by a driver on the horizontal sitting surface. Data exploration is related to the human-centered design process of the kinematic truck seat module. Because the functionality for Sitting in Motion is designed according to functional anatomy the measured area (COP A) is divided into three sub areas identified as three individual sensor groups representing the COP-trajectory of: buttocks (COP B); left hip (COP LH) and right hip (COP RH). Datasets of each sensor group are exported as CVS files containing measured values as local position data within the coordinate system of the pressure sensor mat [X|Y] unitless.



Functional anatomical and anthropometric designed kinematic truck seat module following the driver's intuitive and individual movement behavior with projection of sensor groups visualized by dynamic pressure distribution measurement via COP-trajectory.

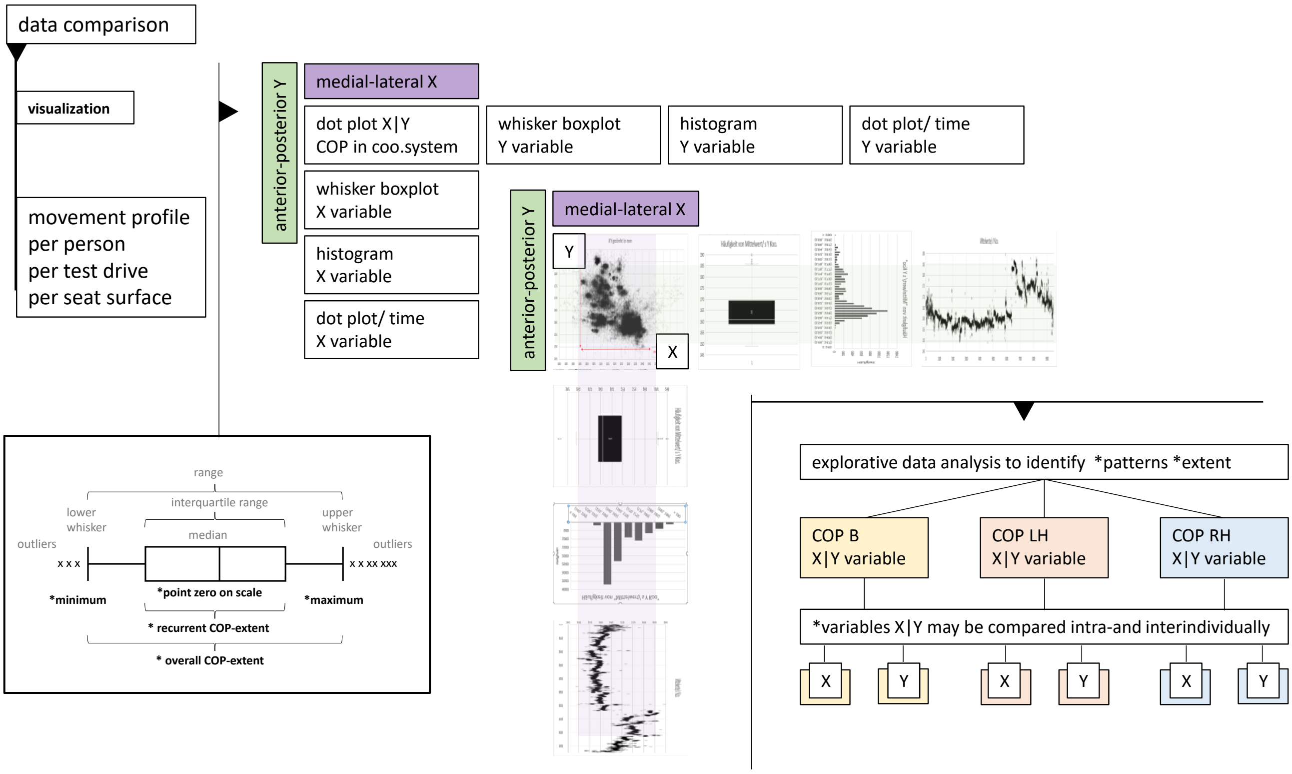
Moving on setting up a methodology to analyze the three sub areas' COP-trajectories, the two-dimensional data sets of the COP-coordinates [X|Y] are divided into their one-dimensional parameters [X] and [Y] to name axis movement according to joint movement possibility. This allows a specific analysis of the medial-lateral and anterior-posterior extent of overall movement during a driving period according to functional anatomy. Data modification goes on with this classification to achieve comparable variables. The recorded data is translated into information data on a metric scale in Millimeters [mm]. After converting the measured values into [mm], the data set will be condensed to means per second according to recorded frequency (8Hz = mean of 8 following values = one value per second). Then the median of each time series is calculated to normalize the data sets median to a zero-reference point on a scale within a coordinate system in [mm]. Through this transformation, the data set was prepared for comparable evaluation by robust descriptive statistical values, enabling quantification of movement range—referred to here as COP-Extent—along functional anatomy taking into consideration pelvis and hip joints and their movement axes on the seat surface.



Robust descriptive statistics according to interpretation of range of motion derived from functional anatomy – direction of movement according to identified joints projected on the horizontal seat surface.

Results

The data sets recorded during the experimental sessions were subjected to descriptive statistical evaluation and interpreted as a COP-Extent to be defined as [range of motion] over time in [mm] of IQR and ΔWHISKER of the one-dimensional COP parameters [X] and [Y] of COP B, COP LH and COP RH to achieve intra- and interindividual comparable variables. Through this approach, objectivity was established in quantifying movement behavior as response of varying seating properties. The data derived from the kinematic truck seat module - designed for the benefit of movement - were compared against those from a conventional series production seat, which provides no intended functionality for freedom of movement. Data comparison may start with the visualization of each recorded COP-trajectory stating a movement over time per test person (dependent variable) on a seat device (independent variable). Starting off with a dot plot diagram of [X] and [Y] coordinates in the coordinate system, this information is enriched with whisker boxplot, histogram and dot plot/ over time diagrams – following the movement directions defined according to functional anatomy. Therefore, the data set for [Y] axis movement extent will be read from left to right and data set for [X] movement extent will be read from top to bottom. This bidirectional, statistical visualization strategy enables a comprehensive overview of COP-Extent patterns at first glance. An exploratory data analysis may be performed within the time series to identify patterns and extent for the variables [X] and [Y] for each sensor group to be compared intra- and interindividually. This enables the interpretation of Sitting in Motion not merely as a static parameter, but as an emergent expression of continuous behavioral dynamics under the influence of design-specific functionality.



Visualization of the calculated one-dimensional COP parameters [X] and [Y] in [mm] as comparable descriptive statistical, independent, time series variables.

Conclusion

An evaluation methodology for Sitting in Motion defines the human (biological system) identified with the ability to move and a functional anatomically and anthropometrically existence as dependent variable. The independent variable is the sitting device (technical artifact) that offers (or not) a functional property for Sitting in Motion which can be optimized within its iterative development process manipulating form, material and construction. Evaluating sitting devices by applying COP-Extent [IQR and ΔWHISKER of the one-dimensional COP-parameters [X] and [Y] of COP B, COP LH and COP RH] may therefore inform about the effect of manipulation comparing data with a repetition in measurement. The design/ engineering strategy is adapted to the result and freedom of movement is optimized as manipulation to achieve a level of movement that describes a desired value within the context of principle of cause and effect. A reasoned decision regarding the validity or invalidity of hypotheses may be made based on the observations obtained from this evaluation methodology which conducts a statistical hypothesis test. For a statistical hypothesis test, the data points are understood as magnitudes of difference. The process requires prior hypothesis formulation, an appropriate experimental design, and valid statistical testing procedures. In this sense, Sitting in Motion becomes not merely a conceptual approach, but a testable, design-relevant parameter within the technical development of seating solutions.

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Comparing the vibration protection of five different driver seats in a light-duty van

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ABSTRACT

Occupational operation of vehicles and exposure to whole body vibration (WBV) have been strongly associated with musculoskeletal disorders, predominantly low back pain. Due to height limitations in the vehicle cab, most light-duty vehicles are supplied with static, suspension-less seats. These vehicles, due to transporting heavier loads, often have stiffer suspensions, and as a result, also have higher WBV exposures. In these vehicles, vehicle operators may benefit from low-profile seats with mechanical or air-ride suspensions. Currently, information on the performance of different types of seats in light-duty vehicles is limited, so the objective of this study was to compare the WBV performance of four different light-duty vehicle seats. A 77kg driver drove a light-duty van over a 19 km standardized route in Seattle, Washington. The route contained four different road types: 1) city streets, 2) cobblestone roads, 3) freeways, and 4) a short route with the broad speed humps and short, sharp speed bumps. Five seats were evaluated in the light-duty van, including: 1) a static, suspension-less seat, 2) two conventionally designed a low-profile air-seats, and 3) two low-profile air-ride seats with an alternative suspension deign. Vehicle location and speed were acquired with a GPS logger (1 Hz), and Vibration (1,280 Hz) was continuously measured at the vehicle floor and seat top. Over the whole route, the Seat Effective Amplitude Transmissibility (SEAT) values and time to reach EU action limits were compared across the seats. On the short route with the broad speed humps and short, sharp speed bumps; the static suspension-less seat had the lowest SEAT values and all of the air-ride seats had SEAT values above 100% indicating the seats amplified the exposures. In addition, the performance of the static, suspension-less seat was not that different than the performance of the conventionally designed air-ride seats. However, with the exception of the route containing the speed bumps and speed hump, the performance of the alternatively designed air-ride seats exceeded the performance of the other seats tested, and typically increased the time to reach EU vibration action limits by at least 50%. These results indicate that differences in seat design play a critical role in static, suspension-less and air-ride seat performance. An upcoming and ongoing study at the University of British Columbia will be testing these seats in actual field settings and measuring both seat occupant comfort and seat occupant vibration.

KEYWORDS

Whole Body Vibration, Comfort, SEAT, Transmission

Introduction

Occupational operation of vehicles and exposure to whole body vibration (WBV) has been strongly associated with musculoskeletal disorders, predominantly sciatica and low back pain (Burstrom et, al., 2015). Due to the limited height in the vehicle cab, most light-duty vehicles are supplied with static suspension-less seats. These vehicles, which are designed to transport heavier loads, have stiffer suspensions, and as a result, also have higher whole body vibration (WBV) exposures (Blood et al., 2011). In these stiffer-riding vehicles, vehicle operators may benefit from low-profile suspended seats. Currently, there is a limited amount of research on seat performance in light-duty vehicles, so the objective of this study was to compare the WBV performance of a suspension-less seat and four low-profile air-ride seats.

Method

A 77kg driver drove a light-duty Mercedes Sprinter van over a 19 km standardized route in Seattle, Washington. The standardized route contained five road types: 1) city streets, 2) cobblestone roads, 3) freeways, 4) 1m wide short, sharp speed bumps, and 5) 3m wide long, broad speed humps. Five seats were selected to be evaluated in the light-duty Sprinter van, an aftermarket static, suspension-less seat (Static Seat-1), and four low-profile air-ride seats with suspension resting heights ranging between 10 - 12 cm high when the driver sitting in the seat (AirRide-Seat2, AirRide-Seat3, AirRide-Seat4, AirRide-Seat4-T). AirRide-Seat2 and AirRide-Seat3 were low-profile seats that were commercially sold in North America, and AirRide-Seat4 and AirRide-Seat4-T were prototype seats that had a functionally different design and were made by a company called Suspension Systems Technologies (Seattle, WA, USA). The difference between AirRide-Seat4 and AirRide-Seat4-T was that and AirRide-Seat4-T had a 1 liter auxiliary air tank which supplemented the volume of the suspension’s air-spring, and lowered the suspension's resonance.

Vehicle location and speed were acquired with a GPS logger (1 Hz), and z-axis vertical vibration (1,280 Hz) was continuously measured at the vehicle floor and seat top. Over the whole route, the weighted vibration and Vibration Dose Value at the seat and floor, the Seat Effective Amplitude Transmissibility (ratio of the seat and floor-measured vibration), and the time to reach EU daily vibration action limits were calculated.

Results

As shown in Table 1, after driving over the whole 19 km route at roughly the same speed, there were larger differences across the seats in the continuous, cyclical A(8) exposures compared to the cumulative, impulsive VDV(8) exposures. The alternatively designed air-ride seat with the auxiliary air tank (AirRide-Seat4-T) had the lowest exposures, SEAT values, and the longest time to reach EU daily vibration action limits, followed by the alternatively designed air-ride seat without the auxiliary air tank (AirRide-Seat4). In contrast, the exposures in the static seat (Static-Seat1) and the two other conventionally designed air-ride seats (AirRide-Seat2 and AirRide-Seat3) had higher seat-measured exposures, SEAT values, and shorter durations of time to reach EU daily vibration action limits.

Table 1 –Comparisons across seats in z-axis A(8) and VDV(8) exposures, SEAT values, vehicle operation time to reach EU Daily Vibration Action Limits (DVAL Time), and vehicle speed over the whole route .

	A(8)				VDV(8)				
	Floor (m/s^2)	Seat (m/s^2)	SEAT	DVAL Time	Floor (m/s^2)	Seat (m/s^2)	SEAT	DVAL Time	Speed
Static-Seat1	0.51	0.48	95%	8.6 hrs	12.5	11.6	92%	3.0 hrs	27.5
AirRide-Seat2	0.50	0.50	100%	8.1 hrs	12.3	11.6	94%	3.0 hrs	28.0
AirRide-Seat3	0.54	0.47	87%	9.0 hrs	13.5	10.9	81%	3.9 hrs	26.9
AirRide-Seat4	0.52	0.40	75%	12.7 hrs	12.4	10.5	84%	4.5 hrs	30.4
AirRide-Seat4-T	0.52	0.35	67%	16.3 hrs	12.5	9.0	72%	8.0 hrs	29.2

Table 2 – Comparisons across seats in z-axis A(8) and VDV(8) exposures, SEAT values, vehicle operation time to reach EU Daily Vibration Action Limits (DVAL Time), and vehicle speed when driving over the cobblestone roads.

	A(8)				VDV(8)				
	Floor (m/s^2)	Seat (m/s^2)	SEAT	DVAL Time	Floor (m/s^2)	Seat (m/s^2)	SEAT	DVAL Time	Speed
Static-Seat1	1.14	1.10	96%	1.7 hrs	22.0	20.4	93%	0.3 hrs	16.5
AirRide-Seat2	1.30	1.00	77%	2.0 hrs	24.8	18.1	73%	0.5 hrs	17.3
AirRide-Seat3	1.22	1.05	86%	1.8 hrs	23.6	20.1	85%	0.3 hrs	17.4
AirRide-Seat4	1.05	0.61	58%	5.4 hrs	19.1	10.6	55%	4.4 hrs	18.3
AirRide-Seat4-T	1.14	0.60	53%	5.6 hrs	21.6	11.0	51%	3.8 hrs	17.2

Table 3 – Comparisons across seats in z-axis A(8) and VDV(8) exposures, SEAT values, vehicle operation time to reach EU Daily Vibration Action Limits (DVAL Time), and vehicle speed when driving on the freeways.

	A(8)				VDV(8)				
	Floor (m/s^2)	Seat (m/s^2)	SEAT	DVAL Time	Floor (m/s^2)	Seat (m/s^2)	SEAT	DVAL Time	Speed
Static-Seat1	0.53	0.51	96%	7.7 hrs	11.4	10.5	92%	4.5 hrs	95.8
AirRide-Seat2	0.54	0.45	83%	9.9 hrs	11.0	8.4	76%	11.1 hrs	89.5
AirRide-Seat3	0.51	0.45	88%	9.9 hrs	11.4	9.4	82%	7.1 hrs	89.2
AirRide-Seat4	0.45	0.32	71%	19.5 hrs	9.4	5.7	61%	52.2 hrs	84.7
AirRide-Seat4-T	0.48	0.31	65%	20.8 hrs	11.0	5.9	54%	45.5 hrs	74.6

Table 4 – Comparisons across seats in z-axis A(8) and VDV(8) exposures, SEAT values, vehicle operation time to reach EU Daily Vibration Action Limits (DVAL Time), and vehicle speed when driving over the route with the speed bumps and speed humps.

	A(8)				VDV(8)				
	Floor (m/s^2)	Seat (m/s^2)	SEAT	DVAL Time	Floor (m/s^2)	Seat (m/s^2)	SEAT	DVAL Time	Speed
Static-Seat1	0.54	0.55	102%	6.6 hrs	12.9	12.8	99%	2.1 hrs	22.2
AirRide-Seat2	0.42	0.47	112%	9.1 hrs	11.7	13.5	115%	1.7 hrs	21.8
AirRide-Seat3	0.53	0.61	115%	5.4 hrs	13.2	16.3	123%	0.8 hrs	21.0
AirRide-Seat4	0.52	0.61	117%	5.4 hrs	12.6	16.9	134%	0.7 hrs	23.7
AirRide-Seat4-T	0.43	0.46	107%	9.5 hrs	11.4	13.4	118%	1.7 hrs	21.7

Tables 2 and 3 show the vibration exposure results from the roughest and smoothest roads respectively, the cobblestone roads and the freeways. Here again, the alternatively designed air-ride seats with and without the auxiliary air tank (AirRide-Seat4 and AirRide-Seat4-T) had the lowest exposures, SEAT values, and the longest time to reach EU daily vibration action limits. Again, in contrast, the exposures in the static seat (Static-Seat1) and the two other conventionally designed air-ride seats (AirRide-Seat2 and AirRide-Seat3) had higher seat-measured exposures, SEAT values, and shorter durations of time to reach EU daily vibration action limits.

Finally, Table 4 shows the vibration exposure results from driving over the route with the broad speed humps and short, sharp speed bumps. The static suspension-less seat had the lowest SEAT values, and all of the air-ride seats had SEAT values above 100%, indicating the air-ride seats amplified the exposures.

Impact

When vibration exposures were averaged over the whole route, the performance of the static, suspension-less seat was not that different than the performance of the conventionally designed air-ride seats. However, with the exception of the route containing the speed bumps and speed humps, the performance of the alternatively designed air-ride seats exceeded the performance of the other seats tested, and typically increased the time to reach EU vibration action limits by at least 50%. One very important limitation was that on the road segment with the speed bumps and speed humps, only one fixed, and relatively fast speed was tested, and the seat performance on the speed bumps and speed is very likely to be speed-dependent.

The largest performance differences were measured on the cobble stone roads and freeways. Although not demonstrated or shown with the current results and analysis methods, the large performance differences were likely predominantly due to differences in suspension friction and function. The conventionally designed air-ride seats had dampers that applied a constant force to the seat occupant during seat operation (linear suspension dynamics) whereas the alternative designed seat's damper proportionally increased the force applied to the seat as the seat compressed (active-like, non-linear suspension dynamics). The net result of the design differences was the alternative suspension could use a damper with less damping which reduced both the static and viscous friction of the damper and suspension during operation. This important design difference manifested itself with the substantially superior performance difference on the cobblestone roads and city streets.

Finally, the auxiliary tank, which was added to one of the alternative suspensions, improves suspension performance over the whole route and particularly on the road segment with the speed bumps and speed humps. The auxiliary tanks was designed to improve the suspension performance by reducing suspension resonance. These results indicate that differences in seat design play a critical role in seat performance. An upcoming and ongoing study at the University of British Columbia will be testing these seats in actual field settings and measuring both seat occupant comfort and seat occupant vibration.

Acknowledgments

Aspects of this study were previously presented at the 57^{th} UK Congress on Human Response to Vibration (Johnson et al., 2024).

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Three adaptive systems for Posture variation in a vehicle seat increasing comfort

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ABSTRACT:

This paper evaluates three innovative seat systems designed to encourage movement: 1) A system where the seat pan and backrest angles adjust dynamically, 2) A system where passengers control a game by lifting their legs and 3) a soft robotic module that inflates and deflates in response to pressure changes. Five experts compared these systems by interviewing the authors and discussing the outcomes of the interviews with the participants in the tests. All three systems demonstrated a positive impact on comfort or discomfort. However, interviews with participants revealed a preference for having control over the system. This suggests that systems allowing user interaction, such as playing a game or customizing pressure settings, may be the most desirable.

KEYWORDS

Seat, posture variation, comfort, in seat movement, control

Introduction

A growing number of scientists in the field of ergonomics are of the opinion that it is more important to vary posture (and avoid the static postures) than to design seating for the ideal posture (e.g. Lamsal et al., 2023). To sit is to be physically inactive. According to Commissaris et al. (2014), physical inactivity is associated with cardiovascular disorders, type II diabetes, depression, obesity and some forms of cancer, with millions of people dying prematurely due to an inactive work style. Long periods of uninterrupted sitting while at work is one of the risk factors (Buckley et al., 2015). Other studies show the importance of small human body changes while sitting. For instance Dieën et al. (2001) analysed the effects of three dynamic office chairs on trunk kinematics, trunk extensor EMG, and spinal shrinkage. The results showed that trunk movement and back muscle activity (m. erector spinae EMG) were affected by the different office tasks performed. Spine length was significantly increased after working in a dynamic office chair compared with the same length of time spent in a static chair. While this variation can be achieved by a mechanism within the seat, alternating sitting and non-sitting activities seems to have effects as well. Sammonds et al. (2017) showed that walking had a positive effect on reducing discomfort in between two sitting periods. Kruithof et al. (2025) discuss in-chair movements (ICM) which can be considered as an indication for discomfort (e.g. Telfer et al., 2009; Maradei et al., 2015), but other studies have argued ICMs to be a tool to prevent discomfort, by exercising (e.g. Sammonds et al., 2017), mechanically moving seats (e.g. Tanoue et al., 2016), movement via a built-in massage system (e.g. Durkin, et al., 2006) or a moving lumbar support (e.g. Kolich et al., 2001).

With this in mind, it is interesting to consider the ways in which human body movement can be facilitated in an airplane or car seat. Of course, there are limitations attached to this in seat movement. When driving a car, for instance, it is unwise to move around too much as we need to pay attention to the traffic and in an aircraft seat moving too much might disturb the neighbors. Three innovations seemed to be potentially interesting to stimulate ISM. The effects of these innovations are already tested and described in the literature (Bouwens et al., 2018; Roozendaal et al., 2022 and Van Veen, 2016). However, it is the question how these systems would be appreciated.

Method

In this paper three seat systems that stimulate human movement are evaluated: a system where the seat pan and backrest angle change, a system where passengers control a game by lifting the legs while seated and a soft robotic seat that can inflate and deflate by sensing the pressure under the sitting bones.

In a session with five experts (in the field of soft robotics (1), ergonomics (2x), seat design (1) and seat moving systems (1)), the three systems are evaluated. Before the session all participants studied the three papers (Bouwens et al., 2018; Roozendaal et al., 2022 and Van Veen, 2016). In the session additional information was given by the authors of the three papers. These concerned mainly the interviews after the three experiments. Then a discussion started with pro and cons of each system and feasibility. In addition, the data of the interviews with the participants in the experiments were shared and discussed and documented.

Results

In the first system (system 1) the seat pan rotates from -1 to + 1 degrees and the back rest from 0 to + 1.5 degrees (backward). This was chosen after evaluating several angle changes. The main reason was that the middle mirror in the car could be used without disturbance (see figure 1).

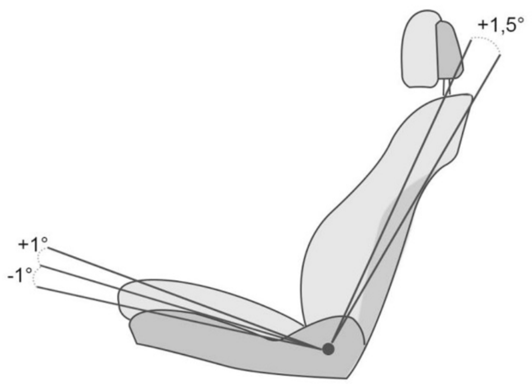

Figure 1: The variation in seat pan angle and backrest angle applied by Veen (2016). Positive effects on comfort were observed compared with a static seat that was identical in form.

A test with 21 participants showed that comfort and support were significantly better in the dynamic configuration, with participants feeling notably more active, energetic, stimulated, pleasantly surprised, pleased, comfortable, accepting and calm. The static configuration, conversely, left participants feeling marginally more tired and significantly more bored.

In the second (system 2) experiment 12 participants were sitting two times 3.5 hour in an aircraft seat. Six participants started by 3.5 hour sitting and playing the game every half hour and the other six participants started in a the static situation (see figure 2).

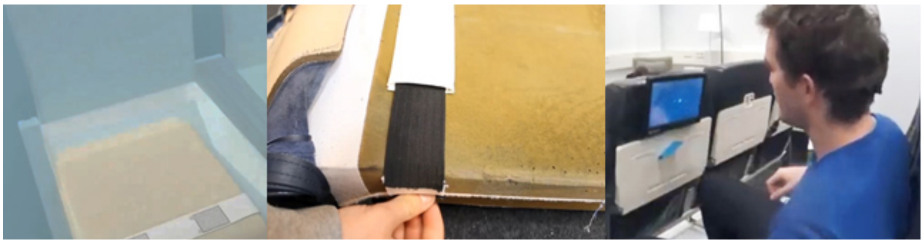

Figure 2: Left: the position of the game sensors (under each leg one sensor) in an aircraft seat. Middle: placing the sensor under the upholstery. Right: a participant lifting right leg (Bouwens et al., 2018).

A ball could be steered, lifting the right leg the ball goes to the left and lifting left leg the ball goes to the right. Lifting both legs the ball goes forward. Playing the game every half hour increased the comfort significantly compared with static sitting (n=12).

The third system (system 3) is a softrobotic system and has a pneumatic actuation and embedded sensors, the module is able to change its shape and stiffness (Roozendaal et al. 2022). Two modules were placed in a seat pan under the sitting bones (see figure 3). The modules having the same hardness as the rest of the seat and the modules fully blown had a higher discomfort than the modules having the hardness determined by the end user.

Figure 3: Left: the position of both soft robotic modules. Right: a participant evaluating the seat pan (Roozendaal et al., 2022).

In the session evaluating the systems the most mentioned advantage of system 1 was that in car seats where electrical systems that adjust the seat pan and back rest, it is easy to implement and it creates comfort without being aware of the slow movement in the seat. However, the fact that sometimes occupants were not aware of the system was also seen as a disadvantage. Occupants might feel insecure because something happens what they are not aware of.
The most mentioned advantage for the aircraft seat (system 2) was that participants experienced it as fun to do the activity especially compared with the card in the seat pocket which is now in some aircraft seats with exercise instructions. Still the question remained whether neighbours will not be disturbed by the active person.

For the third system the advantage was that occupants are in control and can even determine the pressure in the bladder and it might even vary when occupants are too long in one posture, which was seen as a good point. The disadvantage of the third system was that it still is rather complex to implement and the robustness needs additional testing. This was for all three systems an issue. The experts mentioned that all systems are tested in the lab (system 1 driving simulator; system 2: in aircraft seats in a lab; system 3: also in the lab). How it will work under real live conditions certainly needs to be studied. Regarding the expert preference, it was clear that participants prefer to be in control and therefore system 2 and 3 are preferred as it looks as if occupants are being in control. System 2 has the advantage that occupants themselves make the movement and experience it as a fun thing to do, while in the other cases the seats makes you move. It is to be discussed whether this is a real disadvantage.

Discussion

All three systems seem to have positive effects on comfort. This makes sense as other studies also show that variation of posture has positive effects on the comfort perception (Lueder, 2004; Dieen et al., 2001). All three systems are tested in the laboratory, which implicates that further long term testing in the field is still needed. Also, robustness needs to be tested in all systems. The most feasible options seem system 1 (changing angles) and system 2 (gaming) as they can be implemented without too much effort. If the car has a system for electrically changing the seat pan and back rest an algorithm should be added based on the experiment of Veen (2016). For the aircraft seat the two sensors needed for steering the game can be placed under the upholstery and Wi-Fi connected to the games, which seems rather simple.
In interviews after the experiments the participants mentioned that they preferred to have control, indicating that the system where participants play the game and choose the pressure themselves might be preferable. This being in control has been described before as well by Vink (2023). But also in other areas this being in control is seen as important. Moertl et al. (2021) for instance, describes that personal control over heating allowed for lower optimal temperatures than without such control.

Acknowledgements

The authors would like to acknowledge the support of BMW for performing this research.

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A preliminary investigation of preferred backrest shape

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ABSTRACT

Due to large variability in anthropometric dimensions of user population, the design of one seat for all is challenging, especially for the seats used in transport. To investigate the variation in preferred seat parameters among user population, we built a reconfigurable experimental seat at Gustave Eiffel University (Univ-Eiffel). More recently, a new backrest system composed of 263 hydraulic cylinders was built, capable of 1) controlling the contact pressure distribution on the backrest by varying the geometry of the contact surface, and 2) measuring the contact force distribution and the geometry of the corresponding backrest surface. The present study aims to present a preliminary study to investigate the preferred backrest shape in an upright and reclined condition to meet the current interest in relaxing and sleeping activity during travel. The preferred backrest shapes obtained from 28 participants were analyzed using PCA to investigate their main variation trends.

KEYWORDS

Comfort, Seat, Backrest shape, Reconfigurable seat

Introduction

People travel by train, car, airplane and other transportation means for work and leisure. The seat, in direct physical contact with the human body, plays a key role in their comfort experience during travel. Due to large variability in anthropometric dimensions of seat user population, the design of one seat for all is challenging especially for the seats used in transport. Despite many studies on seat comfort/discomfort, quantitative specifications or digital tools for seat design are still lacking. This is supported by a review by Hiemstra-van Mastrigt et al. (2017). One reason is that seating comfort/discomfort depends on many factors such as anthropometry, posture, seat geometry, material property, sitting time, activity, etc., and their interactions. As most existing studies have been carried out using a real seat or an experimental seat with a very limited number of variable parameters, it is difficult to isolate the effects of a seat parameter and to investigate its interaction with other parameters.

In recent years, with help of a reconfigurable experimental seat including an adjustable seat pan surface with 52 cylinders, the preferred seat geometries self-selected by sitters when varying some seat design parameters such as seat back and seat pan angles were investigated (Wang et al., 2019). The pre-shaped foam support based on an optimal seat pan surfaces obtained experimentally improved comfort experience and reduced the foam quantity (Wang et al., 2021). More recently, an adjustable backrest surface composed of 263 hydraulic cylinders was built allowing the investigation of backrest comfort (Wang and Beurier, 2025). In this work, an experiment was carried out to investigate the sensitivity of pressure variation and preferred backrest shape for both upright and reclined seating conditions to meet the current interest in relaxing and sleeping activity during travel. The objective of this paper is to present the preliminary results concerning the preferred back shapes.

Method

Participants. Twenty-eight males and females, ranging from 159 to 180 cm in height and 19 to 33 kg/m² in BMI (Body Mass Index), participated in the study.

Reconfigurable seat. The Univ-Eiffel's reconfigurable experimental seat with the new backrest composed of 263 cylinders was used (Figure 1). As the study was focused on backrest comfort, a seat pan of an existing eco-class airplane seat was used and fixed on the seat pan support of the experimental seat. The seat pan and seat back were positioned so that PRC, the position of rotation axis of the backrest, was the same as the seat H-point measured by SAE H-point Machine (SAE J4002-2010) when all backrest cylinders were at their zero position. To adjust backrest shape, participants could select or deselect one cylinder, or the cylinders of one row and all cylinders via the tactile screen of a tablet, and then adjust their height.

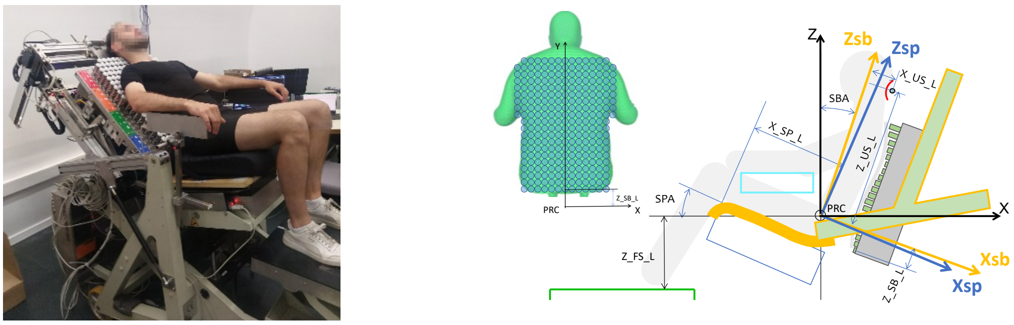


Figure 1. Experimental set-up showing a participant with a seat back angle of 50° and different seat parameters

Test procedure. Two seat configurations with 20 and 50 degrees seat back angles (SBA) from the vertical and a 15 degrees seat pan angle (SPA) were tested to represent an upright and reclined condition. The seat back height (Z_SB_L) was adjusted so that the shoulders of the participants fit within the backrest surface. The fore-aft seat pan position (X_SP_L) was also adjusted to have a two-finger distance between the popliteal fossa and the seat pan front. To shorten the backrest shape adjustment process, an initial shape was automatically obtained at first corresponding to a uniform distribution of contact forces among the 263 cylinders. For this, all cylinders were set at their zero position initially and the 'GO-OUT' command was used with the force thread (Fmax) of 0.5N and target height of 45 mm to move the cylinders to fit the back shape of a participant. A cylinder stops moving when the contact force is higher than Fmax or its position reaches its target height. From this initial backrest shape, a set of about 20 cylinders covering the right part of the whole contact surface was pre-selected. For each randomly selected cylinder, the experimenter moved it out until the participants felt its pushing to determine the pressure sensitivity map. After this part of pressure sensitivity study (approximately 60 minutes including breaks), participants were asked to modify the backrest shape according to their preference using three main commands: 'GO-OUT' to increase the pressure of a contact area, 'DISTRIBUTE' (by opening the valves of selected cylinders while maintaining the valve of the general circuit closed) or 'FREE' (by opening the valves of selected cylinders and the general circuit) to reduce local pressure peaks. Prior to self-adjustment, participants were instructed to use different commands.

Data processing and analysis. 10 trials among 56 (28 participants x 2 seat back angles) with an irregular backrest surface were discarded after visual check. In addition, if a cylinder had a difference in position higher than 40mm from its closest neighbors (4 at the most), its height was replaced by the mean height of its closest neighbors. A principal component analysis (PCA) was performed to inspect the main variation trends of preferred backrest shape. A backrest shape was characterized by the position of each cylinder in the local coordinate system of backrest cylinders (Figure 1).

Results

The main variations in preferred backrest shape along the first 4 principal components (PC), explaining more than 60% of variance, are shown in Figure 3 for both upright and reclined seating conditions. Compared to the reclined seating (SBA50), the upright seating (SBA20) (Figure 1Figure 2), has a smaller contact area on average due to lower contact force and a larger variation in the backrest vertical translation (Z_SB_L). By visual inspection, PC1 mainly represents the variation in contact area probably due to body size. The variation along PC2 is mainly located in the shoulder area including the upper arms, probably due to arm movement. PC3 and PC4 mainly represent variation in the lower back area, which can also be observed in PC1 and PC2. There is a variation in width, especially at the mid height, probably due to the waist to hip width ratio variation.

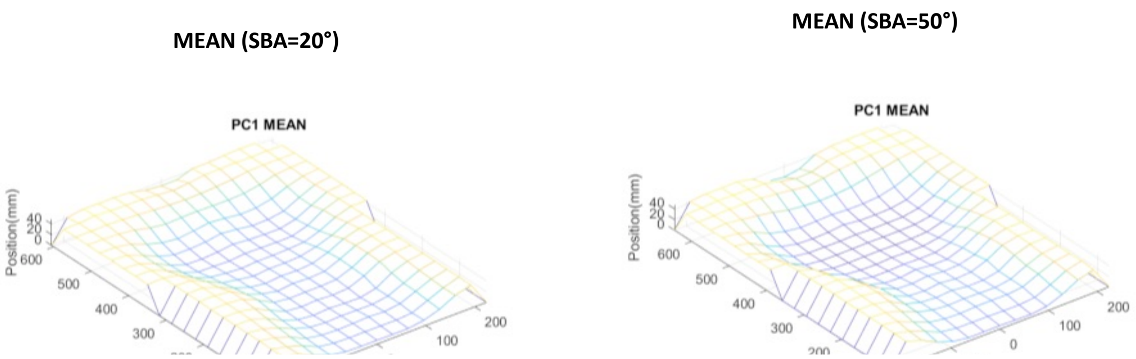
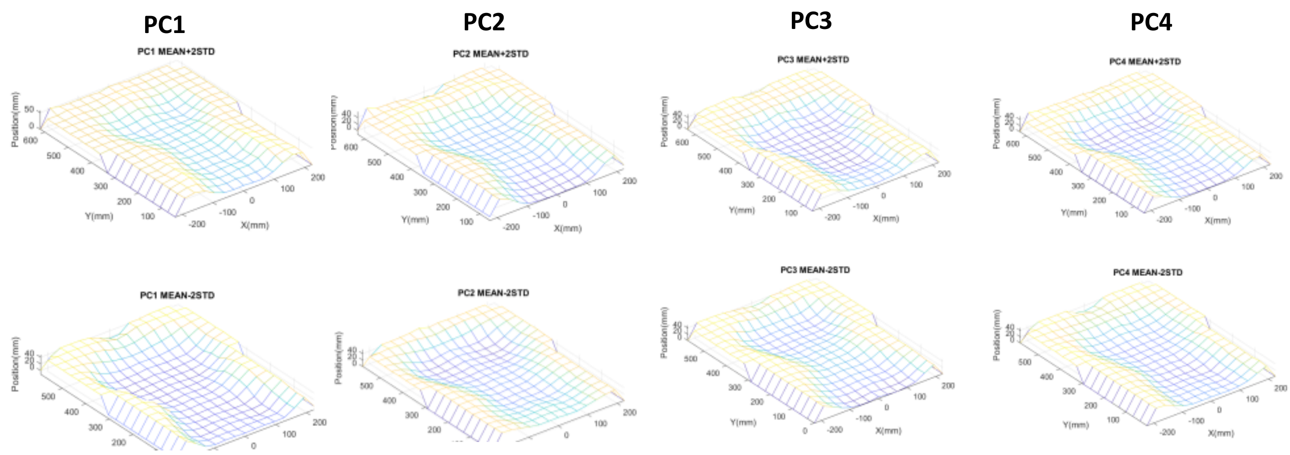
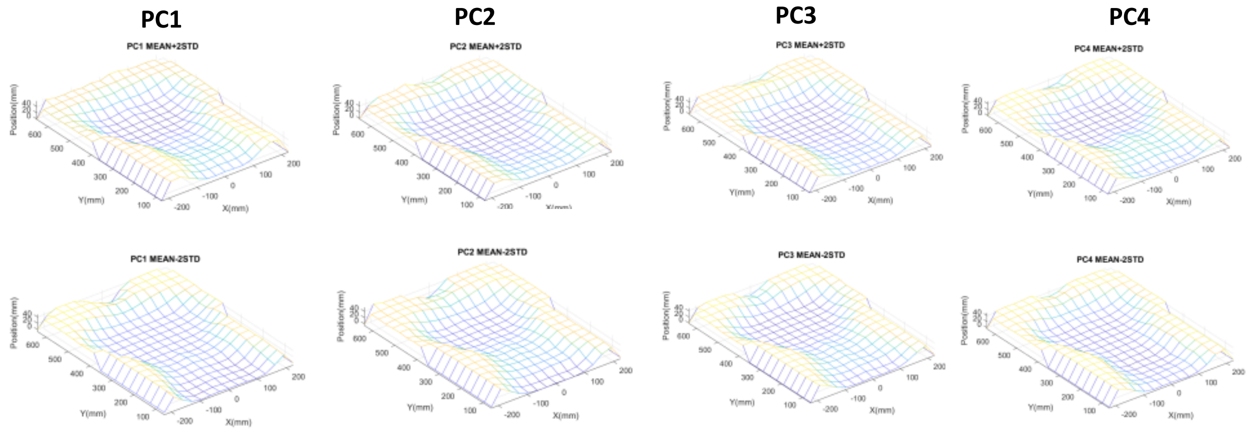


Figure 2. Mean preferred backrest shapes for both SBA20 (A) and SBA50 (B) seating conditions



(A) SBA=20°



(B) SBA=50°

Figure 3. Variation of preferred backrest shapes along the first 4 PCs ranging from mean score– 2 STD (Standard deviation) to mean score + 2 STD for both SBA20 (A) and SBA50 (B) seating conditions

Conclusion

The present study shows the main trends of variation in the preferred back shapes self-selected by 28 participants for both upright and reclined seating conditions. Apart from the variation related to body size change, the observed shape variation in the lower back area may suggest that a lumbar support adjustable in depth and height is required. Large variation in the upper backrest area could also be due to position variation of the upper arms, suggesting that the backrest should be shaped to accommodate the arm movements. As the surface formed by the cylinders is non-deformable, a slight postural variation can generate local pressure peaks especially in the scapular area due to very thin soft tissue covering the scapula. It turned out that participants could take much time to remove pressure peaks. An adjustment procedure should be suggested to better guide participants including exploring pressure variation in different contact areas (e.g., lumbar and neck), and to avoid an irregular contact surface. Further investigations are needed to include more participants of different body sizes and several activities to build parametric models of preferred backrest shapes.

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Comfort driven design of style-constrained seat

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ABSTRACT

The seat is one of the most important components of the car and performs multiple, often conflicting, functions; furthermore, it is the component with which the user mostly interacts while driving or being passenger. Therefore, the seat must provide the proper static support and lateral and longitudinal restraint during handling manoeuvres without compromising user comfort, regardless of percentile. The aim of the paper is to define a methodology that is able, by receiving as input the contact pressure distribution maps at the human-seat interface and the design constraints, to drive the generation of Class A surfaces that guarantee, not only a very appreciable aesthetic quality, but also, and above all, the higher right comfort to the user. The idea behind this work is based on the change of design paradigm that reverses the generative process, no longer based on the dictates of style, which constrains all following design-steps; in this work we propose to define a design flow that is guided by perceived comfort, appropriately evaluated on the basis of detected or simulated pressure profiles, and that, on the basis of the first findings can drive the stylists in the respect of the aesthetic/design tradition of the company. In summary, a design process is proposed that starts from the experimental pressure maps of an existing seat, analyses and verifies the most problematic areas, and consequently modifies the contact surface by generating a new geometry. In this recursive loop, the designer proposes new style sketches that will previously be verified by virtual models through pointwise modifications of the previously correlated FEM model. This new design approach was tested in a real Seat-development design process for evaluating comfort performance gaining towards style diktats.

KEYWORDS

Car seat design, Surface design, Pressure map, Human-Centred Design, Aesthetic, Style

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Introduction

The design of automotive seat backrests, particularly the central area of the padding known as the "central specchiatura," is traditionally based on established ergonomic surface models. Variations in shape and proportions are typically influenced by the brand's design language and by the intended seat typology. Generally, two main categories of seats are recognized: racing and comfort. These differ primarily in terms of adjustability, surface contouring, and foam thickness. Racing seats are designed to provide high levels of dynamic support during sporty driving conditions, but they are not conceived to ensure long-term comfort. In contrast, comfort seats aim to enhance the overall driving experience through increased foam thickness, fine-tuned adjustments to suit individual needs, and wider, less constraining surfaces to better distribute the occupant's weight as demonstrated in the study [1]. This paper proposes a redefinition of the backrest's central padding by accurately replicating the anatomical morphology of the human spine as already done in [2] and in [3] for special seats. Particular focus is placed on correctly modelling the spine's natural curvatures—cervical, thoracic, lumbar, and sacrococcygeal, whose measurement can be performed using a kyphometer [4]. Once the backrest surface is shaped according to these anatomical curves, the contact pressure distributions will be evaluated to determine whether peak values decrease or become more evenly distributed [5], and hence whether the surface provides improved comfort as highlighted in [6] [7]. Recent studies confirm the effectiveness of applying biomechanical models and numerical simulations to optimize seating comfort in automotive contexts [8] [9].

Method

Modified backrest's solid model

The modelling of the A-side of the backrest foam, i.e. the surface directly in contact with the user's back, was based on the spinal geometry of an anthropometric dummy (50th percentile European male). Specifically, three vertebrae were selected: L4, T7, and C5, as they geometrically correspond to the inflection points of the spine's natural curvature (Figure 1). This approach aligns with recent contributions in the literature that emphasize detailed modelling of the interaction between the human body and the seat, based on anthropometric data, in order to improve both static and dynamic seating comfort [10][11].

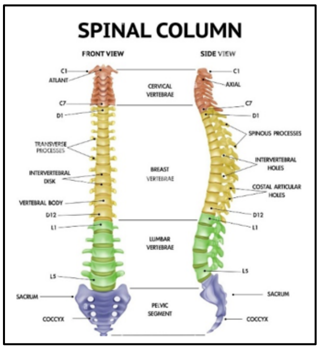

Figure 1: Anatomical structure of the human spinal column, shown in front and side views.

Their positions, referenced from the seat's H-point, were imported into a CAD environment (CATIA V5-6 R2021). A spline curve was created to represent the spinal profile in the sagittal plane, connecting the three vertebral points. To ensure a smooth and anatomically accurate shape, tangency (direction and magnitude) and curvature (radius and direction) conditions were imposed at each control point. These geometric parameters were parametrized, allowing for future variations and optimization of the backrest surface according to ergonomic needs. To generate the full ergonomic surface, three cross-sections were defined at the levels of the selected vertebrae. These sections were built as parametrized circular arcs, inspired by the geometry of an existing high-performance sports car seat. Their shape ensures proper contact and support along the user's back. Using the lofting tool (multi-sections surface), the cross-sections were interpolated along the guide spline to create a continuous and smooth surface for the A-side of the foam (See figure n.2). Finally, to complete the solid model of the cushion, the generated surface was shaped to replicate the lateral and rear geometry of the original foam block. The side surfaces were obtained by extruding the boundary of the A-side, and all surfaces were then joined together to form a closed volume suitable for FEM analysis.

FEM Analysis

The seat model at the dummy-seat interface (foams and leather covering) was meshed using elements with a characteristic length of 10mm to ensure the proper interaction between the anthropometric dummy and the seat. The other components such as: connection parts between seat-cushion and backrest, reinforcements and seat rails, were mashed with shell elements and considered as rigid body because they have small deformations with respect to the forces involved. Only the seat shells were considered as deformable because are in direct contact with the foams.

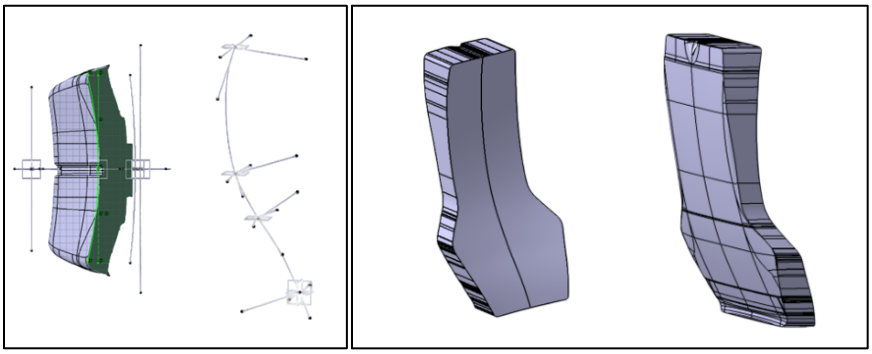

Figure 2: Lofted surface generated from transverse sections and guided by the anatomical spine spline (left) and Modified backrest's solid model (right).

Material properties were assigned to each component; for the cushion's foams, a 9kPa and a 7kPa ones were chosen respectively for seat-cushion and backrest. The logic of creation and assignment of the contacts' properties between the components followed that of the real seat. For example, the contact between the cushion and backrest's foams with their respective shells is a Tied contact, as in the actual seat these components are glued together. Finally, the positioning of the dummy (50th percentile European Man) was done by respecting design constraints such as: H point, heel point and wrist constraints to reflect real-car positioning.

Results

Figure 3 shows the pressure distribution on the seat-backrest obtained through FEM simulations: (a) the standard seat geometry, and (b) the modified version. The backrest is divided into six zones: upper and lower back (left and right) and two lateral bolsters.

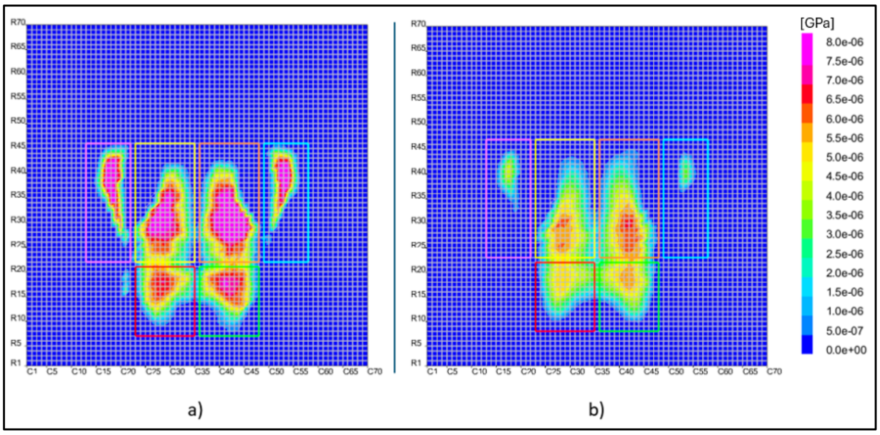

Figure 3: a) Standard backrest's Pressure map; b) Modified backrest's Pressure map

In the following table are summarized the results in terms of: Max Pressure, Average Pressure and Pressure Gradient obtained on each zone. In the standard configuration (a), high peak pressures were recorded in all zones, especially in the Upper Back areas and the bolsters, where values exceeded 7.8 [kPa]. The average pressures in the Upper/Lower Back zones were also high (around 2.4 to 2.8 [kPa]), suggesting a strong and irregular contact. Pressure gradients were particularly high in the Right Upper Back zone, reaching up to 3.17 [kPa].

Table 1: Quantitative comparison of Maximum Pressure, Average Pressure, and Pressure Gradient across the six functional backrest zones for Original configurations (a) and Modified one (b).

Zone	Max Pressure [kPa]		Avg Pressure [kPa]		Pressure Gradient [kPa]	
	(a) Standard	(b) Modified	(a) Standard	(b) Modified	(a) Standard	(b) Modified
Right Upper Back	7.93	6.73	2.36	1.88	3.17	0.664
Left Upper Back	7.88	7.32	2.55	2.21	1.38	0.732
Right Lower Back	7.05	5.51	2.41	1.97	1.12	0.893
Left Lower Back	7.86	6.09	2.77	2.20	1.41	0.898
Right Bolsters	7.93	4.38	1.14	0.338	1.38	0.424
Left Bolsters	7.94	3.22	1.06	0.167	1.27	0.322

In the modified configuration (b), the contact is more uniformly distributed, with a clear reduction in peak pressures (up to 40% lower in most areas). The bolsters show a significant decrease in both peak and average pressures, suggesting less unwanted lateral loading. Upper/Lower Back have more balanced values, and pressure gradients are lower, which means the contact is smoother and more uniform. So, objectively, the configuration (b) is more comfortable.

Conclusion and Discussions

The modification of the backrest shapes, that affects especially the foam thickness and contact surface, was implemented to follow the natural curve of the driver's spine [3] [12] (based on a 50th percentile European male), clearly improved how pressure is distributed across the backrest. Both peak and average pressures were reduced, especially in the central back and side support areas, showing that the contact between body and seat became more uniform. In a sports car, where seats must provide both comfort and body support and stability during dynamic driving, this result is especially important. Reducing peak pressures helps avoid discomfort or fatigue over time, while still maintaining the lateral support needed during sharp turns or fast maneuvers. The decrease in pressure on the bolsters suggests that the body is better supported in the center part of the backrest, so the bolsters now serve their true purpose (providing lateral stability) without carrying too much load on shoulders. The lower pressure gradients seen in the modified seat means that contact between the back and the seat happens more smoothly, without sudden pressure changes. This improves comfort and gives the driver a better sense of connection with the seat: these aspects are really important in sports driving because, up to professional test-drivers, real feedback from the seat and body stability are key-role players. From an ergonomics point of view, the new foam profile supports a more natural and stable sitting posture. This can improve comfort during long drives while also helping the driver staying better positioned and in control during dynamic phases. However, some limitations must be considered. The analysis was carried out using FEM simulations only, without experimental validation such as pressure mapping or user feedback. In addition, the results come from static and simple dynamic simulation, does not take into account sporty acceleration/braking and vibrations that are particularly important in sports driving scenarios. In summary, with this methodology, even a small change to the internal seat foam (when based on human body shape and pressure behavior) can significantly improve both comfort and performance. These findings confirm the value of using anthropometric and ergonomic design early in seat development, especially for vehicles where driving experience and body control are priorities.

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Aiming for a car seat with lower carbon footprint and higher comfort

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ABSTRACT

In this project a more sustainable car seat is developed where the foam and cover were replaced by a polyester thermoplastic material. Thirteen participants compared this seat to a benchmark. It showed no significant differences in comfort experience, but some areas for improvement were discovered.

KEYWORDS

Foam, material, car seat, comfort, discomfort

Introduction

For our future on the planet attention is needed for sustainability. A circular economy could contribute to sustainability. However, the measurement and assessment of circularity processes are not yet a common practice in the car seat manufacturing companies. In this study an attempt has been made to make the parts of the car seat circular, which means that at the end of the life the seat parts can be reused. Additionally, the weight is reduced to save material and a lighter weight design contributes to reducing energy consumption while driving. The comfort of a car seat is important as well, as a more comfortable product can contribute to a better market position.
The focus in developing this more sustainable and comfortable seat was on the soft parts contacting the human body, which is the upholstery and padding. Now usually a foam pad is used, which is rather thick to prevent that the human body feels the hard parts of the shell. This has two drawbacks. Firstly, much material is needed to create comfort which creates weight and material which might be a problem end of life. Although polyurethane can be recycled chemically and mechanically, landfill is currently still the way of disposing polyurethane, which is an environmentally unfriendly solution (Kemona & Piotrowska, 2020). The second drawback is that this is also taking space from the interior. A thicker back rest means for instance less leg room for the occupant behind the seat. Just reducing the foam thickness of a cushion on a standard architecture (foam pad and seat cushion structure) could lead to feeling hard points of the structure, which is not a comfortable solution for the occupant. A polyester 3D thermoplastic cushion structure is therefore potentially a good solution as it is more flexible and could allow a lower thickness of the padding.

In this project this new type of shell and padding has been developed. The shape of the shell is formed in such a way that it fits to the contour of the human body. On top of this flexible shell a thin layer of approximately 20 mm polyester thermoplastic is placed covered by a polyester textile. This way materials are not mixed. Using one material is better for circularity as separation is not needed at the end of life of the product. Developing this structure for the back rest was quite easy as there is not so much pressure between the back rest and the seat. On the seat pan, there is more pressure by the human body (Yao et al., 2023) and in a pretest there were pressure peaks measured around the sitting bones and the vibration transfer function was also not good. This means that vibration of the car is not damped that well. After some trial and error, space in the thermoplastic layer was made under the sitting bones and placing a doubledonut formed piece of foam in this area seemed to solve these problems (see fig. 1).

Fig. 1. A space in the material where the double donut foam could be placed

The PU foam was placed loosely, not glued, also to enable material separation at the end of life, which is good for circularity. The question is whether this seat was appreciated by end-users. To establish the effects on comfort a comparison was made with a benchmark seat, which was a Mercedes A class seat. The research question is:

What is comfort and discomfort in the new developed seat compared with a Mercedes A class seat?

Method

To answer the research question 13 participants (6 female and 7 male; average body height 1.77 m, sd 0.104) were invited to sit in the new developed seat and in the bench mark seat. The test subjects were asked to walk around for approximately five minutes and do some light stretching to neutralize their body posture before starting the evaluation.

Fig. 2. Seat B (benchmark) and seat A (new prototype) in the test set-up.

The evaluation began with the new seat (Pure Essential prototype seat (Seat A)), followed by the benchmark seat (Seat B, see fig. 2). The order was the same for all test subjects throughout the evaluation. The test subjects were given a tablet where they answered the questionnaire. The test subjects were asked to take a seat and answer question while being seated.
The position of the seat was predefined and both back rest angles were equal, participants were only allowed to change the horizontal distance to the pedals. The evaluation per seat took 15 minutes. The comfort rating for seat parts (like rear cushion insert, cushion length, thigh support and bolsters) could be made on a scale from -2 to +2, where -2 was too soft, too tight and too flat, while + 2 was too firm, too long, too steep. For questions on overall comfort, comfort of the seat pan and the back rest participants where participants were asked to rate the comfort on a 10-point scale, where 3-4 is poor and 9-10 excellent. It was checked whether the distribution was normal and in those cases the t-test for paired comparison was used to check the difference between both seats and in other cases the Wilcoxon test was used. In both cases a $p<.05$ was seen as significant. Additionally, an interview was performed on the experience of the elements of the seats.

Table 1. Average rating for the seat parts on a scale from -2 to +2, where -2 was too soft, too tight and too flat, while + 2 was too firm, too long, too steep.

	seat A new	seat B benchmark
rear cushion insert firmness	0,1	0,4
rear cushion insert support	-0,2	-0,2
overall cushion length	0,2	-0,6
thigh support contact area	-0,1	-0,5
thigh support pressure	-0,4	0,2
cushion bolster fit hold	0,5	-0,6
cushion bolster feel firmness	0	0,3
cushion bolster shape contour	-0,9	0,2
average deviation from zero	0,3	0,375

Results

In table 1 the scores on the different parts of the seats are shown. Both seats have on average approximately the same deviation from zero. For seat A the cushion bolster shape contour is too flat and for seat B the cushion bolster fit is too wide and the overall cushion length too long.
Also, thigh support pressure is experienced as quite low. In table 2 the overall comfort scores are shown. There were no significant differences between the two seats. There is a slight difference (not significant) in the sense that seat A has a bit lower comfort score.

Table 2. Overall comfort scores, seat comfort and back rest comfort on a scale 1-10 for the two seats (n=13)

	overall comfort				seat pan comfort				backrest comfort			
	mean	SD	p=		mean	SD	p=		mean	SD	p=	
seat A	6.69	1.38	.119	Wilcoxon	7.08	1.38	.24	paired t-test	6.54	1.71	.087	Wilcoxon
seat B	7.31	1.89			7.46	1.2			7.31	2.01		

The results of the interview were that the cushion of the Pure Essential was favoured by the test subjects except for the cushion bolsters. They mentioned that it could be due to the concave geometry of the seat cushion which gave the bolster the same softness as the seat, which is too soft and could not offer adequate side support, but this needs to be studied further. However, the feedback on the area of the insert in the Pure Essential cushion was more positive than that of the benchmark seat, which could justify the measure taken to optimize the cushion comfort by adding the 'doubledonut'.

Discussion

In answering the research question '*what is comfort and discomfort in the new developed seat compared with a Mercedes A class seat?*' scientifically no significant differences could be shown. This could mean that with the same comfort a more sustainable seat could be made. However, care should be taken in adopting this conclusion as the number of participants is low (13) and all participants had the same order in testing, which could have resulted in order effects. However, to increase comfort there are possibilities for improvement. For instance, the bolsters could be firmer and the overall comfort may be improved. Additionally, the hardness at the thigh areas could be improved. Other limitations were that comfort and discomfort were evaluated after seating for 15 minutes, which is short as discomfort increases in time (Smulders et al., 2016). In reality the comfort could be different as factors like vibrations and movements felt during driving, lighting and temperature control were excluded.

It could be that the low fidelity first view of the prototype might play a role in the overall comfort. Other studies also mention the effect of low fidelity on the comfort perception (Vicente et al., 2023). Another drawback of the study as that measurements on the seat like pressure distribution (Yao et al., 2023) and seat hardness recording (Wegner et al., 2020) were not studied in a scientific way and could not be part of this paper. On the other hand, the study shows that the comfort is comparable to a current well sold seat and there are two clear areas of improvement: the bolsters and the thigh area, showing the importance of this research.

Conclusion

It is hard to establish a difference in comfort between a full developed seat and a prototype. The new developed seat showed no significant differences with the benchmark seat. However, some areas for improvement were discovered, showing the importance of user research.

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Determining the Cooling Effects of Textiles: An Overview

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ABSTRACT

The human body's ability to regulate its core temperature is essential for survival and optimal function. In warm environments, cooling the body is particularly important to maintain health and minimize the risk of heat-related illnesses. Textiles can support the cooling of the human body, and in recent years, more textiles with cooling properties have come onto the market. This paper provides an overview of the different methods for evaluating the cooling effects of textiles, focusing on physical measurements and physiological cooling mechanisms. The initial warmth perception, denoted as Q_{max}, is critical in understanding the comfort provided by different fabrics. Additionally, evaporative cooling, which occurs via the evaporation of sweat or water, is assessed using standardized procedures such as DIN SPEC 60015, ASTM F2371, and ASTM F3628. These methods ensure uniform and reliable assessments of cooling textiles. The paper compares these methods and discusses their advantages and disadvantages, highlighting the importance of selecting the appropriate cooling mechanism and test method based on the application area.

KEYWORDS

Cooling effect, textiles, Sweating guarded hotplate, sweating, thermal manikin

Introduction

The human body's thermoregulation system allows it to maintain a stable internal temperature despite external fluctuations. In warm environments, cooling mechanisms such as sweating and vasodilation are crucial to prevent heat-related illnesses. Sweating is a natural process where sweat evaporates from the skin, removing heat in the process. Vasodilation, the widening of blood vessels, also helps dissipate excess heat by increasing blood flow to the skin's surface.

In recent years, textiles with cooling properties have gained popularity, especially in functional and sportswear. These textiles aim to support the body's natural cooling mechanisms and keep the wearer comfortable in hot environments. They utilize various technologies, such as moisture-wicking fabrics that quickly transport sweat away from the skin, or materials that enhance evaporation, thereby lowering skin temperature. [1]

Despite the growing prevalence of such textiles, the effectiveness of these cooling properties often remains unclear to consumers. There are numerous products on the market, each claiming different levels of cooling performance, making it challenging for the client to make informed purchasing decisions. Therefore, understanding the methods used to evaluate the cooling effects of textiles is essential. [2]

This paper aims to provide an overview of the methods used to evaluate the cooling effects of textiles, focusing on physical measurements and physiological cooling mechanisms. It examines how different materials and technologies influence cooling performance, and the measurement techniques used to determine the effectiveness of these textiles. By gaining a better understanding of these evaluation methods, consumers can make more informed decisions, and manufacturers can further optimize their products to ensure the comfort and safety of the wearers.

Method

Four primary methods for assessing the cooling effects of textiles are discussed: the Initial Warmth Perception (Q_{max}), the Heat Loss Tester WATson (DIN SPEC 60015), the Sweating Hot Plate (ASTM F3628) and the Sweating Heated Manikin (ASTM F2371).

Initial Warmth Perception (Q_{max})

The Initial Warmth Perception (Q_{max}) method measures the thermal sensation when a textile first comes into contact with the human skin. It is critical for understanding the comfort provided by different fabrics, especially in terms of how warm or cool they feel immediately upon touch. This measurement is conducted separately from the other methods to specifically assess the initial thermal sensation. The Q_{max} value is determined by measuring the peak heat flux that flows from a heated copper plate into the textile surface upon contact. The copper plate is heated to a specific temperature, and the textile sample is placed on the plate. The heat flux is measured, and the Q_{max} value is calculated. [3] [4]

Heat Loss Tester WATson (DIN SPEC 60015)

The Heat Loss Tester WATson according to DIN SPEC 60015 measures the evaporative heat loss of textile materials by simulating human thermoregulation. The test device WATson consists of a heated plate with sweat glands, placed in a climate chamber. The textile sample is placed on the heated plate, which is maintained at a constant temperature of 32°C, and the environmental conditions, such as temperature, humidity, and wind, are controlled. The procedure involves placing the textile sample on the heated plate in a dry state, heating the plate to a constant temperature, and supplying water to simulate liquid sweating which occurs at a high activity level (high metabolic rate). The heat loss due to evaporation is measured over time. The test is conducted in three phases: dry phase, sweating phase, and drying phase. In the sweating phase, the evaporative heat loss is measured, providing insights into the cooling power and wicking power of the textile. In the drying phase, the drying time of the textile is assessed. [5] [6]

Sweating Hot Plate (ASTM F3628)

The Sweating Hot Plate method measures the cooling energy provided by wicking liquid moisture and evaporating it from clothing materials. The test involves a hot plate with sweating pores, and the cooling energy is measured during a simulated sweating phase and a drying phase. The plate is maintained at a constant temperature of 35°C, and water is supplied at a controlled rate to simulate liquid sweating. The procedure starts by placing the textile sample on the hot plate and heating the plate to a constant temperature. Water is then supplied to the plate to simulate sweating, and the heat flux is measured. The test is conducted in three phases: initialization phase, sweating phase, and drying phase. During the initialization phase, the heat flux is measured to establish a baseline. In the sweating phase, the heat flux is measured while water is supplied to the plate, quantifying the cooling energy released by the textile. In the drying phase, the heat flux is measured until the textile is dry, calculating the total energy released during drying, cooling efficiency, and chilling potential of the textile. [7] [8]

Thermal, Sweating Manikin (ASTM F2371)

The Sweating Heated Manikin method is a sophisticated approach for measuring the cooling effects of textiles. This method involves using a thermal, sweating manikin that simulates human sweating to assess the heat removal rate of personal cooling systems. The manikin is placed in an environmental chamber, where its surface is heated to a constant temperature of 35°C. Water is supplied to the manikin's surface to mimic sweating, and the heat removal rate is measured. The manikin is divided into multiple zones, each with its own heating and sweating control, allowing for detailed analysis of different body parts. The procedure begins by dressing the manikin in the test garment and setting the chamber conditions to simulate the desired environment, such as temperature and humidity. The manikin is then heated to a constant temperature, and water is supplied to simulate sweating. The heat removal rate is measured over time, providing insights into the cooling performance of the garment. This method offers detailed measurements of the cooling rate and duration of cooling, accurately accounting for evaporative cooling, which is the primary means of heat transfer in humans. [9]

Results

The comparison of the four methods highlights their respective strengths and limitations:

The Initial Warmth Perception (Q_{max}) provides immediate feedback on the thermal sensation of textiles, which is important for consumer comfort. It is a straightforward measurement that can be easily conducted. However, Q_{max} does not provide information on the long-term cooling performance of textiles. It focuses solely on the initial sensation and may not reflect the overall cooling efficiency of the fabric.

The Heat Loss Tester WATson (DIN SPEC 60015) is designed to evaluate the evaporative cooling performance of textiles under controlled conditions. It offers valuable insights into material properties like cooling power, wicking power, and drying time. However, it does not consider garment design and fit and may not fully replicate the dynamic conditions experienced during physical activity. It is less complex than the Sweating Heated Manikin method.

The Sweating Hot Plate (ASTM F3628) provides a comprehensive analysis of the cooling energy and efficiency of textiles, offering clear metrics for comparison. It quantifies the cooling energy released during sweating and drying phases and provides detailed insights into cooling efficiency and chilling potential. However, it focuses on material-level assessments, does not consider garment design and fit, and may not fully capture the complex interactions between the body, clothing, and environment.

The Sweating Heated Manikin (ASTM F2371) is ideal for assessing personal cooling systems, offering detailed and realistic measurements of cooling performance. It accurately accounts for evaporative cooling and allows direct comparisons of different cooling systems. However, it is complex to set up and operate and may yield unrealistically high cooling rates for ambient air circulation systems due to continuous surface saturation and low relative humidity in the chamber.

The comparison of the four methods highlights their respective strengths and limitations. The Thermal, Sweating Manikin method is best suited for assessing personal cooling systems and providing detailed, realistic measurements of cooling performance. However, it is complex and may yield high cooling rates under certain conditions. The Heat Loss Tester WATson is ideal for evaluating the evaporative cooling performance of textile materials. It is less complex and provides valuable insights into material properties but does not account for garment design and fit. The Sweating Hot Plate method offers a comprehensive analysis of cooling energy and efficiency. It is straightforward and provides clear metrics but focuses on material-level assessments and may not fully replicate dynamic conditions. The Initial Warmth Perception (Q_{max}) method provides immediate feedback on the thermal sensation of textiles, which is important for consumer comfort. It is a straightforward measurement but does not provide information on long-term cooling performance.

Conclusion

Textiles with cooling properties are essential for maintaining thermophysiological comfort in warm environments. The choice of the appropriate cooling mechanism and test method depends on the application area. The Sweating Heated Manikin method is suitable for assessing personal cooling systems, while the Heat Release Tester WATson method provides a detailed evaluation of textile materials. The Sweating Hot Plate method offers a comprehensive analysis of the cooling energy and efficiency of textiles. The Initial Warmth Perception (Q_{max}) method is crucial for understanding the immediate thermal sensation of textiles. Understanding the differences between these methods is crucial for accurately assessing the performance of cooling textiles.

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Preferred design features for cycling clothing comfort

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ABSTRACT

This study investigated design preferences for cycling clothing among competitive cyclists. An online survey was conducted to gather opinions on fit, design features and perceived comfort of cycling jerseys. 115 cyclists completed the survey. The survey targeted road and off-road cyclists, with a focus on participation in competitive events.

The results showed that tight jerseys and padded bib shorts are preferred for training, while skinsuits are favoured by over 40% in competition. Most cyclists prefer jersey sleeve lengths that extend at least halfway down the upper arm and shorts with a length between 1/2 and 2/3 of the thigh. Elasticated cuffs are commonly favoured for both sleeves and leg grippers.

Fit is a critical factor, with the waist and back length of jerseys and the bib length and chamois position of shorts being the most challenging to fit. Female cyclists reported more difficulties with shorts fit, particularly concerning thigh fit and chamois width, compared to male cyclists.

Overall, the study indicates that preferences for cycling clothing are generally similar across genders. These findings provide insights for clothing manufacturers to enhance the design and comfort of cycling apparel, addressing the specific needs and preferences of competitive cyclists.

KEYWORDS

Comfort, cycling, clothing, survey, cyclist.

Introduction

Cycling clothing for competitive riders is worn for many hours during training and competition. Detailed design features can make riders accept or reject designs based on anecdotal evidence, fashion and media. For sports garments, fit and comfort have been identified as the most important factors for purchasing decisions, with a higher ranking than price (Wilfling et al., 2022). The fit, fabric and design of cycling clothing has been shown to be more important than thermal properties for comfort (Teyeme, 2020). A user survey showed that fit of cycling clothing influences the perceptions of moisture permeability, with better fitting garments being perceived as having good breathability (Teyeme et al., 2022).

Design of cycling clothing can vary in terms of materials and pattern. Some elements (e.g. sleeve length) can vary more than other elements between brands and designs (Teyeme et al., 2022). Example features include leg grippers ranging from rubberised strip to 200mm bands; sleeves being laser cut or with a seamed elastic edge; pads (chamois) being multiple designs. Cycling shorts with a chamois pad are designed to be worn without underwear to maximise comfort and reduce chafing (Harrison and Edey, 2023), but their design and fitting method varies between brands.

This study aims to elicit current opinion on cycling clothing design, technology and fashions, to obtain an up-to-date view of cyclists' preferences.

Method

115 cyclists completed an anonymous online survey on 'Design and Comfort of Performance Cycling Clothing'. Section 1 focused on personal information including age, participation in events and hours ridden per week. Section 2 focused on cycling jerseys (tops) and considered preferences for training and competition, sleeve design, and which parts of the jersey is most difficult to fit. Section 3 focused on cycling shorts and considered preferences for training and competition, leg design, which parts of the shorts are most difficult to fit, and the design of the chamois.

The study was promoted via social media, cycling clubs and race teams and was specifically targeted at competitive cohorts. The study was approved by Nottingham Trent University research ethics committee (1890793).

Participants were classified into 'road' and 'off-road' groups. Road riders were classified as those who participated in 6 or more club rides, sportives, road races, or time trials in the past 3 years. Off-road riders were classified as those who participated in 6 or more mountain bike (MTB), gravel or cyclocross (CX) events in the past 3 years. Those who participated in both road and off-road events were classified into both groups.

Results

Respondents comprised 67 males, 47 females, 1 unspecified. Each of the 5 age categories included at least 14 respondents and ranged from 18-22 years to 60+ representing Junior/U23, through to Super Veteran UCI race categories. 84% had ridden in a social group (club ride) in the past 3 years; 46% had participated in 'Sportive/Grand Fondo' that are considered non-competitive. Off-road competition were the most popular race disciplines (CX 64%, MTB 51%, gravel 42%). Road competition had participation of 36% and 35% for time trials and road racing respectively. 69% rode for more than 7 hours per week.

There were differences between preferred jersey and shorts in training and competition ($p < 0.001$, χ^2). This is as expected as skinsuits are designed for competition use providing aerodynamic benefits, ideal placement of garment components in race posture, consistent fit and lower weight. Skinsuits have less opportunity to carry spares and nutrition in pockets, cannot be easily adjusted, are less compatible with bathroom breaks and costly, meaning that they are rarely used in training as shown here. Tight jerseys were preferred by 76% of the sample during training; 18% preferred loose. In competition 53% preferred 'tight' with 42% preferring 'skinsuit' jerseys. Padded bib shorts with straps were preferred by 82% of the sample during training. In competition 46% preferred padded bib shorts with straps, with 43% preferring skinsuits. The trend was observed across both genders and across disciplines (Figure 1).

Figure 1. Preferred types of cycling jersey (left) and shorts (right) in training (top) and competition (bottom) for male and female road and off-road cyclists.

Preferred jersey sleeve length was at least 1/2 way down the upper arm with 49% preferring 'about 1/2 way between shoulder and elbow' and 43% preferring 'about 2/3 way between the shoulder and elbow'. The most popular shorts length was 1/2 to 2/3 thigh length (51%). 10% preferred shorter; 38% longer. Males had a consistent preference for longer sleeve and leg lengths (Figure 2). The most preferred sleeve edge and leg cuffs were sewn-on elasticated cuffs. Male cyclists showed more preference than female cyclists for silicone grippers for both sleeve and shorts.

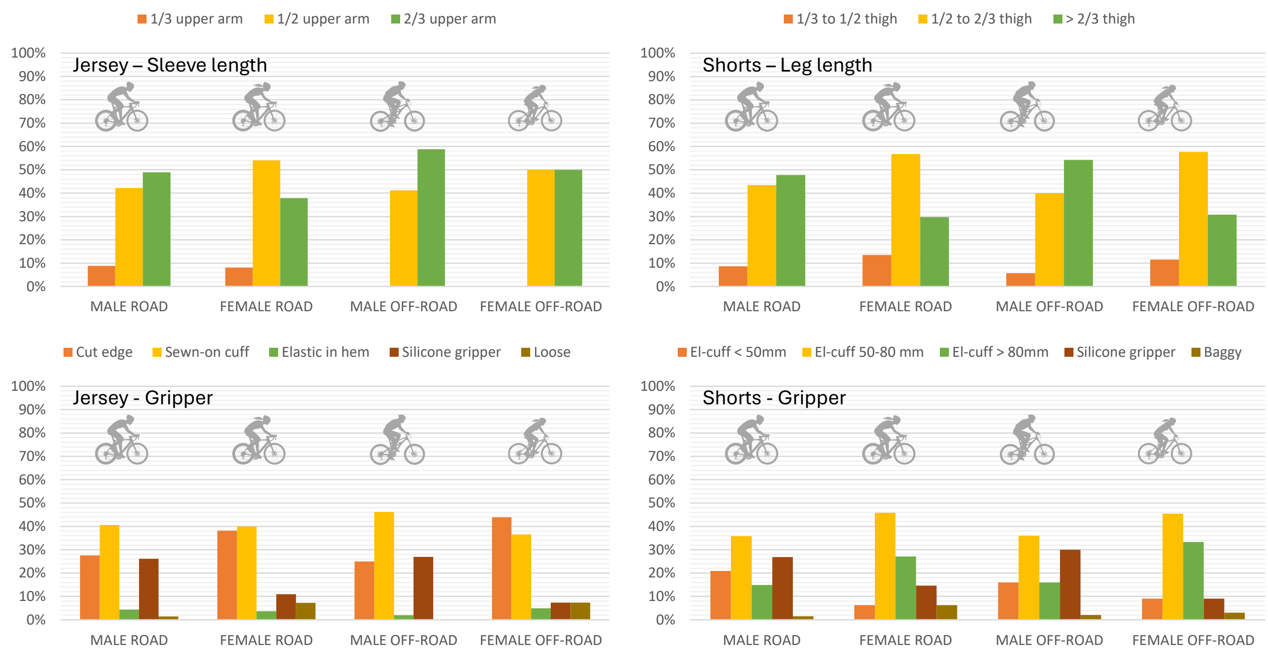

Figure 2. Preferred designs of cycling jersey (left) and shorts (right) for sleeve / leg length (top) and gripper (bottom) for male and female road and off-road cyclists.

Preferred jersey sleeve length was at least 1/2 way down the upper arm with 49% preferring ‘about 1/2 way between shoulder and elbow’ and 43% preferring ‘about 2/3 way between the shoulder and elbow’. The most popular shorts length was 1/2 to 2/3 thigh length (51%). 10% preferred shorter; 38% longer.

The most preferred chamois thickness was 10-14mm (52% of respondents). 42% of females preferred thickness greater than 15mm compared to 29% of males, although this difference was not statistically significant. Male and female groups both considered pad shape, quality of stitching to fix to shorts, padding material, and position in the shorts as the top 4 considerations for comfort. Females considered pad shape more important than males ($p<0.05$, χ^2). It should be noted that cycling shorts are gender-specific and have different designs of chamois for men and women.

The waist and back length were reported as the most difficult part of a jersey to fit (Figure 3). The bib length and chamois position were considered the most difficult parts of shorts to fit for both males and females. Thigh fit (too tight) and chamois width were more difficult to fit for females than males.

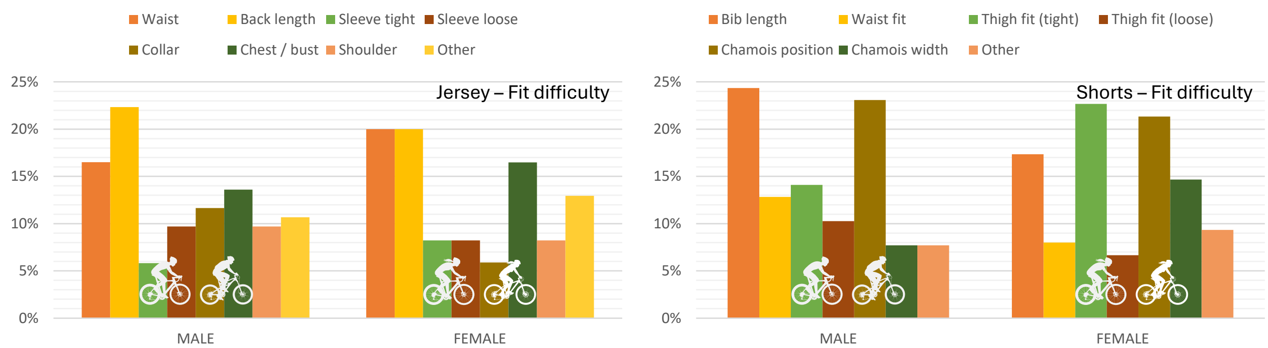

Figure 3. Most difficult parts of cycling jerseys (left) and shorts (right) to fit for male and female cyclists.

Conclusions

This study has shown that preferences for cycling clothing are generally similar for males and females. The shortest designs of arms and leg lengths were the least popular. Elasticated cuffs were the most popular grippers for arms and legs. Females found more difficulties in fit for chamois than males. This study provides a baseline of clothing design factors that are considered important by cyclists and can help target future development of sports apparel.

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Reducing Garment Mass for End-User Comfort

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ABSTRACT

Minimizing additional mass of clothing garments for human performance is a well-recognized ergonomic principle. Definition of the maximum acceptable mass of clothing products has been attempted in several studies. However, the perceivable thresholds for differences in mass, in addition to the hedonic sensory experiences elicited in response to the mass of clothing has received lesser attention. The aim of this research was to investigate the relationship between perceptions of heaviness with actual garment mass.

15 healthy males volunteered to take part in this study and visited the laboratory on two separate occasions. During visit one, participants provided their perception of heaviness for 34 physical masses, ranging from 0.8 to 8kg to the upper body. Mass was applied using a weighted vest to remove impacts of garment design, fit or style. During visit two, to determine the impact of garment design, style and fit on perceptions of mass, actual garments ranging from 350g to 2.5kg were applied to the upper body. The perception of heaviness was provided.

Strong and significant relationships exist between perceived heaviness and actual mass. An impact of garment design, style and fit on the perception of heaviness was observed. A jacket will be perceived heavier compared to a weighted vest of the same weight. This upward shift in perception for jackets may be caused by uneven distribution of weight across the body.

Investigation of the relationship between perceived heaviness and actual mass has enabled the development of a model for lightweight perception. This easy-to-use tool is directly used in new product development efforts to provide developmental targets for lightweight value propositions. Moreover, as many garment manufacturers and companies make claims about lightweight, the tool is used to validate these claims relative to end-user perception.

KEYWORDS

Clothing, Mass, Perceived Heaviness

Introduction

Minimising additional weight of clothing garments for human performance is a well-recognised ergonomic principle, particularly for the development of protective and military clothing and to a lesser extent, clothing for sport and recreational activity. Definition of the maximum acceptable weight of clothing products has been attempted in several studies. For example, the maximum weight of an industrial helmet is claimed to be under 300 g (Abeysekera 1992) and a shoe mass less than 440 g per pair has been reported to have no detrimental effect on running economy relative to barefoot (Fuller et al. 2015). However, the perceivable threshold for differences in weight and the hedonic sensory experiences elicited in response to the weight of clothing has received lesser attention.

In the field of psychophysics, several models have been proposed to quantify relationships between weight and the perceived response by an individual; Weber's Law, Fechner's Law and Stevens Power Law. These models have identified weight discrimination thresholds, indicating the smallest change in weight that a person could sense when the weight of an object remains constant in one hand and is increased or decreased in the other hand. In the context of clothing, this may be representative of an in-store or sales environment, whereby consumers evaluate products using their hands. However, during wear and in the absence of centrally generated input to the muscle with active lifting, the perception of weight, although still possible, may be considerably different. Thus, cutaneous inputs such as contact force and pressure with fabric-to-skin interactions, may be important stimulus parameters for feelings of lightness/heaviness, and for emotional responses of pleasantness or comfort.

Recent research concerning how running shoe mass is perceived during wear (perceived heaviness and perceived comfort) revealed poor relationships between the perception heaviness and actual mass with short evaluation times (1 min: $r = 0.28$ and 5 min: $r = 0.33$). Moreover, a relationship between perceived shoe comfort and perceived mass was not observed (1 min: $r = 0.07$ and 5 min: $r = -0.07$), suggesting shoe comfort and mass to be unrelated (Saxton et al. 2020).

Although findings from Saxton et al. (2020) provide insight into the perception of mass for shoes, it is important to note that these observations were based upon the mass of five shoes, limited in range (220 g to 362 g). Consequently, all shoes were rated similarly as "neither heavy nor light" and "comfortable". A greater range in actual mass is likely to be required to pertain the true relationships between perceptions of heaviness and comfort with actual mass. Moreover, evaluations of the perception of mass have not been assessed for garments worn on the body.

The aim of this study was (1) to investigate the relationship between perceptions of heaviness and garment mass and (2) to determine if the perception of heaviness changes over time with short duration of wear.

Method

15 healthy, physically active males (35 ± 5 yrs., 78 ± 11.4 kg.,174.9 ± 4,6 cm) volunteered for this study and came to the laboratory on two separate occasions. Inclusion criteria for this study were as follows: 1) no history of sensory-related disorders or muscle-skeletal injuries in the past 12 months; 2) being physically active (i.e., performing 150-300 mins of moderate intensity aerobic physical activity per week; 3) chest size of 96-101 cm, representing a t-shirt size medium. Experimental procedures were fully explained to each participant before obtaining written informed consent. The study was conducted within the confined of the World Medical Association Declaration of Helsinki for research using human participants.

During visit one, upon arrival to the laboratory, participants changed into a test base-layer provided by the researcher. The application of mass to the upper body was achieved using a weighted vest (Hyperwear, USA). A weighted vest was used to isolate the impact of garment mass on perception independently from the design and fit of a jacket. The vest consists of 84 pockets and uses high-density steel weights to adjust to a lighter or heavier weight capacity. The individual bars weigh ~64 g each and can be easily added or removed from the vest. Each pocket can hold two weights and weights can be arranged across pockets to allow for even weight distribution. The vest weighs 284 g when unloaded. To ensure that the weighted vest was in contact with the skin over the upper body but not restricting breathing or movement, two pressure sensors (Pliance, Novel, USA) were used to measure and standardize the pressure applied by the vest on the lateral and medial sides of each participant when the vest was unloaded and loaded with weight.

A 10-min baseline period was used to introduce and familiarise participants to the perceptual scale for heaviness. The Borg CR100 scale (Borg and Borg, 2001) was selected having been used extensively for a diversity of applications including evaluation of strength and subjective force. Participants were instructed to provide their perceived heaviness for the base-layer (78 g), for the weighted vest without any weight added (284 g) and for the weighted vest when loaded (8 kg). Participants were instructed to provide their perceptual results after donning the jacket, after 1 min and 5 min of wear. This procedure ensured all participants were competent in using the perceived heaviness scale and in providing ratings when required by the investigator.

Following familiarization, perceived heaviness was evaluated for 34 physical masses, applied to the upper body in a counterbalanced order. Evaluations were made nude (0 g), for the base-layer (80 g), for the vest (284 g), and base-layer plus vest (364 g). Between the range of 350 – 1 kg the mass in the jacket increased in 50 g increments. Between the range of 1.5 – 8 kg the mass in the jacket increased in 500 g increments. This approach was adopted to develop a sensitive relationship within a lower mass range typically observed for clothing but also large enough to see how the relationship changes with increased mass.

Participants were required to provide perceived heaviness with donning of the weighted vest and after 1 minute of wear. To understand the impact of wear time on the perception of mass, 18 masses were worn for 5 mins and subsequently rated. A recovery period of at least 30 s was provided between vest applications. Participants remained standing during application of the weighted vest but could sit during the recovery period. The testing sequence was counterbalanced to minimise any order effect.

During visit two, to determine the impact of garment design, style and fit on perceptions of mass, 18 jackets from defense and workwear end-uses were selected. These jackets ranged from 350g to 2.5kg. Jackets were applied to the upper body in a counterbalanced order. Participants were required to provide ratings for perceived heaviness upon immediately donning of the jacket, after 1 min and 5 mins of wear. A recovery period of at least 30 s was given between applications.

Results

Strong and significant relationships exist between perceived heaviness and actual mass (0-8 kg) when controlling for jacket design, style and fit ($r > 0.90$, $p < 0.05$). The relationship did not change over time from immediate donning, after 1 min or 5 mins of wear. Strong and significant relationships were also observed between perceived heaviness and actual mass (0-2.5 kg) when evaluating jackets different in design, style and fit ($r > 0.90$, $p < 0.05$). Comparison of the forementioned relationships (independent of garment design vs jackets different in design/style and fit) revealed an upward shift in perception for the same mass. In other words, for the same mass, a jacket will be perceived heavier compared to a weighted vest where jacket design is not a feature.

Conclusion

The application of the weighted vest allowed for the fundamental relationship between garment mass and perception to be evaluated independently of garment design. This was then translated to the real world by understanding the impact of garment design, style and fit on perception of mass. For jackets differing in design, style and fit, they were perceived as heavier than jackets of the same mass when controlling for design. This upward shift in perception for jackets may be caused by uneven distribution of weight across the body. For example, jackets with a tight cuff around the wrist or more weight in the sleeves (from padding, protection, pockets), were reported to dominate the perception of weight compared to jackets where weight was evenly distributed across the body.

Investigation of the relationship between perceived heaviness and actual mass has enabled the development of a model for lightweight perception. This easy-to-use tool is directly used in new product development efforts to provide developmental targets for lightweight value propositions. Moreover, as many garment manufacturers and companies make claims about lightweight, the tool is used to validate these claims relative to end-user perception.

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Impact of thermal insulation in protective gear on firefighter heat strain

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ABSTRACT

Firefighters perform various high-intensity tasks while wearing heavy and semi-permeable protective gear. Research studies indicate the potential harmful impact on firefighter heat strain when adding additional layers and thickness to the turnout gear. Wearing ballistic vests with turnout gear, therefore, may increase the risk of heat strain to the firefighters. While each layer in a firefighters' PPE system contributes in a different way to the overall level of protection, all layers also increase the risk of heat strain due to increased thermal insulation. Heat strain is the total reactions of the body when it is exposed to a high-temperature environment that can cause hyperthermia, heat stroke, dehydration, etc. Therefore, the firefighter turnout gear contributes to a significant amount of heat strain during their occupational tasks as ballistic vests are multilayered and non-breathable, impeding proper ventilation of the metabolic heat and sweat through the fabric to the environment. Therefore, the research outlined an empirical approach to quantify heat strain by assessing the thermal insulation of six firefighting clothing combinations emphasizing how ballistic vests affect heat transfer in the torso area. Results demonstrated that a substantial increase in thermal insulation occurred when ballistic vest was added to the firefighting gear. This study also investigated the comparative analysis of the tested ensembles to emphasize the need for optimized solutions to balance safety and heat strain mitigation for firefighters.

KEYWORDS

Firefighter, ballistic vest, turnout gear, thermal insulation, heat strain.

Introduction

According to the US Fire Administration, only approximately 4% of emergency calls to fire departments in 2020 were related to live fires, and 64% of the reported calls to fire departments were associated with a wide range of non-fire scenarios, including mass shootings, medical emergencies, hazardous materials, search and rescue operations, and civil unrest (U.S. Fire Administration, 2020). Between 2019 and 2024, 122 incidents occurred in the USA where firefighters were shot and killed while responding to active-shooting scenarios. After firefighters became targets of violence, fire departments requested funds to make ballistic vests standard personal protective equipment (PPE). Research studies indicate the potential harmful impact on firefighter heat strain when adding additional layers and thickness to the turnout gear (McQuerry et al., 2018). Wearing ballistic vests with turnout gear may not only increase the risk of heat strain (Kunz & Chen, 2005) by reducing heat dissipation but also contribute to discomfort, restricting movement and increasing sweat accumulation due to increased thermal insulation. Thermal insulation measures the ability of a material or system to reduce the transfer of heat. A high value of thermal insulation indicates the reduction of heat transfer from the surface of the body to the environment. However, there is a distinction between the thermal insulation of fabrics and clothing ensembles. Thermal insulation of the fabrics is associated with fiber composition, weave structure, thickness, and moisture management capabilities (Ukponmwan, 1993). On the other hand, clothing insulation takes into account a number of variables including air gaps between clothing layers, air layers adjoining the outer surface of the clothing, fabric thickness, and overall impact of all pieces in the clothing ensemble (Matusiak & Sybilska, 2016). Thermal insulation can be expressed as the formulas below

$$R_{ct} = \frac{T_s - T_a}{\frac{Q}{A}} = R_{cl} + \frac{1}{f_{cl}(h_c + h_r)} = R_{cl} + \frac{1}{f_{cl}} R_a$$

Where, R_t = total thermal insulation in $m^2 \cdot °C \cdot W^{-1}$; T_s = Temperature of test surface in °C; T_a = Temperature of air layer in °C; Q= Power required to maintain the test surface temperature (W); A= Surface area of test section in m^2, R_{cl} = ensemble intrinsic thermal insulation in $m^2 \cdot °C \cdot W^{-1}$; f_{cl}= clothing area factor; h_c = convective heat transfer coefficient in $W \cdot °C^{-1} \cdot m^{-2}$; h_r = radiative heat transfer coefficient in $W \cdot °C^{-1} \cdot m^{-2}$; R_a = thermal insulation of the boundary air layer in $m^2 \cdot °C \cdot W^{-1}$

Methods

1. **Test ensembles:** To quantify the thermal insulation, six firefighting ensembles were tested: E1) station uniform; E2) station uniform + ballistic vest; E3) station uniform + turnout suit; E4) station uniform + turnout suit + ballistic vest worn under turnout jacket; E5) station uniform + turnout suit + ballistic vest worn over turnout jacket; E6) station uniform + turnout suit + ballistic vest with hard plates. Level IIIA (NIJ certified) ballistic vests were used for E2, E4, E5, and E6 ensembles and level III hard plates were inserted in front and back of E6.

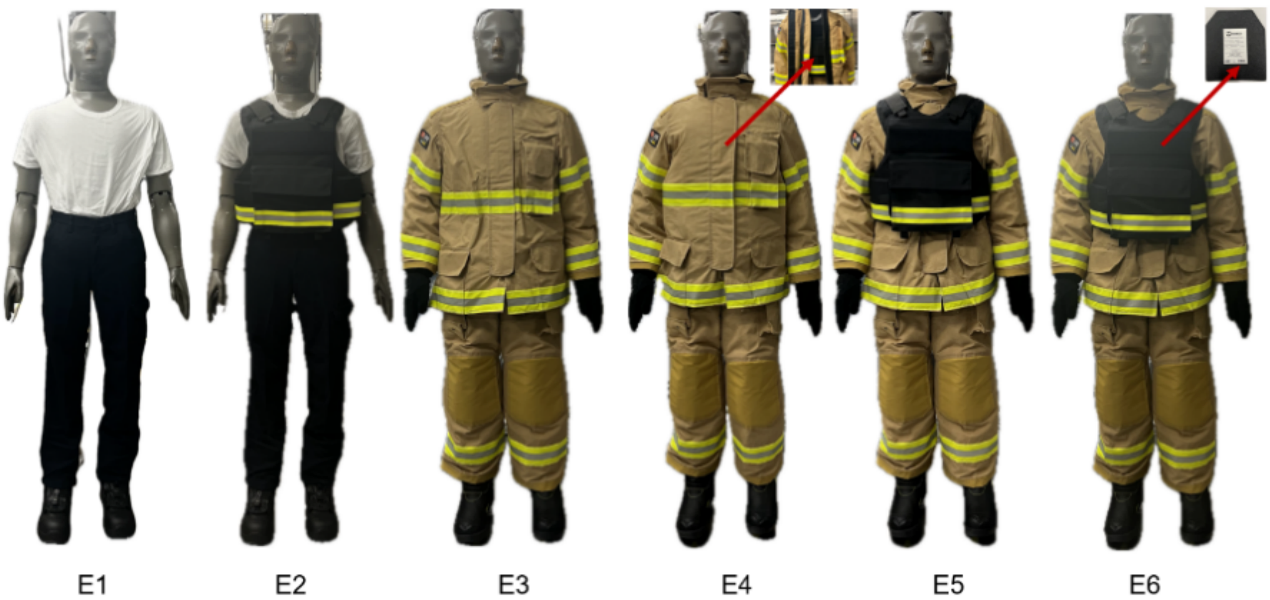

Figure 1. List of test ensembles

2. **Test conditions:** Dry test was conducted to assess the thermal insulation of the clothing ensembles following the ASTM1291 standard (ASTM F1291, 2022). The mean surface

temperature of the manikin was 35 °C ∓0.1 °C. The air temperature, relative humidity and wind speed in the test chamber were 15°C, 55-65%, and 0.4 m/s respectively.

Results

The thermal insulation (R_t) values for E1, E2, E3, E4, E5, and E6 in the torso area were 0.166, 0.331, 0.463, 0.622, 0.652, and 0.631 $m^2 \cdot °C \cdot W^{-1}$ respectively. The results evidently depicted a progression of thermal insulation values in the torso area with adding layers. R_t increased from 0.166 $m^2 \cdot °C \cdot W^{-1}$ in E1 (baseline-without ballistic vest) to 0.331 $m^2 \cdot °C \cdot W^{-1}$ in E2 (with ballistic vest added).

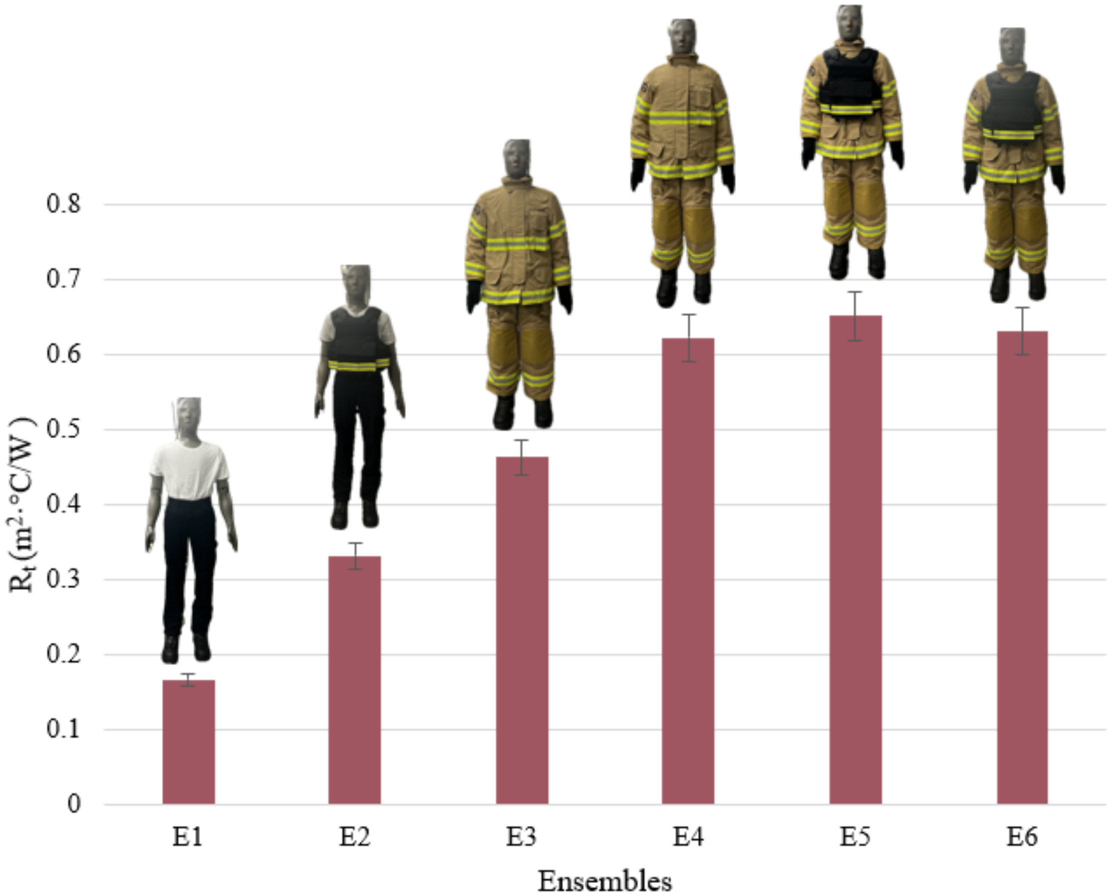

Figure 2. Thermal insulation of firefighting clothing ensemble in conjunction with ballistic vest

The relative increase in R_t from E1 to E2 is approximately 99%, which indicated twice the thermal insulation with the addition of the ballistic vest. The further increase in R_t through E3 to E6 up to 0.652 $m^2 \cdot °C \cdot W^{-1}$ demonstrated the compounding effect of additional layers in the firefighting turnout ensemble. The substantial increase in R_t from E1 to E2 is due to the dense materials in ballistic vests that is designed to provide ballistic protection that inherently reduced heat transfer. The further increase in R_t through E3 (baseline-without ballistic vest) to E6 was caused by the added layers of turnout suits. The additional layer of ballistic vest in E4, E5, and E6 increased the thermal insulation further. Despite adding hard plates to the ballistic vest in E6, it had a R_t of 0.631 $m^2 \cdot °C \cdot W^{-1}$ which is lower than E5. It indicated that adding hard plates reduced air gaps and created more contact points for heat transfer which led to the lowering of thermal insulation of E6.

Conclusion

Firefighters may experience heat strain as a result of the ensemble's reduced ability to dissipate heat, which is directly correlated with the increased thermal insulation provided by the ballistic vest and extra layers. Reduced heat loss from the body due to increased insulation raises core and skin temperatures and boosts cardiac output. In addition to causing physiological strain, this heat accumulation lowers general comfort, which makes it difficult for firefighters to perform their duties effectively. Discomfort from excessive heat and sweat accumulation can contribute to fatigue, decreased focus, and impaired decision-making, further increasing the risk of heat-related illness such as heat stroke, hyperthermia and performance degradation.

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Effect of passive head motion on motion sickness caused by roll motion

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ABSTRACT

To investigate the effect of passive head movement on motion sickness, we conducted an experiment using a low-frequency rotation motion generator. In the experiment, we tried to change the passive head movement by attaching weights to the heads of the participants or having them wear neck pillows and then measured the head movement and conducted a subjective evaluation of motion sickness. The participants sat in a car seat installed in the center of the motion generator and were exposed to sinusoidal roll motion with a peak angle of ±10 degrees and a frequency of 0.1 Hz for 30 minutes. The results showed significant differences between experimental conditions in both head movements and the motion sickness scores. High positive correlations between the motion sickness scores and the roll, pitch and lateral head movements were found, but the correlation with yaw movement was low.

KEYWORDS

Motion sickness, Head motion, MSDV, Roll oscillation

Introduction

In autonomous vehicles currently under development, there are concerns that motion sickness (MS) will increase when drivers perform non-driving tasks such as watching videos or using smartphones while the vehicle is in autonomous mode (e.g., Diels and Bos, 2016).

Kato and Kitazaki (2006) conducted field tests using a minivan and reported that strengthening head and body restraint reduced low-frequency head movements and MS in second-row passengers, and that there was a positive correlation between lateral and vertical head acceleration and MS evaluation. Wada and Yoshida (2016) investigated the effect of head tilt on MS during passenger car rides. They reported that head tilt in the centrifugal direction reduced MS in passengers compared to head tilt in the opposite direction while turning.

Regarding the effects of head rotation on MS, Guedry et al. (1990) used sinusoidal rotational movements around the vertical axis, varied participants' head postures relative to the rotation axis, and compared the incidence of MS. They reported that the average discomfort ratings induced by pitch and roll movements were significantly higher than those induced by yaw movements. However, since this experiment was conducted with movements around the vertical axis, the applicability to seated passengers in environments where gravity is acting remains unclear.

In this study, we investigated the effects of head movement patterns on MS by measuring passive human head movements and evaluating MS score under low-frequency roll oscillation.

Method

A low-frequency rotational motion generator used in this experiment. Roll oscillation of a closed cabin (2.0 m high, 1.5 m wide, and 1.5 m deep) was generated by a ball screw actuator capable of 12 degrees (0-p) of roll displacement. Participants sat on a vehicle seat attached to the center of the cabin floor such that the center of rotation was at the H-point of the seat (500 mm above the cabin floor) and wore a loose lap belt for safety reasons. The backrest angle was 23 degrees from a vertical direction. Participants were asked to keep their heads in touch with a headrest and watch a video on a 14.0-inch LCD display which was attached to the cabin wall during the oscillation. And then, they were exposed to sinusoidal roll motion with a peak angle of ±10 degrees and a frequency of 0.1 Hz for 30 minutes in the following four conditions (Fig. 1).

- Normal (NML): Normal upright posture.
- Neck Pillow (NP): A participant wore a pneumatic neck pillow for travel around the neck in a normal upright posture.
- Weight-Front (WF): 300 grams of weight was attached to the forehead of a participant.
- Weight-Side (WS): Two 150 grams of weights were attached to the left and right sides of a participant's head.

(a) Neck Pillow (NP) (b) Weight-Front (WF) (c) Weight-Side (WS)

Fig 1. Experimental conditions

The participants were asked to rate their illness every minute using a scale from 0 to 6 (0: no symptoms; 1: any symptoms, however slight; 2: mild symptoms, e.g., stomach awareness but not nausea; 3: mild nausea; 4: mild to moderate nausea; 5: moderate nausea but can continue; 6: moderate nausea and want to stop) (adapted from Golding and Kerguelen, 1992). The test was terminated if an illness rating of 6 was reached or the scheduled experimental time had elapsed. If the test was interrupted before the scheduled experimental time was reached, an illness rating of 6 was assigned to the time between the experiment interruption and the experiment completion.

Acceleration (longitudinal, lateral, and vertical) and angular velocity (roll, pitch, and yaw) were measured continuously on the participant’s head, thorax, and the oscillating cabin floor using wireless hybrid sensor WAA-010 (Wireless Technology Co. Ltd., Tokyo, Japan). Angular velocity data was differentiated with respect to time and transformed into angular acceleration. The linear and angular acceleration was frequency-weighted using W_f frequency weighting, and the motion sickness dose values (MSDVs) defined in ISO2631-1 (1997) were calculated for every test.

Healthy twelve adults (one woman and eleven men) aged 19 to 56-yr participated in this study. They all gave their informed consent to participate in the experiments, which was approved by the Ethics Committee of the Seating Division, NHK Spring Co., Ltd.

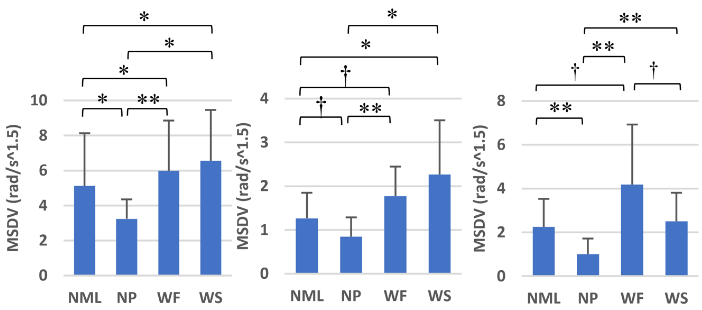
Within-subjects statistics were used to compare the results between the conditions. The order of the experimental conditions was counterbalanced to remove the order effects. Non-parametric statistical methods were used throughout for data analysis except correlation analysis. Multiple Comparison

Procedure was applied for significant tests. Firstly, p-values for all pairs were calculated using the Wilcoxon signed-rank test (two-tailed). Then the values were adjusted using the Holm-Bonferroni Method to control the family-wise error rate (FWER) (Holm, 1979 and Wright, 1992).

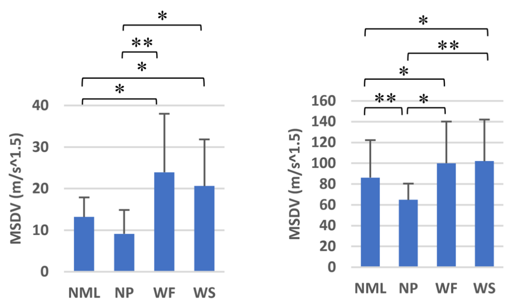
Results and discussion

Fig. 2 shows the results of the comparisons of means of MSDVs at the head. As intended, differences in MSDV were observed between the four experimental conditions. MSDVs were lowest in NP condition, followed by NML condition in all directions. In roll and pitch direction, the highest MSDVs were observed in WS condition, followed by WF condition. In lateral direction, those in WF and WS were almost the same. On the other hand, MSDV in WF condition was highest in yaw and longitudinal direction. The results of statistical analysis showed that there were significant differences or trends between most conditions as shown in the figure.

Comparisons of means of accumulated illness ratings (AILs) are shown in Fig. 3. The AIL was lowest in NP condition and highest in WS condition. Significant differences or trends were found between all conditions except NML and WF. The correlation coefficients between medians of AILs and medians of MSDVs at the head were 0.889 in roll, 0.889 in pitch, 0.236 in yaw, 0.887 in lateral direction, and 0.657 in longitudinal. Here, the calculated maximum inertial acceleration in lateral direction at head height (approx. 600 mm above H-point), ± 0.04 m/s^2, is much smaller than the component of gravitational acceleration acting in the lateral direction of the head due to the rolling inclination of the cabin, ± 1.7 m/s^2. Hence, the effects of the inertial acceleration on MSDV can be ignored.



(a) Roll direction (b) Pitch direction (c) Yaw direction



(d) longitudinal direction (e) Lateral direction

Fig 2. Comparisons of means of MSDVs at the head (NML: Normal, NP: Neck Pillow, WF: Weight-Front, WS: Weight-Side; **: p<0.01, *: p<0.05, †: p<0.10)

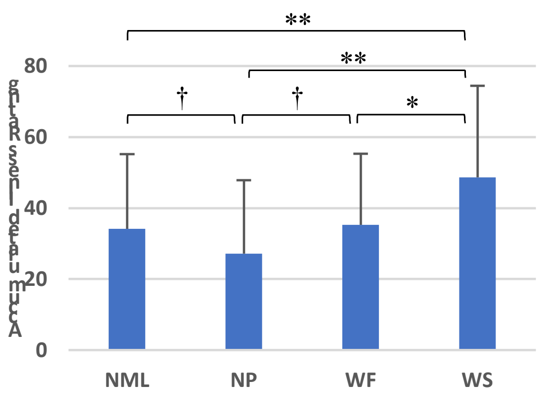


Fig 3. Comparisons of means of accumulated illness ratings (NML: Normal, NP: Neck Pillow, WF: Weight-Front, WS: Weight-Side; **: p<0.01, *: p<0.05, †: p<0.10)

The results suggest that the reduction of MSDV calculated from head motion is effective in reducing MS, and the head yaw motion affects less MS than other rotational motions. This result is consistent with the results obtained by Guedry et al. (1990).

In this study, we put weight on the participants' heads to modify the dead motion and found that they changed the head motion and the degree of MS. However, though we intended to modify the head roll, pitch, and yaw motion independently, there were correlations between the motions in each direction. One possible reason is the structure of the human body. Since the human body constitutes a complex link mechanism, it may not be easy to provoke independent head motion in each direction. Another possible reason is the location of the weights attached to the head. By modifying the mounting height and/or the distance from the center of gravity of the head, and so on, it might be possible to control the head motion independently.

Conclusion

In this study, to investigate the effects of human head motion on MS, we set up experimental conditions where passive head motion changes when participants are exposed to low-frequency roll motion, and measured head motion and MS scores during the motion. The results confirmed that the intended differences in head motion between experimental conditions occurred, and that there were also significant differences in MS scores. Furthermore, the correlation between head MSDVs and MS scores was found to be very high in the roll, pitch, and lateral directions, and fairly high in the fore-aft direction, but low in the pitch direction. In the next step, we will investigate the relationship between head motion and MS under linear motions similar to those experienced in automobiles, such as fore-aft and lateral motions, with the aim of developing car seats with optimal motion sickness reduction functions.

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Critical Anthropometric and Body Composition Factors Influencing Long-Term Seating Comfort

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ABSTRACT

Long-term seating comfort is essential in automotive design, as prolonged sitting can lead to discomfort, fatigue, and musculoskeletal complaints. While anthropometric factors like stature and hip width are well studied, the role of body composition parameters remains underexplored. This study evaluated their combined impact across two 2-hour simulated automated vehicle sessions with 17 participants. SVR models achieved R^2 values of 0.46 (comfort), 0.67 (discomfort), and 0.66 (fatigue). Comfort was influenced by seat type and anthropometry; discomfort by time and lower-body dimensions; and fatigue by body composition and anthropometry. These findings support the integration of both anthropometric and body composition measures into seat design to enhance long-duration comfort.

KEYWORDS

Anthropometry, Body composition, comfort, discomfort

Introduction

Long-term seating comfort is a multifaceted topic that has attracted wide attention in automotive interior design (Mansfield et al., 2020; Sabri et al., 2022; Vink et al., 2025). Extended periods of seating during long-distance travel often lead to a decline in comfort levels and an increase in discomfort (Kernytskyy et al., 2021). This can result not only in reduced productivity and negative user experiences but also in long-term musculoskeletal issues and health complications (Suzanne Hiemstra-van Mastrigt et al., 2017).

Anthropometry, which refers to the measurement of human body dimensions, has been extensively studied in relation to seating comfort (Naddeo et al., 2021). Factors such as stature, sitting height and hip width directly affect how individuals interact with seating surfaces, influencing postural support and pressure distribution (Liu et al., 2020; Y. W. Song et al., 2024). However, body composition, comprising parameters like body fat percentage, muscle mass, and visceral fat, has received comparatively less attention in this context (Naddeo et al., 2024)). These factors could play an equally significant role in shaping seating experiences by affecting biomechanical and physiological responses, such as pressure tolerance and metabolic activity (Wang et al., 2021; Zhao et al., 2019). For instance, individuals with higher body fat percentages may experience greater thermal discomfort due to reduced heat dissipation (S. Hiemstra-van Mastrigt et al., 2016), while those with lower muscle percentages might lack the necessary support for prolonged seating (Deros et al., 2015). Additionally, variations in visceral fat and metabolic rates could influence susceptibility to pressure-related discomfort or fatigue over time (Choi et al., 2021; Ibrahim et al., 2010).

Despite these interactions, the combined influence of anthropometry, body composition, and long-term seating comfort remains underexplored (Parida et al., 2019; Rikaz et al., 2019). This is particularly important for passengers in automated vehicles, as Non-Driving Related Activities (NDRAs) become dominant (Cai et al., 2024). Passengers are engaging in a wider range of activities, further underscoring the need for seating systems that can accommodate diverse physiological and biomechanical needs.

This study aims to evaluate the impact of anthropometric dimensions and body composition on long-term seating comfort. By integrating subjective feedback (Anjani et al., 2021) with objective measurements(Y. Song & Vink, 2021), we examine how factors such as time, seat types, anthropometric characteristics, and body composition influence comfort and discomfort during prolonged sitting.

Method

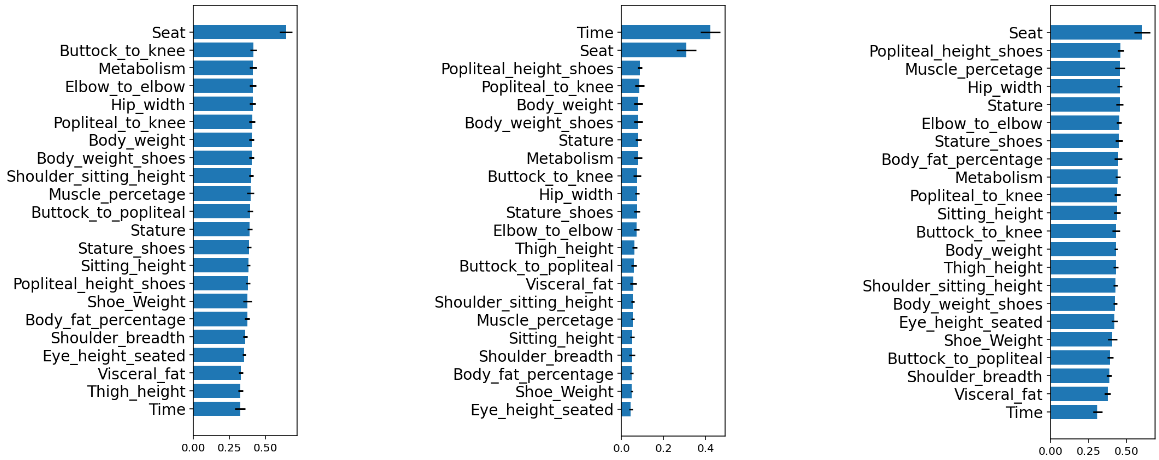
The experiment was conducted at the Comfort Lab, Delft University of Technology, involving 17 participants (mean age: 23 years, 53% male, 47% female) over two consecutive 2-hour sessions in a vehicle buck simulating an automated vehicle, separated by a break averaging 40 minutes. Most participants (71%) identified as West European, with a minority from East and Central Asia (24%).

Anthropometric measurements were collected prior to the first session. The experimental protocol included pre-experiment preparation, two randomized seating sessions, and a break during which participants were free to engage in typical activities such as walking or eating. Participants completed questionnaires on comfort, discomfort and fatigue every 20 minutes during each session using Borg's CR10 Scale for consistency (Anjani et al., 2021).

The data collected during the experiment were processed using a self-developed Python. Although the dataset was not large enough to support the development of a large neural network model (Yang et al., 2021), various machine learning algorithms were evaluated, including Support Vector Regression (SVR), k-Nearest Neighbors (KNN), Linear Regression, Random Forest, Decision Tree, Gradient Boosting, etc. Among these, SVR demonstrated better predictive performance across all three target variables. To optimize the SVR models, hyperparameter tuning was conducted via grid search with 5-fold cross-validation for each model. After training the three SVR models, permutation importance (Y. W. Song et al., 2024) methods were employed to assess the contribution of seat types, anthropometric, body composition, and temporal factors to predictions.

Results

For Comfort, the optimized SVR model achieved a Mean Squared Error (MSE) of 1.95 and an R^2 of 0.46. For Discomfort, the best model yielded an MSE of 0.91 and an R^2 of 0.67. Lastly, for Fatigue, the fine-tuned model achieved an MSE of 1.82 and an R^2 of 0.66. Here the R^2 (coefficient of determination) indicates the proportion of variance in the target variable explained by the model. Higher R^2 values, closer to 1, reflect stronger predictive performance, while lower values suggest limited explanatory power. For example, an R^2 of 0.67 for discomfort means the model explains approximately 67% of the variance in discomfort scores.



(a) (b) (c)

Figure 1: Permutation Importance (horizontal axis) of seat type, anthropometric, body composition and time parameters for (a) comfort, (b) discomfort and (c) fatigue

Figure 1a shows the permutation importance of various seat types, anthropometric, body composition, and temporal features in predicting Comfort. The most influential factor is seat type, followed by several anthropometric dimensions. Among them, Buttock to Knee, Elbow to Elbow, and Hip Width exhibit the highest predictive power, indicating the importance of both lateral and vertical postural support. Additional key anthropometric features include Shoulder Sitting Height, Popliteal to Knee, and Sitting Height, underscoring the relevance of seat back and thigh support. Body composition factors, particularly Metabolism, Body Weight, and Muscle Percentage, show moderate contributions, likely reflecting their role in pressure distribution and seating interface fit. Time has relatively lower importance in Comfort prediction, suggesting that comfort perception is more dependent on static body-seat interaction than on the duration of sitting.

As illustrated in Fig.1b, Time is the most important feature for predicting discomfort, highlighting the accumulating effects of prolonged sitting on discomfort perception. While Seat type ranks second, anthropometric features such as Popliteal Height (with shoes), Popliteal to Knee, and Buttock to Knee show moderate importance, emphasizing the need for adequate lower body support and lateral space. In terms of body composition, Metabolism and Body Weight show some influence, while Body Fat Percentage and Muscle Percentage contribute to a lesser degree. Overall, Discomfort appears to be more time-dependent than Comfort, with a notable influence from lower-body anthropometry and physiological characteristics.

For fatigue (Fig.1c), seat type is the most influential factor, followed by a mix of anthropometric and body composition features. Key anthropometric predictors include popliteal height (with shoes), elbow-to-elbow, and hip width, highlighting the role of vertical and lateral support. Body composition measures, particularly muscle percentage, body fat percentage, and metabolism, also contribute substantially. While time has some influence, it is far less significant than for discomfort, indicating that fatigue is primarily driven by physiological and biomechanical load rather than duration of sitting.

Conclusion

These findings offer key insights into the occupants of long-term seating experiences: Comfort is primarily influenced by seat design and anthropometric parameters, particularly in dimensions related to lower body and torso posture, such as Buttock to Knee, Shoulder Sitting Height, and Hip Width. Discomfort is significantly driven by Time, confirming that prolonged static postures intensify discomfort, especially when combined with suboptimal lower-body support (e.g., Popliteal Height, Stature). Fatigue is best predicted by a blend of seat fit, body composition (e.g., Muscle Percentage, Metabolism), and anthropometry, suggesting that metabolic load and posture-related strain accumulate over time.

In summary, the study underscores the need for ergonomic seat designs that accommodate individual anthropometric variability while mitigating physiological and physical stress over time. Interventions to enhance comfort and reduce fatigue should prioritize postural support, while discomfort can be alleviated by managing seating duration and movement.

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Motion sickness in passenger cars: Effects of motion direction, frequency and magnitude

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ABSTRACT

Driving automation turns drivers into passengers in their own vehicles. As passengers typically suffer much more from carsickness than drivers, this is generally seen as a potential obstacle for the acceptance of automated vehicles. The only international standard for motion sickness is based on research on seasickness, involving studies with vertical motion only. Because in cars horizontal motion is more dominant than vertical motion, it is as yet unclear to which extent this standard can be applied to carsickness. In this study, we investigated differences in motion sickness between different motion directions, including effects of acceleration frequency and magnitude.

KEYWORDS

Carsickness, Motion sickness, Acceleration, Frequency, Direction

Introduction

The ISO 2631-1 (1997) standard on the effects of mechanical vibrations on the human body includes a prediction model for motion sickness. This model is based on extensive research regarding motion sickness due to vertical accelerations, with sickness operationalized as the percentage of the normal population that reaches emesis due to motion exposure. It includes a frequency weighting function, which predicts the strongest impact of accelerations around 0.17 Hz, with sickness decreasing towards both lower and higher frequencies. Several studies (e.g., Griffin & Newman, 2004; Htike, 2021; Salter et al., 2020) have applied this model to predict motion sickness in automated vehicles, despite indications that it may need to be modified for horizontal accelerations (Donohew & Griffin, 2004). Moreover, while emesis is a suitable outcome criterion for seasickness, it would be much more useful to be able to predict pre-emesis symptoms of motion sickness for vehicle passengers, as this may be used to adapt vehicle motion and reduce carsickness. In three laboratory experiments, we investigated the differences in motion sickness between different motion directions (longitudinal, lateral and vertical), acceleration frequencies (from 0.03 to 3.2 Hz) and acceleration magnitudes (0.5 to 4.0 m/s^2), using periodic motion in two different motion simulators. In total 107 participants provided regular ratings of their motion sickness by means of the Motion Illness Symptoms Classification scale (MISC: Bos et al., 2005; Reuten et al., 2021) during motion exposure, as well as Motion Sickness Susceptibility Questionnaire scores (MSSQ: Golding, 2006) regarding their susceptibility to motion sickness and Simulator Sickness Questionnaire scores (SSQ: Kennedy et al., 1993) after each motion exposure.

Method

In total, 107 participants (42 males, 65 females; mean ± SD age: 33.8 ± 13.3 years) were recruited to participate in the three experiments. The largest group (n = 72) took part in the experiment with longitudinal motion, while sample sizes were smaller for the lateral (n = 27) and vertical (n = 33) experiments. Some participants did multiple experiments. Participants were only included if they reported to have suffered from motion sickness at least once in the past three years, were aged between 18 and 60 years and in good general state of health according to self-report. All participants gave their written informed consent before participation and were paid for their participation.

Participants were exposed to continuous periodic motion with several different sinusoidal motion profiles. In the longitudinal experiment, motion frequency varied between 0.03 and 3.2 Hz and peak acceleration between 0.5 and 4 m/s^2 (see Figure 1). Each participant was scheduled to experience three randomly chosen combinations of frequency and peak accelerations in different test sessions, separated by at least 24 hours. Not all combinations were tested, but all peak accelerations were tested with 0.2 Hz, while all frequencies were tested with 2.0 m/s^2 peak acceleration. In the lateral experiment, a subset of these conditions was tested. In the vertical experiment, only a peak acceleration of 2 m/s^2 was used, in combination with frequencies between 0.24 and 3.2 Hz. Participants were exposed to the motion profiles in the enclosed cabin of a motion simulator, seated in a safety seat with headrest and secured by a 5-point safety belt. They could only see the inside of the cabin and auditory motion cues were masked by white or pink noise played over headphones.

During motion exposure, participants reported their motion sickness using the 11-point MISC scale every 2 minutes. The MISC scale allowed participants to rate their motion sickness symptoms according to their severity (MISC 0 = no motion sickness symptoms; 1 = some discomfort, but no specific symptoms; 2-5 = symptoms other than nausea, in increasing severity; 6-9 = nausea in increasing severity, possibly with other symptoms; 10 = emesis). Between MISC ratings, they performed an 90 s auditory 1-back task to control their attention. Motion exposure lasted 20 minutes, or until participants reported a MISC rating > 6, indicating more than mild nausea. Before the first test session, participants filled out the MSSQ. After each test session, they also filled out the SSQ.

	Axis		**n**	**Frequency (Hz)**									**Peak acceleration (m/s^2)**			
				0.03	0.06	0.1	0.2	0.24	0.4	0.8	1.6	3.2	0.5	1.0	2.0	4.0
1.	**Longitudinal**	X	72													
2.	**Lateral**	Y	33													
3.	**Vertical**	Z	29													

Figure 1. Motion conditions in the three experiments. In Experiments 1 and 2, not all combinations of frequency and peak acceleration were tested.

Results

While all combinations of motion direction, frequency and magnitude caused significant motion sickness, both the MISC data and the SSQ results (in particular the Nausea subscale) confirmed a clear dependency on motion frequency. For longitudinal and vertical motion, motion sickness increased most rapidly when participants were exposed to accelerations around 0.2 Hz, with less severe motion sickness for both lower and higher frequencies. This effect is illustrated in the example MISC data shown in Figure 2 for longitudinal motion with a peak acceleration of 2 m/s^2. While for the lowest (0.06 Hz) and highest (1.6 Hz) frequencies shown in the figure none of the participants reached a MISC value above 6, this was often the case for frequencies closer to 0.2 Hz. Statistical analysis (using Cumulative Link Mixed-effects Models) showed that MISC values increased most across all three motion directions when participants were exposed to 0.2 Hz. For lateral motion, the frequency effect was less clear, with similar MISC effects for 0.2, 0.4 and 0.8 Hz. Across frequencies and directions, motion sickness severity increased log-linearly with acceleration magnitude, with the increase in motion sickness as a function of acceleration leveling off at higher accelerations. Motion sickness ratings were on average lower for lateral motion than for longitudinal motion, after correcting for frequency and magnitude effects. As several participants were exposed to lateral motion after having participated in the experiment on longitudinal motion, this may be attributed to habituation due to repeated exposures. Re-analysis of the data from only those participants who took part in one experiment did not show a difference in motion sickness severity between lateral motion on the one hand and longitudinal and vertical motion on the other. The results for the SSQ largely confirmed the MISC results. Moreover, participants who scored high on the MSSQ also on average showed a larger increase in MISC ratings during motion exposure, regardless of motion direction, frequency or magnitude.

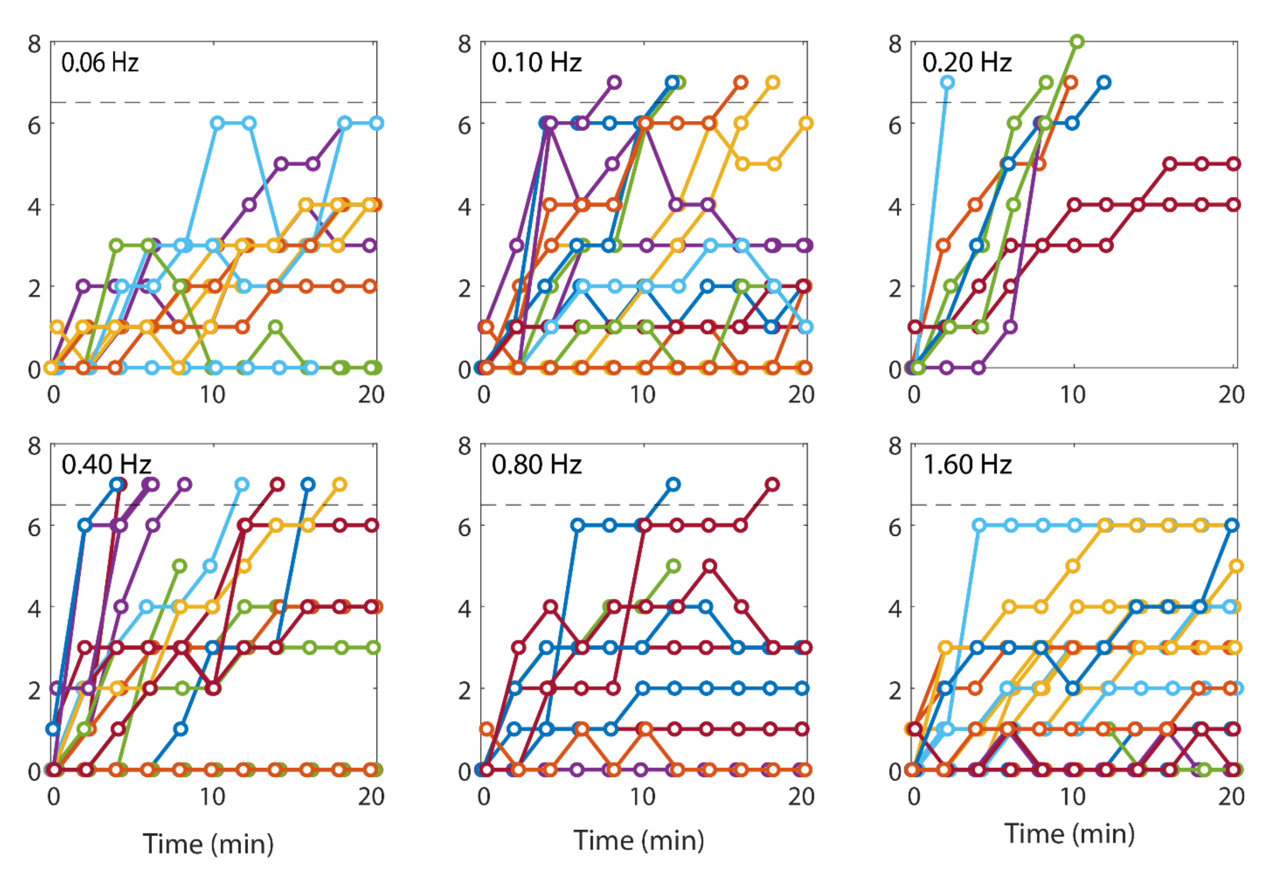

Figure 2. Example MISC data collected during motion exposure. Each panel shows individual MISC data for a different motion frequency (indicated in the top left corner) with a peak acceleration of 2 m/s^2 and motion along the longitudinal axis. Different colours in each panel represent data from different participants (sometimes the same colour is used for multiple particpants).

Conclusions

Our results may form the basis for an extended model of motion sickness, building upon the ISO 2631-1 (1997) model for seasickness. Our results suggest that, like the probability of emesis, the accumulation of pre-emesis symptoms of motion sickness is also frequency dependent, but that the weighting function differs from the one for emesis as reported in the ISO 2631-1 standard. While as a first approximation a common frequency weighting function may be used for motion along the three cardinal axes (Bos et al., 2024), our results suggest that this may need to be further refined in future research. Compared to the ISO 2631-1 model, the frequency effect appears to decrease less quickly above 0.2 Hz for longitudinal and vertical motion. As a consequence, motion sickness measured by pre-emesis symptoms may be underestimated for this range of frequencies when predicted from the ISO model. In addition, the peak of the frequency weighting function may be less clear for lateral motion. This has important implications for the application in automated vehicles, for instance when adapting velocity control or body control to reduce passenger carsickness.

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Enhancing UX in Automated Vehicles through Biophilic Interfaces: Insights from Prospective End Users

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ABSTRACT

Can biophilic design - the integration of natural elements such as waterfalls, animals, plants, and flowers - enhance the user experience in automated vehicles? This study explores this question through a rigorous three-phase methodology. In Phase 1, semi-structured interviews were conducted with 10 experts from the fields of Human Factors, Biophilia, Psychology, and Mechanical Engineering, selected through purposive sampling until theoretical saturation was reached. The promising insights from this phase informed Phase 2, in which 22 participants engaged with a dynamic driving simulator after being exposed to natural elements integrated as mixed-reality interfaces. Subsequent interviews assessed trust, stress, and satisfaction. Phase 3 involved a controlled experiment with 61 participants interacting with a static driving simulator, where they experienced nature-inspired interfaces before participating in follow-up interviews. The collected qualitative data were analyzed thematically using MAXQDA Analytics Pro 20. Thematic analysis identified six key themes, trust and acceptance, technical feasibility, User Driving eXperience (UdX), comfort, intention to use/buy, and emotional connection. The findings provide valuable insights for designers in integrating natural elements into automated vehicle interfaces, fostering both innovation and enhanced user experience. Given the global challenge of trust in automated vehicles, nature-inspired interfaces may serve as a novel approach to bridge this gap, ultimately facilitating wider adoption of automated vehicle technology.

KEYWORDS

Human-Centered Design, Biophilic Design, User Experience, Automated Vehicles, Qualitative Study

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Introduction

Automated vehicles' interiors are changing from being just functional to being designed spaces where efficiency and user experience are equally important (Kim et al., 2023). Users' emotional connection to vehicles become more significant when they give up control of the driving experience (Song et al., 2023). This emotional bond, which is also known as user experience (Berni & Borgianni, 2021), can influence important user feelings such as trust or stress (Sousa et al., 2022). Despite advancements in automated vehicle (AV) technology, many AVs' interfaces continue to appear impersonal and overly mechanical, reflecting a limited incorporation of human-centred design principles. This shortcoming is especially significant in light of the persistent public scepticism toward AVs, indicating that interface design has not sufficiently addressed user trust and engagement (Mosaferchi et al., 2023; Seet et al., 2020). Therefore, in-vehicle interfaces in automated vehicles can play a crucial role in not only ensuring safety and functionality but also in enhancing the travel experience by fostering a sense of trust, comfort, and enjoyment (Large et al., 2019). Biophilia theory was introduced by Edward Wilson (1984) (Wilson) to create a connection between human and nature to lessen daily stress and improve psychological wellbeing and positive feelings such as calm and trust (Zhong et al., 2022). Biophilic design represents an environment which includes green spaces and some other natural elements such as soil, water, fire, and so on (Barbiero & Berto, 2021). Despite being widely used in workplace and architectural design, its potential in automated vehicles yet remains largely untapped (Pandita & Choudhary, 2024). Although only a limited number of studies have explored the application of Biophilic design—both directly and indirectly—in AVs, some have aimed to understand its potential impact on end-users' experience, stress levels, and trust (Li et al., 2021). Notably, one of the foundational studies in this area was conducted by the authors of the present paper, serving as an initial step in this direction (Mosaferchi et al., 2025). Regarding this concept, the current study tried to understand what academic and lay experts think about applying some Biophilic elements inside automated vehicles as interior interfaces.

Method

This study employed a three-phase qualitative methodology to explore the potential of Biophilic design in enhancing user experience within automated vehicle (AV) interfaces. Totally, ninety-two academic and lay experts attended to the study in 3 different steps, and the data were analysed using MAXQDA Analytics Pro 20. In all 3 steps, demographic questions such as their experience with AVs, or having ADAS in their personal cars, were also asked. Additionally, the consent form was completed by participants in the experimental parts. All participants took part voluntarily and were acknowledged with a small gift valued at less than €5.

Phase 1 – Non-interventional Expert Interviews: Semi-structured interviews were conducted with 10 experts from the fields of human factors, psychology, Biophilic design and architecture, mechanical engineering, and artificial intelligence. Participants were selected using purposive sampling and interviews continued until theoretical saturation was reached. The goal of this phase was to gather fundamental insights into the relevance, feasibility, probable advantages and disadvantages/dangers, and perceived benefits/potential user experience of integrating natural elements as audiovisual internal interfaces. Each interview lasted 40 minutes and was conducted online using Microsoft Teams software.

Phase 2 – Dynamic Simulation with Controlled Experiment: Building on the findings of phase 1, 22 participants (12 F, 10 M, Italian students at BSc, MSc, and PhD levels) interacted with a dynamic driving simulator featuring Biophilic elements embedded through mixed-reality interfaces. A dynamic driving simulator was employed in a controlled lab setting at the University of Salerno in Italy, within the Human-Centred and Vehicle Design Simulation Lab. The setup included three 65-inch displays providing a 120-degree field of view, along with an adjustable seat, steering wheel, pedals, and surround sound system. BeamNG software powered the driving simulation environment and Unity game engine v. 2022.3.36f1 was utilized for developing the interventions. To deliver the Biophilic interventions, a Varjo XR-3 headset was used to create immersive overlay-based visual experiences within the driving simulator environment. The Biophilic environment included a variety of natural features: a bird in a wooden cage was placed over the gear to visually signify the fully automated nature of the vehicle; two virtual waterfalls were positioned on the left and right, covering the side monitors; and a cluster of green bushes was layered over the steering wheel, reinforcing the absence of manual control typical of a Level 5 automated car. Additional greenery was placed in front of the dashboard, without obstructing the forward view. It was further enhanced by audible ambient sounds such as birdsong and flowing water. The experiment started without interventions, then after 3 minutes of fully automated driving (FAD), they were given headsets and experienced 10 minutes of FAD with the Biophilic interior design. Following the simulation, semi-structured interviews were conducted (~10 minutes) to assess participants' perceived levels of trust, stress, comfort, satisfaction, and they were asked some open-ended questions to explain how they felt and thought about all interventions.

Phase 3 – Static Simulation with Controlled Experiment: Due to wide range of emotions about all of 4 Biophilic elements (water, green space, bird, wooden parts) which were applied in the previous phase together, the researchers decided to investigate even the user experience for each element alone. So, a larger sample of 61 participants (50 M, 11 F, only non-European students of Technische Hochschule Ingolstadt in Germany to prevent the probable effect of green environments in Europe on their responses) took part in a mixed-design experiment with a half-cab static driving simulator where they were exposed to nature-inspired interface designs prior to engaging in follow-up interviews. All 4 driving scenarios were created via IPG CarMaker v.12, which lasted 12 minutes of FAD totally. Participants were randomly divided into 3 groups with a between-subject design and used a Meta Quest 3 headset to see the interventions which were developed by Unity game engine v. 2022.3.36f1; group A experienced a scenario with some flowers and bushes which covered the steering wheel and created greenery interior interfaces (N=21) in the order of visual-only, audiovisual, and auditory-only, group B faced a scenario containing some waterfalls located on the steering wheel and as central displays (N=21) following a fixed sequence: auditory-only, visual-only, then audiovisual, and group C had a driving scenario including a bird inside a wooden cage, a kitten, and a puppy (N=20) followed the order audiovisual, auditory-only, then visual-only. The interviews were performed at the end of the test and lasted approximately 15 minutes. This phase aimed to evaluate emotional response, usability, and user intentions in a more controlled setting.

Results

Thematic analysis of qualitative data from all three phases of the study, conducted using MAXQDA Analytics Pro 20, yielded six overarching themes: trust and acceptance, technical feasibility, User Driving eXperience (UdX), comfort, intention to use/purchase, and emotional connection. These themes emerged consistently across expert interviews, dynamic simulation feedback, and group-based experiments in the static simulator. However, the setting, exposure type, and sequencing all affected their relative importance and expression.

Trust and Acceptance: Trust emerged as a critical psychological factor influenced by both the presence and presentation of Biophilic elements. Early expert interviews suggested that in the experience of AV travel, natural sensations could act as emotional anchors. This view was supported by participants in the simulator phases, particularly in group B, who reported greater willingness to rely on vehicle autonomy when emotionally engaged through relaxing, living symbols such as waterfalls. One participant noted, "*I felt like I didn't need to control the car—it felt like I was being cared for*", and another one claimed that "*I liked napping since it felt like I was reclining on the beach, even if there were some risky driving*". The audiovisual modality strongly supported trust-building.

Technical Feasibility: Concerns around implementation were raised mostly by experts and second-phase participants. Experts warned against "overuse" of Biophilic features or creating interfaces that distract more than they support. Participants in phase 2 occasionally reported concerns due to limited side visibility caused by visual elements. In phase 3, group C participants expressed worry when animals moved around, fearing they might engage in potentially disruptive behaviour — for example, touching buttons or controls that could interfere with the car.

User Driving eXperience (UdX): Biophilic design had a clear effect on perceived driving experience. Participants described the AV cabin as "*more welcoming*", "*fun*", "*novel and innovative*", and "*comfortably alive*" when natural elements were integrated. In particular, the combination of visual and auditory input contributed to a sense of immersion and presence, which was repeatedly linked to reduced boredom and improved satisfaction.

Comfort: Comfort was deeply intertwined with Biophilic design. Across all groups, the audiovisual condition was reported as the most balanced and pleasant. The auditory-only condition, especially when experienced without visual context, received mixed reactions—some described it as "relaxing" especially for waterfalls, while others called it "*confusing*" or "*isolated*". In particular, the dog's barking and the cat's meowing caused them to unintentionally search for the source of the noise.

Intention to Use/Buy: Intention-related themes surfaced more clearly in the third phase. In the third phase of the study, group A and B participants who interacted with flowers/bushes and waterfalls respectively, expressed a surprisingly strong desire to encounter similar interfaces in real-world vehicles, even framing them as features they would "look for" in future purchases. Others, particularly in Group C, were more cautious, noting they would prefer such interfaces (animals and birds) to be optional. Nevertheless, exposure to Biophilic elements increased openness to AVs in general, especially they mentioned that it is worthy to pay more for an AV with these interventions.

Emotional Connection: This theme stood out most clearly in the responses of those who engaged with waterfalls and animals or multisensory stimuli. Participants described feelings of affection, familiarity, and warmth—sometimes even assigning personalities to virtual elements. A recurring sentiment was that these designs made the car feel "less robotic" or "more human-centred" The effect was particularly strong in those exposed to audiovisual elements first, suggesting that initial affective engagement plays a formative role in shaping overall experience.

In summary, the MAXQDA-assisted analysis reveals that Biophilic design can play a pivotal role in shaping how users relate to automated vehicles—emotionally, perceptually, and functionally. Its success, however, depends not only on what natural elements are used, but how they are introduced, and users interact with, in what sensory combination, and at what moment in the AV experience. Although, using these relaxing components excessively might have negative effects, including discomfort or fatigue.

Conclusion

This study explored how integrating natural elements into automated vehicle (AV) interfaces can shape user experience. Across expert interviews and simulator sessions, Biophilic design—especially when audiovisual—was found to foster greater trust, comfort, and emotional connection. Participants often described these environments as more human-centered, trustworthy, and calming, particularly when sounds like waterfalls and birdsong were combined with visuals. However, respondents also highlighted significant subtleties: features like animals prompted questions about cleanliness and distraction, while sound-only configurations occasionally felt confusing. Despite their general receptivity to Biophilic features, respondents stressed the importance of careful, optional, and context-sensitive design. Depending on how, when, and in what sensory form it is introduced, Biophilic design may prove to be a potent instrument for increasing AV acceptance, according to these studies. Future studies should look at cultural variations, long-term use, and real-world implementation issues to help improve these interfaces for wider use.

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Seat comfort assessment through pressure map analysis: a tool for automated Mergl-model mapping

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ABSTRACT

One of the most common method to experimentally assess the perceived comfort while seating is the analysis of pressure map at the interface between the seat-parts and the seated human. Several pressure-distribution based methods have been developed for analyzing objective data coming from user experience or experimental setups. The Mergl model is one of the most used in data analysis for synthetizing the output data in a few-parameters dataset. In fact, in the Mergl's Comfort Model, the human body is divided into different comfort zones, each of which has a different physiological response to pressure, and allows for detailed analysis of the distribution of pressure in different body zones. The main goal of this paper is the development of a tool that is able to process data of Pressure-mats, using the Mergl's model, and to create a dataset of few parameters that describes the pressure map through the most commonly used measures: mean pressure, pressure peak, pressure distribution, Variance in space and time. The study is based on an experimental dataset acquired through the use of the XSensor mat: the automated tools allows to take as input the pressure data (experimental or simulated), due to the interaction between the user and the seat, and to automatically identify the Mergl's partition of pressure map in seat-referenced areas. The developed tool allows also to extract, for each area, parameters like pressure peaks' value and location, average pressure and load distribution. This information, returned by the software in a clear and detailed way, provides an accurate view of the phenomenon, and can be used by designers or researchers to modify seat design or study interventions to improve driver comfort. The tool has been used for analyzing experiments' data and was able to reveal differences between drivers, taking into account individual anthropometric characteristics and differences among seats while used by the same user.

KEYWORDS

Pressure Map, Mergl model, Automated tool, Human-Seat interaction, Feature extraction

Introduction

Thirty years of scientific literature show that the best way to be able to objectify comfort is to record and analyze the pressure map at the human-seat interface [1; 2] and relate that data to subjective parameters obtained from questionnaires [3]. Most of the commercial software that allows real-time acquisition of the interface map already has the ability to manually divide it into zones and evaluate the pressure trends within these zones, but only in terms of peak pressure and mean pressure. However, it has been seen [4] that basing this assessment only on these two aspects is limiting since to get a more comprehensive view of the whole phenomenon it is necessary to consider an higher number of parameters: contact area [5, 6], contact force [7], percentage of load

[5], variance, coefficient of variation [8], pressure gradient [9]. Each of these factors are closely related to (dis)comfort.

Usually, a large amount of time is needed to manually extract these features and calculate their values. For this reason, the software "SPA360-Seat Pressure Analyzer" has been developed in order to have the possibility, in the user experience feature extraction phase, to analyze the acquired pressure map in a quasi-automatic way and, in the postprocessing phase, to return a series of tables in which all the parameters that are used for objectively determining (dis)comfort, were calculated for each zone, thus minimizing time. This first version of the software is based on Mergl's Comfort Model [2]; the SPA360 software, starting from the pressure map acquired with the XSensor mat [10], divides it into the 17 Mergl zones and, for each of them, automatically calculates: peak pressure, average pressure, contact area, variance, coefficient of variation, contact force, and percentage of load on the zone along the time of acquisition.

Materials and Method

Test description

A sample of 50 people having different age, gender and anthropometric characteristics has been used for acquiring data. The full dataset of the sample is in the following boxplot:

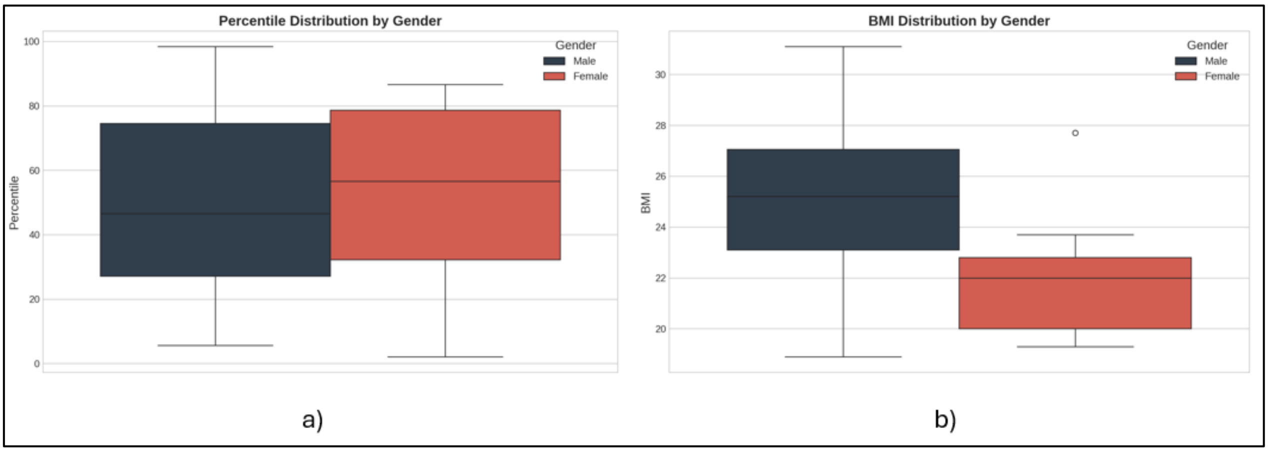

Figure 1: a) Percentile distribution according to gender; b) BMI distribution according to gender

Pressure maps have been acquired by XSensor pressure mat for 3 minutes with a sampling of 27 frames per second. The time of 3 minutes was decided to ensure that the human body could settle completely inside the seat and to average the effects of micro-movements. During this time, the testers were asked to wait while standing still. Three minutes of acquisition have been merged in a single averaged (in time) map , for pressure analysis, in order to grab one dataset from each tester and avoid an overflow of redundant data.

The in-lab experimental setup

A fully-adjustable seating buck equipped with car seat (B-Segment Car), pedals, gear-shift and steering-wheel, was used for in-lab experimental analyses. The XSensor pressure mat was positioned to fully cover the seat surface, ensuring optimal sensor placement and precise alignment with the seat's central axis following this standardized procedure: 1) Seat covering; 2) Alignment of pressure sensors rows with horizontal reference point opportunely tracked on the seat; 3) Fixing the pressure mat with double sided adhesive tape on quite-flat surfaces; 4) Check of sensors position by picking some reference points; 5) Blocking the rear part of pressure mat on the seat using tape.

Proper mat alignment and fit are critical to ensure that pressure map acquisition is reliable and free of background noise.

The in-car experimental setup

The same experimental setup was repeated inside a real car (a B-segment car) in order to acquire the pressure map in a real car-environment. Pressure mat for in-car acquisitions was positioned following the same procedure that was carried out for the in-lab experiments; in order to have a direct comparison and to decouple the experiment from the variability of the environment, the same seat was used as in the experiments done in the lab.

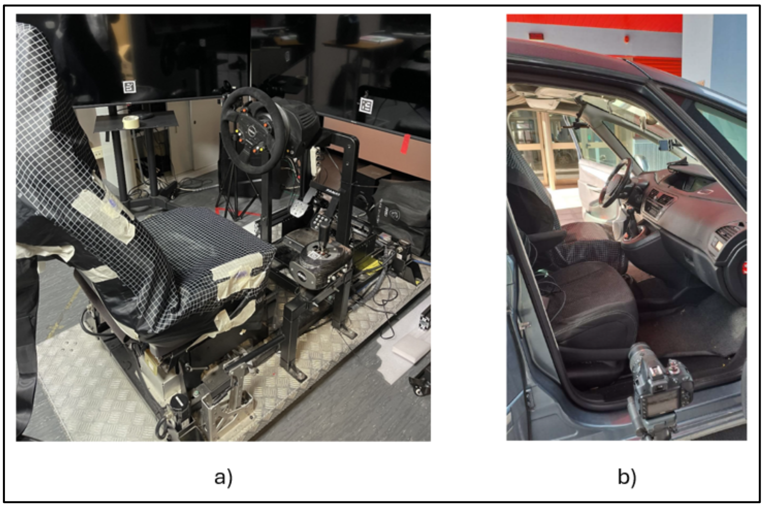

Figure 2: a) Laboratory Seating Buck; b) In-car Experimental setup

Development of in-house software

Data acquired by XSensor software are downloaded in MSExcel® format and uploaded in SPA360 that has been programmed in Phyton language. The strategy of analyzing data is based on some preventive steps to set the analysis and the execution of main tasks for identifying areas.

XSensor data are exported to MSExcel® in .csv format for being transformed in a table that is used as input for SPA360 whose main interface asks for the position of head/foot on the map and on the used Comfort Model. The default model is the Mergl one, but SPA360 is open to be customized for other Comfort models based on pressure analysis. As first step, the user can divide with a line the map between Seat-Pan and Backrest parts in order to separately analyze them. The user can define a centre line for dividing left part from the right part of the seat and two lines for setting the position of the bolsters' bounds, both for seat-pan and for backrest. The software automatically filters and delete the outlines values. Finally, SPA360 is able to recognize the Mergl map on the basis of this criteria:

1) Recognizing the starting and the ending point of the map using a threshold on active cells per row ("active cell" is a cell that measures a pressure greater than zero);
2) A sub-matrix of the whole XSensor-matrix is extracted and the number of cells that belongs to each of Mergl map's part is calculated in proportion of Mergl map's parts itself;
3) Each part is recognized and all parameters are calculated.

Results

Once the pressure map analysis is completed, the software saves all related images in a single folder, and generates an Excel file containing, for each zone, the peak pressure, the average pressure, and the minimum pressure values, along with detailed information related to the contact area. Additionally, the Excel file includes a summary worksheet, named “Results Tables,” which allows for faster and more intuitive data examination, facilitating the comparative analysis of the information recorded for each zone.

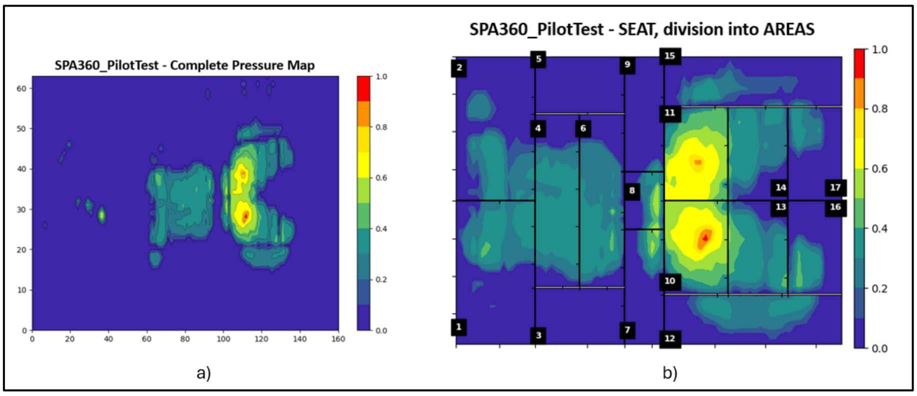

Figure 3: a) Row pressure map from XSensor; b) Final division with the Mergl's Comfort Model in SPA360

SPA360_PilotTest -

SEAT CUSHION

Max Pressure [N/cm2]		Average Pressure [N/cm2]		Load Percentage [%]	
Area 10	0.95	Area 10	0.52	Area 10	26.43
Area 11	0.81	Area 11	0.52	Area 11	27.11
Area 12	0.35	Area 12	0.24	Area 12	8.84
Area 13	0.52	Area 13	0.32	Area 13	13.14
Area 14	0.48	Area 14	0.3	Area 14	12.12
Area 15	0.4	Area 15	0.22	Area 15	5.16
Area 16	0.45	Area 16	0.3	Area 16	4.2
Area 17	0.37	Area 17	0.26	Area 17	3.05

BACKREST

Max Pressure [N/cm2]		Average Pressure [N/cm2]		Load Percentage [%]	
Area 1	0.45	Area 1	0.28	Area 1	22.33
Area 2	0.4	Area 2	0.25	Area 2	19.68
Area 3	0	Area 3	0	Area 3	0
Area 4	0.41	Area 4	0.31	Area 4	24.88
Area 5	0	Area 5	0	Area 5	0
Area 6	0.49	Area 6	0.3	Area 6	21.95
Area 7	0.55	Area 7	0.32	Area 7	4.68
Area 8	0.56	Area 8	0.33	Area 8	5.66
Area 9	0.41	Area 9	0.25	Area 9	0.76

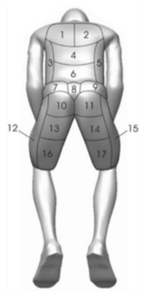

Figure 4: Example of MSExcel Summary Table Results

About 100 maps have been processed (50 in lab and 50 in-car) and Mergl map has been calculated both manually and with SPA360. The results are quite the same, with an error in recognizing the map’s parts and the pressure values always lower than 5%. Finally, the use of the software has been tested also in-car application for examining driver postures during a standard simulated ride, obtaining very good results.

Conclusion

The developed software was able, in more than 100 tests, to analyze a complete pressure map coming from a full-seat covering pressure mat (XSensor) and to recognize the Mergl map independently from percentile and user task. This feature allows to quickly collect information for comfort analyses and to compare different seat with a wide range of users. Validation on experimental data demonstrates the ability of the tool to distinguish variability between users due to anthropometric differences and variability between different seat configurations. One limitation of the software, while using it for in-car acquisition, is due the unawareness of vibration effects on pressure values, especially the ones coming from bumps or dynamic stresses. The second limitation has to be recognized in the effects, on pressure maps, when the acquisition is done on seats with complex geometries, like sporty-car seats. In that cases the errors in recognizing the Mergl map can be higher. Finally, the software is not able to recognize user-movements that can cause a Pressure mat movement on the seat, so measuring and averaging wrong maps.

Nevertheless, the proposed identification logic can be replicated also on different maps, like the Yao-Vink Model for plane seats [4] and on different kinds of seat, just changing the thresholding rules.

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Vibration isolation in neonatal transportation systems using a resilient biasing device

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ABSTRACT

The impact of vibration on neonatal health and wellbeing during transport has been a significant concern, necessitating the development of vibration isolation systems. Variations in road conditions, driving styles, and ambulance types contribute to the complexity of mitigating vibrations during neonatal transport. Current isolation methods include suspension systems, damping systems, and mattress selections. However, ongoing research and innovation in vibration mitigation technologies are crucial to ensure the health and safety of neonatal patients during transport. This paper introduces a newly invented and patented resilient biasing device capable of storing elastic energy (Afazov, Mansfield et al., 2023) and effectively isolating vibrations. This study investigates the vibration isolation capability of this device and explores its potential application in neonatal transport systems using an experimental system and modelling. Both experimental and finite element analyses results demonstrated that the resilient biasing device can effectively isolate vibrations. Comparative analyses of predicted transmissibility between the resilient biasing device and a helical spring revealed that the resilient biasing device exhibits lower vibration transmissibility values in the transverse and longitudinal directions while maintaining similar performance in the vertical direction.

KEYWORDS

Resilient biasing device, vibration isolation, neonatal incubator, finite element analysis

Introduction

The impact of vibration on neonatal health during transport has been a subject of concern. Studies have highlighted the potential risks and the need for effective vibration isolation systems. Bowman et al. (1988) found increased mortality in preterm infants transferred between tertiary centers, suggesting a link between transport and deteriorating health. Mansfield (2004) and Karlsson et al. (2011) identified health problems in adults due to vibrations, including stress to the nervous system, and increased blood pressure suggesting negative wellbeing and discomfort. These findings underscore the importance of addressing vibration exposure in vulnerable populations, such as neonates. Vibrations during neonatal transport vary due to road conditions, driving style, and ambulance model (Kehoe et al., 2024).

Current methods of vibration mitigation in ambulances include suspension systems, stretcher damping, and mattress selection. Pier, Misuraca, and Mandt (2024) compared different suspension systems and found liquid suspension systems to be the most effective. Kuren and Shukla (2005) showed that thicker wheels on stretchers provide better damping, while Gajendragadkar et al. (2000) highlighted the importance of selecting appropriate mattresses to avoid resonance. These methods aim to reduce the transmission of vibrations to the patient, thereby improving comfort and safety. Incubator suspension systems have been developed to further reduce vibration exposure. Goswami et al. (2020) described active vibration control systems that use sensors, controllers, and actuators to cancel out vibrations. Air-spring based systems use pressurized air chambers to reduce vibrations, while floating patient support systems, as discussed by Sabota, Aghili, and Segars (2013), allow the incubator to move freely, reducing vibrations in multiple axes. Wang et al. (2020) demonstrated quasi-zero stiffness systems that can dampen over 70% of vibrations, and McManus et al. (2002) described magnetorheological fluid-based systems that use MR fluid to change viscosity and reduce vibrations. Further considerations include focusing on vertical vibrations, as emphasized by Guruguntla et al. (2023), and optimizing vehicle speed and routes to reduce vibration exposure, as suggested by Blaxter et al. (2017). These strategies, combined with advanced vibration isolation systems, can significantly enhance the safety and comfort of neonatal transport.

Afazov and Mansfield et al. (2023) invented and patented a novel resilient biasing device capable of storing elastic energy. This device functions similarly to a mechanical spring, providing effective vibration isolation. The primary objective of this paper is to investigate the vibration isolation capabilities of this device and explore its potential applications in neonatal transport systems.

Experimental System

The system depicted in Figure 1 was designed and prototyped to simulate ambulance-induced vibrations encountered during neonatal transportation. Fixed to an electrodynamic LDS V780 shaker system was an aluminum plate interfaced with a prototype 42kg rigid neonatal incubator via four resilient biasing devices to emulate a suspension system. The devices were designed using PLA material and 3D printed. The four resilient biasing devices were designed with a thickness of 3.8 mm, height of 96 mm and extrusion width of 120 mm. The shaker system delivered harmonic sinusoidal vibrations at an acceleration amplitude of 0.1 g (0.981 m/s^2) and frequencies in the range of 0 - 80 Hz. The vibration transmissibility was obtained as the ratio of the acceleration amplitudes from accelerometers mounted on the plate and incubator.

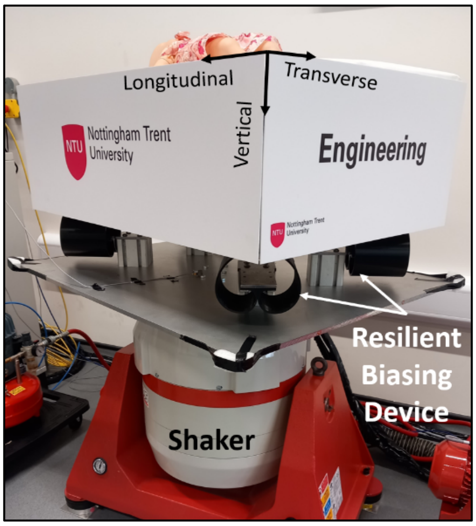

Figure 1: Experimental system

Finite Element Analysis (FEA) Models

FEA models were developed in ANSYS (Figure 2) to represent the experimental system. The resilient biasing devices were modeled with shell elements and thickness of 3.8 mm was specified to represent the experimental system. Other thickness values were investigated where the thickness value was changed. The mass of the prototype neonatal incubator is represented as a point mass attached to the resilient biasing devices using rigid beam elements connecting the point mass with the finite element nodes at the top of the device. Young's modulus of 3.8 GPa, Poisson ratio of 0.41, and density of 1250 kg/m³ were used for the PLA. A static analysis was performed at a gravitational load of 9.81 m/s^2. The predicted stresses were used as an input into a modal analysis where the natural frequencies and mode shapes in the range of 0 – 100 Hz were predicted. The predicted mode shapes and natural frequencies were inputted into random vibration analysis. An acceleration profile representing 0.1 g (0.981 m/s^2) for frequencies in the range 0 – 100 Hz was applied at the fixed nodes. A damping ratio of 0.04 was applied. The predicted accelerations at the top of the resilient biasing devices were used to determine the vibration transmissibility. For

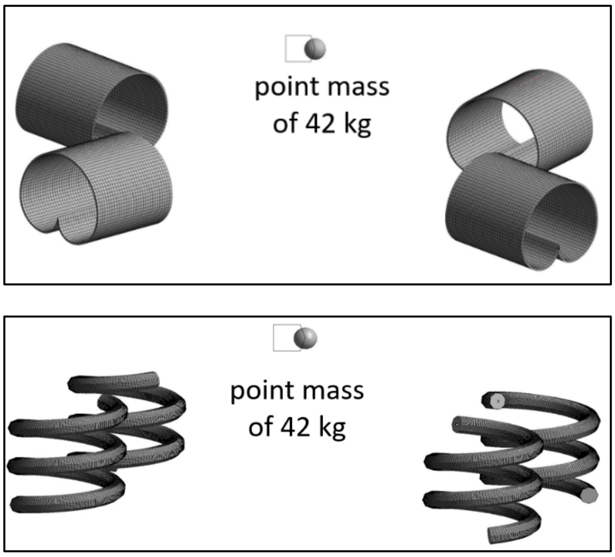

Figure 2: FEA models using the device and helical springs

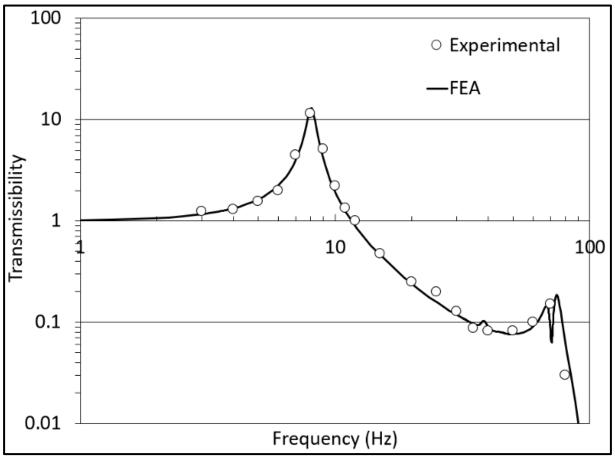

Figure 3: Comparison of the experimental and modelled transmissibility (vertical direction).

comparison a finite element model was developed for helical springs with a pitch of 60 mm, a diameter of 156 mm, and a wire diameter of 16.65 mm, using the same material properties for PLA and damping ratio of 0.04.

Results and Discussion

Similar results were obtained between the experimental and FEA predicted transmissibility in the vertical direction, particularly evident around the compression resonance at 8 Hz (Fig. 3). Above 12 Hz transmissibility dropped below 0.1 (90% isolation).

The design of an incubator suspension needs consideration of ambulance characteristics, including structural dynamics, road and engine dynamics, and driving style (Uchima and Idehara, 2024). Consequently, for effective vibration isolation within this frequency range, a reduction in natural frequency is needed, necessitating stiffness adjustments. Both suspension systems were re-modeled to exhibit similar vertical stiffness, material properties, and design space. However, it's noteworthy that the helical springs were about 3.46 times heavier than the resilient biasing devices. The resilient biasing device could reduce the resonant frequency in all directions simultaneously (Figure 4) whilst the helical springs properties were only improved in the vertical direction. This comparison highlights the capability of the resilient biasing device to isolate vibrations in multi-directions and achieving lightweighting.

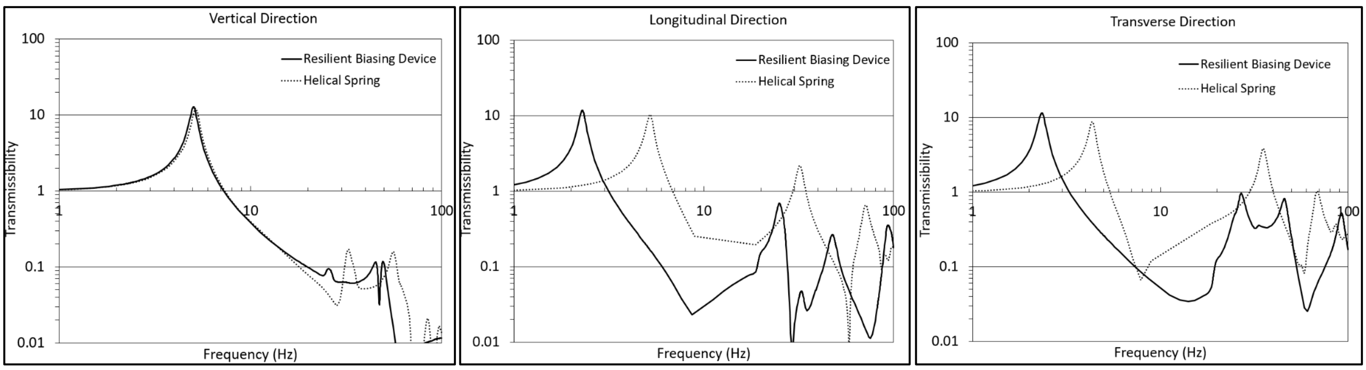

Figure 4. Transmissibility for the device and helical spring in the vertical, longitudinal and transverse directions (FEA data).

Conclusion

An experimental system and finite element models of a prototype neonatal incubator using a novel resilient biasing device shows effective isolation of ambulance-induced vibrations encountered during neonatal transportation. Comparative analysis of predicted transmissibility for systems using resilient biasing devices and helical springs revealed that the resilient biasing device exhibits lower transmissibility values in the transverse and longitudinal directions while maintaining similar performance in the vertical direction. It was found that for the same compression stiffness and resonance frequency using the same material, the resilient biasing devices was 3.46 times lighter that the helical springs. Overall, the resilient biasing device shows promising potential for isolating vibrations in multi-directions, which could lead to innovative design solutions for neonatal incubators and other transport applications.

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Computational Modeling of Human-Seat Interaction for Optimal Headrest Positioning

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ABSTRACT

Modern vehicle seats often include adjustable features that allow passengers to customize their seating position for optimal comfort. One key feature is the headrest, which is typically adjustable in height to accommodate passengers of different sizes. Some designs offer additional adjustability, such as rotation or tilt angle adjustments. However, determining the ideal headrest position for optimal comfort remains challenging due to numerous variables, including individual differences in passengers' anthropometric characteristics, seating activities, and seat configurations, such as backrest inclination. Compared to empirical methods, computational methods are significantly less time-consuming and do not require physical prototypes for experimental testing. This study employs a computational model to simulate human-seat interaction, including sitting posture kinematics and predicted headrest supporting force under various seating conditions. The model shows a strong correlation with experimental data ($\rho = 0.863$), supporting its use in predicting customized headrest positions aligned with comfort guidelines related to headrest contact loading. The proposed model can be applied to ergonomic seat design and automated support systems to enhance passenger comfort.

KEYWORDS

Headrest ergonomics, user-centered design, human modeling, comfort

Introduction

The transportation vehicle seat headrest serves a fundamental role in both safety and ergonomics. Primarily, the headrest acts as a support and restraint for the head-neck region, helping to prevent neck injuries in emergency situations (Aerospace Standard AS8049D). Beyond its safety function, the headrest provides ergonomic support, stabilizing the head and neck for comfortable resting positions. Literature shows for over 62% of observed postures when sitting in the aircraft seat, the headrest is utilized to improve relaxation (Liu et al., 2019). Although aircraft seats or other kinds of seats are usually equipped with ergonomic or adjustable mechanisms on the headrest, such as the raised cushion thickness and extendable headrest height adjustment, issues are still observed that the cabin seats may have inadequate head support for taller passengers, leading to excessive neck bending and fatigue; therefore, liftable headrest mechanisms have been applied. Sensor-based solutions for head-neck support improvement were also generated and proven to be effective in improving the passenger's experience (Tan Cheefai, 2010).

However, determining the ideal headrest position for optimal comfort remains challenging due to numerous condition variables involved, including individual differences in passengers' anthropometric characteristics, seating activities, and seat configurations, such as backrest inclination. Various seating conditions, resulting from the combination of the numerous factors mentioned above, become difficult to achieve in a physical experiment setting. Compared to empirical methods, computational approaches offer substantial advantages, notably reduced time requirements and the elimination of physical prototypes for testing. By adjusting specific input variables, computational models can efficiently simulate varying seating conditions, making them particularly useful for overcoming the limitations of experimental methods during early-stage design.

This study presents a seated human model that describes the interaction between the body and both the backrest and headrest surfaces. The application of the presented model contributes to understanding the headrest ergonomics and developing practical guidance for comfortable seat configuration and adaptive support systems.

Method

The primary contribution of this study is the development of a model that captures the interaction between the head and the headrest. The upper body along with the seat backrest is modeled to represent the trunk posture associated with a given backrest inclination. This trunk posture serves as the foundational reference for predicting the movement and positioning of the head and neck region. The modeling framework is implemented using MATLAB R2022a.

First, the backrest and headrest are modeled as flat rectangular boxes to effectively represent their orientation and relative positioning. Both components share a width of 50 cm, while the heights are set at 50 cm for the backrest and 18 cm for the headrest. The headrest's position relative to the backrest is defined by three key parameters: vertical height (H), horizontal protrusion (D), and rotation angle (θ_H). These parameters are referenced from the front top edge of the inclined backrest (inclination angle. θ_B) within the sagittal plane, as illustrated in Figure 1.

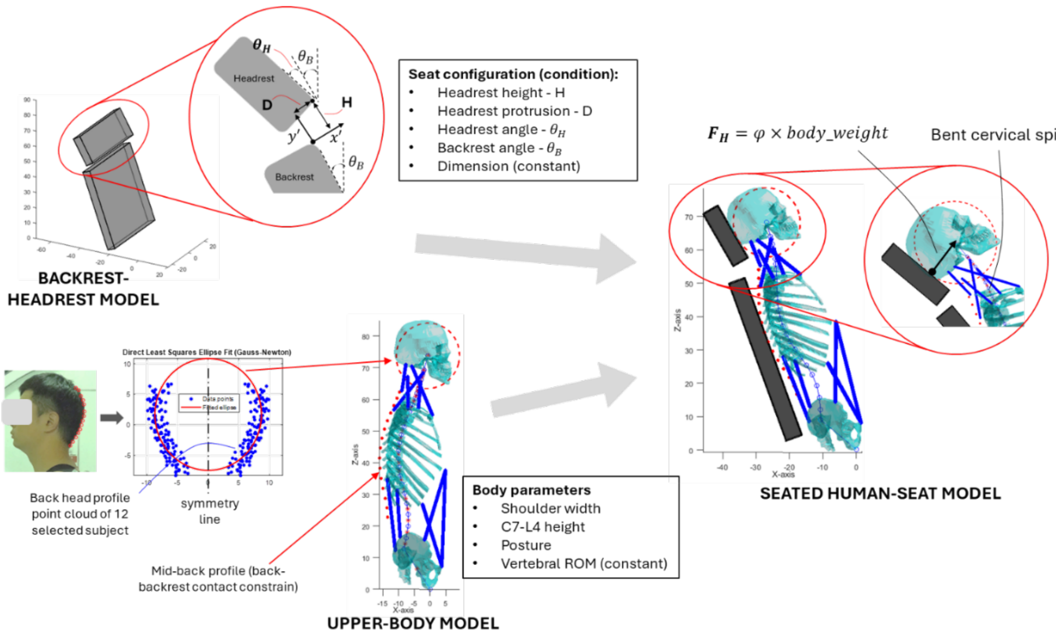

Figure 1. Modelling of the simplified seat and the human upper body

Second, the upper body model was modeled with three key elements. 1) Sitting posture kinematics: the upper body follows a pattern of movement due to the fallibility of the spine in compliance with the inclination of the backrest, as the trunk is not a single solid body. A slouched spine (Kitazaki & Griffin, 1997) was selected as the datum posture for the spine posture variation, and the intervertebral disc 3-axis range of motion (ROM) data (White & Panjabi, 1990) was used to determine the ratio of rotation at each spine joint to form the target posture. Because this model has different contact constraints on the back and the neck, the thoracolumbar ($1 < n \leq 17$) and shoulder-neck region (n>17), divided by the average back-backrest contact boundary at T3 level (Zhong et al., 2025), are computed separately, referring to Eq (1). P_n is the position of any spine joint, $\mathbf{R}$ is the rotation matrix; $\boldsymbol{\theta}_{0_{yj}}$ is the initial joint angle that forms the datum posture; K is the rotation factor ($0 \le K \le 1$), defining the extent of bending in three axes. As this study only investigated the sagittal movements, K_x and K_z both equal to zero. Similarly, the neck was modeled using the same method, with fewer links in the neck region (T3-C1). The rotation factor (k) applied in the cervical region (n>17) defines the movement of the neck. 2) Midback profile: the shape of the midline of the back in the sagittal plane, which was used to represent the back geometry interacting with the backrest surface. 3) Back-head profile: The sagittal shape of the back of the head is based on pictures taken from the lateral side of selected 12 subjects from previous studies (Zhong et al., 2025). It is approximated by fitting an ellipse to the head profile point cloud using a least-squares approach with the Gauss-Newton algorithm, resulting in the half-lengths of the major and minor axes, denoted as a and b. The local origin and orientation of the fitted ellipse are then aligned with the head center, corresponding to the top joint of the spine model.

$$P_n = \begin{cases} \sum_{i=1}^{n}\left\{\left(\prod_{j=1}^{i} \boldsymbol{R}_y\left(\boldsymbol{\theta}_{0_{yj}} + (K_y)ROM_{y_j}\right)\boldsymbol{R}_x\left((K_x)ROM_{x_j}\right)\boldsymbol{R}_z\left((K_z)ROM_{z_j}\right)\right)[0\ \ 0\ \ l_i]^T\right\}; & 1 < \mathrm{n} \le 17 \\ P_{17} + \sum_{i=18}^{n}\left\{\boldsymbol{R}_{17}\left(\prod_{j=18}^{i} \boldsymbol{R}_y\left(\boldsymbol{\theta}_{0_{yj}} + (k_y)ROM_{y_j}\right)\boldsymbol{R}_x\left((k_x)ROM_{x_j}\right)\boldsymbol{R}_z\left((k_z)ROM_{z_j}\right)\right)[0\ \ 0\ \ l_i]^T\right\}; & \mathrm{n} > 17 \end{cases} \tag{1}$$

Third, the human-seat model is constructed based on the interaction between the configured seat geometry and the scaled upper body model leaning against the seat surfaces. The posture of the thoracolumbar spine is determined by identifying the intersection point between the backrest surface and the midline profile of the upper body. This intersection is located using the sign change in the cross-product between $v_{backrest}$, the vector along the backrest surface, and v_{back_i}, the position vectors of mid-back profile points relative to the lower edge of the backrest. Similarly, the position of the head and neck is constrained by a tangent intersection with the headrest surface. The back head profile approximated as a fitted ellipse, is shifted and rotated in the sagittal plane and expressed analytically as shown in Eq. (2), where (x_0, y_0, θ) represent the ellipse center coordinates and rotation angle, all defined as functions of a spine curvature parameter k. The headrest surface in the sagittal plane is modeled as a linear function $z = px + q$. The tangent contact condition between the head ellipse and the headrest is formulated as a repeated root condition of a quadratic equation (Eq. 3), whose discriminant equals zero. Solving this equation yields the only unknown variable, k_y, which characterizes the sagittal bending of the neck in response to the contact constraint. A graphical illustration of this modeling process is provided in Figure 2.

$$Ax^2 + Bxz + Cy^2 + Dx + Ez + F = 0 \tag{2}$$

$$A = a^2 sin^2\theta + b^2 cos^2\theta;\ \ B = 2sin\theta cos\theta(a^2 - b^2);\ \ C = a^2 cos^2\theta + b^2 sin^2\theta$$
$$D = -2x_0A - z_0B;\ \ E = -2z_0C - x_0B;\ \ F = Ax_0^2 + Cz_0^2 + Bx_0z_0 - a^2b^2$$

$$(Bq + 2Cpq + D + Ep)^2 - 4(A + Bp + Cp^2)(Cq^2 + Eq + F) = 0 \tag{3}$$

Next, the headrest supporting force is estimated based on the modeled interaction between the human body and the seat configuration. Under static sitting conditions, the head–neck region can be treated as a single rigid body pivoting at its base, with its weight counterbalanced by the supporting force from the headrest surface. The supporting force, which acts normal to the headrest surface, can be calculated using moment equilibrium with lumped mass assumption (head-neck gravitational force of 7.83% body weight (Ramachandran et al., 2016) acting on the head CG). In this study, several potential joints from the lower cervical and upper thoracic spine (T5 to C5) were tested as candidates. For each, the resulting headrest force was computed and compared to the data obtained from a previous seating experiment involving 26 subjects. The pivot point yielding the lowest mean average error (MAE) relative to the measured forces was selected.

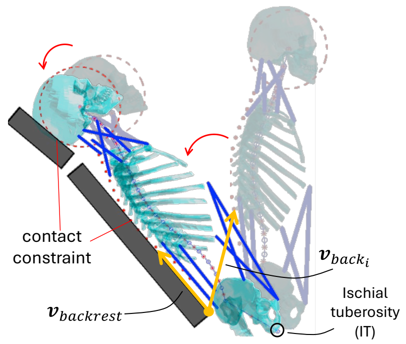

Figure 2. Modeling process of human-seat interaction

Results

Based on the developed human-seat model that simulates the trunk–backrest and head–headrest interaction, the upper body sitting posture kinematics for a given backrest inclination and body type were first determined by solving the key spinal movement parameters ($\boldsymbol{K}$ and $\boldsymbol{k}$), as illustrated in Figure 1 and Figure 2. Subsequently, the supporting force from the headrest under these conditions was calculated using data from 130 seating trials involving 26 subjects with varying body types across backrest inclinations ranging from 20° to 60° relative to the vertical. Outliers (5) with substantial errors were excluded from the analysis. Various candidate pivot points were evaluated for simulating the headrest force, and the joint located below the T5 vertebra yielded the lowest mean absolute error (MAE) of 7.6 N. The simulated headrest forces showed a strong agreement with the experimental data, exhibiting a high Pearson correlation ($\rho = 0.863$), as shown in Figure 3. A correction constant of 6 N was then applied to the force model, which further reduced the MAE to 5.4 N while maintaining a similar standard deviation.

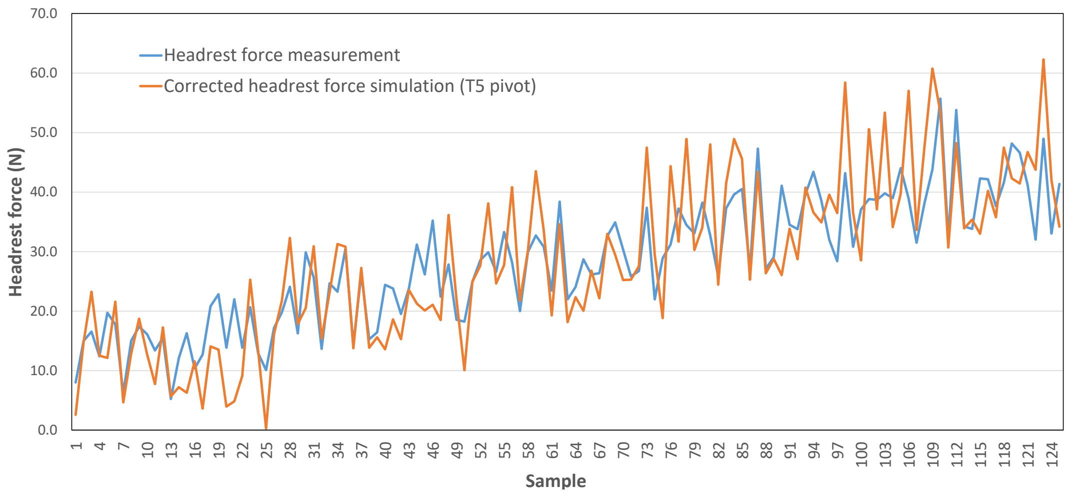

Figure 3. Headrest force measurement and simulation results

Conclusion

A human-seat interaction model based on computational dynamics has been developed in this study. Different test conditions are used as input variables to simulate the sitting posture and supporting force from the headrest, using a selected pivot point at the T5 vertebra that provides the most realistic results. The theoretical head–headrest interaction model can be used to identify the optimal headrest position based on comfort guidelines related to headrest contact loading, enabling faster iteration and allows for customized headrest design across various seat inclination angles and occupant body types.

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Achieving Comfort for Children's Products

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ABSTRACT

Children have no influence on the design of the products they use and no legislative power to influence their improvement. Also, they have few advocates, and beyond product standards there is little organized knowledge about their ergonomic and comfort needs. Purchase decisions for children's products are based on many factors not relevantly connected to ergonomics, including color, "cuteness-factor", perceived safety and price. As a result, children's products are frequently associated with comfort challenges, not only for the child but also for the adult responsible for setup and adjustment. This paper examines how adult-mediated interactions with such products can influence child comfort, emphasizing the dual-user interface inherent in design. Drawing on over three decades of comparative product testing, we analyse ergonomic deficiencies, physiological and psychological sources of discomfort, and highlight design trends that contribute to or mitigate these issues.

KEYWORDS

Children's products, dual-interface, product design, comfort, ergonomics

1. Introduction

Children's products often present intrinsic comfort limitations and have elements that cause discomfort. These products typically feature a dual-user interface: the child is the end-user, while an adult - usually a parent or caregiver - is responsible for adjustment, positioning, and maintenance. This duality renders the adult an essential agent in achieving or compromising ergonomic functionality. Consequently, adult discomfort, stemming from unintuitive interfaces, time-consuming setup, or physical strain, can directly translate into suboptimal configurations, ultimately affecting the child's experience.

2. Types and Sources of Discomfort

Arising discomfort in children's products can be of physiological or psychological nature, stemming e.g. from inappropriate dimensions, insufficient adjustment ranges, or cluttered design.

2.1 Physiological Discomfort

Physiological discomfort in children frequently results from poorly designed or non-adjustable features such as seat depth, footrests, seat angle, or backrest height. Resulting unphysiological body positions lead to compensating movements and fidgeting. Rigid, thermally uncomfortable surfaces (e.g., hard or heat-dissipating materials) exacerbate discomfort, particularly in cold weather conditions. Furthermore, poor ventilation and unsuitable material selections contribute to adverse microclimatic conditions also in hot conditions in strollers, car seats, and bicycle trailers. This is especially relevant for young children, whose thermoregulation is less effective due to their surface-mass ratio.

2.2 Psychological Discomfort

Psychological discomfort for children often relates to restricted visibility. For instance, strollers and buggies with front-facing seats prevent children from seeing their caregivers, and in rear-mounted bike seats, the child's view is almost completely blocked by their parent's back. Many children's bicycle frame geometries induce them to adopt a forward-leaning posture, restricting a child's visual field. For adults, psychological discomfort may arise from ambiguous user manuals, overly complex adjustment mechanisms, or inaccessible features—often resulting in avoidance behavior or incorrect product use.

3. Key Determinants of Comfort

In products designed for prolonged sitting - such as strollers, high chairs, and car seats - the adjustability and quality of elements like seat depth, footrests, angle of inclination, and material surface properties are key contributors for enabling comfortable postures. If adjustments are overly complex or time-intensive, adults often neglect them, or apply minimal effort, resulting in non-ergonomic configurations (e.g., incorrectly set footrest height leading to unsupported leg posture).

4. Methodology

While there are many national and international standards defining methods for assessing design and safety of children's products, they rarely refer to comfort. Therefore, technical assessments and measurements from standards need to be enhanced by adapted methods.

For our product assessment, research data is generated from several sources: technical assessments conducted by experts and empirical user testing with both children and adults. The systematic comparative evaluation of children's products assesses dimensions such as:

- Product size and geometry
- Adjustability and mechanical operation
- Ergonomic and safety features (e.g. pinch points)
- Usability and handling by adults
- Clarity and comprehensiveness of user manuals

Observational studies with lay users of the product groups document user behavior, including typical adjustment strategies and coping mechanisms employed by adults and children in response to discomfort (e.g., avoiding backrest contact due to excess seat depth). Insights gathered from household use, user questionnaires and interviews further refine the input.

In order to evaluate anthropometric fit for the respective user group, functional measures are the basis for evaluation. They constitute the product dimension as available in use. For example, seat depth can be reduced by backrest geometry (shape / angle). In analysis, different physical human models (PHM) are applied to assess various aspects, for example, 2D extendable templates or 3D child models with correct body part weight distribution (see fig. 1). Pinch and shear points and other potential injury points are determined according to standards and expert experience. Also, forces are assessed that pertain to safety-relevant mechanisms such as belt buckles. Observation and questionnaire data are mainly employed to evaluate product usability.

Fig. 1: Different Physical Human Models (PHM) and human test subject

In the evaluation of data, it is particularly critical to account for the extensive anthropometric variability within the user group "children" and to ensure that the currently available—albeit scarce—data are utilized with methodological accuracy.

5. Results

The assessments provide a good differentiation of the product or product group and can document product change over time. Two typical products from this segment will now be emphasized, which demonstrate the importance of continued focus and further development.

5.1 Example 1: Strollers

Ventilation and visibility improvements in strollers illustrate notable progress. A decade ago, mesh inserts for airflow and visibility were rare. In contrast, our 2024 evaluation found all 12 tested bassinets incorporated mesh elements—eight of which were positioned in the front of the bassinet, allowing forward visibility even for prone infants. Depending on the position even supine infants were enabled to observe their surroundings[1]. In twin models, side mesh panels also supported visual interaction between siblings. This innovation improved the internal microclimate under sun exposure dramatically. The design shift toward well ventilated strollers may represent a counter-trend and response to the prior trend of dark, thermally insulating fabrics.

5.2 Example 2: High Chairs

High chair design has also advanced, focusing on ease of adjustment. Historically, changes in seat height or depth required time-consuming screw mechanisms. Modern innovations, such as one-handed lever-based systems, have significantly improved usability. Nonetheless, some models retain complex, unintuitive designs. To accommodate a wide age range—from infancy through adolescence—manufacturers increasingly implement more continuous or fine-graduation adjustment systems. However, poorly proportioned seat depths remain prevalent. Excessive seat

[1] These mesh inserts can also be closed to shut out the surroundings, allowing for privacy or sun shading

depth often causes edge pressure on the knees or leads children to extend their legs unsupported, resulting in slouched postures or disengagement from the backrest.

Insufficient footrest depth is another recurring issue, particularly for older children. When only the heel or mid-foot can be supported, the position lacks stability. Children may respond by sharply flexing their knees and resting on the balls of their feet, compromising postural variety and long-term comfort.

There are always products in the field that find good or even excellent solutions, and sometimes innovations. By published consumer test results, there is benign pressure on manufacturers to improve their products. Recommended solutions are:

- infinite or finely graduated adjustability, especially for the most relevant aspects of upper body and leg support
- ease of use for parents so that the settings are applied
- creating good visibility and age-appropriate configuration

Conclusion

Children's comfort in seating products is highly contingent on both product design and the adult user experience. Products that streamline adjustability and improve physiological and psychological conditions—such as ventilation, visibility, and stable support—demonstrate superior ergonomic performance. Continuous innovation, informed by empirical testing and user-centered design, remains critical. Independent consumer testing plays a pivotal role in driving product quality and encouraging manufacturers to prioritize comfort-enhancing features.

To support an evidence-based design processes, it is imperative to collect new, valid anthropometric data specific to children and to make such data accessible to both manufacturers and testing authorities. Only through the availability of comprehensive and representative datasets can ergonomically sound and child-appropriate design solutions be systematically implemented.

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IEC/IEEE 82079-1:2021-9 „Erstellung von Nutzungsinformation (Gebrauchsanleitung) für Produkte - Teil 1"

Head Support and Pillow Usage for Napping in an Automotive Seat

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ABSTRACT

As automated driving becomes more widespread, the demand for comfortable upright sleeping in vehicles is growing. Proper head and neck support is crucial for a pleasant seated sleeping experience, particularly in upright positions where discomfort often occurs in these areas. This study investigated head support requirements for upright and reclined seats using two seat back angles: 120° and 140°. Sixteen participants took a 30-minute nap in seats equipped with an integrated headrest and a small pillow for neck support. Comfort and discomfort scores, along with head movements and pillow placement, were assessed through questionnaires and video observations. The findings revealed low comfort scores for head/neck support at both angles, though the 140° angle showed significant improvements in reducing discomfort. Participants at 140° made fewer head movements, with the pillow being more frequently and effectively used. Most participants positioned the pillow at the back of the head, aligning with common sleeping habits and suggesting a preference for backward head support. However, some used the pillow laterally or even for arm support, highlighting a need for more versatile solutions. The results emphasize the need for a head support that minimizes forward, lateral, and backward head movements while accommodating diverse user preferences. While a basic square pillow provided some improvement, the study underscores the potential for enhanced designs to improve seated sleeping comfort. These insights offer input for designers and engineers to develop improved head support solutions for mobility applications, addressing functional needs for better travel sleep experiences.

KEYWORDS

Comfort, Sleep, Mobility, Cushion, Head movement

Introduction

The need for comfortable upright sleeping will increase as sleep in the automotive context becomes more common with the introduction of automated driving (Cai et al., 2024; Wilson et al., 2022). A proper head and neck support is needed to facilitate a comfortable seated sleep experience (Bouwens et al., 2018). In upright seated angles the discomfort is especially high in the head and neck area during sleep (Caballero-Bruno et al., 2022; Vledder et al., 2024). Therefore this study looks into head support requirements for a comfortable head/neck support in an upright and a reclined seat during napping, based on head movements and pillow placement.

Method

Sixteen participants (mean age: 26 ± 2.64, mean stature (mm): 1713 ±10.00, mean body mass (kg); 67 ±16.79, 8 male and 8 female) took a 30-minute nap in a BMW zero gravity seat with a seat back angle (SBA) of 120° and 140° and a seat pan angle (SPA) of 20°. A nap of 30 minutes or less can alleviate daytime sleepiness (Hayashi & Abe, 2008). Participants with sleep-related illnesses were excluded from the study (self-reported), and participants who tended to take naps more often, were fast sleepers, and could sleep easily anywhere were selected. Each participant slept in the two SBA conditions on two separate days. All naps started between 17:00 and 20:30. The used seat included an integrated headrest (Fig. 1), and a small square pillow which was available for neck support. The sleeping environment (Fig. 1) was silent, and the light was dimmed. To avoid further disturbance by light during the sleeping period, a sleeping mask was provided to the participants. After the nap, the participant was awakened by an alarm of relaxing nature sounds.

(a) (b)

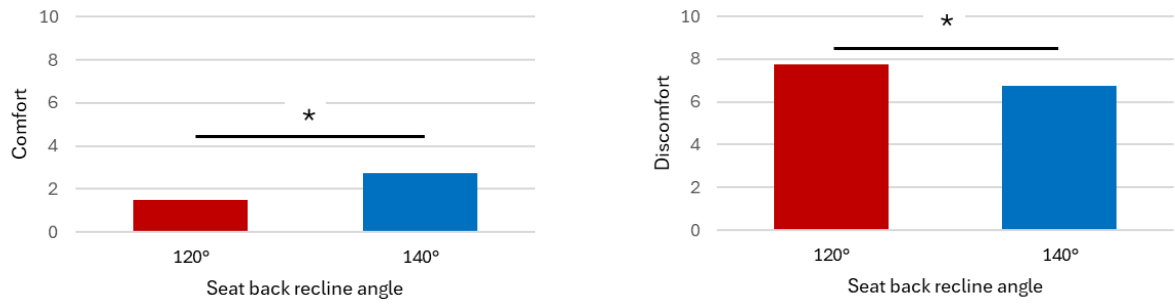
Figure 1. (a) Research setup with the camera on the right. (b) The research seat through the camera view with the seat in the backrest angle 120° (top) and 140° (bottom).

Prior to the study, the purpose and protocol of the research were explained to the participants and they were asked to sign an informed consent, which was approved by the ethical committee of the Delft University of Technology (ID: 3711). Additionally, on the day of the research, participants were asked not to drink coffee or other energy drinks before the research. Half of the participants started with the SBA 120° and the other half with the SBA 140°.

The comfort/discomfort score of the experienced neck support (10-point Likert scale) and the comfort of the experienced seat per seat part were gathered through a questionnaire after each sleeping period. Additionally, head motion and pillow position observations were gathered through video recordings. Results of the questionnaires regarding the two SBA angles were tested for significant differences ($p<.05$) using the Wilcoxon signed-rank test.

Results & discussion

The results show that the head/neck support received low comfort and high discomfort scores at both 120° and 140° SBAs (Fig. 2), indicating a clear need for improvement. The comfort score was significantly higher and the discomfort score was significantly lower at the 140° SBA compared to that of the 120° setup ($p<.05$). A likely explanation is that at 140°, the impact of gravity might have less effect on the head/neck in 140° compared with 120°, as the headrest supports a greater portion of the head's weight in the more reclined position. This more reclined posture likely decreases forward tilting forces, which may account for the fewer total head movements and reduced occurrences of 'falling forward' observed at 140° compared to 120° (see Fig. 3).



(a) (b)

Figure 2. (a) Comfort score of the head/neck support, (b) discomfort score of the head/neck support, *p<.05.

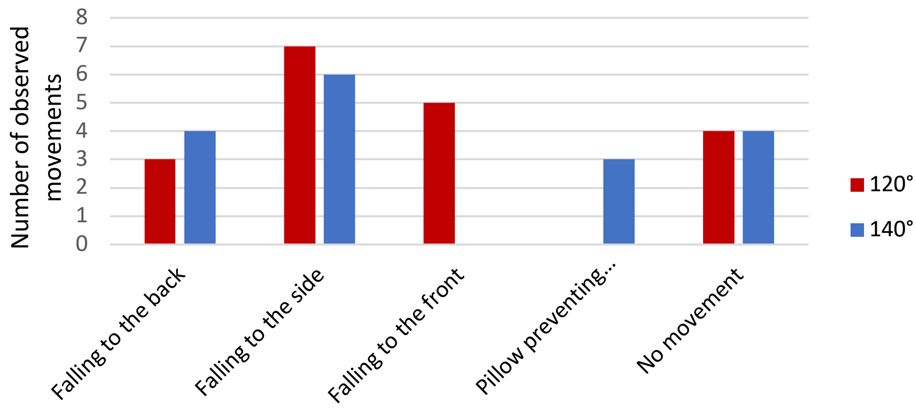


Figure 3. Number of head movements.

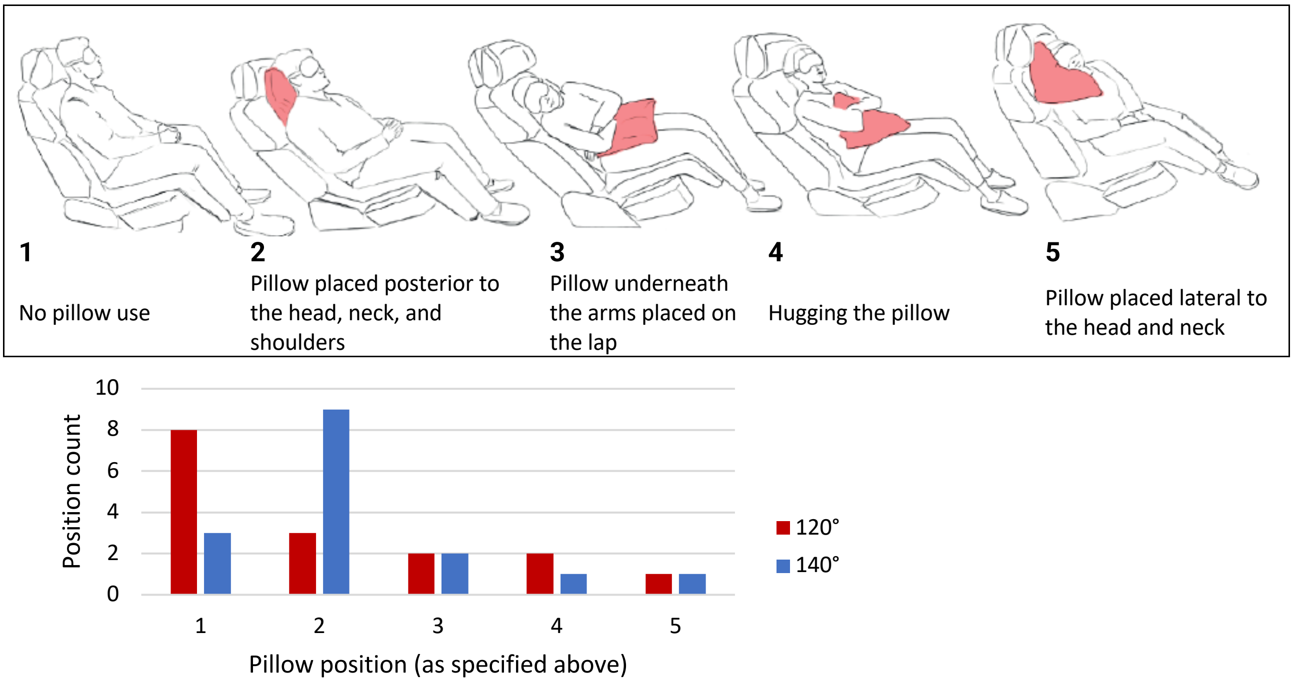


Figure 4. Number of participants observed in the above-specified pillow positions

Fig. 4 shows five defined pillow positions and how often they occurred in the two scenarios. The pillow was more frequently used at 140° compared to 120°, leading to better support of the head and preventing unwanted head movements. More head movement is correlated with higher discomfort (Bouwens et al., 2018). Most participants placed the pillow at the back of their head, allowing them to rest it backward, suggesting that this position is perceived as the most comfortable. Some also place the pillow on the lateral side of the head. This could be related to the overall preferred sleeping positions. The most preferred sleeping postures in a normal bed are lateral and supine sleeping (Skarpsno et al., 2017a; Vink et al., 2025). The placement of the pillow in the neck cavity on top of the shoulders could indicate a habit of using the shoulders to spread the weight of the head support on a different location than the neck. In the long term, this might lead to discomfort in other areas.

The number of participants not using the pillow in the SBA 120° was higher than expected. This could be attributed to the integrated headrest of the used seat in this study. Preferably, the angle between the tragus and the seventh cervical vertebra should be between 40.6° and 43.7° (Bouwens et al., 2018). Based on the used seat and the integrated headrest, for 120° this angle is smaller (approx. 30°), pushing the head forward, in the 140° SBA this angle is larger (approx. 50°). Most participants could not reach the headrest, and the headrest surface was considered to be ‘hard’. Highlighting the need for adjustability for the variation in users.

Interestingly, the pillow was not only used as head support but also placed underneath the arms. The alternative use of the pillow could indicate the need for additional arm support to reduce muscle tension in the shoulders/neck, the need for a blanket to regulate body temperature during sleep (Caddick et al., 2018), or the need for a comforting/secure feeling during sleep (‘hugging’ the pillow).

This study also has some limitations; the age range is limited, and sleeping behavior changes with age (De Koninck et al., 1992; Milner & Cote, 2009; Skarpsno et al., 2017b). Future research should take this into account. Additionally, discomfort was recorded after approximately 40 minutes, which is rather short (Sammonds et al., 2016). Smulders et al. (2016) showed that discomfort increases more after 40 minutes. Although the total time in the seat would be around 40 minutes, including filling in the questionnaires and explaining the research, the sleeping period was less than 40 minutes. The discomfort results should be considered as a first impression, and further research is needed to further define discomfort around the head/neck support.

Some participants fell asleep almost immediately, though not all. Future research should include some time to fall asleep and choose a time of day when people are tired and can fall asleep. However, in a real-world setting, passengers might already choose a time of day for a nap when they are tired; in this case, difficulty falling asleep is less of a concern.

Conclusion

This study highlights the importance of effective head support in enhancing sleeping comfort during upright and reclined seating. It can be concluded that future head support designs should prevent head movement in all directions, forward, sideways, and backward, to maintain a stable and comfortable posture. This aligns with previous findings by Bouwens et al. (2018), who also addressed that restricting head motion is essential for travel pillow comfort. Although the square pillow used in this study was simple in design, it already improved comfort, especially in more reclined positions, highlighting the fundamental role of head support in the overall comfort experience. These insights can inform future research and practical design efforts aimed at optimizing sleeping comfort in seated environments.

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Posture changes of different body parts in the upright and reclined sleeping context

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ABSTRACT

Sleeping during a train trip, a flight, or in the seat of a car is a frequently seen activity. In automated vehicles, sleep will also be possible for drivers. Upright sleeping is not very comfortable and the comfort and discomfort experience is influenced by the backrest recline angle. The (dis)comfort might be influenced by the possibility of taking certain sleeping postures in different recline angles and switching to different postures, as changes in posture can alleviate discomfort. This study investigates the amount of position shifts for the head, arms, trunk, and legs in seats with a backrests recline ranging from 110° to 150°, and in one flat stretcher (180°) during a nap. The results of sixteen participants show large differences in body part position shifts between the backrest recline angles and between the body parts. Trunk movement appears to be linked to participant anthropometry, head movement is linked to human body breadths (hip, elbow-to-elbow, shoulder), and BMI specifically is connected to trunk, leg, and arm movement. The high number of head position shifts in all angles except 150° and 180°; and the high number of trunk, leg, and arm position shifts in the most upright angle (110°); indicate a need for more body support. The low number of trunk and leg movements in 120°-150° suggests the need for more freedom of movement, supported by negative correlations between trunk movement and anthropometry.

KEYWORDS

Position shift, napping, mobility, comfort, movement

Introduction

Upright sleeping in a seat is a common activity of passengers during travel (Bouwens et al., 2017; Cai et al., 2024; Groenesteijn et al., 2014; Molin et al., 2020). The comfort and discomfort of this activity improves significantly if the backrest angle is more reclined (Vink et al., 2023; Vledder et al., 2024). Additionally, Vledder et al. (2024) argue specifically that a minimum backrest angle of 130° is required for a comfortable nap, and various studies link sleep quality with nocturnal movements (Skarpsno et al., 2017). Sammonds et al. (2016) linked an increased discomfort to a higher frequency of body fidgets and movements, introducing the idea of ‘freedom of movement equals comfort’. This study investigated the research question: ‘*How does the change in seat back recline angle influence the amount of movement shifts for different body parts during upright sleeping?*’.

Method

Sixteen participants (mean age: 24.1±3.7, mean stature (mm): 1702±390, mean body mass (kg): 65.1±15.7) completed six 90-minute naps in five seats which differed in back rest recline (110°-150°) and one flat stretcher (180°)(Fig. 1). Participants with sleep-related illnesses, and those who reported having a hard time falling asleep were excluded. Following the Delphi method and based on video recordings, the positions of the head, trunk, legs, and arms were observed and coded every 10 minutes by two researchers. A third researcher reviewed and resolved any discrepancies between their codes. For all body parts, left, right, and neutral were coded. Other codes included for the head: up, down, or neutral; for the trunk: stomach, back, or leaning/rotated to a side; for the legs: straight, one or both legs flexed/folded, or one or both crossed; and for the arms: both straight, both flexed/folded, or one or both crossed. With the use of these codes, the number of movement shifts per body part per hour was determined. Additionally, participants' anthropometry was measured. Data analysis was done using Python, and the Wilcoxon signed-rank test was used to determine significance between body part pairs and between backrest angles. Additionally, Spearman correlations are calculated for correlation analysis.

Figure 1. Part of the research setup, showing the seat and flat stretcher

Results and Discussion

Figure 2 shows the mean movement shifts of the head, trunk, legs, and arms per hour. In the seat back angles (SBA) 110°-150°, the head shows significantly (<.05) more movement shifts compared to the trunk, legs, and arms. In the SBA 180°, this difference is smaller. For SBA 130°, there is also a significant difference between the trunk and arm movement shifts, and in 150° between the legs and arms. The number of head movements is lower in the angles 150° and 180° compared to the other angles. Trunk and leg movement decrease towards 130° but increase again towards 180°. Most arm movement occurs at 110° and 180°, with an increase at 130° as well.

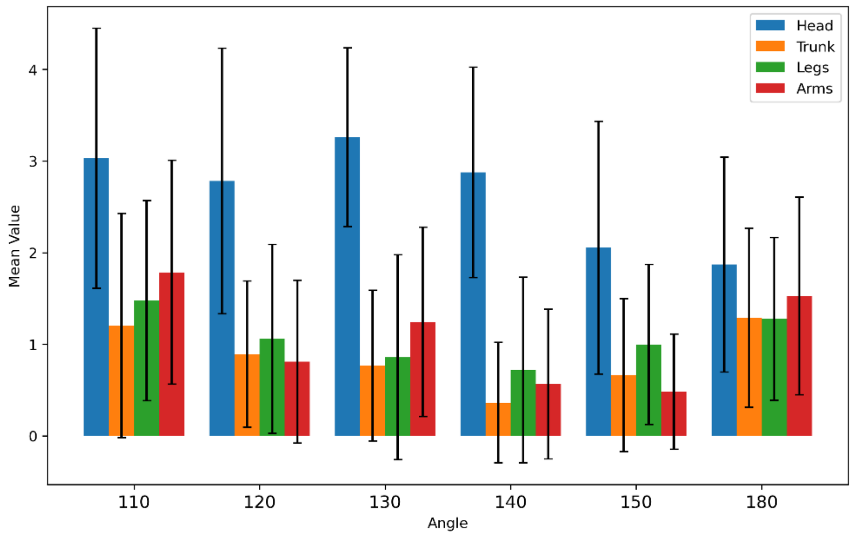

Figure 2. Mean movement shifts of the head, trunk, legs, and arms per hour by backrest recline angle with error bars.

The correlation between the body part shifts and the participants' anthropometry is shown in Figure 3. BMI correlates with movement in all body parts except the head. This correlation indicates that participants with a lower BMI showed more in seat movements. The relation between BMI and nocturnal body movements is also described in the literature (Skarpsno et al., 2017). Head movement correlates with hip, elbow to elbow, and shoulder width. Trunk movement correlates with most anthropometry measurements except stature and hip width.

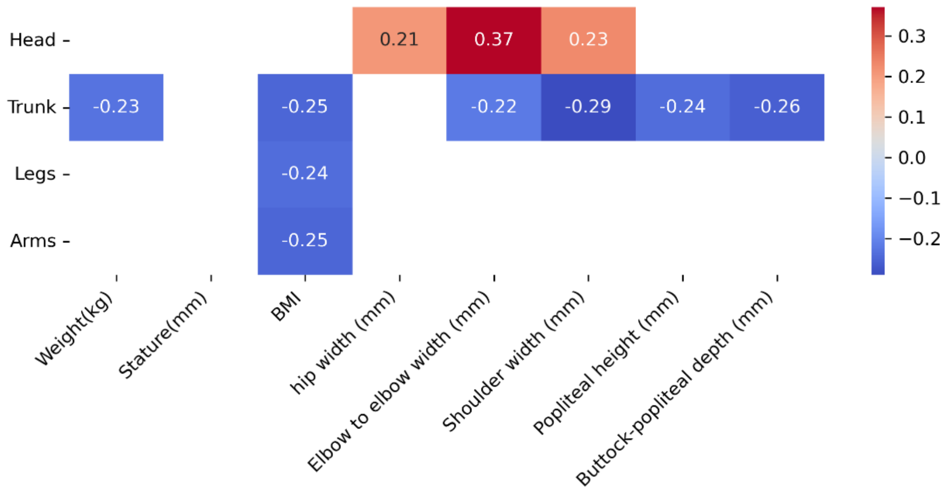

Figure 3. Spearman correlation matrix of the body part position shifts/h versus participant anthropometry, only showing significant values (p<.5) with correlation values ≥.2.

The head movement from 110° to 150° is possibly influenced by the need to relieve neck muscle strain by searching for a biomechanical neutral position (Bouwens et al., 2018), as neck discomfort is specifically high in 110° and 120° (Vledder et al., 2024). Participants with more body width (hips, shoulders, and elbow-to-elbow) seem to move their heads more often during sleep. It is unclear how this would relate to discomfort in the head area. Perhaps it could relate to the head position and how the head is supported by the arms on the armrests, but to find a clear explanation, further research is necessary.

The differences in movement shifts of the trunk and legs between SBAs might be the result of an interplay between movement to alleviate discomfort and the possibility of movement. Or as Kruithof et al. (2023) put it: movement can be seen as a measure of discomfort, but also as a tool to alleviate discomfort. In 110° and 120°, local postural discomfort is high (Vledder et al., 2024), and participants move to dissolve discomfort (discomfort-triggered adjustments (Yao et al., 2023)). In 130°-150°, the body moves towards neutral body angles (Han Kim et al., 2019). Therefore, less discomfort is experienced, but the seat and body angles might also restrict movement. Movement restrictiveness by the seat (for instance, by the width between armrests) could be reflected in the correlation between the anthropometry and trunk movement. Participants with a higher body mass, elbow-to-elbow width, shoulder width, popliteal height, and buttock-popliteal depth have a lower trunk movement frequency. At 180°, the discomfort is low, but more freedom of movement is possible. The 180° condition could be considered the ‘preferred’ condition. If this is the case, future seat development should strive to limit movement of the head and aim to find a balance between offering body support and facilitating more movement in the trunk, leg, and arm area in the angles 120°-150°. Movement could be facilitated by considering anthropometric variability within the population. Where support should be added to the seat, is an important topic for future studies.

There are some things to consider when interpreting the outcomes in this study. The blanket or the camera angle sometimes obstructed some parts of the body, and certain movements of the head or the arms could have been missed. Future studies could consider using accelerometer sensors to measure movement more accurately, as applied by Skarpsno et al. (2017).

Future studies should also include a broader age group; the participants' age range within this study is limited. From the literature, we know body movements during sleep vary with age (De Koninck et al., 1992; Skarpsno et al., 2017). Additionally, continuous observation instead of observations in 10-minute intervals will lead to a better comparison of the movement frequency with existing literature. Finally, this article mainly describes the frequency of movements, but future research could additionally look into the amplitude of in-seat movements as described by Kruithof et al. (2023). It would be valuable to explore whether discomfort can be inferred from discomfort-triggered adjustments, or whether sleep and awake states can be identified by movement frequency.

Conclusion

This study indicates that head movement may be primarily triggered by discomfort. Movement in other body parts could also be related to the possibility of movement. Head discomfort appears to be associated with insufficient support. Based on the findings in this study, sleep might be better facilitated by providing full body support at a SBA of 110°, and specific head support when the SBA is in the range of 110° to 140°. Additionally, at SBA angles between 120° and 150°, the right tradeoff between offering more support and facilitating freedom of movement in a seat should be considered. Variability in body size should also be taken into account. The outcomes can be used in future seat design to facilitate a more comfortable sleep experience during travel.

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Towards a more efficient train use: A VR case study evaluating a comfortable night/day train design.

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ABSTRACT:

Twenty four young participants (average age 26.5 years) evaluated 12 train interiors for night and 4 for day trains in a VR environment. The interiors had for instance different shielding between the seats and beds. Participants had to select the preferred layout and explain why. The results show a difficult balance between privacy and security within the day and night train interior. Privacy is important, especially in the night train. Although women tend to prioritize safety. A low or a high 'back wall' in between seat rows is mostly preferred over no wall during the night. Next to that, a high back wall is mostly preferred over a closed compartment and some people prefer only shielding at their head area instead of the full length of the bed. Another aspect that is more important for the night train is noise cancellation. Next to privacy, the possibility of having interaction with other train passengers and a spacious look is relatively more important in a day train. This study gives a first impression of factors that are of influence to the privacy and security experience in day and night train travel. For future studies, it is advised to use a real train environment with participants of various ages, as this study was done in VR with young participants, and choose a limited interior changes to enable a more systematic review of the results.

KEYWORDS

Privacy, train interior, comfort, privacy, security,

Introduction

The path towards a sustainable society is still uncertain. One thing is certain: mobility must become sustainable. The night train is a more sustainable alternative to flying and a suitable replacement for trips up to 2000km (Goeverden et al., 2019), and 38% of all flights departing from the largest airport in the Netherlands are within a range of 750km (Donners & Kantelaar, 2019). However, operating a night train profitably is not an easy task (Roel, 2023). Night train carriages cannot be used during the day, or in day trains it is hard to sleep during the night. Besides travel time and travel cost, the comfort level of the interior is important in choosing between an airplane or a night train (Vink et al., 2022). According to Kantelaar et al. (2022), perceived night train comfort is most influenced by the accommodation of privacy, and privacy and security are important for comfort in sleeper trains (Out & Hiemstra-van Mastrigt, 2024). Moreover, additional issues like comfort with sleeping, personal security, and sharing cabins matter (Buh and Peer, 2024). It is unknown which elements in the train interior contribute to privacy and security. Therefore, this research looks into the privacy and security needs during day and night train travel by changing interior elements in a VR train environment.

Method

To arrive at a more sustainable travel, a case study was performed in designing a convertible train interior (convertible between day and night), and the opinion of end-users on the interior was gathered. Different train coach interior layouts were designed for day and night with various shielding elements. The sense of privacy and security was evaluated. Twenty four participants (average age 26.5 ± 14.4; 10 male, 14 female, 10 had experience in the night train) experienced the different layouts of the train coach in VR. A three-dimensional train coach was modelled in Blender, incorporating 16 different layouts, including 4 daytime scenarios and 12 nighttime scenarios (see figure 1 for three examples of the nighttime scenario). The layouts mainly differed in the type of shielding between seats. Remembering 16 different layouts is impossible for end-users. Therefore, during the VR experience, participants were shown 2 scenarios each time, from which they had to choose the one they preferred. For the remaining scenario, the participants had to rate orally the privacy and feeling of security in the scenario that was chosen in the end: *'Rate the design on your feeling of privacy from 1-10 and explain why? (1 is no privacy and 10 is full privacy).'* And '*Rate the design on your feeling of security from 1-10 and explain why? (1 is no security and 10 is full security)'*
This routine was repeated for 4 day scenarios and 12 night scenarios separately. Additionally, the luggage storage preferences for nighttime travel and daytime travel were asked. The open questions were analysed by clustering and counting the positive and negative reasons. The descriptive statistics were calculated using Microsoft Excel.

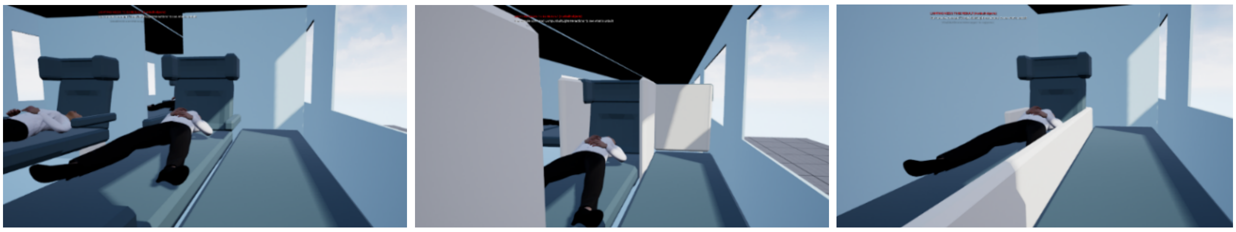

Figure 1. Three of the 12 nighttime scenarios as shown to the participants in VR. Left: only a high back wall, middle: a quite high back wall and a shielding at head level between two beds, and right: a high back wall and a low shielding between two beds.

Results

The main reason for choosing a scenario by the 24 participants appeared to be privacy (see Fig. 2). In the interviews this 'privacy' aspect was explained. A low or a high 'back wall' is mostly preferred over no wall during the night. Next to that, a high back wall in between seat rows is mostly preferred over a completely closed compartment, and some people prefer only shielding at their head area instead of the full length of the bed. There was a difference between male and female, with men generally preferring enclosed spaces at night while women tend to favour more open environments at night. Another aspect that is more important for the night train is noise cancellation. The possibility of having interaction with other train passengers and a spacious look is more important in a day train. Although safety was not explicitly mentioned, 'social control' and 'overview' are considered to be related to the feeling of safety; if counted together, this becomes the second most important factor. Additionally, some participants mentioned that oppressive feelings should be avoided by day, and being too close to other participants during day and night. When the interior included shielding completely around the sleeping area, some participants even described the area as 'feeling like a coffin'.

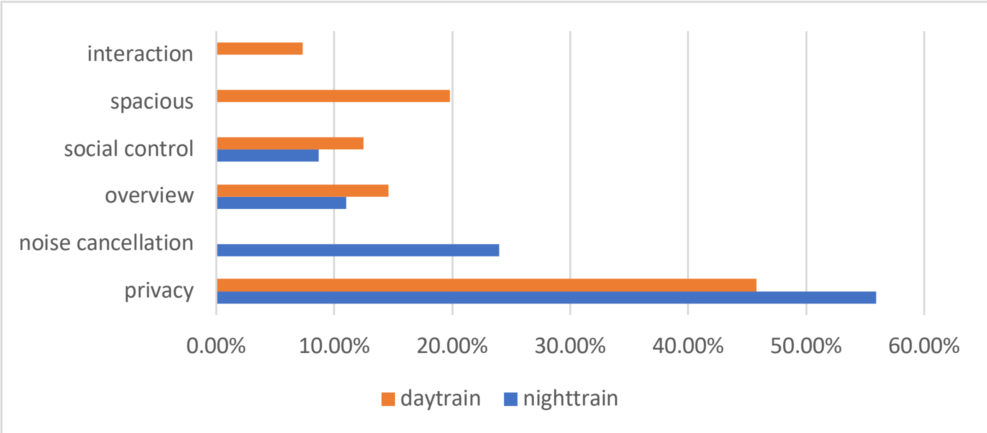

Figure 2. Percentage of the total number of times a reason is mentioned for choosing a scenario in a day- and night train by the 24 participants (each participant evaluated the night train as well as the day train).

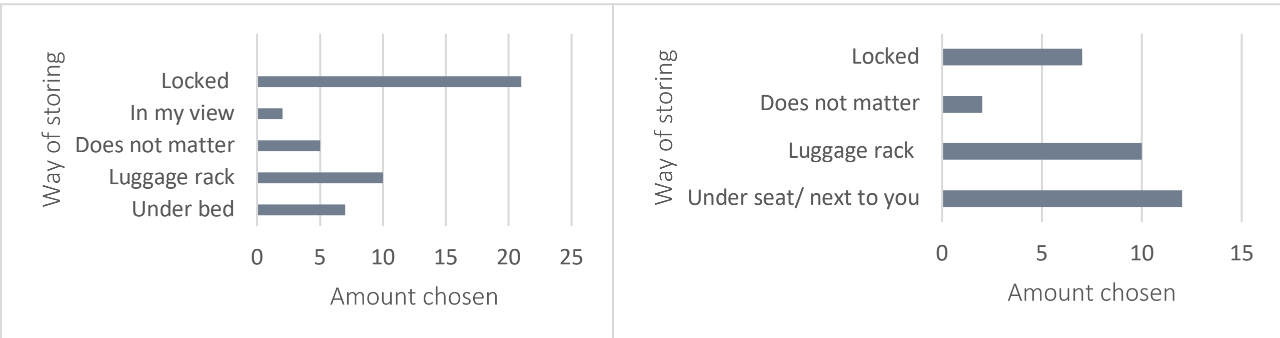

Figure 3. The number of times a way of luggage storage was chosen for nighttime travel (left) and for daytime travel (right)

The preferred place for luggage storage differed for the night and day train (see Fig. 3). At night, more passengers want their luggage locked, while during the day, people prefer to have the luggage under the seat as it is easily reachable.

Discussion

The results of this study emphasize the importance of privacy and security within train interiors. And shows a delicate balance between privacy and security. This corresponds with the literature where it is described that the feeling of privacy and security in night trains is found to have a major impact on the sense of comfort (Kantelaar et al., 2022). For most people, having their luggage locked at night is important, for daytime, a lock is not always necessary.

This study shows that shielding around the seat is preferred for privacy reasons. Other studies also show the importance of shielding in transport. Medeiros et al. (2022) showed, for instance, that passengers even try to shield themselves from others with their laptops. The openness is preferred because of the sense of security it gives in the form of social control and creating an overview. This points to the balance between privacy and security. Males vote more for an enclosed environment, while women seem to prefer a (semi) open environment because of more social control during the night. Another study from Condon et al. (2007) also shows the differences in how women and men experience public spaces due to societal attitudes, behaviours and structures that contribute to their feelings of vulnerability.

Comparing the needs between daytime and nighttime travel, the importance of privacy and security differs in this context. For both daytime and nighttime travel, having a certain amount of privacy and security is important, but passengers' privacy and security needs are higher, and also different, during the night (Flohr et al., 2024). During daytime travel, privacy is most important, but spaciousness and overview is also valued. This can be facilitated by having a partly open environment, e.g. by having a high back wall in between seat rows. During the night, people are not awake, so they prefer to rely on social control and therefore preferably on an open environment, compared to, i.e., sharing a closed compartment with a stranger. Although men in this case find privacy and noise cancellation slightly more important than women do.

Finally, luggage storage was mentioned by the participants. Storage of luggage with a locking mechanism is essential at night, emphasizing the significance of security during nighttime travel. For daytime travel, a lock on luggage is not essential but in some daytime scenarios it can provide extra comfort (for example, on long journeys travelling alone). Next to that, the majority of respondents prefer the top rack as a storage place for luggage for nighttime travel. This preference may be related to easy access to luggage, as well as a sense of space and openness in the traveller's immediate vicinity. For daytime travel, travellers prefer to keep their luggage as close to them as possible (for example, on the seat next to them, under their seat or also in the luggage rack. This is affirmed in other studies as well (e.g. Alberda et al., 2015).

This study has limitations. Not all participants scored all scenarios. Two scenarios were presented to the participants, from which they had to choose the better one until they had seen all scenarios, and one best scenario remained. This means that each participant followed a different protocol. This was done since after showing many scenarios most people do not remember all scenarios and often the last one gets more attention (Do et al., 2008); we can remember only 7-9 scenarios (Miller, 1956). The downside of this approach is the difficulty in comparing between participants. On the other hand, the preferences for scenarios were rather clear. As a result, no statistical analysis could be made. It is not possible to say scenario X is perceived as significantly more comfortable than scenario Y. Furthermore, the mean age of the participants is around 26 and the study was done using VR. The question is whether, in a real environment and with other age groups the results would be the same, also taking into account the influence of proxemics to other passengers. Moreover, both inexperienced and experienced night train passengers were asked which may also affect the perception of privacy and safety, and thus the choices between layouts.

This study provides insight into feelings of privacy and security within daytime and nighttime train interiors. Train designers could use these results when creating new layouts for daytime and/ or nighttime trains. An idea might be to implement the findings in a design that can be transferred from day train to night train and repeat this study in real life by various age groups.
Future studies could also elaborate on the importance of speech privacy and noise levels in the train carriage environment between day and night, given that noise levels influence the comfort in train interiors (Vledder et al., 2023), and noise cancellation is also mentioned as an important factor in this study. Balancing interior noise with the openness of an environment, could be partially optimized by using interior surface materials for speech privacy (Jang et al., 2016).

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Pro and cons of using pocket springs in mattresses: a comfort study

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ABSTRACT

Human-centred design asks for wellbeing and comfort of the customer/worker when interacting with a product. The mattress of a bed is a typical product whose relevance in everyday life of people is under-evaluated. Fortunately, this behavior is quickly changing and the customer wants to understand the product he/she buys and asks for more comfortable and for scientifically assessed products. In the last few years many researchers and designer have developed ideas and solutions to make the human-sleep as better as possible, introducing new materials and new constructive solution. Nevertheless, some solutions that have a great impact on mattress market, like the pocket spring ones, are based on marketing analysis and not really on scientific principles. The common experience of some manufacturers and users is a decay of comfort performances and a negative feedback about the use of that kind of mattresses after a few times. This study intends to investigate, under a mechanical point of view and using a previously developed comfort assessment method, the interaction among users and pocket spring-based mattresses, in order to understand the effects of this technology on the perceived sleeping (dis)comfort and give some guidelines about the right design choices to create and produce them. A preventive FEM study has been performed in order to correlate the mechanical behavior of the mattress depending on materials and springs' layout and stiffness. After that, an experimental campaign has been done in order to have an experimental/numerical model that is able to describe the interaction between a body in supine position and the mattress. Finally, an analysis on mechanical parameters of the mattress has been done in order to understand pro and cons of using pocket spring technology and to drive the mattresses' designer to avoid common design mistakes.

KEYWORDS

Pressure map, mattress design, sleeping comfort, FEM models, comfort

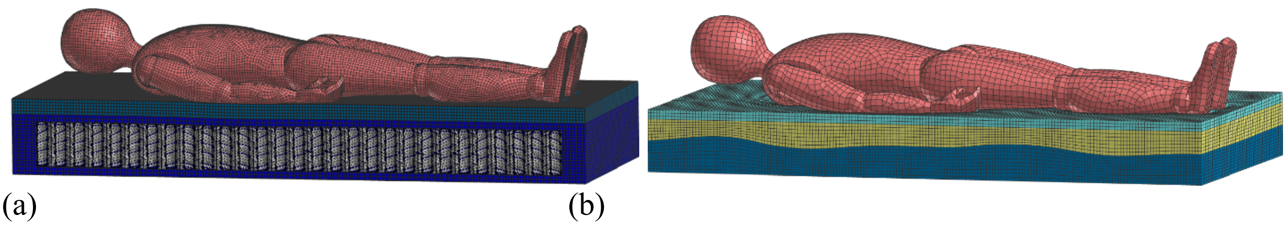
Introduction

The growing demand for mattresses capable of ensuring high comfort and ergonomic support has led research efforts toward increasingly objective and repeatable evaluation methodologies.

Early studies primarily relied on subjective assessments, such as the Boston Mattress Satisfaction Questionnaire (BMSQ), which was validated on a large population sample to evaluate comfort, firmness, temperature, and overall satisfaction (Robbins et al., 2025). Cross-cultural analyses have further highlighted how comfort perception can vary significantly based on geographic and habitual factors (Vink et al., 2021). Moreover, studies on expectation effects have demonstrated that preconceived notions can significantly alter user perception, even when mattress properties remain unchanged (Naddeo et al., 2015). In parallel, objective methods based on actigraphy and pressure mapping have been developed to quantify sleep quality and comfort. Comparisons between latex and spring mattresses showed improvements in sleep efficiency and onset latency when using technologically advanced solutions (Tonetti et al., 2011), while studies on hammock versus bed users revealed that sleep parameters were more strongly influenced by BMI and sex than by the type of sleeping device itself (Estrella & Sandoval, 2020). Layered mattress structures have been linked to improved pressure redistribution, decreasing peak pressure zones and increasing low-pressure contact areas, resulting in higher subjective comfort ratings (Ren et al., 2023). Additional studies have shown that both bed heating (Xia et al., 2020) and thermal conditions at the user-mattress interface (Califano et al., 2017) can significantly affect perceived sleep quality, especially in elderly populations. Recent advances in scanning and sensing technologies have enabled more sophisticated modeling approaches. The integration of 3D body surface acquisition with pressure distribution measurements and finite element (FE) simulations has been used to predict mattress surface indentation and assess spinal alignment in a supine position (Wu et al., 2018). Smart bedding frameworks equipped with sensor arrays and data-driven regression models have identified key comfort determinants such as sleep posture, body mass, and material stiffness at different bedding layers (Bai et al., 2024). Several studies have focused specifically on numerical modeling through the Finite Element Method (FEM). PU foams with nonlinear compressive behavior have been analyzed to predict contact pressure peaks and load distribution (Benkhettou et al., 2023). Hyperelastic formulations have been used to highlight the trade-off between pressure relief and spinal misalignment in soft vs firm foam mattresses (Khatir et al., 2025). This overview highlights the need for an integrated approach that combines accurate experimental material characterization (springs, fabrics, and foams), detailed CAD modeling, and validated FEM simulations. The present study fits within this framework, proposing a digital workflow for the modeling and comparative evaluation of foam and pocket spring mattresses with the goal of optimizing comfort and guiding design improvements.

Method

The two types of mattresses were Computer-Aided Design (CAD) modelled and analyzed through Finite Element Method (FEM) simulations. This activity was made possible by three preparatory and sequential phases: experimental characterization of the mechanical behavior of materials, CAD modeling of the components and validation through FEM simulations. Springs, fabrics and foams were tested under the ASTM standard rules in order to obtain mechanical and physical parameters. The characterization results were used for creating Material models to be used in Finite Element Method (FEM) modeler in Explicit (time integrated) Non-Linear solving conditions (Naddeo & Cappetti, 2020). Following the material characterization phase, each component was modelled in CATIA® by Dassault Systemes CAD environment. The final phase involved FEM simulations using ESI Visual Environment®.



(a) (b)

Figure 1. FEM simulation: (a) Sectioned pocket spring mattress (b) Foam mattress

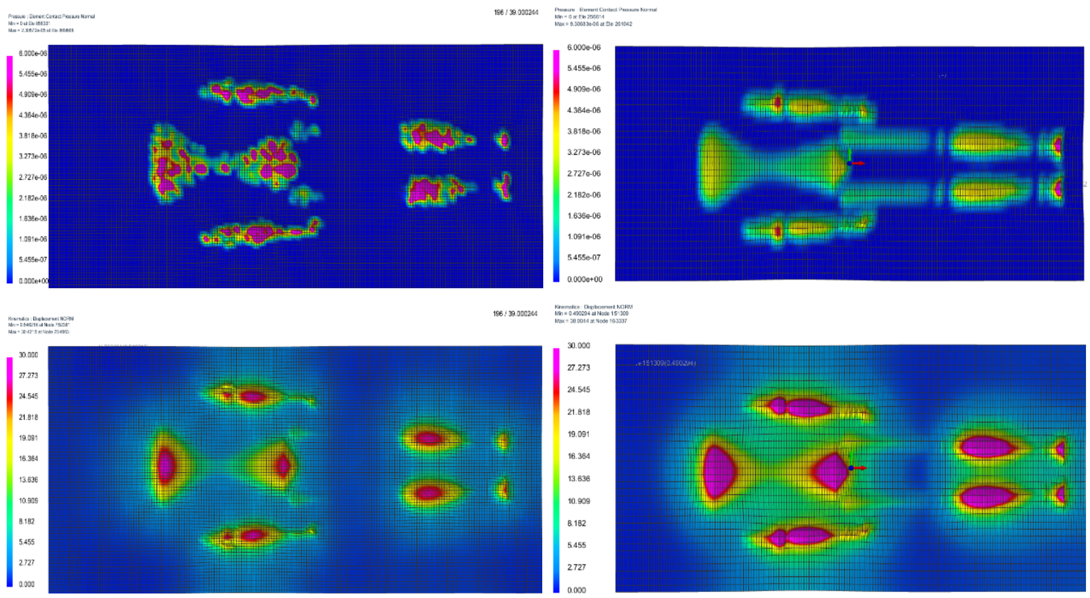
In order to analyze the main differences and to highlight pro and cons of Pocket Spring mattresses, a comparison with a high-end full foam mattress has been done. Each component was tested virtually in conditions replicating the laboratory experiments; numerical/experimental correlation gave always results with a negligible error between data. Following this tuning process, the two digital twins of the mattresses were modelled and subsequently analyzed (and compared) through FEM simulations (see Figure n. 1).In order to simulate the interaction between user and mattress, a supine mannequin, representing the 50%male, with rigid body segments was used in order to understand the effects of mattresses composition on the pressure profiles. The FEM simulations were performed on a 16core CPU with 32Gb of memory and lasts about 16 hours each.The used comfort criteria for evaluating the comfort performances due to material characteristics and layout of the mattress was the one developed in (Naddeo, 2021). This criterion considers the qualitative pressure distribution, the mean and the variance of the pressure, the peak of pressure, the body sinking and, finally, the way to adsorb the pressures by the layers of the mattress. Each of them is evaluated on a 0-10 scale as described in (Naddeo, 2021) and opportunely weighted for giving a final evaluation.

Simulation results gave us very different values among the mattresses. In the following table are summarized the mean results obtained by simulation

Type of mattresses tested	Pocket spring	Foam
Number of nodes with pressure greater than zero (in % on total nodes)	9%	18%
Average pressure (kPa)	5,777	2,808
Maximum pressure (kPa) – FEM contact	42,988	16,238
Median pressure (kPa)	4,679	2,761
Qualitative index pressure distribution	8	9
Qualitative index of pressure distribution in the shoulder/back area	8	9
Qualitative index of load transfer to the bearing structures of the mattress	9	9
Index of comfort at the interface	6,5	8,4

Table 1. Simulations' results

Analyzing the results, it can be seen that objectively the foam mattress is more comfortable. The potential use of the developed workflow is in the possibility to change the characteristics of any mattress part in order to understand the variation on pressure distribution and consequently, the variation in comfort perception due to design parameters' changes. In the following Figure n.2, some results from a virtual Design of experiment.



(a) (b)

Figure 2. (up) Pressure distribution (down) displacement map.
(a) Pocket spring FEM mattress (b) Foam FEM mattress

The comparison between the two mattress models reveals differences in mechanical response at both component and system level. The pocket spring mattress exhibits higher peak pressures, particularly in the back region, while the foam mattress shows a more uniform pressure distribution. Average body sinking is higher in the foam configuration, indicating a softer response of the upper layers. As a result, load distribution and postural support differ between the two designs, with implications for comfort and pressure relief.

Discussion and Conclusions

The proposed workflow enabled the capture of the mechanical behavior and comfort-related performance of different mattress architectures. The close agreement between experimental and numerical data (within a 5% error margin) demonstrates the accuracy of the entire simulation process, from material modelling and geometric representation to the final mattress performance, confirming that the numerical results closely align with real-world outcomes. The comparison between the two mattress types highlights the influence of structural composition on pressure distribution and body support. The pressure maps and derived comfort metrics suggest that design variations at the component level can significantly affect the overall comfort perception. In particular, of the two architectures analyzed, the foam one seems to be more comfortable. The adoption of the FEM procedure, along with established comfort criteria, ensures consistent and repeatable evaluations, overcoming the limitations of experimental or subjective methods, while also enabling parametric studies and what-if analyses for design optimization and product development. The analyses highlighted the evident differences between full-foam and pocket springs mattresses. As the simulation shows, the pocket spring mattresses avoid a deep sinking in the mattress but not allow to better distribute the pressure on the surface, so not guaranteeing a better comfort feeling in the user. It's necessary to said, the distribution of mechanical stresses inside the mattress and the energy-adsorption by the metallic materials (spring) avoid a concentration of stresses that, in the foams, causes a very quick degradation of mechanical properties of the foam itself (D'Arienzo et al., 2022). Finally, a very interesting result under the design point of view, is the possibility to change and adapt the spring behavior, and consequently the pressure distribution, by simply changing the diameter of the spring and the spring layout inside the mattress as shown in (Naddeo & Cappetti, 2020). Having autonomous-isolated spring in a fabric frame allows the designer and the manufacturer to easily create a personalized mattress on the basis of anthropometric characteristics of the user. On the other side, the stress concentration and the energy absorption of fabric pocket represent the Achille's heel of this kind of mattresses: the fabric has to interact with metallic material for a long time and these stresses can easily cause breakage and fibers' consumption that brings to a leakage of connection among the springs and, consequently a dramatic change in mechanical behavior of the whole mattress. Designers' efforts have to spend in order to understand how to counteract this effect and create a very durable and affordable mattress. Overall, this study supports the integration of simulation-driven design in the mattress industry, offering a pathway toward more personalized and scientifically grounded comfort solutions.

Limitations

Although the study provides valuable insights into mattress comfort, some limitations must be admitted. The mannequin used for the simulations were modelled with a rigid body structure that do not represent the real human structure. Future work could benefit from FEM simulation of more detailed anthropomorphic mannequin (less rigid) to validate and refine the results.

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Foam Stiffness, Damping and Dynamic/ Vibration Effect on Comfort: Theory

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Abstract

Foam behavior has many aspects, but comfort studies as often generalize that behavior simply as "stiffness" and sometimes a nebulous quality of "feel." Furthermore, seat engineers typically have limited their specifications of stiffness to ILD and specifications of feel to density. These descriptors are wholly inadequate and reliance on them can lead to products that don't meet comfort expectations. Theoretical understanding can lead to better descriptors and specifications of foam behavior. By applying a standard spring-mass-damper model and the associated classical performance metrics to polyurethane foam, one can glean insights into the biomechanical user experiences that are perceived as comfort.

Keywords

Dynamic, Vibration, Viscoelastic

Background

Seat Comfort is often the domain of specialists in Human Factors whose training is necessarily broad across many fields but may not be in depth in some mechanical aspects. Vibrations, vibro-acoustics, dynamic behavior, controls theory, frequency domain analysis and their related studies are some such areas not widely included in Human Factors curriculum, but they have great impact on perception of ride comfort. Our hope is that this paper can serve as a brief tutorial in some of the vocabulary and methods of these fields and their application to seat comfort. This material is well-established in mechanical engineering textbooks, so sources would be too numerous to cite.

Dynamic behavior is simply how a physical system responds to external forces applied to it in a time-varying manner. If the system response doesn't vary over time, it is a static system. The components of the physical system must be examined for their behavior (constitutive laws) and how the components interact (topology) must also be examined. These are then translated into the equations of motion for the physical system, and then behavior descriptors are found that relate to comfort perceptions.

There are three basic components distinguished by their behavior. Components that have a change in displacement in response to force, such as a spring, are considered as having a 'zero-th' order response, as displacement involves no derivatives. Components that have a change in velocity in response to force, such as a shock absorber or dashpot, are considered as having a first order response, as velocity is the first derivative of displacement. Components that have a change in acceleration in response to force, such as mass (our beloved F=ma), are considered having a second order response.

The most common description of zeroth order response Hooke's Law, where force is proportional to displacement x:

$$F = kx$$

In this instance, the proportionality constant k is known as stiffness. This equation shows an explicitly linear relationship, and while most theoretical concepts of dynamic behavior start with linear relationships, we shall explore the implications of non-linearity later.

The most common description of first order response is damping (no eponym), where force is proportional to velocity $\dot{x}$:

$$F = b\,\frac{dx}{dt} = bv = b\dot{x}$$

(*We will use the dot notation for derivatives going forward)*

The proportionality constant b is known as damping. Note that some conventions use 'c' instead of 'b' but we will use b throughout. Friction is related to damping but has certain stick/ slip behaviors that don't follow a simple proportionality.

The most common, and most famous, description of second order response is Newton's second law, where force is proportional to acceleration $\ddot{x}$:

$$F = m\,\frac{d2x}{dt} = ma = m\ddot{x}$$

Here m is mass, and in one sense it is part of the definition of force rather than a proportionality constant.

Many large and complex systems can be simplified into arrangements of these three basic entities, spring, damper and mass, based on their (dynamic) behavior under force.

The most traditional configuration of these elements in basic form is the spring-mass-damper with the spring and damper parallel. In the case of foam behavior, we often consider the mass of the foam to be negligible compared to an occupant, so the simplified version looks like this:

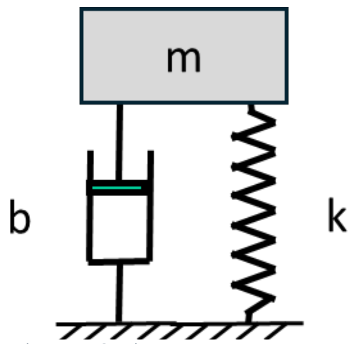

Figure 1 Spring-Mass-Damper

Traditional vibration theory starts with the negligible damping case, as it is difficult to incorporate in large scale models, and we will do the same. An idealized spring-mass system with no friction or damping, once set into motion, will oscillate continuously in simple harmonic (sinusoidal) motion.

Conservation of energy tells us the kinetic energy of the mass's motion plus its potential energy due to spring will remain constant.

$$K.E. = \frac{1}{2}\mathbf{m}\dot{x}^2 \qquad P.E. = \frac{1}{2}\mathbf{k}x^2$$

At the top of the motion, the mass is instantaneously still with kinetic energy of zero while the potential energy is at the maximum. In the middle of the oscillation, the kinetic energy is at its maximum while the potential energy is zero. In the absence of friction or other damping, the motion will go on forever. If the occupant really represents the mass, they would bounce along forever if the foam or seat had no damping effect. [This would represent 100% resilience as defined by many foam specs as a target. It is the author's personal opinion that this choice of target is due to misunderstandings of the role of component behaviors.]

The frequency of the free oscillation (bouncing) is known as the *natural frequency* designated as ω_n. The equation of motion is:

$$x = A \cos \omega_n t$$

Thanks to judicious definition of units, this frequency, as expressed in radians, is directly calculated from the spring constant and the mass:

$$\omega_n = \sqrt{k/m}$$

(Reminder: Frequency in Hz = radians/ 2π)

Free vibrations are extremely rare in real life, especially in seated humans, due to damping (discussed later) and the fact most systems have external forces (/motions/ vibrations) acting on them. When a system is subject to an external sinusoidal force (as a wavy road or engine vibrations), it will tend to respond at both its natural frequency as well as that of the forcing function. In reality, the response at its natural frequency is damped out and the system follows the forcing function. However, the system will resonate at its natural frequency; that is, the response will grow larger as the forcing function's frequency approaches the system natural frequency. This is known as resonance and is because the forcing function is adding energy/ motion to the system in sync with its own desired free motion. It adds energy up as the system moves up and adds it down as the system moves down. When the frequencies are not close, the direction of energy (phase) tends to cancel out.

The typical test of this dynamic performance is a transmissibility (also transmissivity) test in which a mass representing an occupant is place on a seat or foam block and the entire system is subjected to a forcing sinusoidal motion (either displacement or acceleration, depending on equipment) whose frequency is slowly swept from low frequency (often 1 Hz) to high (often 12 Hz or 20 Hz, depending on set-up). The resulting curve is graphed as output (resulting response of mass) over input (forcing function) across the frequency range:

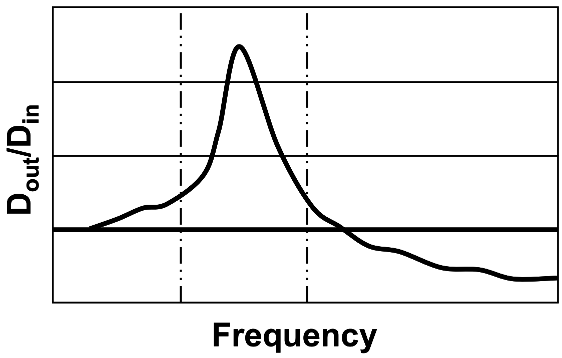

Figure 2 Typical Transmissibility Results

This is similar to the Bode plot from electrical engineering except it is not on a logarithmic scale and it doesn't show phase. The important points to note are the frequency where the peak is (the (damped) natural frequency), the height of the peak, and the frequency at which the response (ratio) drops below unity (=1). One important aspect not shown on the plot is that the phase changes from 0 degrees (in phase) to 180 degrees (out of phase) at the resonance frequency.

The resonance peak is crucial because the human body has many resonance peaks, but primarily one of the main torso viscera. Depending on an individual occupant's mass and stiffness (affected by ratio of adipose tissue to muscle), that resonance peak is usually between 4 Hz and 6 Hz. If the seat resonance is in that range, superposition says that the occupant's viscera will resonate out of phase with the pelvis, and this is a source of great discomfort.

While damping has an effect on transmissibility in limiting the size of the resonance peak, it has a greater influence on comfort for energy management on single events, like potholes.

In modeling system response, there are two types of idealized inputs: Impulses and steps. An impulse is defined as an instantaneous (duration is near zero) impact of near infinite force such that the integral of the area = 1. The resulting response will approximate the system's free response. A hammer blow is typically used to approximate an impulse for testing, especially in modal testing. Experimental methods that can produce controlled impulse suitable for seat comfort are rare.

A step response is an immediate but permanent change from one operating state to another. The idealized version has a dimensionless value. It is typical of a control system that changes to a new set point. In the automotive world, it would be akin to driving off a height change such as a curb. The resulting response will also approximate the system's free response. The typical experimental method is to drop a mass representing the occupant from a designated height; the change the seat sees is no load immediately changing to the load of the mass (plus a little inertial force). The response will be the sinusoidal free response decreasing according to the damping.

In the case of pure damping (i.e., no spring) the motion of the mass is described by:

$$x = \mathrm{A}e^{-\zeta\omega t} \quad \text{where } \zeta \text{ is the damping factor (defined below)}$$

When the full spring-mass-damper model is used, the step response is defined by the superposition of the sinusoidal motion with the damping:

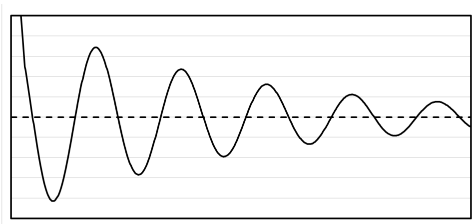

Figure 3 Step Response of Damped Oscillator

$$x = e^{-\zeta\omega_d t}(\mathrm{A} \cos \omega_n \, t)$$

The peaks can be used to find the period (inverse of frequency) of the oscillation. Typically the height of the peaks are used to find the logarithmic decrement δ which is related to damping factor:

$$\zeta = \frac{\boldsymbol{\delta}}{2\pi}$$

The frequency of the response here is the damped natural frequency ω_d. It differs from the (undamped) natural frequency ω_n :

$$\omega_n = \frac{\omega_d}{\sqrt{1-\zeta^2}}$$

There is an ideal or *critical* damping with $\zeta = 1$ where the oscillations (underdamped) just barely go away, but if the damping is higher (overdamped), the seat feels harsh and abrupt in its response to the disturbance, much like an automobile with shock absorbers that are too stiff.

The ideal seat has enough dynamic damping while enabling the spring to return to an equilibrium position quickly. To achieve this, the damper should be chosen to have a damping value b that balances the specific mass and spring:

$$\mathrm{b} = \mathrm{m}\sqrt{k/m} \quad \text{or } \mathrm{b} = \mathrm{m}\,\omega_n$$

Foam stiffness, Damping and Dynamic/Vibration Effect on Comfort: Examples

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Abstract

Foam behavior has many aspects, but comfort studies as often generalize that behavior simply as "stiffness" and sometimes a nebulous quality of "feel." Furthermore, seat engineers typically have limited their specifications of stiffness to IFD and specifications of feel to density. While there are useful static tests for comfort to maximize the feel and fit of the seat, they need to be combined with dynamic tests that correlate to what a driver or occupant experiences when they are in the vehicle, so that all aspects of comfort are considered. Reliance on only static tests can lead to products that don't meet comfort expectations. If there are shortcomings from a dynamic perspective, they are typically realized during a ride and drive event and documented on the ride survey. Dynamic tests can be run on the foam or seats to validate or invalidate a concern raised by a participant such as lack of support, a dead feeling seat, or high vibrational inputs. The previously explored theoretical considerations are used to highlight specific static and dynamic foam tests. Samples of foam were created in groupings of near-identical IFD and density and they were tested for targeted static and dynamic behaviors of interest and the results analyzed.

Keywords

Static, Dynamic

Introduction

Polyurethane foam is the material of choice for automotive seating because of its unique cellular nature. In one material you have both spring and damping characteristics, which are ideal for the dynamic seating conditions encountered when operating an automobile. If foam was purely a spring it would be too unstable for the occupant when riding over bumps or hitting a pothole. Conversely, if it was just a damper it would feel dead and unresponsive and not provide any feedback to the occupant. This feeling is often associated with an undesired bottomed-out seat.

Foam is also different from most other materials in the vehicle interior because it is manufactured by combining multiple chemicals, in liquid form that react with each other and cause the material to expand and fill the individual seat pad tool. The heat generated by the chemical reaction along with an external heat source like an oven causes the foam to gel and become solid.

Since foam is produced from multiple chemical ingredients, there is a very broad range of foam types and properties that you can formulate and achieve. For this paper I am focused on the foam used in automotive seat cushions, which can be varied greatly even within this specific application. For example, a seat pad can contain foam that ranges in hardness from 4 to 14 kPa or densities from 45 – 85 kg/m^3. Because density and hardness are decoupled many combinations of hardness and density are achievable.

Once foam is produced with a specific formulation, it must be tested afterwards to confirm that it meets the customer's criteria. If the criterion does not include static and dynamic tests, you will not get a complete picture of the materials performance level from a seat comfort perspective

This paper focuses on the importance of measuring the dynamic response of a foam material used in automotive seat cushioning, and not just relying on static properties to define its requirements for seating applications. The static properties and durability testing that many Automotive OEMs specify in their material specifications, along with targeted requirement levels, do a good job at making sure the foam in the seats will perform well, from a reliability standpoint, over the life of the vehicle. These tests are in place to basically ensure the quality of the chemicals, and the process used to make the foam are acceptable. Unfortunately, these properties do not relate to the comfort performance of the foam when it is in use in a seat beyond hardness and how far the occupant sinks into the seat initially.

During a static or low speed test on foam the material does not experience the same input conditions that it sees in a vehicle during use.

Static tests do not compress the foam quickly, so the percentage of open and closed cell content in the foam has a minimal effect on the results. When you compress foam quickly the air in the cells within the foam is forced out at a high rate and the ease or difficulty at which this happens influences dynamic performance.

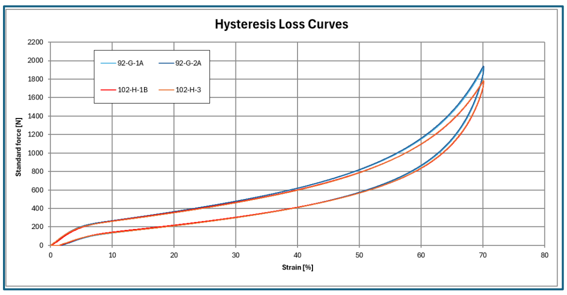
When you sit on a seat your body transfers heat to it. When the seat is in a moving vehicle the movement of the vehicle causes the foam in the seat to compress and uncompress which causes friction between the cell walls in the foam core. This friction creates heat that causes the cell walls to soften. Based on the chemical composition of your foam the cell struts response to heat can differ and change the support level of the foam over time. With foam being an insulator, the heat does not dissipate quickly, and it can continue to build the longer the seat is occupied.

Hysteresis Loss is a static test that has been linked to durability and damping performance. While this property is a good indicator of foam resilience, it does not always directly correlate to a foam's dynamic performance level. Foams can have the same hysteresis loss levels and generate different damping or vibrational outputs. As far as durability is concerned hysteresis loss generally correlates well to long term durability, but not always to short term.

Method

Molded foam test coupons were made using the same basic foam formulation with only the index level and solids content varied to create two foam types with the same basic hardness and density levels. The only static property that showed a difference between the two foam types was hysteresis loss, which at 2% is a minor difference. Most foam standards specify hysteresis loss as a maximum value and these two foams would be considered the same. The static data generated from the samples is very similar and shown below:

Coupon ID	Height (mm)	Hyst Loss (%)	25% (N)	40% (N)	50% (N)	65% (N)
92-G-1A	100.67	29.71	419	618	816	1438
92-G-2A	100.74	29.59	420	620	821	1453
102-H-1B	100.11	27.77	410	602	789	1353
102-H-3	100.29	27.93	404	597	786	1357



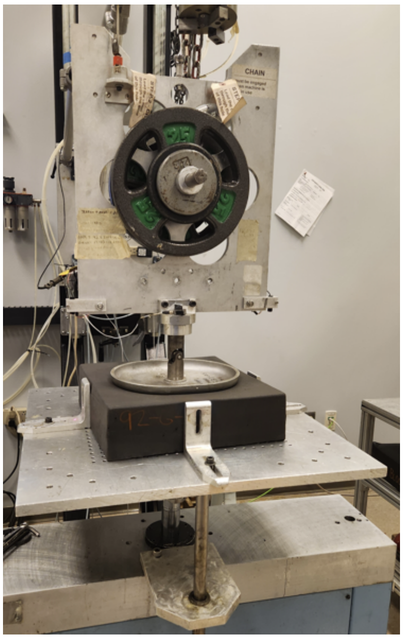
ISO 2439, Method C with additional deflection points reported

Coupon ID	Core Density (kg/m^3)	50% CFD (kPa)
92-G-3	52.79	10.62
102-H-1A	52.03	10.72

Core Density and CFD tested per ASTM D3574

The foam coupons were then subjected to three dynamic foam tests, Creep, Vibration, and Damping to see if the dynamic properties were aligned with the static ones or if they differed.

The tests were performed at the Woodbridge Comfort Lab with an industry standard tester.



Creep Test	Mass (kg)	Form	Disp. (mm)	Frequency (Hz)
	50	Tekken with a swivel	+/- 15	2.3

The mass is free floating and it's position was documented at the beginning of the test and at 30 minute increments during the test. The position measurement was made with the mass at rest after a 60 second dwell

Vibration Test	Mass (kg)	Form	Disp. (mm)	Frequency (Hz)
	50	Tekken with a swivel	+/- 2.5	Sweep 1 - 20

JASO B407-87 with noted modifications

Damping Test	Mass (kg)	Form	Drop Height (mm)
	50	Tekken with a swivel	20 above surface

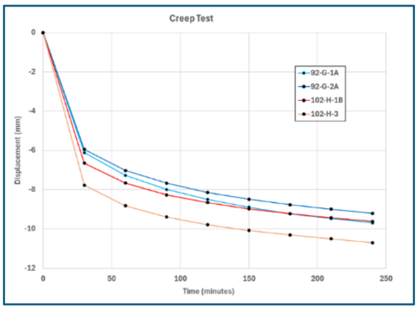
JASO B407-87 with noted modifications

Results

The foam coupons were subjected to three test methodologies described above and the results from the two foam types were compared to each other.

Creep

A free-floating mass is placed on the test coupon and rests there for sixty seconds to allow it to come to equilibrium. This initial deflection is documented as the test starting point. A +/- 15 mm sinusoidal deflection is input to the base of the foam coupon and continues for 30 minutes. The test is paused to allow the mas to come to equilibrium and the deflection point documented. This is repeated until the test reaches its four-hour test duration.



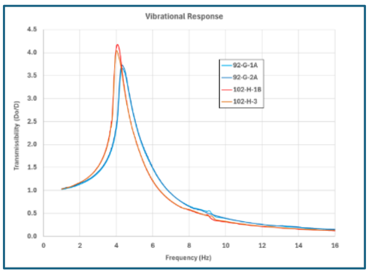
Sample ID	Creep (mm)
92-G-1A	-9.69
92-G-2A	-9.21
102-H-1B	-9.62
102-H-3	-10.70

The creep values generated by the two foam types were similar and their performance would be considered the same. From a test value standpoint these values are not ideal, and this foam would most likely not be judged favorably in a short-term comfort ride of one to four hours. This is mainly because of the high hardness and medium density combination of the foam formulation.

The hysteresis loss value of the "92" foam type was about 2% higher than that of the "102" type, which indicates that it is less resilient than the "102" type. Based on this its creep performance should be worse than the "102" type, but it was not.

Vibration

A free-floating mass is placed on the test coupon and rests there until it comes to equilibrium. A constant +/- 2.5 mm sinusoidal deflection is input to the base of the foam coupon during a frequency sweep of 1- 20 Hz. The mass deflection is documented and ratioed against the constant deflection input to produce a transmissibility curve.



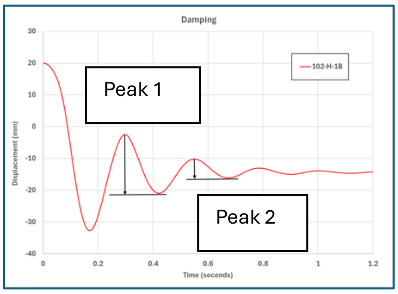
Parameter	Samples: 92-G-1A	92-G-2A	102-H-1B	102-H-3
Transmissibilty @ Resonance (D/Do):	3.66	3.73	4.18	4.04
Transmissibilty @ 6 Hz (D/Do):	1.48	1.48	1.20	1.21
Resonance Frequency (Hz):	4.33	4.33	4.06	4.03
Dampening Frequency (Hz):	6.84	6.84	6.38	6.41

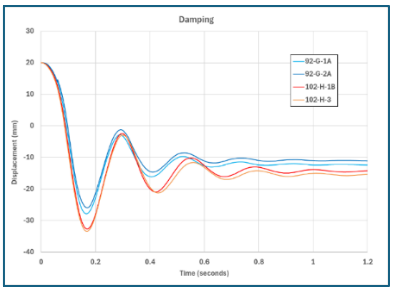
The vibration test did measure a difference between the two foam types. The peak transmissibility level of the "102" foam is higher than the "92" foam and its resonant frequency is a bit lower. This indicates that the "102" type would transmit higher vibration levels to the occupant.

Damping

This is a drop test that releases a mass 20 mm above the surface of the coupon and records a displacement trace versus time until the mass oscillation stabilizes. As the energy from the drop dissipates, the rebound height of the test peaks decrease until the mass comes to rest. The decay of the consecutive test peaks is used to calculate a damping value. A more resilient or spring-like material will generate a damping trace with higher peaks and a greater number of them than a less resilient or higher damped material. A higher damping value equates to a higher material damping performance.

The materials used to generate this data were not very resilient, so the damping trace only generated two curve peaks that were usable for the calculation.





Sample ID	Damping
92-G-1A	1.382
92-G-2A	1.438
102-H-1B	1.140
102-H-3	1.229

The lower value of the "102" type indicates that it will provide less damping than the "92" type. This agrees with the vibration test, as can be seen in the higher transmissibility number for the "102" type. Once again, we see a response that is not evident in the static data.

Additionally, there is a difference in the dynamic hardness of the foams as illustrated by the higher deflection of the "102" type, about 5mm, versus the "92" type. This difference was not apparent in the static hardness test.

Conclusion

The two foam types tested were formulated to have the same static properties, specifically hardness and density. If you were only specifying this foam by its static properties, you can get different dynamic outputs, as illustrated in the damping and vibration test results, that may have a negative impact on an occupant's perception of the comfort of the seat. As noted above, the difference between the foams tested for this paper were minor and not representative of the very broad chemical differences of the foam used throughout the industry that is made by different companies and supplied by various chemical manufacturers. With all these variables affecting the final foam pad, it is recommended that the dynamic properties are controlled as well as the static ones, so the final product delivers the highest level of comfort

An alternative to the SEAT value for assessing vibration-related seat comfort

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ABSTRACT

Currently, there are both subjective and objective ways to measure and compare seat comfort when a seat occupant is exposed to vibration. Subjectively, the seat occupant can rate comfort levels; and objectively, the vibration levels at the seat and floor can be measured and compared using the Seat Affective Amplitude Transmissibility (SEAT) values—which is a ratio of the z-axis, average weighted vibration measured at the seat and floor. Unfortunately, it is not uncommon for there to be a mismatch between the subjective ratings of seat comfort and the objectively measured SEAT values. The purpose of this case study was to evaluate an alternative, objective, vibration-related measures of seat comfort, called Acceleration Spectral Density (ASD) Transmissibility, in a controlled seat test where there were large differences in the subjective assessment of seat comfort between two seats but little to no differences in objective, z-axis seat-measured vibration levels and SEAT values.

KEYWORDS

Discomfort, Whole Body Vibration, Fatigue

Introduction

Currently, there are both subjective and objective ways to measure and compare seat comfort when a seat occupant is exposed to vibration (Zagorski et. al, 2022). Subjectively, the seat occupant can rank the seats from most to least preferred, or subjectively rate comfort levels using some sort of rating scale. Objectively, the vibration levels measured at the seat can be compared, and the floor-to-seat transmissibility can be compared using the Seat Effective Amplitude Transmissibility (SEAT) values (Griffin 1978); which is a ratio of the average weighted vibration measured at the seat, divided by the average weighted vibration measured at the floor.

Unfortunately, for the vibration researcher, it is not uncommon for there to be a mismatch between the subjective ratings of seat comfort and the objective measures of seat comfort using the seat-measured vibration levels and SEAT values. This mismatch between subjective and objective measures can complicate identifying the seat characteristics and/or features that are needed to optimize seat design and maximize seat occupant comfort.

In this current controlled case study evaluating seat comfort, there were large differences in the subjective assessment of seat comfort but little to no differences in objective, vibration-related measures of seat comfort. Therefore, the purpose of this study was to evaluate traditional, objective metrics of seat comfort and a new, objective, alternative vibration-related measure of seat comfort by using, evaluating, and comparing the floor-to-seat transmissibility from the Acceleration Spectral Density between the two seats tested.

Method

A seating evaluation was conducted comparing two different air-ride seats in a fire truck. One air-ride seat was a 13-year-old low-profile, conventional air-ride seat, and the other was an alternative air-ride seat designed by a company called Suspension Systems Technologies (Seattle, WA, USA). The conventional seat had a damper that applied a constant force to the seat occupant as the seat compressed (linear suspension dynamics). The alternative designed seat's damper proportionally increased the force applied to the seat as the seat compressed (non-linear suspension dynamics). The alternative seat was designed to improve seat comfort through reduced vibration transmission and reduce the shock and discomfort when and if the seat bottomed out..

In the seat testing, an experienced vehicle operator with 29 years of vehicle testing experience evaluated the two different seats. The test vehicle, which was a 9.4m long fire truck, drove over a standardized 25 km test route. Vehicle location and speed were measured with a GPS logger (1 Hz), and z-axis vibration was measured with a self-contained triaxial, MEMS accelerometer (400 Hz) mounted on the vehicle floor and on top of the driver seat.

After the test with each seat, the driver was asked to rate seat comfort using a range starting at 0, which represented "the worst ride ever", to 10, which represented "the best ride ever". The vibration levels at the seat were measured, and the floor-to-seat vibration transmission was measured using the SEAT value. In addition,, a new objective comfort metric was measured using the floor-to-seat transmissibility of the weighted acceleration spectral density (ASD), which was grouped into three frequency ranges: 0 to 6 Hz - below body resonance, 6 to 12 Hz – major body resonance, and 12 to 30 Hz above body resonance. The differences in ASD floor-to-seat vibration, as a function of the three frequency groups, were compared between the two seats.

Results

After driving over the same route at virtually identical speeds, the experienced driver rated the comfort of the conventional seat 4 out of 10 and the alternative seat 8 out of 10 – a substantial difference. The driver specifically noted that they could feel the fine, fatiguing vibrations in their pelvis with the conventional seat, whereas the same fine, fatiguing vibrations were absent from the seat with the alternative design.

As can be seen in Table 1, the weighted vibration levels measured at the seat tops were virtually identical, but due to small differences in the floor-measured vibration, there was a 6% difference in the SEAT values, with the alternative seat having the lower SEAT value.

When the floor-to-seat ASD transmissibility was analyzed, the largest difference in ASD transmission was measured in the region of major body resonance (6 to 12 Hz), with the alternative seat transmitting 16% less vibration. Above body resonance (12 to 30 Hz), the ASD transmissibility was 8% lower with the alternative seat. Finally, below body resonance (0 to 6 Hz), the ASD transmissibility was greater than 100%, indicating vibration amplification by both seats, with the amplification 9% higher with the alternative seat.

Figure 2 provides a graphical representation of the data shown in Table 1. As can be seen in Figure 2, the alternative seat reduced the floor-to-seat transmissibility in both the regions of major body resonance (6 to 12 Hz) and in the region above major body resonance (12 to 30 Hz). It is thought that the dramatic differences in the comfort ratings between seats may be associated with the reduction in floor-to-seat transmissibility with the alternative seat.

Table 1 – Comparisons between seats of weighted vibration measures, acceleration spectral density (ASD) transmissibility, and perceived comfort.

	Weighted Vibration			ASD Transmission			Comfort Rating
	Floor (m/s^2)	Seat (m/s^2)	SEAT	0 – 6 Hz	6 – 12 Hz	12 – 30 Hz	
Conventional	0.73	0.63	87%	108%	75%	58%	4
Alternative	0.77	0.64	81%	117%	59%	50%	8

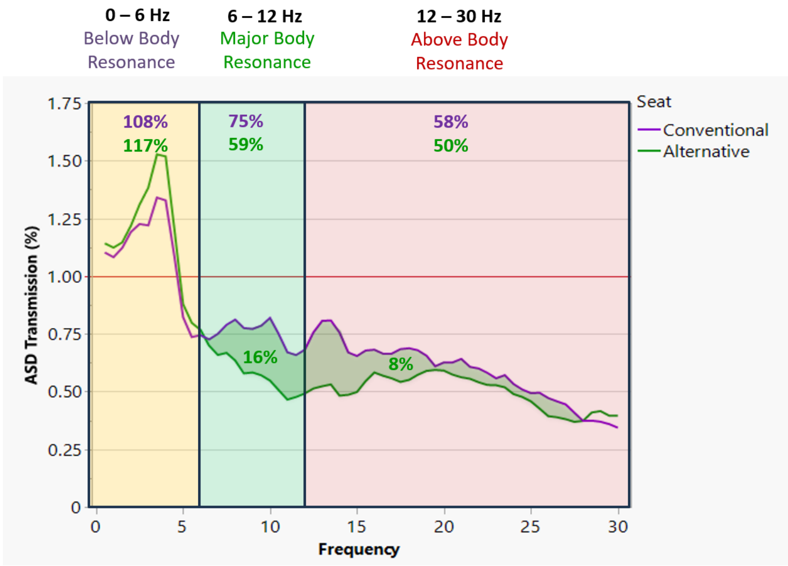

Figure 2 – Graph of the floor-to-seat transmissibility of the acceleration spectral densities (ASDs) from the conventional seat (purple line) and alternative seat (green line).

Impact

Despite nearly identical vibration levels measured at the seat, of all the other objective measures of vibration, the trends and differences in 6 to 12 Hz, and even the 12 to 30 Hz ASD transmissibility, best mirrored the trend of the large subjective difference in the driver-perceived seat comfort. Although not demonstrated or shown with the current results and analysis methods, the difference in (6 – 12 Hz) vibration transmissibility was likely predominantly due to differences in suspension friction and function. Suspension-related friction may span all vibration frequencies, but can be particularly problematic between 6 – 12 Hz. The problem is that friction-related vibration between 6 – 12 not only resonates the seat occupant, but it also can excite the seat pan foam.

This study demonstrated the importance of knowing the frequency content of the vibration experienced by the seat occupant, how vibration content may differ between seats, and how different vibration frequencies may affect seat occupant comfort. In the future, if this method is validated, a new, more sensitive, and objective vibration measure of seat comfort may exist that better corresponds with subjective ratings of seat comfort. This may be particularly helpful when there are apparent subjective differences in seat comfort, but there are small to no differences in traditional objective measures of vibration.

Conclusion

This study demonstrated how evaluating differences in the floor-to-seat transmissibility from ASDs may be used to identify a potentially more comfort-specific, objective measure of seat comfort. The challenge with the SEAT value is that it is a summary measure of the weighted vibration energy over all frequencies, whereas our more targeted, frequency-specific ASD transmissibility measures, focuses on the region of major body resonance (6 to 12 Hz), yielded larger objective differences in seat comfort, and better matched the subjectively rated differences in seat comfort. Additional studies, with larger groups of subjects are needed to validate this new objective measure of seat comfort.

Acknowledgments

Aspects of this study were previously presented at the 57th UK Congress on Human Response to Vibration (Johnson et al., 2024).

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Machine Learning-Driven Evaluation of Automotive Seat Comfort

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[1]Virtual Vehicle Research GmbH, [2]BMW Group

ABSTRACT

The development of automotive seats demands a precise balance between engineering functionality and user comfort - a highly subjective and difficult-to-measure attribute. This work introduces an innovative methodology combining a robotic test rig and machine learning to deliver objective, reproducible, and high-resolution assessments of seat comfort. The test rig features a robotic arm equipped with a spherical probe capable of measuring both total and localized forces and moments on multiple positions of any seat surface. This allows for detailed evaluation of seat components and properties such as foam, suspension, cover materials and cover tension. From extensive measurement data, physically interpretable features were extracted and used to train a machine learning model that accurately predicts key comfort related parameters, achieving classification accuracies between 80% and 100%. High resolution surface scans further enabled precise visualization of comfort relevant characteristics, offering deep insights into the relationship between seat design and perceived comfort. The approach transforms seat evaluation by identifying comfort critical areas with spatial precision and quantifying previously subjective factors. As a result, it streamlines the design process, reduces reliance on time consuming prototyping, and enhances collaboration between engineers and designers. By bridging the gap between physical measurements and human experience, this methodology provides real added value for comfort-driven seat development in the automotive industry.

KEYWORDS

Automotive Seat Comfort, Objective Measurement, Machine Learning, Comfort Assessment, Visualization Techniques

Introduction

In today's fast-paced world, the automobile has evolved into an indispensable companion for nearly half of the European population, with vehicle ownership statistics reflecting this reality (Eurostat, 2017; Jurado, 2014). On average, individuals spend over four years of their lives behind the wheel (CSA Research, 2017), underscoring the critical importance of comfortable seating in enhancing the driving experience. The interaction between occupants and automotive seats plays a pivotal role in musculoskeletal health, particularly given the prolonged static posture associated with sitting (De Looze et al., 2013).

Despite extensive research on subjective evaluations of seat comfort, a significant gap remains in the development of objective methodologies that can accurately assess the myriad characteristics influencing comfort (Vink & Hallbeck, 2012). To bridge this gap, this study introduces an innovative approach utilizing a robotic arm equipped with a custom-designed spherical measurement probe. This cutting-edge setup systematically engages with the seat to capture force responses, enabling high-resolution data collection that reveals the intricate dynamics between seat materials and user comfort. By integrating multi-axis force/torque sensors within the probe, we can achieve detailed mapping of contact force distributions and moment responses during seat indentation. Additionally, the application of a pre-trained machine learning model enhances our analysis, allowing for the classification of various seat components based on their mechanical responses.

This paper aims to illuminate the comprehensive experimental setup, detailing the design of the measurement probe, the capabilities of the robotic arm, and the analytical techniques employed. By harnessing this groundbreaking methodology, we aspire to provide a robust framework for objectively evaluating automotive seat comfort, ultimately paving the way for improved design practices and enriching user experiences in the automotive industry.

Method

To objectively and reproducibly assess the comfort of automotive seats, a comprehensive methodology was developed that pushes a newly developed spherical measurement probe through a robot arm into the seat and thereby records the force interaction between seat and probe. Data from different types of measurements, including single points as well as high resolution surface scans are analyzed by a pretrained machine learning model allowing a classification of the individual seat components. The core of the experimental setup is a UR10e robotic arm (Universal Robots, Denmark), chosen for its high positional repeatability (±0.05 mm) and sufficient payload capacity (10 kg), making it ideal for precise and repeatable multi-point probing tasks. Mounted to the robot is a custom-designed measurement probe, engineered to evaluate stiffness and elasticity properties of the seat material. The probe consists of a 3D-printed hemispherical tip with a diameter of 100 mm. Integrated into this tip are five miniature multi-axis force/torque sensors, each featuring a circular sensing area with a diameter of 20 mm. One of these sensors is positioned precisely at the apex of the hemisphere, while the remaining four sensors are symmetrically embedded around the spherical surface. This arrangement allows for detailed mapping of the contact force distribution and moment responses across the probe surface during seat indentation.

The preselected single points of high interest (comfort points) focus on specific anatomical zones with high ergonomic and comfort relevance such as the buttock and thigh contact, the shoulder region and lumbar support areas. The measurement cycle consists of a perpendicular penetration of the seat surface followed up with a horizontal movement under tension to investigate not only the stiffness of the seat but also the strain behavior of the cover and seat material. High resolution scans are performed in a 1×1 cm grid, with the robot performing vertical indentations at each point. In addition to pure raw force and moment signals, ratio-based indicators were derived, such as the peak local force at a sensor tip relative to the total measured force (Figure 1). These derived features were used as input for the used machine learning approach. The intention behind these features is to once include empirical expert knowledge into the machine learning model but also to reduce the curse of dimensionality problem.

From these measurements, a set of physically interpretable features was extracted. These included indentation depth at defined force levels, local stiffness (as slope of the force-displacement curve), and surface homogeneity across lateral seat areas. These features were selected based on their theoretical relevance to comfort perception and empirical support in literature (Wegner 2020).

To support interpretability and aid communication between engineers and designers, the measurement scan data was visualized in the form of interpolated 2D surface maps. These visualizations allow rapid identification of comfort-critical areas by highlighting pressure peaks, stiffness transitions, and asymmetries. Similar visualization techniques have been proposed as valuable tools in previous comfort analysis studies (Verver et al, 2005; Paul et al, 2014).

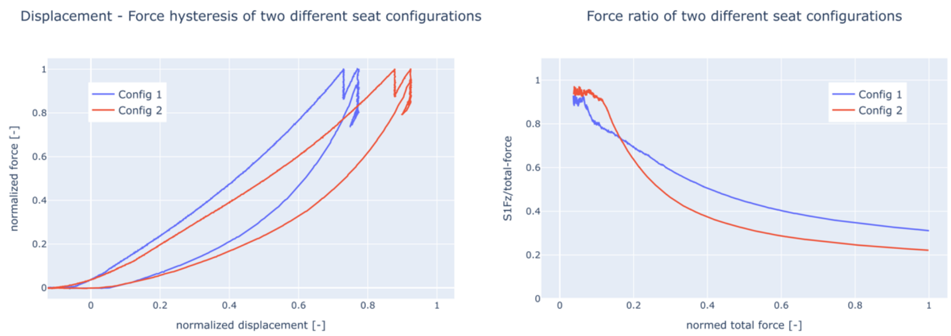

Figure 1: Sensor signal examples for two different seat configurations

To translate physical measurements into comfort relevant categories, a machine learning model based on the Random Forest algorithm was trained. As described by Breiman (2001), Random Forest is an ensemble learning method that constructs multiple decision trees using bootstrapped data samples and random feature selection, improving prediction accuracy and robustness. The model was trained using labeled data from 89 seat variants and evaluated using cross-validation techniques.

Results

The developed robotic measurement methodology provided high-resolution force-displacement data, enabling a detailed analysis of seat comfort characteristics. The results are presented for instance in terms of force-displacement hysteresis curves and force ratio evaluations which can be used for full-surface scan visualizations or can serve as input parameters for machine learning algorithms. The ratio between local sensor forces and total probe force provided insights into pressure concentration effects, which is linked to the tension of the cover. Force-displacement curves recorded during indentation tests revealed characteristics of the seat compound and gave insides in the used seat materials. Softer foam compositions exhibited deeper indentation at a fixed maximum force level, while firmer foam types showed steeper force gradients. Surface scan visualizations provided a spatially resolved representation of force distribution characteristics across the seat cushion and backrest. 2D plots of the displacement at certain force levels can be used to visualize stiffness variations, structural asymmetries, and areas of concentrated loading (Figure 2).

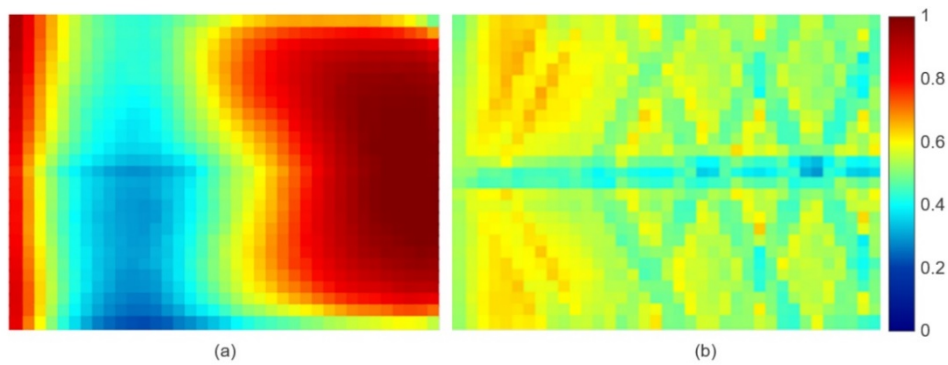

Figure 2: (a) normed indention depth at a fixed force level of a seat pan; (b) ratio of the forces of the tip sensor and the total force of a seat pan

The measurement features extracted from a study involving 89 different seats of the same seat type were used to train a Random Forest machine learning model for classifying seat attributes based on their mechanical responses. Each of the 89 seat variants was measured twice, with systematic variations in cover material, suspension system, foam hardness, and cover tension. The classification results demonstrated high predictive accuracy, confirming the potential of the proposed approach for objective seat characterization. The classification accuracy for cover material type reached 100%, indicating that different seat covers introduce distinct force response characteristics. The suspension system was correctly identified in 97.1% of cases, suggesting that force distribution metrics effectively capture the mechanical properties introduced by underlying support structures. Foam hardness classification, judging if a foam is within or outside of a tolerance boundary, achieved an accuracy of 85.3%, reflecting the model's ability to distinguish between varying stiffness levels based on indentation behavior. The cover tension classification reached 79.4% accuracy, the lowest among the tested attributes, likely due to the complex interactions between fabric tension, foam compliance, and underlying structural elements.

Table 1: Results of the ML classification tool

	Cover Type	**Suspension**	**Foam hardness**	**Cover tension**
CAT1	Type 1-3	standard	within tolerance	standard
CAT2	Type 2	blocked	outside tolerance	too tight
Accuracy	100%	97.1%	85.3%	79.4%
No info. rate	0.76	0.53	0.65	0.53

The summed-up classification results, presented in Table 1, validate the methodology's effectiveness in differentiating seat properties based on physical measurements alone. The combination of force-displacement analysis, full-surface scanning, and machine learning classification provides a comprehensive framework for quantifying seat comfort-relevant attributes, reducing the reliance on subjective user evaluations and accelerating the seat development process.

Conclusion

This study presents a novel, objective methodology for evaluating automotive seat comfort by combining robotic multi-point force measurements, high-resolution surface scanning, and machine learning-based classification. Compared to seat pressure mats, where the pressure distribution depends on the specific anatomy of the individual and can vary significantly, the proposed procedure offers several advantages: the robot applies a highly reproducible and consistent input, the interaction between the seat and the applied force can be analyzed more precisely using five 6DOF sensors, and the measurements can be efficiently automated. The custom-designed probe and systematic test procedures enabled detailed quantification of material and structural seat properties, including foam stiffness, suspension effects, and cover behavior. Force-displacement analysis and scan visualizations revealed comfort-relevant patterns, such as localized stiffness peaks and asymmetric load distributions. The Random Forest model achieved high classification accuracies for key seat attributes, confirming the effectiveness of physical features in predicting perceived comfort. This approach offers a valuable tool for accelerating seat development, minimizing subjective testing, and supporting data-driven design decisions in the automotive industry.

Acknowledgement

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Modeling of Time Series Changes of Leg Swelling in Office Chairs

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ABSTRACT

In the sitting posture, musculoskeletal loads caused by posture and contact loads caused by contact with the chair surface accumulate as physical fatigue over time and significantly affect the seating comfort. The authors have focused on leg swelling as a typical phenomenon caused by prolonged sitting and have developed a prediction formula for leg swelling in driving posture based on time-series measurement of the bioimpedance of the lower leg. However, leg swelling is greatly affected by the height difference between the heart and the foot, which affects fluid circulation, and the prediction equation for automobile seats cannot be used for sitting postures that differ greatly, such as office chairs. In this study, we measured the bioimpedance of the lower leg over time in the office chair sitting and constructed a time-series prediction formula for leg swelling using the initial body pressure distribution, the sitter's anthropometric characteristics, seat height, and seating time as variables. Furthermore, the validity of the prediction was verified using measurement data from other chairs. The prediction formula developed in this study can be applied to the preliminary prediction of seating fatigue in the design and development process of office chairs and to apply a sitting posture monitoring system.

KEYWORDS

Seating comfort, Leg swelling, Bioelectrical impedance, Pressure distribution

Introduction

In the sitting posture, the loads acting on the body are the musculoskeletal loads caused by the posture and contact loads due to contact with the chair. These loads accumulate as physical fatigue over time and significantly affect chair comfort. Musculoskeletal loads can be evaluated by musculoskeletal model analysis or electromyography but contact loads can only be estimated from contact conditions based on pressure distribution and lower extremity blood flow. To evaluate contact loads, the authors (Hirao et al., 2007) focused on leg swelling and conducted a time-series evaluation using leg bio-impedance measurement.

The author's group expanded this method and constructed a prediction equation for the time-series prediction of leg swelling in automotive seats based on time-series measurement of leg bio-impedance as a representative phenomenon corresponding to fatigue caused by contact loads during prolonged seating (Kajitani et al., 2024). However, since leg swelling is mainly caused by gravitational water subsidence due to the difference in height between the heart and the feet, which affects fluid circulation, the prediction equation for automotive seats cannot be applied to sitting postures that differ greatly, such as sitting in office chairs.

In this study, we measured the bio-impedance of the leg over time in the sitting posture of an office chair and constructed a time-series prediction equation for leg swelling.

Method

(1) Measurement method of leg swelling

When sitting in an office chair, leg swelling and decreased blood flow occur due to obstruction of lymphatic flow and blood flow caused by the compression of soft tissues and blood vessels of the body surface in contact with the seat surface.

Leg swelling, which appears as a result of contact loads, occurs when gravity acts on the extremities due to prolonged sitting posture, resulting in increased venous hydrostatic pressure, which causes water, an extracellular fluid, to seep into blood vessels and lymph vessels and accumulate excessively in subcutaneous tissues (Pottier et al., 1969). Methods for measuring leg swelling include the water displacement method (Chester et al., 2002), circumferential measurement method (Jonker et al., 2001), near-infrared spectroscopy (NIRS) (Fujita et al., 2014), digital imaging method (Kawano et al., 2005), and bioelectrical impedance analysis (BIA) (Lukaski et al., 1987).

In this study, the bioelectrical impedance method was employed to measure leg swelling. The body composition analyzer (SK Medical Electronics MLT-600N) was used to measure the increase or decrease in water content from the impedance of biological tissues by applying a multi-frequency current to the lower leg. The value obtained by taking the reciprocal of the impedance to represent the increase in lower leg swelling is the BI value; the equation for obtaining the BI value is shown in Equation (1). The data at the beginning of the measurement were defined as R0, and the measured data were Rt.

$$BI\ value = \frac{1/R_t}{1/R_0} = \frac{R_0}{R_t} \qquad \text{Equation (1)}$$

(2) Experiment conditions and methods

Swelling was measured every 5 minutes for 60 minutes for participants seated in an office chair and working at a desk. Figure 1 shows the office chair A (Okamura Co., Ltd. Sylphy) used in the experiment.

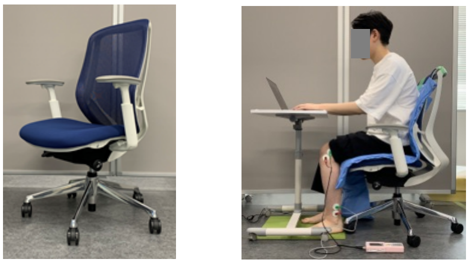


Fig.1 Office chair A and experiment condition

In the experiment, three seat height conditions were set in order to simulate the occurrence of swelling in the lower extremities due to differences in pressure conditions.

C_{Medium} is the standard seat height at which the femur is horizontal. The height from the floor to the knee was set as x, and the height from the floor to the knee was set as 10% higher or lower than x, C_{High} and C_{Low}.

The total duration of the experiment was 90 minutes, including 30 minutes to standardize the state of swelling at the start and 60 minutes for measurement, and measurements were made at different seat heights on different days. The start time of the experiment was fixed for each participant among three times: 10:00, 12:00, and 14:00; when the experiment started at 10:00 or 12:00, it was conducted before lunch, and when it started at 14:00, it was conducted after lunch. Participants were prohibited from sitting for long periods before the experiment; during the 60-minute measurement, they were prohibited from changing posture and were asked to work in an office with bare feet, keeping the soles of their feet on the floor. Eating, drinking, and defecation were prohibited during the experiment.

The experimental procedure was as follows.

(a) Measurements of C_{Medium}, the reference sitting height at which the femur is horizontal, and x, the height from the floor to the top of the knee, were taken for each participant in the experiment.

(b) C_{Low} and C_{High} were calculated from the measured C_{Medium} and the participants sat for 30 minutes at the sitting height of C_{Low}.

(c) After 30 minutes, the initial impedance values were controlled by walking exercise for 5 minutes. During this time, the experimenter adjusted the seat height to C_{Low}, C_{Medium}, or C_{High} , and prepared for measurement of BI value and pressure distribution.

(d) After 5 minutes had elapsed, two electrodes were attached to the upper and lower sides of the lower legs, and the body composition analyzer was connected to the device.

The participants were 14 healthy adults (height: 167.0±9.4 cm, weight: 58.5±8.4 kg), 7 males and 7 females, aged 21 to 23 years.

Figure 2 shows the typical BI values over time and the distribution of seated body pressure under three conditions with different seat heights.

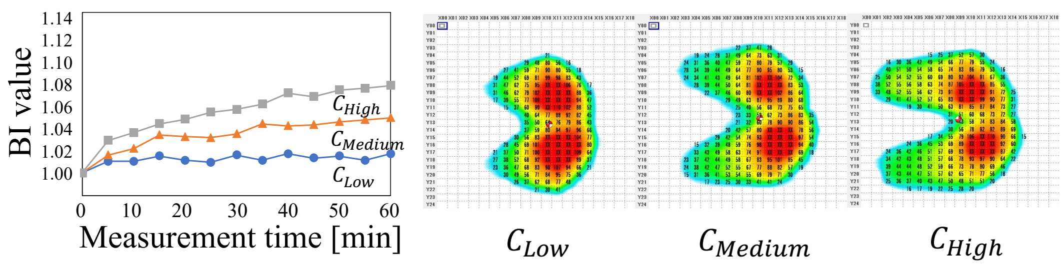


Fig.2 Typical BI value and pressure distribution

Results and Discussion

(1) Construction of a prediction equation for leg swelling

Factors that have been identified as contributing to leg swelling include time (Chester et al., 2002), thigh pressure distribution (Fujita et al., 2010), and height (Chester et al., 2002). Considering these factors, we conducted a multiple regression analysis using the stepwise method with the BI value after t minutes of the measured time series as the objective variable, the measurement time, the physical characteristics of the experimental participants (height, weight, BMI, body fat percentage, etc.), the sitting height standardized by knee height, and the total pressure anterior to the ischial tuberosity standardized by participant's weight as candidate explanatory variables. As a result, a time-series prediction equation for leg swelling, equation (2), was obtained. The adjusted coefficient of determination was 0.475, which is a statistically significant multiple regression equation ($p<0.001$). Figure 3 shows the relationship between the measured and predicted values.

$$y = 6.6456 \times 10^{-4}t - 2.342 \times 10^{-3}b - 9.000 \times 10^{-4}f + 4.788 \times 10^{-4}P$$
$$+1.277 \times 10^{-1}S + 8.751 \times 10^{-1}$$

where,

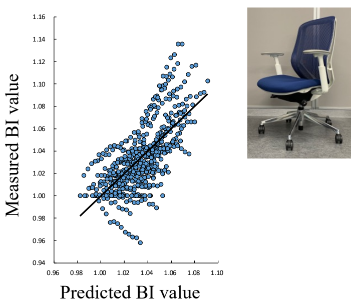
y: BI value t minutes later (leg swelling), t: Elapsed time, b: BMI of participant, f: Body fat percentage of participant, P: total pressure on the front of the seat normalized by participant's weight, S: seat height normalized by the partcipant's knee height from the floor.

Equation (2)

(2) Validation of the prediction equation

The constructed BI value prediction equation was applied to different office chairs B (Okamura Ltd., Visconte) and C (Okamura Ltd., Spher) to verify the validity of the prediction equation. Male and female participants in their 20s were used in the experiment (the number of participants differed between the chairs). The duration of the experiment was 60 minutes.

Figures 4 (a) and (b) show the relationship between the measured and predicted values using equation for each chair, and Table 1 shows the accuracy of the predictions. The results confirm that the prediction equation is independent of the chair and that statistically significant predictions can be obtained.



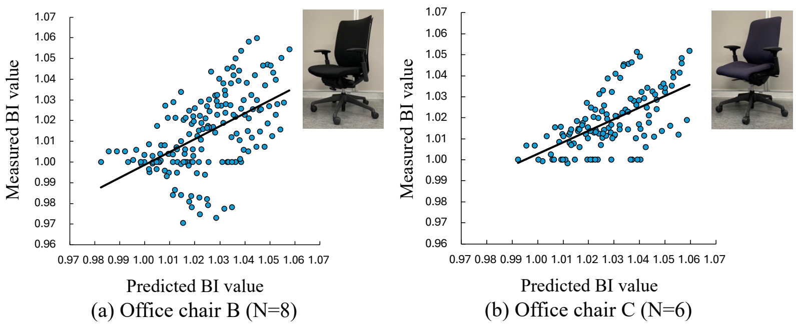


Fig.3 BI values of prediction equation

Fig.4 BI values for validation

Table 1 Accuracy of prediction equation

	Office chair B	Office chair C
Correlation coefficient	0.536	0.630
p-value	p<0.0001	p<0.0001
RMSE	0.020	0.016

Conclusion

In this study, we experimentally constructed a prediction equation for leg swelling after prolonged sitting. By using this equation, leg swelling after sitting can be predicted if the physical characteristics of the seated person and the body pressure distribution during sitting are obtained, thus enabling advanced prediction of seating fatigue in the office chair design and development process. The system is also expected to be applied to a sitting posture monitoring system (Uchida et al., 2023) that induces behavioral changes by providing feedback on the physical condition of the user.

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Comparison of thermal sensation scale responses between languages

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ABSTRACT

Quantifying the human response to the thermal environment, particularly within buildings, is often undertaken with subjective scales. Thermal sensation as defined by ISO / ASHRAE has been the accepted scale for 60 years, this scale was derived and evaluated principally by English speaking researchers. The expansion of both research and environmental assessment around the world does raise the question of translation of subjective scales to other languages. Does the essence of the scale descriptors translate? There is a need to ensure that if thermal sensation data is being collected in non English speaking countries that the translated scale produces the same result. Scales can be relatively easily translated but it is important to evaluate that when they are used in practice that they quantify the stimulus presented accurately. This is particularly important because it enables comparison with existing data and often for dissemination as research will have to be presented in English.

KEYWORDS

Thermal sensation, translation, language

Introduction

The thermal perception evaluation of buildings, indoor and outdoor work / living spaces, vehicles etc is often undertaken with subjective questionnaires. The thermal sensation evaluation has been investigated for over a century, Houghton and Yaglou (1924) Bedford (1946), with different variations of descriptive terms. It is not until Gagge et al (1967) that the thermal sensation scale was finally definitively standardized. This sensation scale (-3 cold, -2 cool, -1 slightly cool, 0 neutral, 1 slightly warm, 2 warm, 3 hot) has become the preferred scale internationally and is used in Standards related to the determination of human thermal comfort; ASHRAE 55 (2023), ISO 7730 (2005) and ISO 10551 (2019). This scale has been widely used in thermal research since the late 1960's. The original scales were developed in English speaking countries but have been widely translated into many other languages. Whilst the translation of descriptors into different languages has been ongoing for decades validation of the scales to elicit the same response to a given thermal stimuli is limited. This study aimed to examine if for those individuals who understand two languages when presented with alternative scales, in this case in either English or Chinese, that they provide the same subjective response to the environmental stimulus they were exposed too.

Method

A between-subjects experimental design was employed to investigate the consistency of thermal sensation reporting across translated subjective scales. A total of 30 participants (15 male, 15 female), all Chinese nationals residing in the United Kingdom for a minimum of six months, were recruited. Participants were assigned to one of three thermal conditions:

Cool: 18.5°C, 50% relative humidity (RH). Neutral: 23.0°C, 50% RH, Warm: 29.0°C, 50% RH

Each condition included 10 participants (5 male, 5 female). Participants wore their own clothing, with instructions to wear trousers/jeans and a shirt, resulting in an estimated clothing insulation of approximately 0.8 Clo, including the seat. Body mass and height were recorded for each participant.

Participants were seated in a climate-controlled chamber for a duration of 120 minutes, during which they were permitted to engage in sedentary activities such as reading or desk-based tasks.

Thermal sensation was assessed using bilingual (English and Chinese) thermal sensation scales (Figure 1). These scales were presented alternately to prevent simultaneous viewing. Participants completed both versions of the scale at three key time points: prior to chamber entry (baseline), at 0 minutes, and at 120 minutes. Additionally, from 10 to 110 minutes, participants were presented with alternating versions of the scale every 10 minutes.

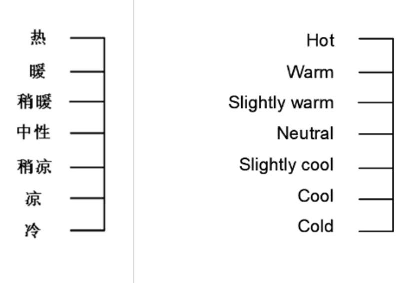

Figure 1 – Chinese / English thermal sensation scales

Participants were also asked to report:

Thermal preference (would you prefer to be warmer, no change, or cooler?)
Environmental acceptability (yes/no)
Satisfaction with the environment (yes/no)

Results

Environmental conditions were stable and constant throughout the experimental exposure and the conditions provided the expected mean thermal response from the participants, Warm, Neutral and Cold.

Figures 2 - 4 show the mean thermal sensation response for both the English and Chinese presented scales. When the English / Chinese thermal sensation responses were both taken at the same time point (pre, 0 mins, 120 mins) participants reported very similar subjective ratings. The alternate presentation of English then Chinese thermal sensation scales showed some minor variation over time as the participants responded to the different thermal environments. The important time frame to consider is from 100 to 120 minutes. By this time participants should have reached a steady thermal state and give consistent subjective responses. This can be seen clearly in the 18.5°C (cool) and 29°C (warm) environments.

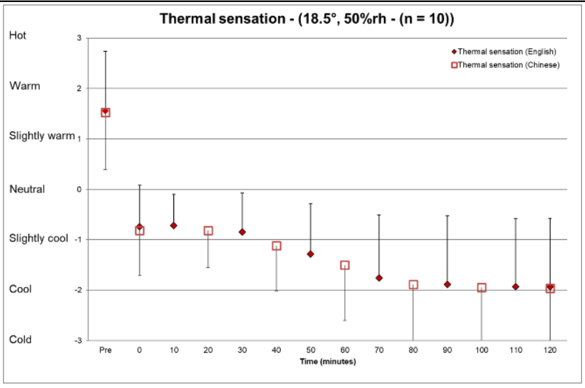

Figure 2 – combined English / Chinese thermal sensation responses - Cool

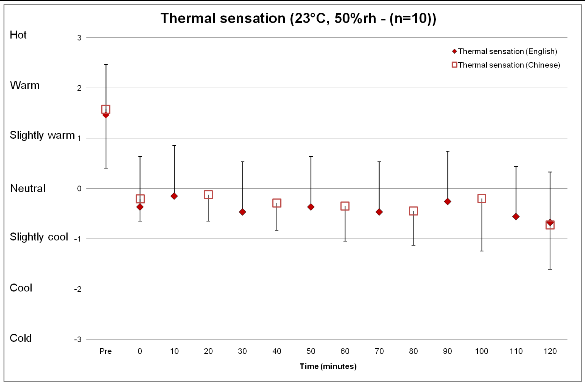

Figure 3 – combined English / Chinese thermal sensation responses - Neutral

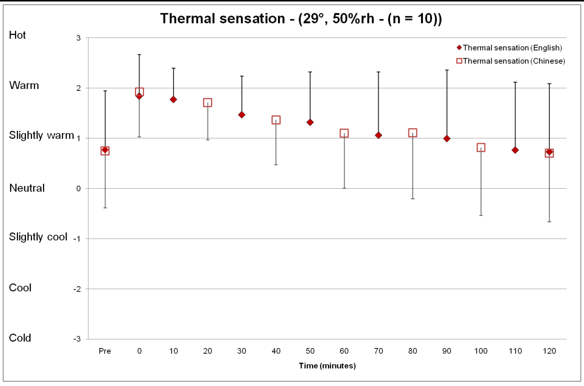

Figure 4 – combined English / Chinese thermal sensation responses - Warm

The data show that the participants are able to interpret the descriptors on the scales similarly in both English and Chinese for the environmental conditions that they were exposed to. This shows the effectiveness of well translated subjective scales in that they are capable of capturing the same response to the stimuli.

The additional metrics of preference, acceptability and satisfaction are detailed in table 1. The preference results align to that which has previously been shown for Chinese populations to prefer warmer air temperatures to western populations, Havenith et al (2020). The acceptability of the environment shows that there can be a variation between the persons thermal state, how they would prefer to feel and if it is acceptable. At 23°C 50% of the participants indicated that they would like to be warmer, but all reported finding the environment acceptable, with one participant only being dissatisfied with the environment.

Table 1 – Summary of end exposure Preference, Acceptable and Satisfaction ratings

	Preference	Acceptable	Satisfaction
18.5°C	Warmer - 90% No change -10% Cooler - 0%	No - 95% Yes - 5%	No - 95% Yes - 5%
23°C	Warmer - 50% No change - 50% Cooler - 0%	No - 0% Yes - 100%	No - 10% Yes - 90%
29°C	Warmer - 0% No change - 70% Cooler - 30%	No - 10% Yes - 90%	No - 10% Yes - 90%

Conclusion

Subjective rating scales, when appropriately translated, can serve as effective tools for quantifying perceptual metrics, particularly in the domain of thermal sensation. This study suggests that such scales exhibit robustness, consistently eliciting comparable subjective responses to thermal stimuli across different linguistic groups. Thermal sensation scales are designed to capture the perception of thermal intensity (e.g., warmth or coolness), rather than thermal comfort specificall. As such, they do not directly assess whether individuals find their thermal environment satisfactory. To evaluate thermal comfort comprehensively, additional questions are required, most importantly regarding the individual's satisfaction with the thermal environment.

It is important to note that a rigorous validation process is essential. This process should confirm that the translated versions achieve linguistic and conceptual equivalence with the original scale, ensuring that the integrity and comparability of the data collected across different language groups is equivalent.

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A predictive passenger car seats comfort model by using deep learning and CAD-CAE methods

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THE WORK IN CONTEXT

Car seat comfort is a critical aspect of automotive ergonomics, yet current design practices remain largely dependent on subjective evaluations and costly physical prototyping. This study introduces a data-driven framework that combines statistical analysis and deep learning with attention mechanisms to predict driver discomfort from pressure distribution data. Using a dataset collected from 192 participants, we analysed biomechanical parameters—such as contact area and peak pressure—across 11 body-parts and correlated them with subjective ratings on a 1–10 Likert scale. The proposed hybrid neural network achieved an R^2 of 0.82 in predicting global discomfort, with peak pressure showing the strongest statistical correlation (Spearman's r = 0.78). Additionally, Finite Element Analysis (FEA) was used to validate design changes suggested by the model, leading to an 18% reduction in peak seat pressure without compromising the structural performances. This approach demonstrates the potential of integrating AI and CAD-CAE to guide ergonomic seat design early in the development process, reducing physical prototypes and improving user comfort.

KEYWORDS

Car seats integrate design, Deep learning, Class A seat surfaces, Pressure map.

Introduction

Seating comfort is a crucial element in automotive ergonomics, directly influencing the driver's well-being and long-term safety [1]. Despite its relevance, seat design processes still largely rely on subjective evaluations [2] and iterative prototyping cycles, which result in long development times and poor generalizability of the outcomes. Recent advances in artificial intelligence and biomechanical sensing technologies open new perspectives toward data-driven seat design [3]. In particular, the integration of deep learning models with physical simulations (CAD-CAE) enables the prediction of perceived discomfort based on objective parameters such as peak pressure, contact area, and pressure distribution variability over specific body parts [4]. This study proposes an innovative framework that combines statistical analysis with neural networks incorporating an attention mechanism, with the aim of identifying the main discomfort factors and estimating the level of subjective discomfort. The model was trained on real pressure distribution data collected from 192 participants and validated through finite element analysis (FEA), in order to preserve the structural performances of new seat geometries [5], [6].

Methodology

The methodology adopted in this study is structured into four main phases, each aimed at building an integrated workflow encompassing data collection, statistical analysis, predictive modeling, and engineering validation.

Phase 1 - Experimental data collection: The experiment involved 192 participants, selected to ensure heterogeneity in body morphology. Each subject was seated on a test bench equipped with pressure-sensitive mats capable of acquiring pressure distribution data across 11 body parts both in backrest and in seat-pan. For each participant, in addition to objective data (average pressure, peak pressure, contact area), a subjective evaluation of perceived comfort was collected using a Likert scale from 1 to 10.

Phase 2 - Data Preprocessing: The collected data were processed through a cleaning pipeline that included Normalization of values to reduce inter-individual variability and detection and handling of outliers using the interquartile range (IQR) method, to exclude measurements distorted by postural errors or sensor malfunctions.

Phase 3 - Predictive Model Architecture: In a manner analogous to the approach adopted by the authors in [7], a hybrid neural network model based on convolutional neural networks (CNNs) was implemented and enhanced with an attention mechanism, with the goal of automatically identifying the most relevant features for discomfort prediction. The model input consists of 45 biomechanical and anthropometric features; the attention layer assigns a relevance score (ranging from 0 to 1) to each feature, improving interpretability; the Model output: estimated level of perceived discomfort.

Phase 4 - Integration with CAD/CAE Simulations: To validate the real-world applicability of the model, the information derived from the analysis was incorporated into a finite element analysis (FEA) simulation workflow using CAD seat models. The goal was to assess the impact of geometry modifications suggested by the predictive model in terms of Reduction of peak pressure and Preservation of the structural performances of the seat.

Results

The results of the analysis combine statistical evaluations, observations on anomalous data, and the performance of the attention-based predictive model. The analysed body parts exhibited significant differences in pressure distribution. In particular, the seat-pan area showed the highest values, both in terms of average pressure (1.03 kPa) and peak pressure (2.4 kPa), whereas the backrest area presented a more uniform distribution with lower values (average pressure: 0.45 kPa; peak pressure: 1.2 kPa). Zones 7 and 11 (thighs) also revealed variable values, with localized peaks (e.g., Zone 7: 1.78 kPa). In Figure 1-the average and the peak pressures are represented for the investigated bodyparts (Figure n.1-b).

The pressure analysis highlights that the seat surface is the most biomechanically stressed area, whereas the backrest demonstrates an effective load distribution. These observations suggest that future design interventions should primarily focus on the seat, aiming to reduce localized pressure, while drawing inspiration from the backrest's support capacity to improve the overall contact system.

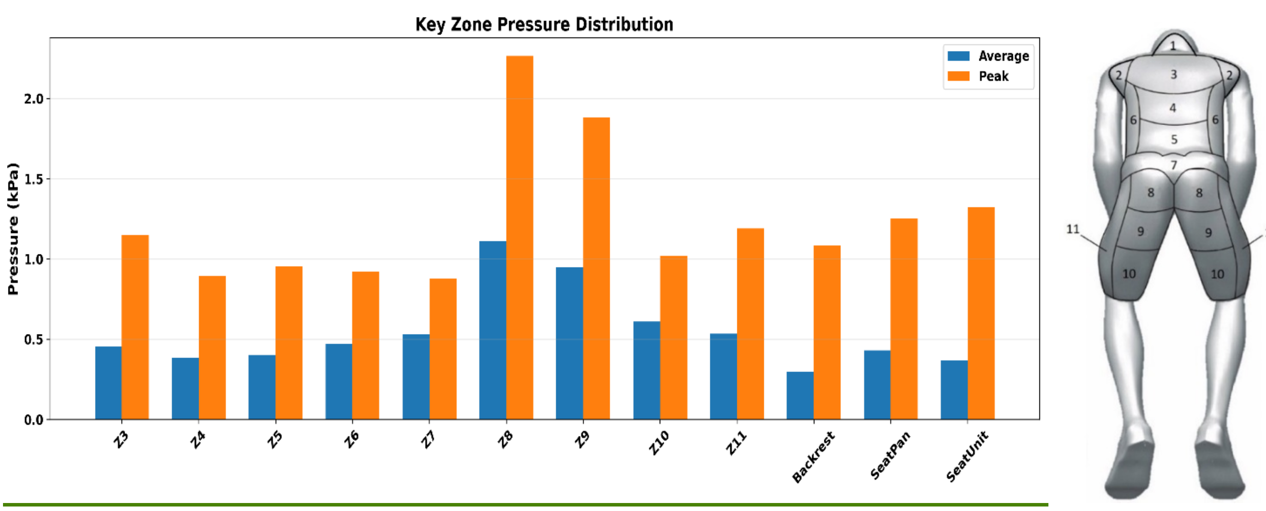

Figure 1. Pressure distribution across body zones (seat zones = highest pressure).

Spearman's analysis revealed significant correlations between certain biomechanical variables and perceived discomfort. Peak pressure in the seat area showed the strongest correlation ($r = 0.78$, $p < 0.001$), followed by seat load percentage ($r = 0.65$, $p = 0.003$). In contrast, contact area was negatively correlated with discomfort ($r = –0.68$, $p = 0.001$), suggesting that more evenly distributed support reduces the sensation of discomfort. As illustrated in Fig. 2, these results guided the selection of key variables for the predictive model; the heatmap highlights that peak pressure ($r = 0.78$) and seat load percentage ($r = 0.65$) are positively correlated with discomfort, while contact area ($r = –0.68$) shows a negative correlation, confirming these variables as key design drivers.

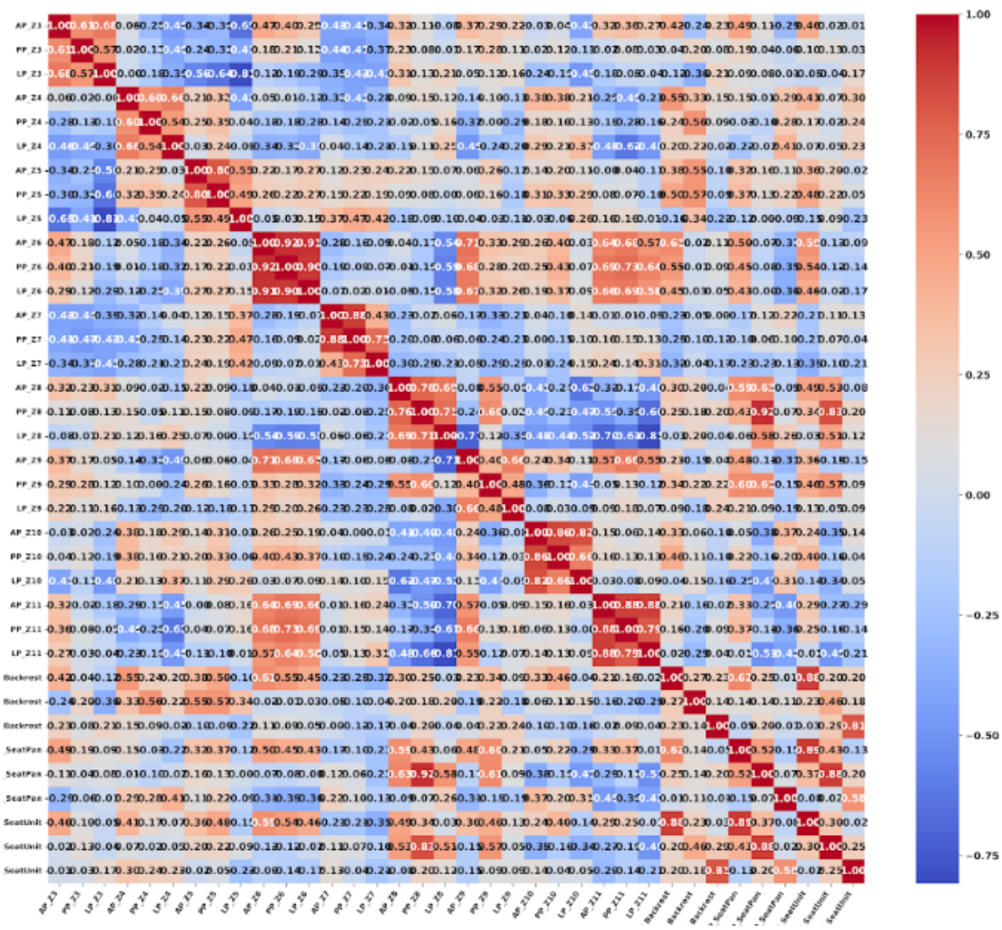

Figure 2. Comfort correlation matrix heatmap (peak pressure vs. discomfort: r = 0.78).

Abbreviations:
AD: Anthropometric Data; **DL**: Discomfort Level; **PSL**: Perceived Support Level; **OPCL**: Overall Perceived Comfort Level; **AP**: Average Pressure; **PP**: Peak Pressure; **LP**: Load Percentage; **Z3-Z11**: Body Zones 3-11; **Backrest**: Backrest Area; **SeatPan**: Seat Surface Area; **SeatUnit**: Entire Seat Unit.

Some Outlier were identified, i.e. subjects n.20 and 24 that exhibited anomalous results.

The initial version of the neural model, lacking an internal weighting mechanism for input variables, showed very limited predictive performance ($R^2 = -2.30$). To overcome this limitation, an attention mechanism was introduced, capable of assigning a relevance score to each variable, thereby improving both the model's predictive accuracy and its interpretability. The attention layer functions similarly to a cognitive process: just as a human reader focuses on key words in a complex text while ignoring less relevant details, the model learns to assign different weights to the 45 input features, highlighting those most influential in discomfort estimation. As shown in tab. 1, peak pressure in the seat area received the highest attention score (0.18), consistent with its strong statistical correlation ($r = 0.78$). This was followed by seat contact area (score = 0.15; $r = -0.68$), and hip width (score = 0.12), which—despite showing a weaker linear correlation ($r = 0.21$)—suggests a potential non-linear interaction between body morphology and seat geometry.

Table 1 – Key features identified by the attention mechanism, with relevance scores and statistical correlations

Feature	Attention Score	Statistical Correlation (r)
Peak seat pressure 1	0.18	0.78
Seat contact area 11	0.15	-0.68
Hip width [cm]	0.12	0.21

The results demonstrate a good convergence between the neural and statistical analyses: both identify peak seat pressure and seat contact area as the main drivers of discomfort. However, significant divergences also emerge—for example, in the case of seat load percentage, which, despite showing a strong statistical correlation ($r = 0.65$), received a very low attention score (0.05). This suggests that while the variable is generally significant, it may be less stable or influential within the predictive context learned by the model. Overall, the integration of the attention mechanism made the model not only more accurate, but also more transparent, providing a valuable tool to support ergonomic design based on objective data.

Discussion and conclusions

The results confirm the effectiveness of the integrated approach based on statistical analysis and neural networks with an attention mechanism in predicting discomfort. Peak seat pressure emerged as the most relevant predictive variable ($r = 0.78$), as shown in Figure 2 and Table 1, followed by seat contact area ($r = -0.68$). The attention mechanism exhibited good consistency with the statistical analysis, while also assigning relevance to variables with low linear correlation, such as hip width ($r = 0.21$), suggesting potential nonlinear relationships. In contrast, seat load percentage, despite being statistically significant ($r = 0.65$), received a low attention score (0.05), indicating possible predictive instability. As shown in Figure 3, the outlier analysis highlighted considerable individual variability in discomfort perception under similar biomechanical conditions. Finally, the integration with CAD/CAE simulations enabled the validation of the geometric modifications suggested by the model, resulting in an 18% reduction in peak pressure while preserving the structural performance of the seat.

This study introduced an integrated approach for predicting discomfort in automotive seating by combining statistical analysis, neural networks with an attention mechanism, and CAD/CAE simulations. The analysis confirmed peak pressure and contact area as the main predictors of perceived discomfort. The neural model showed good consistency with statistical results, and the attention mechanism enhanced interpretability by also highlighting non-linear variables such as hip width. Despite the initial limitations in predictive performance ($R^2 = -2.30$), the model was refined and validated through engineering simulations, achieving an 18% reduction in peak pressure without compromising structural stability. Future developments will focus on expanding the dataset to reduce overfitting, integrating the attention mechanism with lighter and more interpretable architecture such as Random Forests, and adopting digital twin solutions for personalized, real-time simulation.

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Pressure Sensitivity of Human Back in Sitting Postures

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ABSTRACT

With the increasing demands for office work and travel, sitting has become a common behavior in daily life, raising expectations for seating comfort. Various studies on seating comfort have shown that both the pressure sensitivity of the areas in contact with the seat and backrest and the pressure distribution on the seat and backrest play an important role in evaluating seating comfort. Hirao et al. clarified the relationship between thigh pressure sensitivity and pressure distribution in a driving posture using automobile seats. However, prior measurements focused only on the thighs, and pressure sensitivity of the back has not been examined. To address these issues, this study aimed to measure pressure sensitivity in the back. Establishing measurement environment required developing a specialized chair and pressure application device. The goal was to clarify the pressure sensitivity of the back, thighs, and buttocks in a working posture. This was achieved by constructing the experimental setup and conducting sensitivity measurements across the target regions.

KEYWORDS

Pressure sensitivity, Pressure distribution, Seating comfort

Introduction

In considering the comfort level of each person, how the sitting person feels the pressure applied by the chair is very important, and by clarifying this, it can be used to design chairs and seats that are suited to the physique of the sitting person. Vink et al. (2017) considered sensory sensitivity during sitting to be a factor in comfortable seat design and conducted sensitivity measurements on seated individuals. Hirao et al. (2022) proposed a method for defining pressure sensitivity using Stevens' power law. Furthermore, they measured pressure sensitivity in the thighs and examined its relationship with optimal pressure. Kato et al. (2023) extended the research on optimal pressure by evaluating seating comfort under conditions in which pressure distribution was more evenly dispersed. However, the measurement of pressure sensitivity in the sitting posture is limited to the thighs, and sensitivity distribution on the back has not been clarified. To establish an environment for measuring pressure sensitivity in sitting posture, it is necessary to develop an experimental chair and measurement device specifically designed for this purpose. Therefore, the objective of this study is to clarify the pressure sensitivity of the back in the sitting posture.

Method

(1) Pressure sensitivity (Hirao et al., 2022)

In this study, we calculate the perceived pressure actually felt by the seated person. Perceived pressure is obtained by multiplying the actual pressure by sensitivity.

$$\boldsymbol{Pressure_{perceived}} = \boldsymbol{Sensitivity} \times \boldsymbol{Pressure_{measurement}} \tag{1}$$

It is generally known that the relationship between sensation and stimulus follows Stevens' power law (Stevens, 1957). It is known that the relationship between the amount of sensation and the amount of stimulus is represented by using a power n that is unique to that sensation.

$$\emptyset = k \cdot S^{n} . . . \ k : Proportional\ constant \tag{2}$$

Therefore, in this study, the reference point pressure P_1 was used as the stimulation, and the measured pressure P_2 when a feeling of the same pressure was obtained as the sensation, and the proportional constant k was defined as the sensitivity.

Then, using the power law Equation (2), the actual pressure is converted to the perceived pressure.

(2) Experiment environment

Figure 1 shows an experimental chair, which was fabricated to conduct sensitivity measurement experiments in the office chair seating posture. In the 60s, Kohara (Watanabe et al., 2008) presented prototype diagrams of a chair in seven seated postures, including both working and resting postures. It is well known for typical template for chair design in Japan. This experimental chair is capable of reproducing diagrams for light work postures. The seat and backrest each have a structure of 50 boards aligned perpendicularly to the measurement surface, and the gap between the seat and backrest can be opened depending on the participant and the measurement point.

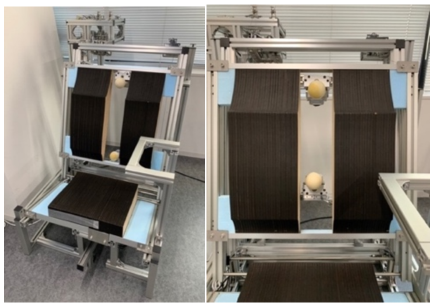

Figure 1. Experimental chair

Figure 2 shows the pressure-application device for measuring. The measurement is performed using two force gauges, and the pressure application device allows them to slide back and forth from the gap between boards.

Figure 2. Pressure Application Device (IMADA digital force gauge DTS-50)

(3) Experiment procedure

In the experiment, the reference and measurement point on the participant's back surface are pressed using a force gauge. The participant signaled when the perceived pressure matched with pressure of reference point. Figure 3 shows scene of experiment.

Figure 3. Experiment

Determination of reference point

The back of the participants is marked for the measurement. Six points were determined as reference points for marking points. Point (a) above the spinal column was defined as the location of the first thoracic vertebra and point (b) as the location of the fifth lumbar vertebra. Points (c) and (d) in the left and right column are the superior and inferior angles of the scapula, respectively.

The results showed that the best reproducibility was obtained when the first thoracic vertebra was used as the measurement reference point. There was no difference in the results of the lines along the scapula. Therefore, we decided the reference point was (a), and measurement points were the spine line on the spinal column and the scapula line aligned with the scapula.

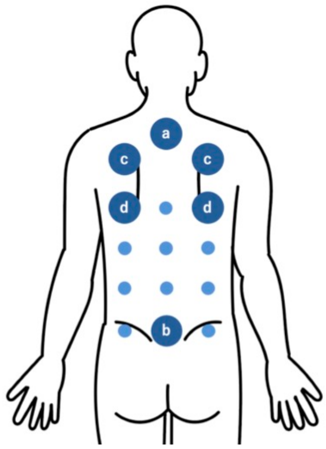

Figure 4. provisional Measurement points

Determination of power-law exponent for the back

There were 12 participants (height: 167±10.22cm, weight: 55.8±9.20kg, age: 23.75±1.14 years) in the experiment. Figure 5 shows the measurement and reference points. To determine the power-law exponent, statistical significance between each set of measurement data was calculated. This analysis was conducted separately for the data in the scapula line and along the spine line. Based on the results, the appropriate exponent to be applied in calculating the pressure sensitivity at each measurement point was examined.

The results showed no significant differences among the data in the scapula line. However, for the data along the spine line, significant differences were observed between upper spine and lower spine. Based on these findings, the power-law exponents were defined as follows.

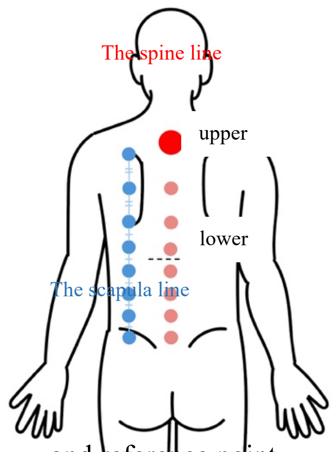

Figure 5. Measurement and reference point

$$\textit{The scapula line}: 1.30 \pm 0.50, \quad \textit{The spine line (upper spine)}: 0.96 \pm 0.31,$$
$$\textit{The spine line (lower spine)}: 1.17 \pm 0.33$$

Based on the results, pressure sensitivity of the back is defined as follows.

$$Sensitivity\ k = \frac{P_1}{{P_2}^{1.30}}\,(scapula)\,, \frac{P_1}{{P_2}^{0.96}}\,(upper\ spine)\,, \frac{P_1}{{P_2}^{1.17}}\,(lower\ spine) \tag{3}$$

From the above, the perceived pressure Equation (1) becomes Equation (4).

$$\begin{aligned} Pressure_{perceived} = k \times {Pressure_{measurement}}^{1.30}&(scapula), \\ {Pressure_{measurement}}^{0.96}&(upper\ spine), \\ {Pressure_{measurement}}^{1.17}&(lower\ spine) \end{aligned} \tag{4}$$

Results

In the experiment, pressure sensitivity of the back was measured using 12 actual participants.

The results of the back sensitivity measurements are shown in Figure 6. In the scapula line, for most participants, there was a general tendency for sensitivity to gradually decrease as the height of the measurement points moved downward. A similar trend was observed along the spine line, where sensitivity decreased with lower measurement point positions, and a marked decrease in sensitivity was observed between upper spine and lower spine.

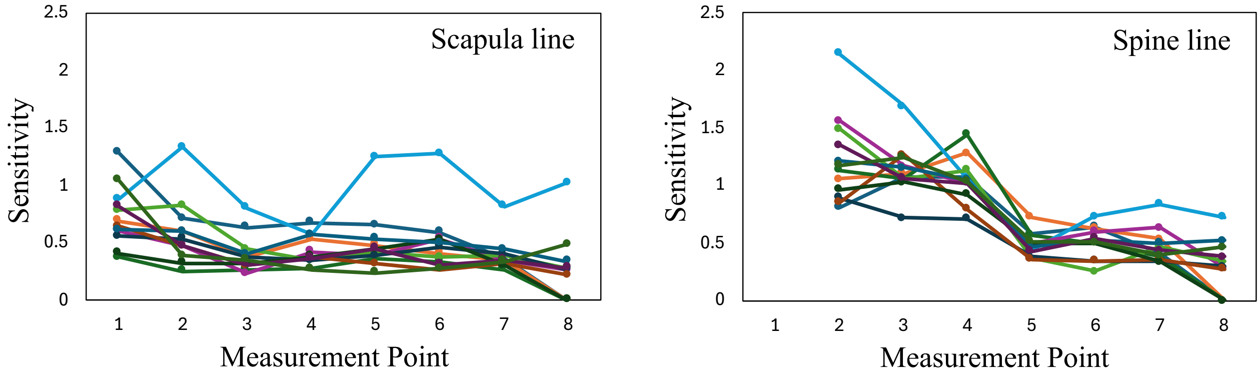

Figure6. Sensitivity distribution

Discussion

Compared to the study by Hirao et al. (2022), the power-law exponents obtained from back sensitivity measurements were generally higher than those obtained from thigh sensitivity measurements. Based on these findings, the back is more sensitive to stimulation than the thighs and likely to exhibit more rapid changes in perceived sensation. Vink et al. (2017) demonstrated that, in back sensitivity measurements, sensitivity is higher around the scapular region and gradually decreases toward the lower back along the spine line. They also reported minimal left-right differences, with sensitivity gradually decreasing as the height of the measurement points decreases. The results of this study show a similar trend to the above.

As the 12 participants were all in their twenties, the age range was narrow, and the participants limited, so it is necessary to expand the age range of participants and increase the overall sample size for more reliable results. In addition, to clarify how pressure sensitivity changes with posture, it is necessary to conduct measurements under different postural conditions. While back pressure sensitivity was measured, its relationship to the actual pressure experienced during sitting are unclear, so it is necessary to link pressure sensitivity with pressure distribution can help identify key factors influencing comfort.

Conclusion

This study clarified the pressure sensitivity of the back in the office chair seated posture using a special experimental chair. These findings contribute to analyzing comfort pressure distribution and the understanding of individual comfort perception in the future. It will allow us to utilize this information in the design of comfortable chairs and seats.

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The Relationship Between Movement and Discomfort in Automotive Seating

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ABSTRACT

Prolonged sitting in automotive environments can lead to discomfort, often reflected through compensatory movement behavior. This study investigates how movements correlate with discomfort under different seat configurations. Seventeen participants each completed four two-hour sessions while seated in distinct conditions (A, B, C and D) and tracked by Azure Kinect cameras. Movements were categorized into three bins based on velocity - small (<5 cm/s), medium (5 - 15 cm/s), and large (>15 cm/s) - and analyzed across six 20-minute intervals. Results revealed that seat conditions enabling frequent micro-movements (Conditions B and D) were associated with more consistent comfort maintenance, while reduced movement frequency was linked to discomfort buildup. Small movement frequency declined after the initial period but increased over time as discomfort accumulated. In contrast, large movements were more prominent early in some conditions (e.g., D), reflecting initial exploration and subsequent stabilization. These findings suggest that seat designs promoting subtle postural adjustments may delay the development of discomfort and improve the long-term seating experience. This study also provides evidence that integrating movement analysis into seat evaluation can enhance ergonomic outcomes in future vehicle interior design.

KEYWORDS

Seating comfort, movement, automotive, ergonomics

Introduction

The relationship between movement and discomfort in seating, particularly in automotive settings, has been extensively studied. Research indicates that poorly cushioned seats create localized high-pressure areas, reducing micro-movements and compelling users to make larger postural adjustments to alleviate discomfort. For instance, Na et al. (Na et al., 2005) highlighted that dynamic, well-cushioned seats encourage frequent micro-movements, thereby enhancing overall comfort. Similarly, Maradei et al. (Maradei et al., 2015) found that hard or inadequately cushioned seats lead to significant discomfort due to pressure build-up, particularly in the buttocks and thighs. This pressure suppresses small, frequent movements and increases muscle fatigue caused by static loading.

The SAE International report supports these findings, noting that insufficient cushioning restricts natural micro-movements and necessitates larger compensatory actions, such as shifting positions or standing briefly (Tasker et al., 2014). Biomechanical principles further elucidate the mechanisms behind these discomfort experiences: poorly cushioned seats generate "hot spots" of high pressure that inhibit subtle weight redistribution and natural posture shifts. This creates a feedback loop in which discomfort discourages micro-movements, leading to more pronounced, large-scale movements such as standing or leaning back (Abdollahzade et al., 2023).

Understanding how discomfort and movement interact over time is crucial, especially as automotive interiors evolve to support longer, non-driving-related activities (Cai et al., 2024). This study aims to explore how movement patterns, quantified using motion-tracking technology, relate to discomfort under various seating configurations.

Method

To evaluate the relationship between movement and discomfort, we conducted a two-hour within-subject study involving 17 participants (9 male, 8 female, mean age: 23.2 years) across four different seating conditions (A, B, C, D). Each participant completed all four sessions on different days. Azure Kinect cameras were used to record skeletal movement data. Comfort and discomfort were self-reported every 20 minutes.

During data processing, captured movement data were interpolated to a uniform 0.2-second interval (5HZ) for consistency. The adjacent speed—defined as the speed between consecutive skeletal frames - was computed for five upper-body joints: Pelvis, Spine_Naval, Spine_Chest, Neck, and Head. Movements were binned as follows:

- Small Movements (Bin 1): <5 cm/s, representing subtle posture adjustments and micro-movements
- Medium Movements (Bin 2): 5–15 cm/s, indicating moderate postural shifts
- Large Movements (Bin 3): >15 cm/s, representing major posture changes and repositioning

The frequency of movements in each bin was counted for each time interval (0–20, 20–40, 40–60, 60–80, 80–100, 100–120 min) and used to assess how seat conditions influenced posture dynamics over time.

Results

Figure 1 shows the frequency of movement events across conditions and bins. Key observations include:

- Small Movements (Bin 1): Conditions B and D resulted in higher frequencies of small movements compared to A and C, especially early in the session. This suggests greater freedom for subtle adjustments, which may contribute to sustained comfort. Frequency declined after the first 20 minutes but rose again in the final interval, indicating discomfort-driven compensatory behaviour.
- Medium Movements (Bin 2): These showed consistent patterns across all conditions and time intervals. Their relative stability suggests they may be driven by natural fidgeting rather than discomfort responses.
- Large Movements (Bin 3): In Condition D, large movement frequency was high initially but declined over time, indicating early repositioning followed by stabilization. In contrast, Conditions A and C exhibited flatter trends, suggesting limited opportunity for significant posture change.

These results demonstrate that the amplitude and frequency of movement are both time-dependent and condition-specific, and that movement behavior may be a valuable indicator of seat comfort.

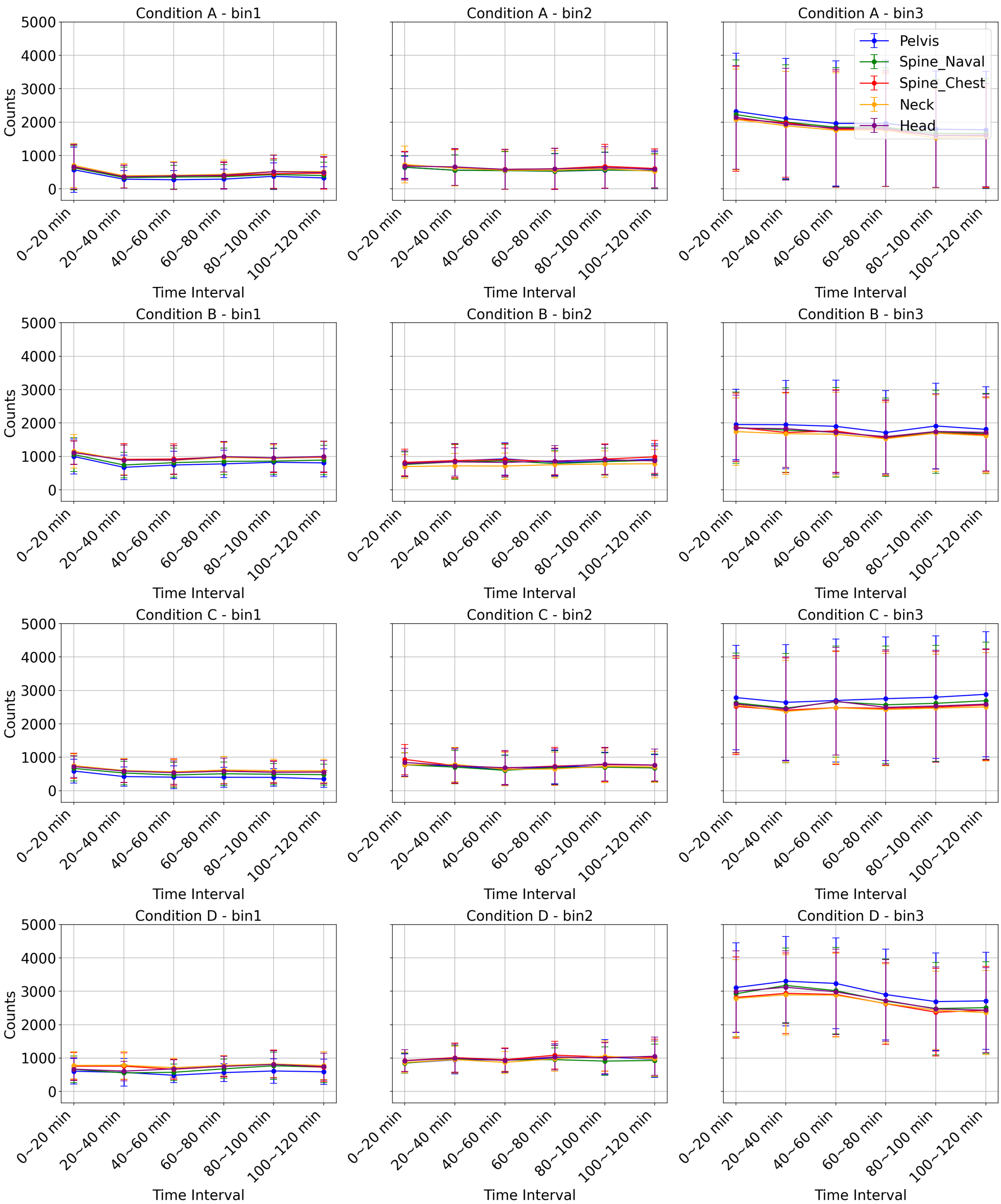

Figure 1: **Figure 1.** Frequency of movements (mean ± SD, measured in 0.2s intervals), grouped by seat condition (A–D), movement bin (1–3), and time intervals

Discussion

The results align with prior literature on comfort-related movement patterns and support the hypothesis that facilitating micro-movements can extend seating tolerance (Kruithof et al., 2025). These insights are particularly relevant for automated vehicle contexts, where passengers are expected to engage in a wider variety of seated activities over prolonged periods (Cai et al., 2024).

This study underscores how both time and seat characteristics shape posture dynamics. Small movements appear to serve a critical function in mitigating early discomfort, acting as micro-adjustments that help maintain postural stability. The observed U-shaped trend over time - characterized by an initial decline followed by a later increase in movement - supports the theory that accumulating discomfort triggers compensatory behavior.

Large movements, especially those noted in Condition D, point to an initial adjustment phase that transitions into postural stability, potentially indicating a more effective seat-body interface. In contrast, seat conditions showing flat or suppressed movement patterns may either inhibit natural movement or fail to support effective repositioning, thereby limiting discomfort relief over time.

Conclusion

This study confirms a strong association between movement dynamics and discomfort in automotive seating. Conditions that enable frequent small movements appear more effective in alleviating discomfort, whereas reduced or flat movement patterns may indicate the development of discomfort. Large movements are more dependent on specific conditions and may reflect either an adaptive response or discomfort-driven repositioning.

Designers should prioritize features that allow subtle postural shifts to mitigate discomfort during long-term use. Future research should integrate pressure mapping and physiological monitoring to further clarify the mechanisms linking movement and discomfort.

Ethics Statement

The Human Research Ethics Committee of Delft University of Technology approved this study (file number 3947 and 5110). Prior to the commencement of each session, informed consent was obtained from all participants.

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Measurement of pressure sensitivity distribution on the back supported by an elastic backrest

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ABSTRACT

We measured the two-dimensional pressure sensitivity distribution of the back under conditions that simulated the body pressure distribution experienced while sitting in an actual vehicle seat. We used an experimental seat that could generate various shapes and body pressure distributions, as well as different spring constants. We designated the front of the thigh as the reference site and applied three different reference pressures. We measured the pressure in each area of the back, producing a subjective pressure intensity equivalent to that at the reference site. Assuming the back's pressure sensitivity was symmetrical, we measured pressure on only one side of the body. Twenty-two participants took part in the experiment: sixteen men and six women. We identified equivalent pressure functions from the collected data that expressed the relationship between the pressure at the reference site and the pressure at various locations on the back. Using these functions, we then calculated the body pressure distributions that would theoretically yield a uniform pressure sensation intensity for each participant. We generated these distributions on the experimental seat at a 50-degree backrest angle. The subjective evaluation results showed that the pressure distribution was more uniform and preferable than leaning against a conventional seat. However, there was greater variation in the evaluations than in previous studies of the seat bottom, and the improvement was smaller.

KEYWORDS

Seating comfort, Body pressure distribution, Stevens' power law

Introduction

The pressure distribution on the seat surface, or body pressure distribution (BPD), is an important indicator of seat comfort. In seat design, the shape and hardness of the seat pads are adjusted to enhance comfort. However, the optimal BPD has not yet been fully elucidated.

Yamazaki et al. (1992) and Hirao et al. (2022) measured pressure sensitivity in the longitudinal direction along the femur using an experimental seat that was cut in half, demonstrating that pressure sensitivity is highest in the anterior femur. Vink et al. (2017) measured the two-dimensional distribution of pressure sensitivity whilst sitting using an experimental seat consisting of wooden boards with multiple 20 mm diameter holes for pressure measurement. Kato et al. (2023) used an experimental seat composed of multiple air cylinders to measure two-dimensional pressure sensitivity distributions in the longitudinal and lateral directions from the buttocks to the thighs. Based on these results, they generated a theoretically uniform sensory pressure distribution on the experimental seat and evaluated it. The results revealed that the body pressure distribution with uniform sensory pressure was evaluated more favorably than that of a conventional seat.

Similar to a previous study on seat bottoms, this study investigated whether a body pressure distribution with uniform sensory pressure on the backrest could provide greater comfort.

Method

Experimental seat

The experimental seat used in this experiment is shown in Figure 1. This seat is an improved version of the experimental seat used in our previous studies (Kato et al., 2023). It is equipped with a total of 116 air cylinders, 58 in the seat bottom and 58 in the backrest. By adjusting the air volume, internal pressure, and height of the air cylinders on the seating surface via computer control, it is possible to generate various shapes, BPDs, and spring constants. Rotatable resin top plates with a diameter of 60 mm are attached to the upper end of the pistons of the cylinders on the seating surface, with a 5 mm-thick urethane resin sheet with a surface similar to the soft tissue of the human body attached to the surface. During experiments, to obtain a more continuous body pressure distribution, a 15mm-thick polyurethane foam sheet was placed on the top plate surface, and body pressure distribution was measured using the XSENSOR LX100 body pressure mat (XSENSOR Technology Corporation, Calgary, Canada).

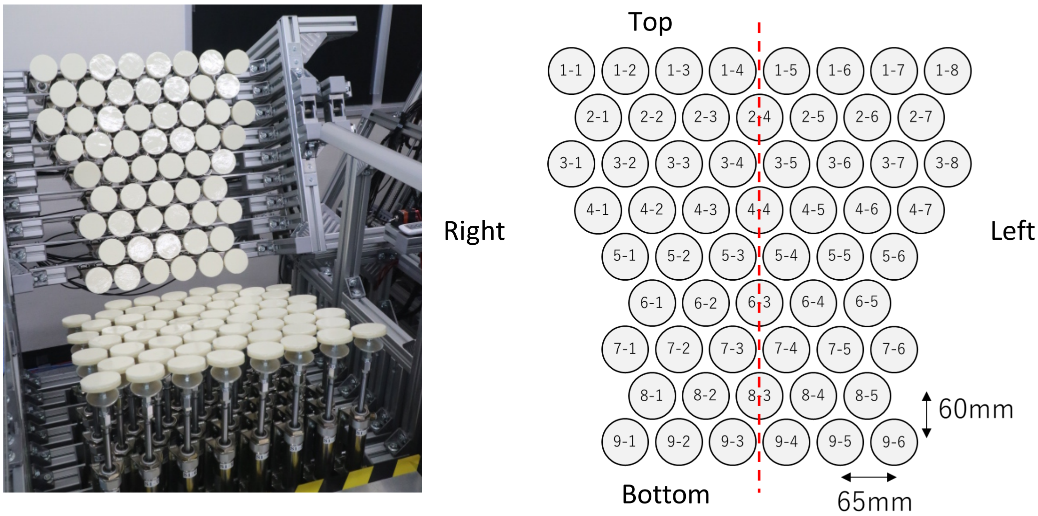

Figure 1. Experimental seat and layout of air cylinders in the backrest

Equivalent pressure function

The relationship between physical stimulus intensity and perceived stimulus intensity is known to follow Stevens' power law (Stevens, 1957). Assuming that human pressure sensation intensity follows Stevens' power law, the following relationship (equivalent pressure function) holds between the pressure at the reference site and the pressure at the evaluation site on the back.

$$\phi_{REi} = k_i \phi_{EQi}^{a_i}$$

where ϕ_{REi} : pressure at the reference site relative to the pressure at evaluation site i, ϕ_{EQi} : subjective equivalent pressure at evaluation site i, k_i : constant at evaluation site i, a_i : power index at evaluation site i.

Measurement and evaluation

The sensory reference position was set at the front of the left thigh. The sensitivity measurement positions were set at various points on the right side of the body that were in contact with the backrest of the experimental seat. Figure 2 shows an example of body pressure distribution on the experimental seat. However, since contact points vary by body type, the number of measurement points ranged from 27 to 42, depending on the participant. During the experiment, subjective equivalent pressure was measured relative to reference pressures of 2.5, 3.0, and 4.0 kPa at the reference site using an adjustment method. The backrest angle was set to 23 degrees at this time.

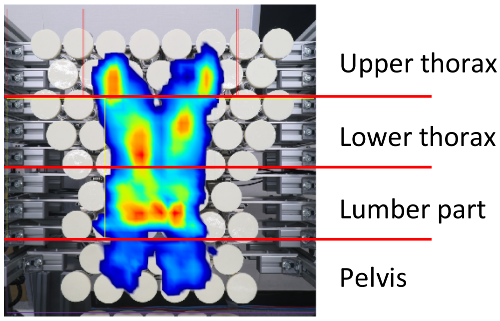

Figure2. Example of BDP on the seat

Next, we identified the coefficients of each equivalent pressure function for each evaluation site using the subjective equivalent pressure data obtained. Then, using these functions, we calculated the theoretical BPD that is subjectively uniform (subjectively uniform BPD). We reproduced this on an experimental seat and evaluated the uniformity (uniform or non-uniform) and preference (good or poor) of the pressure distribution on the back using a 9-level semantic differential method and compared it with a conventional seat. The two were compared in the experiment under a back angle of 50 degrees to evaluate comfort in a reclining posture.

The study included 22 healthy adult participants: Sixteen males and six adult females, aged 24 to 59 years (height: 1.54–1.80 m; weight: 45–85 kg). However, only 21 participants (excluding one male) participated in the uniformity evaluation experiment. All participants provided informed consent and obtained approval from the Ethics Committee of the Seating Division at NHK Spring Co., Ltd.

Results and discussion

Figure 3 shows the relative comparison results of the pressures at each location, which are equivalent to a reference pressure of 4 kPa and are calculated using the equivalent pressure function. Higher pressure areas indicate lower sensitivity, while lower pressure areas indicate higher sensitivity. Regarding sensitivity distribution in the lateral direction, sensitivity was lowest near the center and increased toward the periphery from the middle to lower regions in the height direction. The results of the paired t-test indicated that sensitivity was significantly higher in the peripheral regions than in the central region. Conversely, in the upper region, the opposite trend was observed: the central region had the highest sensitivity, while the peripheral regions had lower sensitivity.

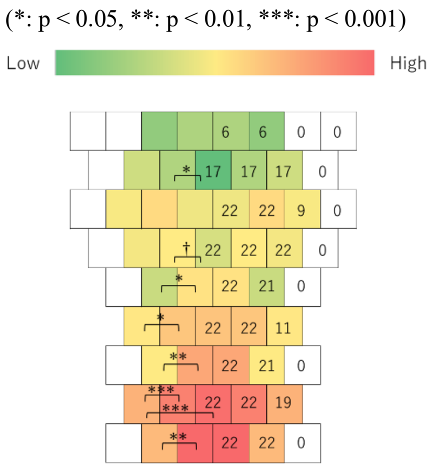

Figure3. Average pressure equivalent to reference pressure (4 kPa); Digits mean the number of participants.

Table 1. Results of test for differences between central parts (Paired t-test); Upper triangular part: t values, Lower triangular part: Number of participants who evaluated subjective equivalent pressure

Top — Bottom

	1-4	2-4	3-4	4-4	5-3	6-3	7-3	8-3	9-3
1-4		0.253	0.095	0.537	0.605	0.311	0.234	0.014	0.003
2-4	6		0.002	0.004	<0.001	<0.001	<0.001	<0.001	<0.001
3-4	6	17		0.232	0.381	0.113	0.006	<0.001	<0.001
4-4	6	17	22		0.016	0.006	<0.001	<0.001	<0.001
5-3	6	17	22	22		0.196	0.007	<0.001	<0.001
6-3	6	17	22	22	22		0.162	0.009	0.002
7-3	6	17	22	22	22	22		0.059	0.003
8-3	6	17	22	22	22	22	22		0.391
9-3	6	17	22	22	22	22	22	22	

Additionally, examining the sensitivity of the central column revealed that sensitivity was lowest in the lower regions and increased with height. Table 1 shows the results of the paired t-test for differences in sensitivity in the height direction between regions. Significant differences were observed between many regions.

The results for the lower part were consistent with the sensitivity measurement results of Vink et al. (2017). However, the results for the upper part showed the opposite trend. Regarding the upper part of the backrest, the topmost measurement points in their experiment corresponded to the third row from the top in our experimental seat. In this area, Vink et al. found that sensitivity was low in the central part and high on both sides. This differs from our results, in which no significant difference was observed between the left and right sides. In our experiment, the number of participants for whom we could conduct sensitivity measurements was particularly low in the first row at the top. As the measurement location moves upward, differences in body parts corresponding to the experimental seat due to individual body differences increase, resulting in greater variability in the measurement data.

Figure 4 shows the comparison results between the experimental seat with a 50-degree backrest angle, the subjectively uniform BPD, and a conventional seat. In the evaluation of pressure distribution uniformity, 16 out of 21 participants rated the experimental seat as having a higher uniformity of pressure distribution, and 14 out of 21 rated its comfort as higher. Additionally, the Wilcoxon signed-rank test results indicated significant differences in both cases, clearly demonstrating the subjectively uniform BPD's effectiveness. However, the results showed greater variability in evaluations compared to the evaluation results of pressure uniformity in the seat bottom from our previous study. This may be due to the longer support surface length of the backrest, variability in posture (i.e., spinal shape), and the possibility that the intended uniform pressure distribution was not fully achieved in the experimental seat. Furthermore, negative impressions from seated posture may have influenced the evaluation results.

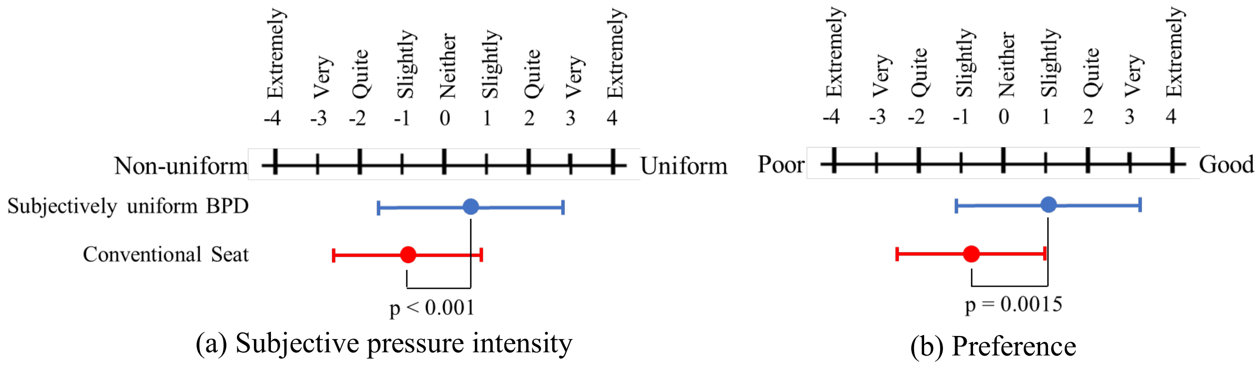

Figure 4. Means and SDs of Subjective Scores at a backrest angle of 50 degrees

Conclusion

We measured the pressure sensitivity distribution of the human back using an experimental seat composed of multiple air cylinders. The results showed that sensitivity in the central back region decreased toward the lower part and increased with height. Additionally, we clarified that sensitivity differs in the lateral direction. A theoretical uniform pressure distribution based on pressure sensitivity characteristics was generated and evaluated. As expected, this distribution provided a more uniform pressure sensation than a conventional seat. However, variability in evaluation was greater compared to the seat bottom and the improvement in favorability was small.

In the future, we plan to explore conditions that ensure comfortable seating posture and pressure distribution and to develop a robust backrest that provides comfort for a wide range of occupants.

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Ergomorphology - Biomimetic Shape-shifting Support Surfaces for Neuromusculoskeletal Health, Safety, and Comfort

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ABSTRACT

Sp1ke structural science technology is a globally patented breakthrough in cushioning and padding, engineered through biomimetic design principles to mimic nature's most efficient load-adaptive structures and optimized for neuromusculoskeletal support. At its core, Sp1ke leverages the concept of ergomorphology—advancing the principals of ergonomic functionality with continuously adaptive shape-shifting structures—to deliver unmatched comfort and synergistic biomechanical efficiency. Inspired by nature's load-responsive and protective architectures, Sp1ke's unique geometry dynamically redistributes pressure three-dimensionally, mitigates impact and vibrational forces, and enhances postural stability. Its intelligent structure adapts to user movement in real time, providing personalized support that aligns with the body's natural load dispersion and positional changes. Applications span high-performance footwear and anti-fatigue mats, ergonomic seating from office chairs to mass transportation, medical rehabilitation and mobility aids, and padding for full body protection, where traditional materials fall short. By harmonizing structural engineering with biomimicry and biomechanics, Sp1ke redefines cushioning—prioritizing not only conventional aspects of comfort like pressure relief but extending physiological harmony to effect homeostasis and long-term neuromusculoskeletal health. This technology imagines new benchmarks for adaptive, science-driven solutions in ergonomic innovation. Unlike conventional foams, gels, and air cushions that are generally amorphous, Sp1ke employs both microdynamics (bubbles in various foamed materials) and macrodynamics (secondary geometric structural elements) to confluently manage weight bearing, lateral shearing and torsion while absorbing impact throughout the structure. Sp1ke exploits ovoid and conical contact nodes within "Tips and Mesh" lattices to initially provide fully progressive resistance to loading. Anisotropic and auxetic geometries interweave those nodes within complex proprietary arrangements of three-dimensionally dynamic compression zones. Products injection-molded from a single, homogeneous material behave under stress as if composed of many layers of progressively dense foams. Hundreds of gentle contact points provide neurovascular stimulation and circulation while enhancing proprioception and muscle activation for better balance, posture, control, and gait.

KEYWORDS - Pressure-positive, neuromusculoskeletal, proprioception, biomimetic, ergomorphology

Introduction

Despite decades of advances in materials science and manufacturing processes – from foams and gels to air bladders, and now 3D printed meshes, critical deficits remain in providing comfortable cushioning solutions for all kinds of seating and lying surfaces, standing mats and insoles. These inefficacies manifest as common issues of discomfort, restlessness, and numbness, and a host of chronic conditions (e.g., sciatica, plantar fasciitis, piriformis syndrome) related to prolonged sitting, standing, or walking, with potentially life-threatening pressure injuries affecting about 2.5 million Americans annually. While myriad pressure mapping studies for products in comfort-focused industries have led to noteworthy improvements in reducing peak loads at bony prominences, musculoskeletal and dermal injuries continue to be prevalent. Recognizing that astronauts exposed to microgravity often suffer debilitating bone mass and proprioceptive loss, pressure is not just a risk factor but must conversely be an essential physiological stimulus for maintaining neuromusculoskeletal health. We hypothesized that next-generation support surfaces must not only distribute and buffer load but actively deliver dynamic, "positive pressure" feedback to maintain homeostasis and encourage movement. Furthermore, optimal cushioning must facilitate somatosensory stimulation, promote oxygen-rich blood flow, support mechanotransduction for proper cellular responses, manage heat and moisture release to avoid flesh maceration, and promote subtle movement.

Although many of the applications that we compose Sp1ke structures for today would most accurately be characterized as comfort solutions, to properly describe the evolution of this technology it is important to state that the inspiration for its inception was for something seemingly quite different. One would not typically correlate the comfort requirements for wheelchair seating with protection from catastrophic impact in aggressive sports like football, yet we may more easily consider comfort and impact protection to be intrinsically interrelated in automobile seating. The genesis of Sp1ke was in fact derived from seeking a solution for attenuating the significant potential for bodily injury and concussion ice hockey. The key objectives were to elongate the stress-strain curve in energy absorption and optimize the attenuation of impact received from any angle through lateral and rotational dispersion, beyond simple compression. Other significant considerations included allowing athletes to remain in homeostasis by minimizing thermal loading, moisture retention (heat and sweat), suppression of natural proprioception (3D awareness of body position and movement), and accumulation of pathogens. To achieve this, we conceived a revolutionary shock damping underlayer to the typically rigid protective outer shells that would effectively replace open-cell, hydrophilic, insulating polyurethane (PU) with an open grid structure of closed-cell, hydrophobic and more resilient foam like ethylene vinyl acetate (EVA). Considering that EVA is substantially stiffer than PU, the concept of conical nodes with soft vulnerable tips was developed to essentially emulate a succession of low-density soft foam to increasing firm and more dense foam layers by simply increasing structural density for fully progressive resistant to loading.

Very quickly we became aware that these Sp1ke protective structures with their unusual ability to disperse load laterally were incredibly comfortable to sit, stand, or lay on. From there, we began to consider that when a person drops into a chair while there may be mild initial impact, there is also the “residual” force of gravity pressing the buttocks against the seating surface. As somewhat of a conundrum we thought of this as “static impact”, however the greater quandary was understanding how sitting on hundreds of undulating spiky tips could be so counterintuitively comfortable.

Henceforth began the journey of investigating everywhere these Sp1ke forms may be exploited to provide exceptional comfort when sitting, standing, laying, and even kneeling. What evolved into more compelling motivation for our effort was identifying that several other innate structural characteristics of this protective solution provide augmented comfort benefits for which all other cushioning forms have been left wanting. Utilizing an open grid matrix structure that offers thermal and moisture release with soft bendable tips in seat cushions, mattresses, and insoles potentially reduces skin maceration and shearing stress – highly prevalent antecedents to discomfort, pain, and pressure wounds. Gentle positive pressure and stimulation (not unlike gentle massage) from Sp1ke tips across a dynamically undulating surface effect mechanotransduction to influence cell recovery, encourage blood/oxygen circulation, aid muscle activation and sequencing, stimulate proprioception for autonomic balance, while positively influencing natural posture and gait.

Method

Tasked with the challenge to investigate, understand, prototype, refine, and evaluate Sp1ke’s efficacy in providing measurable comfort benefits and neuromusculoskeletal support across such broad applications and product sectors has required years of R&D and the incorporation of comprehensive, multi-disciplinary test methodologies, subjects, and environments.

After developing an extensive digital library of structural subcomponents and complex biomimetically-derived CAD models for Sp1ke products that were optimized for each application, we tooled and injection-molded these elaborate geometries to then test a range of material formulations in order to evaluate their performance against various standard characteristics such as durability, compression set, elongation, abrasion, density, hot/cold temperature performance, etc.

Research methodologies have included extensive pressure mapping (both static and dynamic video) by several third parties and internally for office, wheelchair, aircraft, race car, and mine blast seating. Proprietary studies of pressure relief and dispersion have been conducted by a top-three global manufacturer of contract office furniture, leading international manufacturers of aircraft seating, Canada's largest pharmacy chain for wheelchair cushion rental, and a renowned producer of mine blast seating for armored military personnel carriers. The most extensive of these studies over a year tested the hypothesis that an application-specific designed Sp1ke technology cushion roughly 1" thick could perform at parity or outperform any cushion the company could produce from all known materials up to 3" thick in both quantitative and qualitative assessments. The study included over 800 pressure map images, various standard functional performance tests, and qualitative assessment by department leaders and their staff throughout their operations, as well as with attendees at their annual conference of international distributors.

Serta Simmons Bedding tested the most rudimentary prototypes of Sp1ke mattress toppers simply composed of cushions and mats laced together for evaluating comfort, and heat and moisture dissipation against their top-of-the-line mattress constructs.

In assessing blood/oxygen flow with Sp1ke cushions while seated Near Infrared Spectroscopy (NIRS) was employed at UBC, and Doppler flowmetry was used for evaluating blood/oxygen flow while standing on Sp1ke mats with stroke patients at Beijing Tiantan Comprehensive Stroke Center. Balance testing by physical therapists and kinesiologists is frequently applied with various patient groups in assessing the therapeutic value of our mats and insoles against client needs.

Additional testing has included impact assessment for head and body protection and seat cushions, immersion testing for wheelchair cushions, as well as "Squirmin' Herman" durability testing, REACH and FAA 853 burn tests for aircraft cushions.

Independent pressure mapping was conducted at the Hong Kong Queen Elizabeth Hospital (CRSSC) to certify the usage as Sp1ke cushions for wheelchair users in direct comparison to the costly industry leading air cushion, before authorizing patient payment support by the Hong Kong Hospital Authority.

Two world-renowned Olympic Champion track and field coaches have done extensive trials of Sp1ke insoles themselves, among their training staff, and with their athletes. Our insoles and mats are also tested regularly with challenging patients faced with issues like neuropathy, stroke, athletic and work-related injuries in clinics and training facilities across North America. Therapeutic disciplines for usage focus on balance improvement, physical, occupational and massage therapy, osteopathy, orthopaedics, chiropractic, podiatry, athletic performance and recovery.

In support of Sp1ke structural science a series of material science studies were also completed to augment its usability and proof-of-concept for a variety of specialized applications. To meet the rigorous flammability test specifications of the FAA for usage as aircraft seating support surface, polymer development studies were conducted at the engineering departments of the University of Toronto, and York University, Toronto. Subsequent independent studies were completed by us to produce optimized proprietary polymers in the facilities of our manufacturing partner.

This comprehensive testing framework ensures Sp1ke's efficacy across multiple applications while meeting various general and industry-specific standards.

Results

Extensive internal and third-party testing, and exemplary levels of customer satisfaction from well over 100,000 users of Sp1ke products sold internationally (cushions, mats, and insoles) have clearly validated the performance and versatility of this core technology. Although patentability is not *de facto* proof of any product's value or viability, the fact that we've received patent allowances in all 45 global jurisdictions that we applied to certainly speaks to its novelty.

Comparative comfort and pressure relief evaluations against leading foam, gel, air bladder, and other innovative cushion constructs and materials conducted across multiple seating applications (e.g., office, wheelchair, and aircraft seating) have consistently proven Sp1ke's top-tier performance. More importantly, Sp1ke has been quantitatively and qualitatively proven to go far beyond the traditional seating industry performance standards with unique value-added characteristics that warrant recognition as precepts for complete comfort and long-term health. Sp1ke's exceptional comfort proposition encompasses neurovascular stimulation to improve oxygen-rich blood circulation in relief of numbness, sitting fatigue, piriformis and sciatic pain. This revolutionary architecture promotes unrivaled levels of proprioception - essential for autonomic balance and postural awareness, and neuromusculoskeletal integrity. Additionally, Sp1ke provides efficient airflow and moisture release while continuously resetting contact pressure points through subtlest movements. Originally developed for protective padding in contact sports, Sp1ke outperforms amorphous materials in impact testing, innately attenuating shock and vibration, and lengthening the stress-strain curve via elastomeric surface tension and lateral deflection.

The year-long study by a leading office furniture manufacturer concluded that a 1" thick Sp1ke cushion consistently outperformed all other options - up to 3" thick - in terms of pressure redistribution and user comfort. Video pressure mapping highlighted Sp1ke's dramatic ability to dynamically redistribute loads laterally and adjust to user movements through shape deformation, effectively broadening the contact area and reducing peak pressures at key anatomical sites. Highly successful independent assessments by aircraft seat manufacturers resulted in commitments by 4 of the largest companies globally to engage in development of bespoke solutions for their seat frames.

Studies utilizing NIRS and Doppler flowmetry demonstrated enhanced oxygenated blood flow in users when seated or standing on Sp1ke. Kinesiological assessments showed notable improvements in proprioception, muscle activation, autonomic balance, posture, and gait across a broad user base, including those suffering acute or chronic musculoskeletal pain, neurological impairments, even fostering commendable one-foot balance success for patients with insensate neuropathy. Qualitative feedback and user testimonials strongly corroborate quantitative findings, leading to Sp1ke becoming the only product family that is endorsed by the International Osteopathic Association.

Conclusion

Sp1ke geometric principles, and the science of ergomorphology that drives its evolution stands as a highly-adaptable, effective, and valuable hard tech innovation across myriad applications. Complemented by a library of robust and versatile material solutions (e.g. bio-based, rubber and nanographene hybrids, FR) Sp1ke offers industry profound opportunities to reimagine cushioning and padding for remarkable comfort, augmented protection, and synergy between human forms and our environment for exceptional long-term neurovascular and musculoskeletal wellbeing.

As a single molded structure that utilizes biomimicry, and micro/macrodynamic integration to achieve more than is achieved with costly layering of several other materials Sp1ke products are well-positioned to meet the emerging needs of a circular economy (recyclable and biodegradable).

Imagine a single product so versatile to be equally effective as an anti-fatigue mat for a full-grown man as it is as a gentle infant massage pad. Asked what we'd do with 3D printing? Print Sp1ke!

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Our Science - Vigurus (2025, May 18). Dr. Apostolopoulos Talks About Tensegrity, Mechanotransduction & Sp1ke™ https://vigurus.com/our-science/

Factors Influencing Comfort of Flight Attendants

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ABSTRACT

The comfort of flight attendants is a critical factor in ensuring both their well-being and the overall safety and service quality on board. In this study, a two-step approach method has been used to explore factors influencing comfort of flight attendants. First, three experienced flight attendants shared their experiences. Later, a questionnaire was designed based on the results of first session and 35 valid responses were gathered. The findings reveal that the comfort of flight attendants during their work hours is largely contingent upon their health condition, the work environment, and their expectations of career advancement. Work-related health concerns are diverse, with injuries being a prevalent issue. Among the environmental factors impacting their comfort are turbulence, odors, noise levels, vibrations, temperature, lighting, and color schemes. Physical discomfort and mental strain are identified as the primary contributors to human errors in aviation. Unforeseen situations pose additional challenges to their work. Addressing these factors is crucial in enhancing the overall well-being and effectiveness of flight attendants.

KEYWORDS

Flight attendants, comfort, commercial aircraft

Introduction

The air traffic industry has experienced rapid growth since the early 20th century, and this expansion is expected to continue in the foreseeable future (Arat et al., 2023). Flight attendants play a pivotal role in delivering customer service and adapting to the evolving needs of passengers (Changar et al., 2025). In addition to their service responsibilities, they are also entrusted with ensuring cabin safety (Wang, 2024) The nature of their work and the working environment can be highly demanding (Riaz et al., 2024), often placing flight attendants under significant pressure (MacDonald et al., 2003). As such, improving the comfort of flight attendants in their work is essential for their well-being and job satisfaction.

Many researchers have examined the physical and mental wellbeing of flight attendants. (Rau et al., 2020) studied 62 Chinese female flight attendants and emphasized that work-related musculoskeletal disorders constitute a significant issue. (Ballard et al., 2004) conducted a qualitative study focused on female flight attendants, revealing that mental health concerns arise primarily from isolation, fears of inadequacy as partners and mothers due to job demands, passenger interactions, and inadequate employer protection against workplace hazards and aggressive passengers.(Hong et al., 2023) underscored the notable influence of sleep patterns, diet, physical activity, and relaxation practices on flight attendants' fatigue levels. Organizational factors, individual factors, demographic features, passenger type, physical work environment and content of the flight task are considered as the key determinants of cabin crew's emotional labor behavior (Karanfil & Çoban, 2024).

Despite the past studies, not many studies focused on the comfort of flight attendants and the question "What are the primary factors that contribute to the comfort level of flight attendants during their work?" still remains. To answer this question, the challenges and comfort status of flight attendants during work are explored in this study.

Methods

A two-step approach to research the factors influencing comfort of flight attendants has been conducted. Firstly, three experienced flight attendants, who are also responsible for training of young flight attendants, were invited for a group discussion. The detailed information of participants can be found in Table 1. All the participants have served both single-aisle passenger aircrafts and twin-aisle passenger aircrafts. During the session, they shared their experience working on different aircraft models, discussed the challenges of the work in cabin and factors influencing their comfort under the guidance of the host.

Table 1 Participants information of the group discussion.

Participant no.	Gender	Age	Working years	Aircraft models
1	Female	38	15	Boeing737-700, Boeing737-800L/Max, Boeing767, Boeing787-900
2	Female	54	32	A300, A319, A320, A321, A330, A340-300, A340-600, Fokker100, MD-11
3	Male	40	19	A320, A330, A350, Boeing777

After the discussion session, the recordings were analyzed and used to develop an online survey, which is the main tool for data collection of the second step of the research. The questionnaires were sent out to flight attendants and 35 valid responses were collected. Detailed information can be found in Table 2.

Table 2 Participants information of the online survey.

	Number of participants	Age	Stature(cm)	Mass(kg)	Working experience
Female	26	30.42±3.49	169.04±2.69	55.54±3.54	1-3 years: 8%; 3-5 years: 4%; 5-10 years: 38%; 10+ years: 50%.
Male	9	34.44±4.33	179±3.16	79±7	1-3 years: 11%; 5-10 years: 22%; 10+ years: 67%

Results

Regarding comfort, the most mentioned aspects in the discussion session were: work-related health issues, working environments with interactions involved and expectations of career development. The most common work-related health issues of flight attendants are cervical and lumbar spine problems, varicose veins, otitis media caused by continuing to work while having a cold, urethritis resulting from urinary retention, stomach problems caused by irregular meals, hair loss caused by low oxygen level in cabin, neurasthenia caused by irregular sleep and skin problems caused by dry air. Mental well-being was also mentioned. Besides that, 60% participants of the online survey (21/35) reported they or their colleagues had been injured at work. The injures are mostly related to dealing with ovens (38%), food (25%), trollies (19%) and kettles (17%).

Expectations of career development were mainly about capacity building and human errors. Capacity building could be technical skills such as operating different parts of the cabin, and non-technical skills including communication skills, adaptability, teamwork, self-management and service orientation. 77% of the participants (27/35) consider non-technical skills are more important during work and 94% of them (33/35) think non- technical skills are harder in training. Reasons causing human errors are varied. The most common reasons can be physical discomfort (including fatigue), mental stress, poor short-term reaction, lack of attention and habitual operations. Rankings of the influence regarding these factors can be found in Fig. 1.

Figure 1 Rankings of reasons causing human errors

The working environment determines how flight attendants interact with products and people in cabin. The mentioned environment factors were temperature, humidity, noise, light, color, smell, vibration and turbulence. Impact on comfort during work of these factors are shown in Fig. 2. Kitchen products and control panel were most mentioned interactive products. People could be passengers and other cabin crew. The most challenging part is dealing with unexpected situations of passengers during the trip. Participants reported situations need extra attention they have met in their work and the results are shown in Table 3.

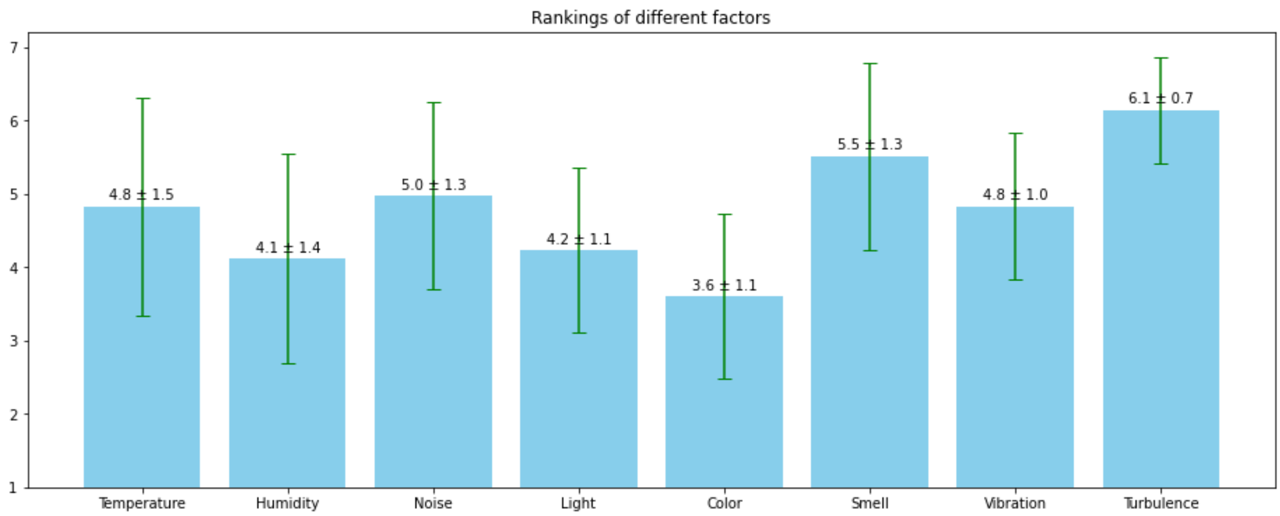

Figure 2 Rankings of different factors influencing comfort during flight attendants' work (1=no influence, 7=severe influence)

Table 3 Situations need extra attention.

Situations need extra attention	Numbers of participants	Proportion
The passenger seat is damaged and needs to be changed.	24	68.6%
The IFE is not fully functional.	21	60%
Power banks caught fire.	7	20%
Sudden illness of passengers.	25	71.4%
Disabled passengers and passengers with severely reduced mobility.	17	48.6%
Children keep crying and yelling loudly.	26	74.3%
The kitchen utensils are not functioning properly.	23	65.7%
The control panel is not fully functional.	21	60%

Conclusion

The findings of this study reveal three primary factors that influence flight attendants' comfort during work: physical condition, career development expectations, and the working environment. Regarding physical condition, health issues and work-related injuries are major concerns. Common health complaints among flight attendants include cervical and lumbar spine problems, varicose veins, otitis media, urethritis, stomach issues, hair loss, neurasthenia, and skin problems. Most injuries are associated with catering services. Career development expectations primarily revolve around capacity building and human errors. For most flight attendants, non-technical skills pose a greater challenge than technical skills. The most significant factors contributing to human errors are physical discomfort and mental stress. The working environment encompasses both the physical environment and unexpected situations that may arise within it. Turbulence is the most influential environmental factor. The most frequently mentioned unexpected situation that can distract flight attendants is the persistent crying and loud yelling of children. This study suggests that more attentions should be given to the health management, training methods and work environment optimization of flight attendants.

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Investigating Differences in Spatial Perception Between a Virtual Reality Environment and a Real-Life Aircraft Cabin Simulator

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ABSTRACT

Virtual reality (VR) technology has gained traction in diverse design domains, yet its integration into aircraft interior design remains underexplored. This study investigates the feasibility of VR as a tool for aircraft cabin design by examining spatial perception disparities between a VR-based cabin environment and a physical simulator. Through a within-subject experimental design, 30 participants performed standardized tasks in both settings. The findings reveal statistically significant differences in spatial perception across multiple dimensions: participants exhibited notable discrepancies in distance estimation during lateral movements (e.g., turning and lateral displacement) and in judgments of horizontal and vertical spatial extents. Additionally, the study highlights critical challenges associated with VR adoption in this context, including user discomfort, inconsistencies in spatial cognition, and difficulties executing precise movements within the virtual environment. These results underscore the need for further optimization of VR systems to align virtual representations more closely with real-world spatial experiences, thereby advancing its applicability in aircraft interior design workflows.

KEYWORDS

VR, Spatial perception, Aircraft interior design

Introduction

Virtual reality (VR) technology has increasingly been employed across various design phases due to its cost-effectiveness and minimal space requirements (Coburn et al., 2017). It has been posited that design issues can be effectively identified through VR when physical prototypes are not feasible (Camburn et al., 2017). In contemporary design practices, VR is utilized in activities such as 3D modeling, virtual prototyping, product evaluation, co-design, and design education (Berni & Borgianni, 2020).

One of the most formidable challenges in the practical application of VR technology lies in imparting a sense of realism to users through the precise rendering of depth and distance (Gibson, 2014). (Waller & Richardson, 2008) conducted 3 experiments including 28 try outs of distance estimation in a laboratory to investigate the fundamental processes of interaction effects in virtual environments and the potential scenarios that might arise. Fourteen of these try outs were dedicated to distance estimation in virtual reality (VR) environments, while the other 14 focused on distance estimation in the real world. The results indicated that, on average, distance estimates in the real world were 99.9% of the actual distances, whereas in VR, the estimates averaged 71% of the actual distances. This suggests that interaction with VR can exert an impact on human perceptual systems. (Murgia & Sharkey, 2009) discovered in their research that, in virtual environments, depth estimation tends to be inaccurate regardless of the environmental conditions or the abundance of depth cues. However, according to (Gibson, 2014), monocular cues such as motion parallax, dynamic shadows, and textured objects can influence visual experience. In other words, in the real world, the richer the depth cues are, the more enhanced/accurate the body-based interactive experience becomes.

The present study investigates the differences in spatial perception between a VR-based aircraft cabin and a real-life aircraft cabin simulator, with the aim of evaluating the potential for expanded use of VR in aircraft interior design.

Methods

A within-subject experiment was conducted with 30 participants (23 females and 7 males). The average height of the participants was 166.2 ± 7.2 cm (range: 154 cm to 182 cm), and the average weight was 61.8 ± 6.9 kg (range: 50 kg to 78 kg). The average BMI was 22.4 ± 2.3 (range: 18.4 to 27.5). Each participant completed the same tasks in both a virtual reality cabin and a real-life cabin simulator. The entire experiment was conducted in three days. The setup of the first day and the third day were for real-life tasks. The setup of the second day was for VR tasks. To mitigate fatigue effects, half of the participants started on the first day and the other participants started on the second day. To guarantee the safety of participants, the seats were removed for VR setup. The VR equipment used in this study was the VIVE Focus 3. The simulator represented a sector of the C919 aircraft, with a projection screen designed to enhance depth perception (Fig.1).

Figure 1. the C919 simulator with projection.

Figure 2. a participant experiencing VR setup.

In each setup, participants first maintained their hands at a consistent horizontal level and gestured a distance of one meter. They then gestured the position one meter above the ground. Following this, they were instructed to move one meter in four directions (forward, backward, left and right). Lastly, they were asked to turn 45 degrees to the left and right. All movements and angles were based on personal judgment, without the use of measurement tools. The researchers measured the distances and angles after each movement, but did not inform participants of the results. At the end of experiment, each participant was asked about the difference they experienced in the two setups.

Data was gathered and subsequently assessed for normality using the Shapiro-Wilk test. The results showed that not all the data distributed normally. To compare the differences in the perception of the same length between a virtual reality cabin and a real-life cabin, as well as between the left and right sides, the Wilcoxon Rank-Sum test was employed.

Results

Table 1 shows the actual length of movement in different directions, comparing both a real-life simulator and a VR environment. in both real-life simulator and VR environment. Notably, in the VR setting, the distance moved to the left is significantly shorter than in real life. Similarly, the angle of turning left in VR is significantly narrower compared to the real-life simulator. Both the leftward movement distance and the left-turning angle exhibit greater deviations from the intended target in VR. In terms of horizontal distance, participants underestimate the target distance in both the real-life simulator and VR environment. However, within the VR environment, the perceived horizontal distance is significantly shorter, demonstrating a larger deviation. Conversely, the same vertical distance is perceived as significantly longer in VR, showing a smaller deviation compared to the target length.

Table 1 Actual length and angle of movement in different directions

	Real-life simulator		VR environment		P value
	Mean	SD	Mean	SD	
Forward (cm)	101.5	20.8	100.4	24.1	0.903
Backward (cm)	106.9	17.3	100.4	26.3	0.105
Left (cm)	95.7	17.2	86.9	19.8	0.049*
Right (cm)	97.6	17.5	101.1	20.6	0.349
Turn left (°)	45.1	6.1	39.3	10.1	0.011*
Turn right (°)	51	11.7	49.7	14.9	0.374
Horizontal (cm)	96.4	18.8	83.0	21.7	0.002*
Vertical (cm)	90.5	16.2	101.8	12.4	<0.001*

Comparisons were also made regarding the disparities in movements executed in different directions. For tasks in the real-life simulator, the angle of turning right is significantly larger than turning left ($p=0.001$). A similar pattern emerges in VR environment ($p<0.001$). Nevertheless, more differences appear in VR environment. Movement directed towards the right is significantly more extended than those towards the left ($p<0.001$). The perceived estimation of a 1-meter distance horizontally is significantly shorter than the estimation made vertically ($p<0.001$). Correlations between body size and different movement are all very weak ($r<0.2$) or not significant.

In addition to the quantitative analysis, this study also conducted a qualitative exploration of the subjective experiences of experimental participants during the experimental process. A notable and non-negligible difficulty lies in the discomfort experienced by users due to the VR equipment itself. This discomfort primarily stems from two aspects. Firstly, the dizziness induced by rapid scene transitions, which is often attributable to the mismatch between visual information and the actual physical movement state of the body. Secondly, the additional pressure exerted on the user's head and neck by the weight of the equipment, which may intensify the discomfort during prolonged use. These physical discomforts not only affect the comfort level of experimental participants but also interfere with their spatial cognition and behavioral performance. Furthermore, a unique feature of virtual environments is that they deprive individuals of direct visual perception of their own bodies.

This change leads some experimental participants to feel disoriented, struggling to accurately judge the spatial relationships between themselves and the environment. Such ambiguous cognition of one's own position and environmental relationships undoubtedly increases the difficulty of navigation and localization within the virtual environment.

Besides, when performing movement tasks while wearing VR equipment, the participants generally exhibited a sense of uncertainty and mistrust towards their own actions. They tended to be more cautious and deliberate in their movements, fearing that misjudgments or improper operations might lead to accidents. This cautious attitude restricted their freedom of movement and also impacted their exploration and interaction experiences within the virtual environment. Meanwhile, due to the loss of intuitive perception of physical balance in the real environment, the participants generally demonstrated poorer physical balance in virtual scenes, further exacerbating their sense of insecurity during movement.

Conclusion

This study focused on differences in spatial perception between a virtual reality environment and a real-life aircraft cabin simulator. The results of this with-in subject experiment suggest significant differences in spatial perceptions in two different settings regarding turning movements and vertical spatial perception. Smaller movements showed when moving and turning to the left in VR environment. Qualitative findings highlighted challenges associated with VR equipment. In summary, while VR technology offers potential for design evaluation, addressing user discomfort, spatial perception discrepancies, and movement execution challenges is crucial. Future research should focus on strategies to mitigate these issues, enhancing the usability and effectiveness of VR systems.

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Modelling of the contribution of noise, vibration and thermal stimuli to discomfort for aircraft passengers

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ABSTRACT

Future aircraft designs will more sustainable and reduce environmental emissions. Turboprop aircraft can be 60% more fuel efficient in comparison to jet aircrafts but have high vibration and noisier cabins, thus affecting the comfort perception of aircraft passengers. The nature of the noise and vibration is highly tonal and therefore different to that previously studied.

This paper presents the development of a multifactorial model of the human comfort in response to noise, vibration, and thermal stimuli. Data were obtained through a laboratory study where the temperature, noise and vibration were adjusted. A model is generated that allows for mapping of the relative importance of the modalities.

KEYWORDS

Model, Optimization, Cabin, Turboprop, Sustainability

Introduction

The aircraft industry has shown advancements in technology to improve human comfort and to reduce environmental emissions. Worldwide approximately half of air travel is composed of short range flights many of which could be served with a turboprop. In ideal conditions turboprops emit less CO_2 and are more fuel efficient in comparison to jets (Kilic, 2023). However, the cabin noise and vibration in the cabin of turboprop aircraft are higher than jets, therefore reducing the human comfort perception (Vink, 2011). To enable acceptance of future propeller aircraft, noise and vibration environments must be improved.

Noise and vibration from propeller aircraft varies with design of aircraft and the flight phase. Manufacturers need to be able to predict the discomfort that would be experienced by passengers, to understand how acceptable the aircraft will be (Oborne, 1977). Previous studies have shown that subjective ratings of noise and vibration can be matched to generate a level of equivalence (Mansfield et al., 2007) although this has not been demonstrated for signals representative of the turboprop aircraft environment. However, studies using a turboprop showed that noise and vibration were high priority in context to human comfort in an aircraft cabin (Vink et al., 2022).

With the need to reduce emissions, future aircraft concepts are being actively pursued that include propeller propulsion. The vibration and noise experienced in turboprop aircraft is different to that experienced in jets (Bellman et al, 2004). Turboprops are dominated by tonal vibration relating to the blade pass frequency and turbulent wake interactions with the airframe. Jets have less tonality in the noise and vibration experienced in the passenger cabin. The temperature in an aircraft cabin can also vary due to the flight phase, time of day, and position in the aircraft. Whilst most current aircraft make use of hot bleed air from the jet engine for air conditioning systems, future electrically powered aircraft will not have opportunity to use this power source and therefore will need dedicated heating systems adding weight. To optimize the design of future propeller aircraft, an improved understanding of passenger perceptions of aircraft comfort is necessary.

Methods

Laboratory experiments occurred in the environmental chamber, Department of Engineering, Nottingham Trent University. An aircraft cabin environment was replicated by synthesised noise and vibration from a turboprop aircraft presented via a vibration simulator and loudspeakers. Whilst seated on a BAE146 passenger seat, participants were presented with each combination of 10s samples of noise and vibration, after a calibration and familiarisation procedure (Figure 1). Noise was presented at each of 78, 82, 86 and 90 dB(A); vibration was presented at each of 0.75, 1.5, 2.25, 3.00 m/s^2 r.m.s. comprising a multi-tonal signal. This procedure was repeated at four different temperatures between 19˚C to 32 ˚C.

After each combination participants were asked to give the subjective ratings of comfort based on noise, vibration, and thermal discomfort using scales adapted from ISO2631-1 and ISO 7730 (Figure 1). Overall discomfort was assessed using an adapted 100-point Borg CR-100 scale with verbal anchors Participants were also required to select whether they would prefer to change the temperature or reduce the noise or the vibration to improve comfort. This question used a forced choice protocol. Data were analyzed using MATLAB R2020a and SPSS. 20 volunteers aged between 19-52years participated in the experiment. The study was approved by NTU research committee.

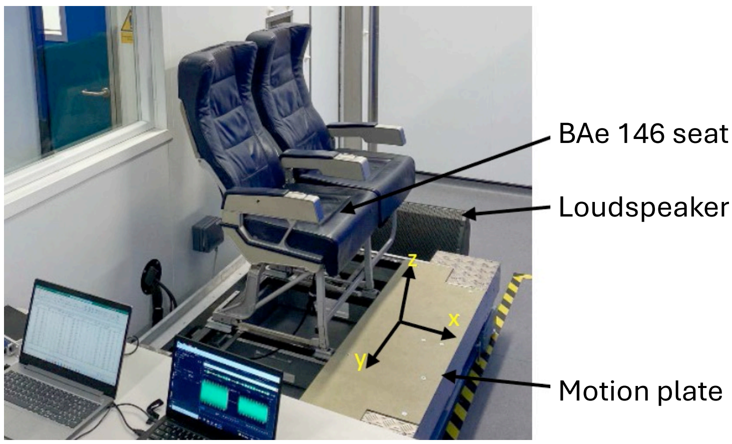

Figure 1. Experimental set up

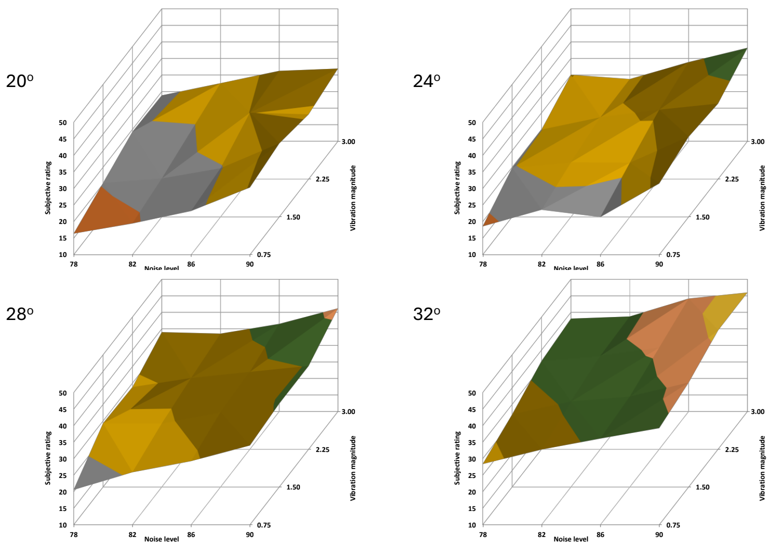

Figure 2. Measured overall discomfort.

Results

As expected, mean ratings of noise increased with noise level and mean ratings of vibration increased with vibration ($p<0.0001$). There was no indication of a cross-modal effect; i.e. ratings of noise were not affected by the vibration and ratings of vibration were not affected by the noise (n.s. 2-way ANOVA). These effects were observed at each of the four temperatures. Overall discomfort increased with noise, with vibration, and with temperature (Figure 2).

Preferences for reducing noise or vibration shifted to those modalities as the intensity of the stimulus increased (Figure xx). Considering those modalities that were selected at the preference by more than 50% of participants (Figure xx), temperature was not a priority at 20 or 24 deg, but became dominant at 32 deg, apart from those stimuli where there were the highest magnitudes of noise and vibration. These data show that, even for short duration stimuli, noise and vibration can dominate subjective responses, under hot conditions.

Preferences for reducing noise or vibration shifted to those modalities as the intensity of the stimulus increased (Figure 3). Considering those modalities that were selected at the preference by more than 50% of participants (Figure 3), temperature was not a priority at 20 or 24 deg, but became dominant at 32 deg, apart from those stimuli where there were the highest magnitudes of noise and vibration. These data show that, even for short duration stimuli, noise and vibration can dominate subjective responses, under hot conditions.

20 deg C

	78 dB	82 dB	86 dB	90 dB
3.00 m/s²	V	V	N	N
2.25 m/s²	V	V	N	N
1.50 m/s²	V	N	N	N
0.75 m/s²	N	N	N	N

24 deg C

	78 dB	82 dB	86 dB	90 dB
3.00 m/s²	V	V	V	N
2.25 m/s²	V	V	N	N
1.50 m/s²	V	N	N	N
0.75 m/s²	NP	N	N	N

28 deg C

	78 dB	82 dB	86 dB	90 dB
3.00 m/s²	V	V	V	N
2.25 m/s²	V	V	N	N
1.50 m/s²	V	NP	N	N
0.75 m/s²	T	NP	N	N

32 deg C

	78 dB	82 dB	86 dB	90 dB
3.00 m/s²	V	V	V	N
2.25 m/s²	T	T	NP	T
1.50 m/s²	T	T	T	N
0.75 m/s²	T	T	T	N

Figure 3. Preference for changing modalities. V: vibration >50%, N: noise >50%, T : temperature >50%, NP : no preference (none reached 50%).

Polynomial digital models of the human were created for noise discomfort, vibration discomfort, and overall discomfort. Models were fitted to individual data points, whereas RMS error (%RMSE) was calculated to the mean data. For noise and vibration discomfort, RMS errors were less than 4% in all cases. Models followed patterns as expected in the data, showing increases in discomfort with noise and vibration.

For models that are designed to represent noise discomfort and vibration discomfort the polynomial model parameters were dominated by those addressing the modality of interest, indicating little cross-modal interaction. A linearized general model was developed using a machine learning algorithm. This method allowed for the prediction of the overall discomfort on the basis of 4 model parameters such as Noise, Vibration, Temperature and Overall. Testing the model on mean data from 20 participants showed an RMS error of 6.4%. The simulated cabin temperatures were designed to be in a range where discomfort would increase with temperature. However, if the temperature falls below 20 degrees, participants could feel discomfort due to cold.

Acknowledgement

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Optimal Headrest Position for Comfort Based on User-Preferred Adjustment

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ABSTRACT

The aircraft seat headrest is essential for maintaining head-neck support and passenger comfort during flight. Although adjustable designs exist, the optimal headrest positioning for resting conditions has not been systematically established, particularly across varying seat inclinations and diverse passenger anthropometrics. This study introduces five headrest comfort parameters (HCPs) measured using a customized experimental test rig in a seating experiment with 26 participants. The experiment examined five discrete backrest inclinations (20° to 60°) and four key body parameters: stature, BMI, neck angle, and head angle. The isolated effect of inclination was tested using one-way repeated measures ANOVA, while inclination-body parameter interactions were analyzed using two-way mixed ANOVA. Statistical analysis identified consistent nonsignificant groupings, with averaged values forming the basis for practical headrest positioning guidelines. Results demonstrate that both inclination and body anthropometry significantly affect the HCPs, except for the headrest fore-aft depth position D ($p > 0.05$); thus, a constant average value of 2.2 cm can be applied across all conditions. These findings provide quantitative recommendations for optimal headrest placement in inclination-dependent and body-adaptive scenarios, offering valuable insights for seat designers and automated adjustment systems to bridge the gap between empirical research and applied ergonomic solutions for aircraft seats.

KEYWORDS

Headrest ergonomics, user-centered design, ANOVA analysis, anthropometric adaptation

Introduction

Commonly seen aircraft seats may be equipped with ergonomic or adjustable mechanisms on the headrest, such as the raised cushion thickness and extendable height adjustment to position the headrest so that better adaptation in the head-neck region can be provided. Previous studies have also suggested that the headrest should be adjustable, not only vertically but horizontally (Donald D. Harrison et al., 2000) to comply with the natural spine shape, which contains a lordotic profile in both the lumbar and cervical regions. Reed et al. (Reed et al., 2001) reported a recommended head restraint (headrest) geometry of >730mm and 315mm, the vertical and horizontal distance measured from the H-point (based on SAEJ826 H-point manikin) for specifically designed headrest to accommodate preferred occupant head position. Franz et al. (Franz et al., 2012) have also innovated the car seat headrest with different materials and additional neck support. Most studies on car seats are task-based, i.e., the evaluation of headrests is usually based on driving simulations. This proposes limitations of its application on aircraft seats, where passengers spend a long duration of time in a resting condition.

One challenge for the ergonomic design of the transportation vehicle seat is ensuring the product can provide a comfortable experience for different seat settings, such as backrest inclination and different occupant's body characteristics. Seat inclination plays an essential role in headrest assessment as the gravity projection of the body weight on the seat surfaces changes significantly. The inter-individual difference also plays a role in seating experience. Specifically for the head-neck region, our previous study (Zhong et al., 2025) tested the correlation between the upper-body postural parameters and human-seat interaction and found that the different trunk height and head angle (Frankfort plane orientation) affects the neck comfort and the contact force due to the headrest. Therefore, a better level of customization for different seating scenarios should be pursued in seat development.

Current headrest designs do not have systematic assessment or tests to validate their performance under different conditions, therefore in this paper, we propose an experiment methodology using the user-selection test strategy to approach the user-preferred headrest position for different body parameter groups and a wide range of seat backrest inclination. This study enhances the understanding of seating comfort in the head-neck region relative to the headrest position, and the result of this study provides ergonomic guidelines for seat headrest design and system automation.

Method

This study is based on empirical data collection and statistical analysis. The experiment was conducted on a cushioned business aircraft seat with a flexible headrest, and the seating test was performed under resting and static conditions. The participant's anthropometric and demographic information is collected. Then, the participant is asked to sit with different inclinations; during each condition, the most comfortable and preferable headrest position is selected through self-adjustment. The independent variables in this study include body parameters (BPs: stature, BMI, neck angle (NA), head angle (HA)) and seat conditions (backrest inclination: 20°, 30°, 40°, 50°, and 60°). In total, 26 subjects from the university were recruited to participate in this study (14 females and 12 males). The subjects were grouped into different BP groups based on Error! Reference source not found.. This study has been approved by the Research Ethics Board of Toronto Metropolitan University (REB 2024-222).

Table 1. Subgroups of BPs

BP	*Group 1*	*Group 2*	*Group 3*
Stature	short (<1.63m), n=9	medium (1.63m-1.77m), n=10	tall (≥1.77m), n=7
BMI	slim (<20), n=7	normal (20-25), n=11	over-weight (≥25), n=8
NA	NA_I (≤124°), n=7	NA_II (124°-131°), n=10	NA_III (≥131°), n=9
HA	HA_I ((≤ 170°)), n=11	HA_II (170°-174°), n=8	HA_III ((≥ 174°), n=7

The headrest position was defined by three parameters, which include (1) H: (+) headrest height position (2) D: (+/-) headrest depth position, a positive value means protrusion towards the passenger. The same sensor as that of the H measurement was applied. (3) θ_H: (+/-) relative headrest rotation angle referring to the backrest. The angle is derived by the subtraction of the absolute angle of the headrest (WT901C 9-axis IMU) and the backrest inclination angle. A positive value indicates the backward rotation. The illustration of the headrest position parameters is shown in Figure 1. The headrest movements were controlled via a tactile push-button controller mounted adjacent to the seat's left-hand armrest. Also, the headrest cushion integrates a 4×4 pressure sensor matrix (RP-S40-ST) to measure the headrest loadings. The sensor operated at a 10 Hz frequency for the measurements of the headrest load. The seat and headrest setup are demonstrated in Figure 2.

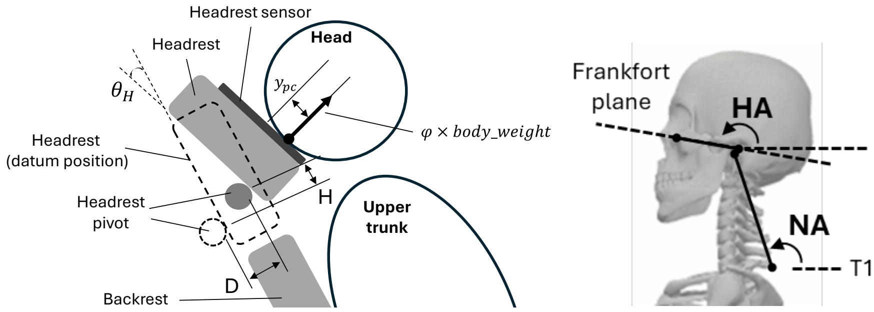

Figure 1. Illustration of HCP (left) and BP of NA and HA (right)

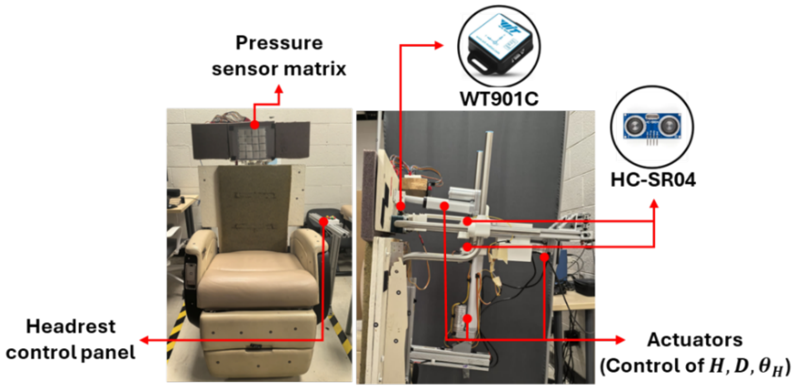

Figure 2. Test setup. WT901C and HC-SR04 are for angle and distance measurement, respectively

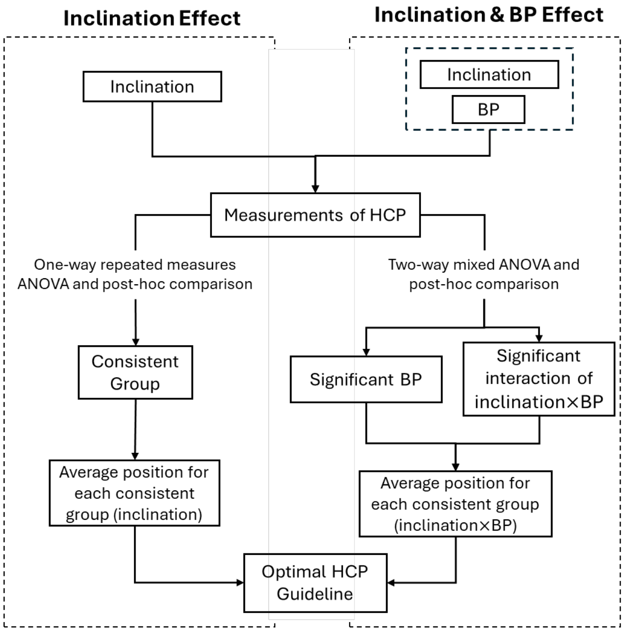

Figure 3. Analysis method to find the suggested headrest range of motion and optimal position

Additionally, the headrest interaction was also measured with the pressure sensor matrix integrated on top of the headrest cushion. The head-headrest interaction includes (1) the head load ratio (φ), calculated based on the net force measured from the headrest sensors divided by the body weight of the subject ($\varphi = (A \sum P_i)/body\_weight$), which allows for the normalization of the headrest force across different body types (Zhong et al., 2025). (2) the head-headrest contact pressure center location (x_{pc}, y_{pc}) referring to the center of the sensor matrix ($\left(x_{pc}, y_{pc}\right) = (\sum(P_i x_i), \sum(P_i y_i))/\sum P_i$). The contact pressure center was calculated from eq2. P_i is the pressure loading measured by each unit of the pressure sensor matrix. The pressure center describes the preferred headrest supporting condition after the subject finds its optimal headrest position. In this study, only y_{pc}, the contact location in the longitudinal direction is considered for the analysis as the case of lateral bending of the upper body was not investigated. In total, five headrest comfort parameters ($\text{HCP} = \{H, D, \theta_H, \varphi, y_{pc}\}$) are selected as the dependent variables to study the influence and relationship with the interested seat and body condition variables.

The objective of this study is to find comfortable headrest positioning guidelines based on specific sitting scenarios, including backrest inclination and different body characteristics. one-way repeated measures aligned-rank-transform (RM-ART) ANOVA and two-way mixed ART ANOVA to analyze the one-factor effect of inclination and multifactorial effect of inclination-body parameter interaction. post-hoc analysis was conducted if a significant difference between different conditions was identified. The analysis method is demonstrated in the flowchart as shown in *Figure 3*

Results

One of the main condition factors considered in this study is the backrest inclination. In total, five inclination angles, from 20° to 60° referring to the vertical direction, were investigated. The results outline the impact of the inclination to the selected headrest parameters (HCP). Figure 4 shows the average values, and the standard deviations based on the collected headrest position and head-headrest interaction measurement, respectively, under different backrest inclinations. Clear trending is observed only on φ, which linearly increases as the backrest inclines more. Based on one-way RM-ART ANOVA and corresponding post hoc analysis, the headrest position parameter can be divided into three groups (insignificant difference within each group, $p>0.05$), each of which has its average value calculated, forming the headrest comfort dimension guideline, as shown in Table 2, without considering the BP of the occupants. With the consideration of BP, in addition to the backrest inclination, the result based on two-way mixed ART ANOVA method and post hoc analysis generates a more comprehensive HCP guideline for headrest position data (Table 3). The reported values can be used as a reference to users' preference of the headrest configuration under specified conditions.

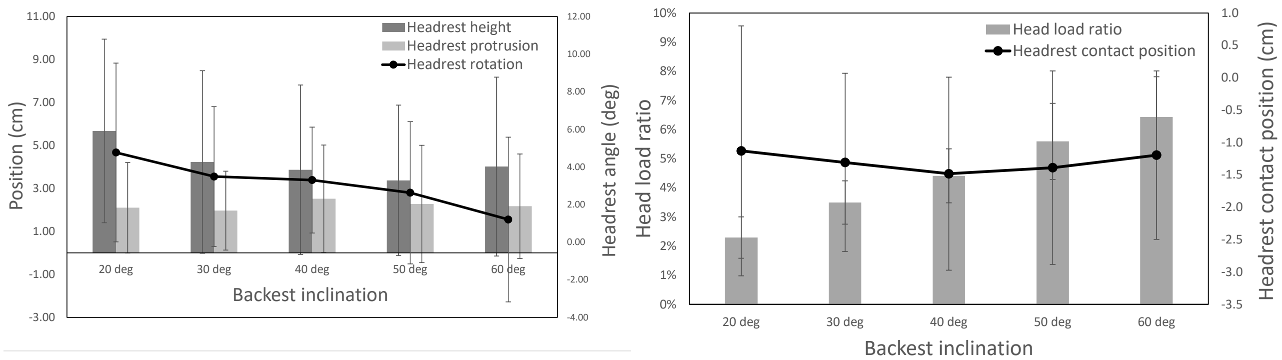

Figure 4. Headrest position parameters (left) and head-headrest interaction (right) under different inclinations

Table 2. Optimal headrest position guideline for backrest inclination

Inclination	H (cm)	D (cm)	θ_H (°)
20°	5.68 (±4.27)	2.21 (±2.31)	3.55 (±3.86)
30° – 50°	3.87 (±3.93)		
60°			1.21 (±4.38)

Table 3. Optimal headrest position guideline for backrest inclination and body parameters

Inclination	**H** (cm)			**D** (cm)	θ_H (°)		
	Stature groups				*HA groups*		
	low	medium	tall		HA-I	HA-II	HA-III
20°	1.81	6.05	10.11	2.21	1.62	3.39	6.76
30° - 50°	0.83	3.83	7.86				
60°					-0.94	1.98	3.69

Conclusion

This study developed an analytical model to evaluate both single-factor and multifactor effects of backrest inclination and body parameters on user-selected headrest positioning and head-headrest interaction dynamics. The results identified seat inclination conditions and body parameters as key influential factors. Based on the result of the analysis, optimal headrest positioning guidelines were created for (1) inclination-only conditions and (2) combined inclination and body parameter scenarios. The headrest contact force measurement was highly sensitive across most test conditions. The results of the study can serve as an ergonomic foundation for intelligent aircraft seat headrest designs and automation systems.

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