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A B S T R A C T

During a driving task, the seat-driver interface is particularly influenced by the external environment and seat features. This study compares the effect of two different seats (S_1 – soft & S_2 – firm) and the effect of visual simulation of different road types (city, highway, mountain, country), on pressure distribution and perceived discomfort during prolonged driving. Twenty participants drove two 3-h sessions (one per seat) on a static simulator. Contact Pressure (CP), Contact Surface (CS), and Seat Pressure Distribution Percentage (SPD%) were analyzed throughout, using two pressure mats positioned on seat cushion and backrest. Whole-body and local discomfort for each body part were rated every 20 min. The softer seat, S_1, induced a greater contact surface on cushion and backrest and a lower SPD%, reflecting better pressure distribution. Pressure profiles were asymmetrical for both S_1 and S_2, with higher CP under left buttock (LBu) and right lower back (RLb) and greater CS under thighs and RLb. Pressure distribution was less homogeneous on mountain and city roads than on monotonous roads (highway and country). Despite the pressure differences between the seats, however, both led to similar increases in perceived whole-body discomfort throughout the driving session. Moreover, the highest discomfort scores were in the neck and the lower back areas, whatever the seat. These findings on pressure variables may have implications for the design of backrests and cushions to ensure more homogeneous pressure distribution, even though this is not shown to minimize perceived driver discomfort.

1. Introduction

With car travel time increasing, the prolonged sitting posture needs to be taken into account by automative companies (Baude et al., 2020). In the automotive context, posture is characterized by its fixity: the driver's movements are restricted by the need to control the vehicle using the pedals, the steering wheel, and the gear box, and to keep looking forward so as to retrieve visual information from the environment and monitor traffic and road conditions (Grieco, 1986; Peng et al., 2015). Over time, this sustained posture can become harmful, adding all the constraints imposed by the driving task and road environment to the biomechanical and vascular consequences of the posture itself. The sitting posture alters spinal biomechanics, inducing a backward tilt of the pelvis and changes in spinal curvature, in particular of the lumbar lordosis (Baucher and Leborgne, 2006; Keegan, 1953; Lee et al., 2014; Nishida et al., 2019). The use of a backrest helps to preserve lumbar lordosis and reduce muscular activity, notably in the erector spinae, relative to work sitting (Andersson et al., 1974; De Carvalho et al., 2010; Makhsous et al., 2003). However, maintaining this posture for a prolonged period may still constrain passive elements of the spine, leading to fatigue, discomfort, soreness, and even back pain (Al-Dirini et al., 2015; El-Falou et al., 2003; Helander and Zhang, 1997; Kamijo et al., 1982).

The main issue for drivers is therefore how to avoid and minimize such painful consequences through a posture that minimizes biomechanical and physiological risks. The automotive industry is addressing

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this through seat design, seeking to enhance the driving experience and reduce perceived discomfort. However, car occupants' discomfort is a subjective physical feeling reflecting the biomechanical and physiological changes experienced and perceived (De Looze et al., 2003). Perceived discomfort is dependent on individual capabilities in response to environmental constraints, seat features, and task characteristics (Vink and Hallbeck, 2012). El-Falou et al. (2003) reported a decrease in driving cognitive performance with the onset of perceived discomfort. Changes in cognitive load, characterized by a loss of attention, may appear with increased driving time (Philip et al., 1999) and partly depend on the road curvature (Matthews and Desmond, 2002). A straight, monotonous road requiring less movement by the driver than a curved road could affect the evolution of discomfort.

Several studies highlight an increase in perceived discomfort with prolonged driving, especially in the lower back region, identified as the body part with the greatest influence on overall discomfort (Magnusson et al., 1996; Maradei et al., 2015; Sammonds et al., 2017; Varela et al., 2019). The buttocks and thighs also appear to play a major role. Their soft tissues (skin, fat, and muscles) undergo compressive constraints (Kolich and Taboun, 2002; Linder-Ganz et al., 2007) and three-dimensional deformations (Al-Dirini et al., 2015; Sonenblum et al., 2013) that have been found to alter local blood circulation and decrease oxygenation (Olesen et al., 2010). Moreover, Oomens et al. (2003) observed that pressure peaks located under ischial tuberosities are responsible for most compressive and shear strains in the muscles close to these body prominences. All this can lead to pain with prolonged driving (Reenalda et al., 2009).

These soft tissue compressions and deformations depend on the driver's anthropometric characteristics and adopted posture, as well as on seat features (Kolich, 2003; Moes, 2007). The seat-body interface is characterized by contact points where the pressure exerted is directly linked to body mass, which determines surface area, and to length of contact. Physical feelings at these points can be annoying if the pressure is concentrated on an overly-small area, or if the contact lasts too long. Pressure distribution analysis is one of the most widely used and reliable techniques to immediately evaluate the interface between the individual and the seat (Andreoni et al., 2002; Dunk and Callaghan, 2005; Zemp et al., 2015). This objective measurement is also recognized as being the most consistent with subjective assessment of discomfort (De Looze et al., 2003).

Keeping pressure distribution as uniform as possible has been shown to be key to delaying the onset of discomfort at contact points and has become a major objective in ergonomic car seat design (Ebe and Griffin, 2001). Although body weight distribution necessarily involves areas with elevated stress and high pressure, like ischial tuberosities, the design aim is to attenuate peak pressure concentrations by trying to make the pressures as homogeneous as possible (Ahmadian et al., 2002; De Looze et al., 2003). Different seat features, in particular shape, composition, and stiffness, have a strong impact on the contact pressure parameters and tissue perfusion of the buttocks and thighs (Makhsous et al., 2012). Over the long term, there may be tissue ischiaema in these areas, depending on the hardness of the foam. Consequently, the differing composition of car seats may lead to different effects on pressure distribution and the ensuing perception of discomfort at general and local level (Cascioli et al., 2016). A seat that minimizes pressure under buttocks and thighs appears to be the most desirable (Milivojevich et al., 2000). However, the ischial tuberosities remain the area subjected to the most compression because they support almost one third of the total seat load (Kilincsoy et al., 2016). Moreover, pressure distribution between these areas seems to vary with time. Pau et al. (2016), assessing crane operators, demonstrated a 6% decrease in mean pressure in the buttocks area and a 10%–20% increase in the thigh area after 4 h of driving. However, while this result gives some indication of how pressure distribution may evolve in a particular context, insufficient data is available on the evolution of pressure distribution during prolonged driving to permit comparisons.

Posture in a car is therefore the result of direct interaction among several factors including the driver's individual abilities, the type of seat, and the driving task itself, subject to road conditions and driving time. Various models have been proposed in the last decade to illustrate the influence of these interactions on (dis)comfort perception (Hiemstra-van Mastrigt et al., 2016; Moes, 2005; Naddeo et al., 2014; Vink and Hallbeck, 2012). All these models explain (dis)comfort as a function of the above factors and identify their possible interactions. Some identify links between human/seat/environmental factors and perceived (dis) comfort, which can be objectively identified through parameters like interface pressure or driver's movements (Hiemstra-van Mastrigt et al., 2016).

Based on these previous observations, our primary aim is to compare the impact of two different car seats on pressure distribution and perceived discomfort under prolonged simulated driving, as represented graphically in Fig. 1. Based on the physiological and vascular effects of firmness suggested in the existing literature, we hypothesized that softer seats offer a homogeneous distribution of pressure and therefore likely minimize feelings of local discomfort. The second objective is to identify the effect of visual simulation of a variety of road types on pressure parameters. These road types realistically represent real driving conditions (traffic, road signs, road features) and the itinerary repeatedly alternates between city, highway, mountain, and country roads. The advantage of our experiment is to offer a controlled environment (free of vehicle dynamics and affording control of environmental parameters such as temperature and weather) allowing pressure variables and feelings of discomfort to be assessed solely in relation to seat hardness and the visual experience of road conditions in a prolonged driving situation. These initial results will be used to explore these factors under real driving conditions in a further study.

2. Materials and methods

2.1. Participants

We performed a power calculation to define beta error probability for our subject group. The sample size was estimated at 20 participants to obtain a statistical power of 90% and significance level (alpha error probability) of 0.05. Participants were required to have held a valid driving licence for 2 years at least. They were excluded if they had suffered back pain or musculoskeletal disorders in the previous two years, if they had a history of spinal surgery, or if such symptoms had required medical follow-up and/or time off work. All participants were recruited through an email campaign at Aix-Marseille Université. The final sample was composed of twenty healthy students or university employees (10 males and 10 females; age 27.8 ± 5.6 years, height 1.73 ± 0.1 m; weight 69.9 ± 14.4 kg) who volunteered to take part in a driving simulator experiment but were naïve about the study's aim of comparing seats and road types. Before the experiment, they gave their written consent and completed a questionnaire about their driving habits. Questionnaire results showed that they had held their driving licence for 8.9 ± 5.9 years, had a daily driving time of 68.2 ± 55.4 min, and drove 12,337 ± 9136 km annually. They were informed that the experimenters would answer their questions at the end of both driving sessions during an individual debriefing. All experimental sessions took place at the Mediterranean Center for Virtual Reality (CRVM, Institut des Sciences du Mouvement E.-J. Marey, France), authorized to perform human studies *(Regional Health Agency - DOS-0515-3092-D)*. Moreover, ethic approval was given by the ethics committee of CERSTAPS *(CNU – IRB000112476-112)*.

2.2. Measurements

2.2.1. Pressure

Throughout the driving sessions, pressure distribution was recorded with two textile pressure sensor mats from XSENSOR® Technology

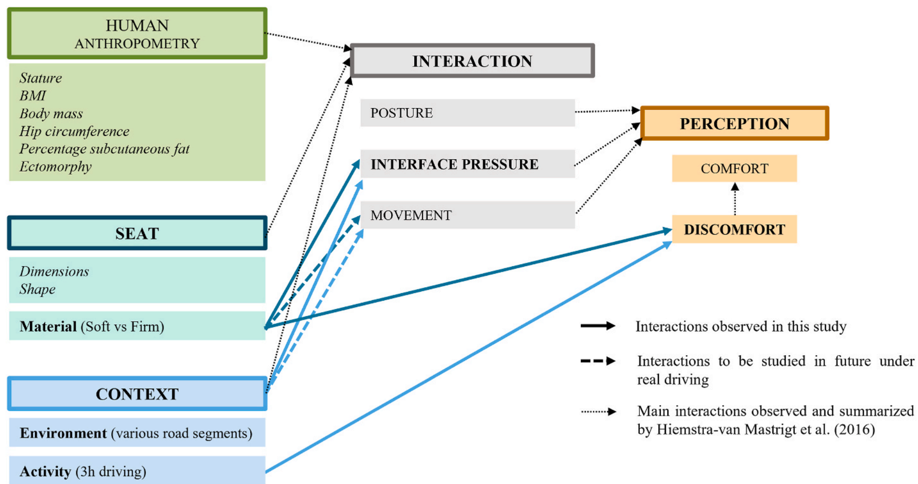


Fig. 1. Graphical framework of our study (overview of possible links between variables influencing (dis)comfort evaluation) adapted from Hiemstra-van Mastrigt et al. (2016). **Bold**: variables studied in this protocol. Italics: variables not studied. Continuous arrows: interactions observed in this study. Dotted arrows: interactions to be studied in future under real driving. Thin dotted arrows: main interactions observed by Hiemstra-van Mastrigt et al. (2016).

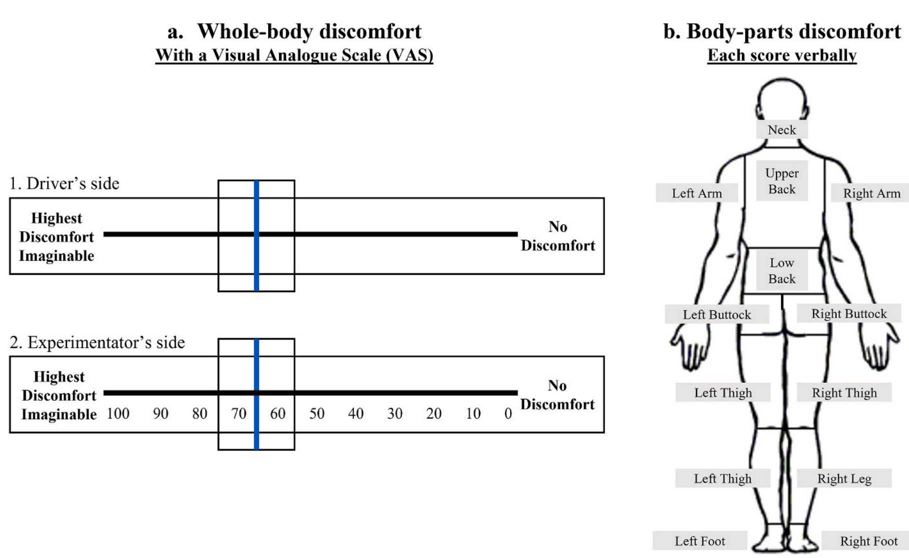
Corporation (Xsensor, Inc., Calgary, Alberta, Canada), one placed on the backrest and one on the seat cushion (model X3 LX100). The backrest mat was composed of 40 × 64 sensor cells (sensing area 50.8 cm × 81.2 cm; mat LX100:40.64.02) and the cushion mat of 40 × 40 sensor cells (sensing area 50.8 cm × 50.8 cm; mat LX100:40.40.02). Sensitivity was set to a working pressure range of between 0.07 and 2.70 N/cm^2 and a measurement threshold of 0.07 N/cm^2. The sampling rate of both pressure mats was adjusted to 1 Hz (Fenety et al., 2000), deemed appropriate because changes in postural behavior have been reported at lower frequency. All pressure measurements were collected via XSENSOR Pro V8.

2.2.2. Discomfort

Two discomfort ratings were obtained during each driving session, at the beginning ($t_{start-0min}$), at the end ($t_{end-180min}$), and every 20 min (t_{20min} to t_{160min}), for a total of 10 evaluations. Participants were required to evaluate their perceived whole-body discomfort using a 100 mm visual analogue scale (VAS) and their local body discomfort verbally for each body part (neck, upper-back, lower-back, arms, buttocks, thighs, legs, and feet) (Fig. 2). Each evaluation was scored from 0 (no discomfort) to 100 (highest discomfort imaginable).

2.3. Driving simulator and seats tested

The driving simulator (Compact Simulator, A.V Simulation, France) consisted of a cockpit with steering wheel, an automatic gearbox, three pedals, and three computer screens (LCD 16:9) to display the driving scenario (Fig. 3). Only the gas pedal and brake pedal were active, replicating the pedals in an automatic car. Moreover, the simulator was equipped with an adjustable force feedback system enabling the steering wheel and the two pedals to be set at forces realistic in terms of maneuvering. The torque of both pedals was programmed to apply the same force as in the Peugeot 3008, our reference vehicle to be used in our next experiment (same protocol under real driving conditions). The values were provided by automotive manufacturer Stellantis, and adjustments were made to the simulator with the associated SCANeR® software. Structural changes were made to the simulator cockpit to allow each tested seat to be inserted as in real car cockpits. The tests were conducted using two different seats from segment C vehicles of leading French car manufacturer Stellantis. While their metal frames and adjustment mechanisms were the same, the seats had different covers and foam densities. One seat had a classic fabric cover, while the other was covered in a combination of fabric and synthetic leather.



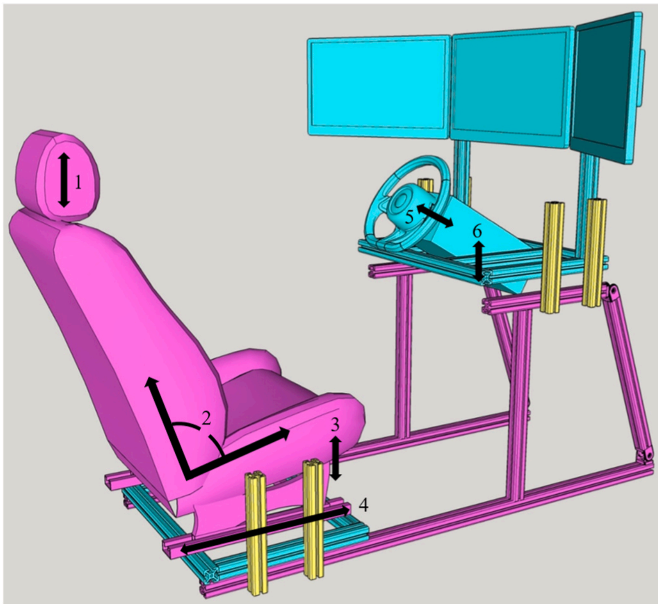


Fig. 3. Model of the static simulator (a). Black arrows represent the different mechanical adjustments possible on the simulator (1. Head-support height; 2. Backrest inclination; 3. Seat height; 4. Fore-aft adjustment of the seat; 5. Steering wheel fore-aft; 6. Steering wheel height). Picture of the simulator (b).

A preliminary study was carried out at CTAG (Automotive Technology Center of Galicia, Spain) to characterize the Height Under Weight (HUW) of both seats. Briefly, a robotic arm applied a progressive load on backrest and cushion up to a maximum of 1050N, in one repetition. The HUW determined corresponds to the maximum displacements of the foam under the force, the results being detailed in a previous article (Lecocq et al., 2020). The first seat (S_1) was considered softer, with a seat cushion HUW of 55 mm, while the second seat (S_2) was considered firmer, its cushion having a HUW of 41 mm. There was little difference in the HUW of the two seats' backrests: 24 mm for S_1 and 23 mm for S_2.

2.4. *Experimental synopsis*

Participants drove in two static driving simulator sessions, one per seat tested, in counterbalanced order. These experimental sessions took place a minimum of one week apart, in a controlled environment with the same room temperature. Each session started at the same time of day (1 p.m.) to minimize the effect of circadian rhythms. To avoid different clothes having any effect on perceived discomfort, all participants wore the same outfits and a pair of flat sneakers during the experiment.

Before each driving session, the pressure mats were placed on the cushion and backrest. Then the participants took their place in the driving simulator and adjusted their position (fore-aft and height adjustments of seat and steering wheel and backrest inclination) to be as comfortable as possible (Fig. 3). These adjustments remained unchanged throughout the driving session. Prior to the beginning of the driving session, the participants were asked to adopt a reference position which consisted in maintaining their hands on the steering wheel, their right foot on the accelerator pedal, and their left foot on the simulator platform with the left knee at a 90° angle. In this position, pressure distribution was recorded for 2 min to be used as a baseline and for data normalization. After this recording, experimenters gave the final instructions for the driving session, explaining that the car was automatic and consequently only the right foot would interact with gas and brake pedals, the left foot being left free. Then the driving scenario was launched on the simulator for a driving session of 3 h uninterrupted.

The scenario, created with SCANeR® software (SCANeR Studio version 1.6, A.V Simulation, France), followed an itinerary divided into 9 road segments representing 4 different road types (highways (Hi), city roads (Ci), country roads (Co), and mountain roads (Mo)). Each road type appeared in at least two segments, so as to observe the effect on pressure distribution of driving on a given road type over time. The same order of road segments (Fig. 4) was used in both driving sessions. Traffic density was programmed to be random, unpredictable, and similar to real driving conditions. Drivers had to respect French driving regulations, including speed limits, and to follow programmed GPS instructions. Moreover, the experimenters pointed out that the simulator was equipped with an automatic gearbox and that consequently only the gas and brake pedals could be activated using the right foot. After 180 min, the driving scenario stopped automatically.

2.5. *Data processing*

A MATLAB program (vR2017a, MathWorks Inc., Natick, USA) was used to process the pressure distribution data throughout the driving task, yielding several pressure parameters. First, Contact Pressure (CP) and Contact Surface (CS) were calculated for both pressure mats, on cushion and backrest. Seat Pressure Distribution Percentage (SPD%) was calculated only for the cushion pressure mat. SPD% was used to describe the uniformity of pressure distribution (Ahmadian et al., 2002) and corresponds to the following equation:

$$\text{SPD\%} \quad = \frac{\sum_{i=1}^{n} (p_i - p_m)^2}{4np_m^2} \times 100$$

In this equation, "*n*" represents the number of activated sensor cells on the cushion pressure mat, p_i is the pressure on an active sensor cell, and p_m is the mean pressure of the n sensor cells. A lower SPD% score indicates uniform and homogeneous pressure distribution.

Second, spatial cutting was performed to divide the cushion and backrest mats into several areas (Fig. 5). For the cushion, the visual limits of the seat bolsters and the edges of buttocks and thighs were used to define six areas: Right/Left Bolsters (RBo/LBo), Right/Left Buttocks (RBu/LBu) and Right/Left Thighs (RTh/LTh). For the backrest, the average coordinates of pressure center calculated for baseline measurements were used to define four areas: Right/Left Upper back (RUb/LUb) and Right/Left Lower back (RLb/LLb). For each seat, each road segment, and each area, CP and CS were calculated.

All pressure parameters were temporally analyzed by road segment, normalized according to the time spent in each segment in each driving session. Averages and standard deviations for each parameter and each segment were calculated for both seats.

2.6. *Statistical analysis*

Normality of all data was verified by the Shapiro-Wilk test and homogeneity of variance was validated by the Levene test. All the pressure parameters and perceived discomfort scores were analyzed using repeated measures ANOVA. A two-way ANOVA (2 *SEATs* x 9 *SEGMENTs*) was applied to analyze the evolution of total CP and total CS for both backrest and cushion; SPD% was analyzed for the cushion only. An additional repeated measures ANOVA (2 SEATs x 9 SEGMENTs x 6 AREAs for cushion or 4 AREAs for backrest) was conducted for CP and CS from backrest and cushion. Finally, a two-way ANOVA (2 *SEATs* x 10 *TIMEs*) was conducted to analyze discomfort scores. When a significant main effet was found, a Newman-Keuls post-hoc test was performed. Differences were considered as significant for $p < 0.05$. For each significant effect, we estimated the size effect using the partial eta squared (partial η^2). All statistical analyzes were conducted with Statistica (v13, TIBCO Software Inc., USA) and pressure analyzes are presented in detail in Table 1.

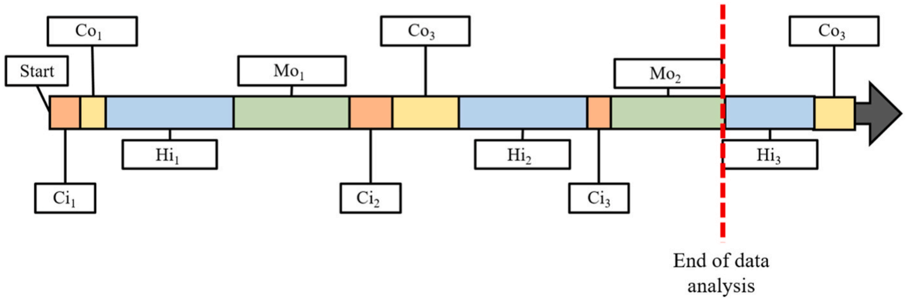


Fig. 4. Chronological order of road segments: 3 stretches of City Road (Ci), 3 stretches of Country Road (Co), 3 stretches of Highway (Hi) and 2 stretches of Mountain Road (Mo). The last two segments were excluded from data analysis so as to consider only segments driven in full by all drivers.

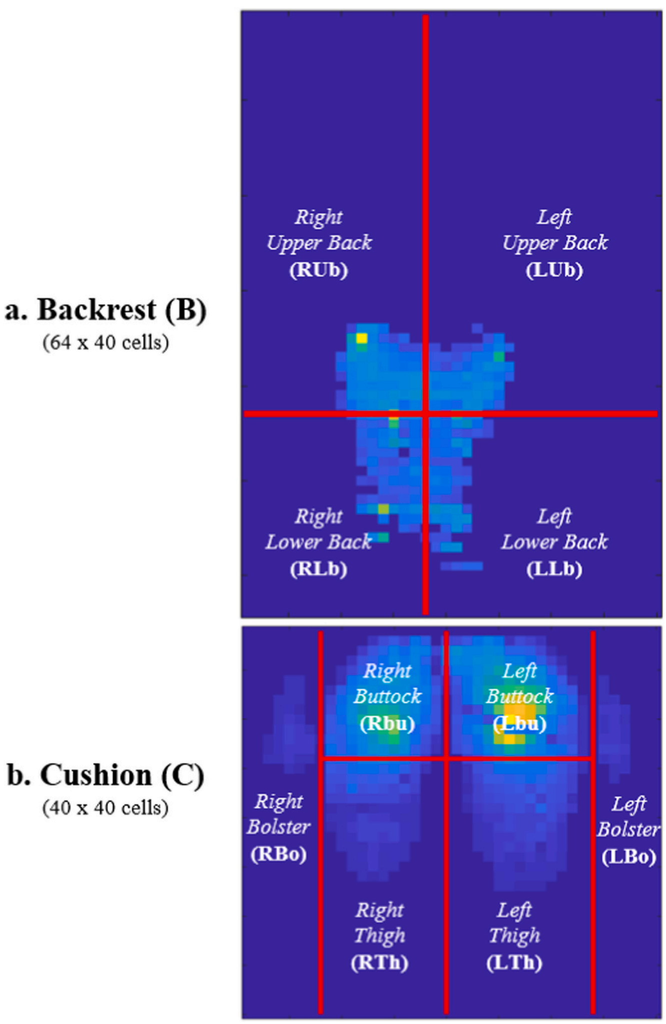


Fig. 5. Visual representation of the spatial division of pressure mats. The backrest (4a) is divided into 4 areas (Right/Left Upper back and Lower back). The cushion (4b) is divided into 6 areas (Right/Left Buttocks, Thighs, and Bolsters).

3. Results

3.1. Cushion

3.1.1. Full cushion mat

Although the main effect of seat type on total Contact Pressure (CP) was not significant, our results reveal a significant effect of *SEAT* on total contact Surface (CS) ($F_{(1,19)} = 43.77$; $p < 0.001$; partial $\eta^2 = 0.697$). The seat cushion of the softer S_1 had a larger contact surface than S_2. Moreover, a main effect of *SEAT* on SPD% was also observed ($F_{(1,19)} = 20.75$; $p < 0.001$; partial $\eta^2 = 0.522$), with a lower SPD% score for S_1 than S_2 throughout the driving session.

A main *SEGMENT* effect was observed on CP ($F_{(8,152)} = 22.46$, $p < 0.001$; partial $\eta^2 = 0.542$), on CS ($F_{(8,152)} = 14.17$; $p < 0.001$; partial $\eta^2 = 0.427$), and on SPD% ($F_{(8,152)} = 10.93$; $p < 0.001$; partial $\eta^2 = 0.365$) for the seat cushion, and post-hoc tests showed that these values steadily increased with driving time. The first four road segments (Ci_1, Co_1, Hi_1, & Mo_1) had lower CP than the subsequent segments, for both seats. Concerning CS, only the first two segments (Ci_1, Co_1) were significantly lower. Finally, SPD% was significantly lower in Co_1 than in Co_2 ($p < 0.001$) and in Hi_1 than in Hi_2 ($p < 0.05$) for both seats (Fig. 6).

3.1.2. Areas of cushion mat

A significant main effect of *AREAS* was observed on CP ($F_{(5,95)} = 29.37$; $p < 0.001$; partial $\eta^2 = 0.607$) and on CS ($F_{(5,95)} = 17.49$; $p < 0.001$; partial $\eta^2 = 0.479$) (Fig. 7).

For CP, regardless of seat and the road segment, the value under left buttock (CP_{-LBu}), was statistically higher than in all other areas ($p < 0.01$ for all). CP_{-LBu} represented 23.22% of total CP for S_1 and 23.78% for S_2 throughout the driving session. CP values under right buttock, and under right and left thighs, were not significantly different and represented respectively 18.43% (CP_{-RBu}), 19.53% (CP_{-RTh}) and 16.68% (CP_{-LTh}) for S_1 and 19.17%, 19.39% and 16.99% for S_2. Both bolsters had significantly lower CP than the other areas ($p < 0.001$ for all). Of the total CP, they represented only 10.87% for S_1 and 9.46% for S_2 for the right bolster (CP_{-RBo}) and 9.27% for S_1 and 11.21% for S_2 for the left bolster (CP_{-LBo}).

Post-hoc analysis of interaction effect *SEAT*SEGMENT*AREA* ($F_{(40,760)} = 2.56$; $p < 0.001$; partial $\eta^2 = 0.119$) showed that right bolster CP (CP_{-RBo}) was significatively higher for S_1 than S_2 throughout the driving sessions ($p < 0.05$ for each road sector). In contrast, left bolster CP (CP_{-LBo}) for S_2 became significantly higher than S_1 from the first mountain (Mo_1) road segment to the end of the driving session ($p < 0.05$, for all road segments concerned). Right thigh CP (CP_{-RTh}) for S_2 was lower than S_1 for the first four road segments (Ci_1, Co_1, Hi_1 & Mo_1) ($p < 0.001$, for all comparisons). Moreover, differences between right and left sides appeared for both S_1 and S_2. CP under the right buttock (CP_{-RBu}) was significantly lower than under the left buttock (CP_{-LBu}) for both seats throughout the driving sessions ($p < 0.001$, for all). Concerning bolsters, S_1 showed CP_{-RBo} significantly higher than CP_{-LBo} in the first 4 road segments (Ci_1, Co_1, Hi_1 & Mo_1) ($p < 0.05$, for all) whereas for S_2, CP_{-RBo} was significantly lower than CP_{-LBo} from the second city segment (Ci_2) until the end of the driving session ($p < 0{,}05$, for all). No significant difference was observed between right and left thighs for S_1. For S_2, CP_{-LTh} was significantly higher ($p < 0.05$) than CP_{-RTh} throughout the driving sessions, except in the Ci_2 and Co_2 segments.

For CS, there were interaction effects *SEAT*AREA* ($F_{(5,95)} = 3.10$; $p < 0.05$; partial $\eta^2 = 0.140$) and *SEGMENT*AREA* ($F_{(40,760)} = 3.04$; $p < 0.001$; partial $\eta^2 = 0.138$). The values for thighs were significantly

Table 1
Repeated-measures analysis of variance (ANOVA) of pressure parameters (CP, CS and SPD%) for cushion and backrest. **Bold**: significant effect (p<0.05). Seat: (S1; S2), Segment: (Ci, Co, Hi, Mo), Cushion Area:(RBo, RBu, RTh, LBo, LBu, LTh) or Backrest Area: (RUb, RLb, LUb, LLb).

CUSHION														
Contact Pressure (CP)	ddl	F	*p-value*	partial η2	Contact Surface (CS)	ddl	F	*p-value*	partial η2	SPD%	ddl	F	*p-value*	partial η2
Seat	(1, 19)	3.20	0.09	0.144	*Seat*	(1, 19)	43.77	**0.000***	0.697	*Seat*	(1, 16)	20.75	**0.000***	0.522
Segment	(8, 152)	22.46	**0.000***	0.542	*Segment*	(8, 152)	14.17	**0.000***	0.427	*Segment*	(8, 152)	10.93	**0.000***	0.365
Area	(5, 95)	29.37	**0.000***	0.607	*Area*	(5, 95)	17.49	**0.000***	0.479	*Seat * Segment*	(8, 152)	1.74	0.09	0.084
*Seat * Segment*	(8, 152)	0.41	0.91	0.021	*Seat * Segment*	(8, 152)	0.88	0.53	0.044					
*Seat * Area*	(5, 95)	2.08	0.07	0.099	*Seat * Area*	(5, 95)	3.10	**0.012***	0.140					
*Segment * Area*	(40, 760)	1.20	0.18	0.060	*Segment * Area*	(40, 760)	3.04	**0.000***	0.138					
*Seat * Segment * Area*	(40, 760)	2.56	**0.000***	0.119	*Seat * Segment * Area*	(40, 760)	0.85	0.73	0.043					
BACKREST														
Contact Pressure (CP)	ddl	F	*p-value*	partial η2	Contact Surface (CS)	ddl	F	*p-value*	partial η2					
Seat	(1, 18)	5.15	**0.036***	0.223	*Seat*	(1, 18)	18.78	**0.000***	0.511					
Segment	(8, 144)	1.29	0.255	0.067	*Segment*	(8, 144)	1.73	0.097	0.087					
Area	(3, 54)	5.96	**0.001***	0.249	*Area*	(3, 54)	4.78	**0.005***	0.210					
*Seat * Segment*	(8, 144)	0.94	0.483	0.050	*Seat * Segment*	(8, 144)	1.10	0.365	0.058					
*Seat * Area*	(3, 54)	2.15	0.104	0.107	*Seat * Area*	(3, 54)	2.94	**0.041***	0.141					
*Segment * Area*	(24, 432)	6.46	**0.000***	0.264	*Segment * Area*	(24, 432)	7.91	**0.000***	0.305					
*Seat * Segment * Area*	(24, 432)	0.96	0.52	0.051	*Seat * Segment * Area*	(24, 432)	1.12	0.312	0.059					

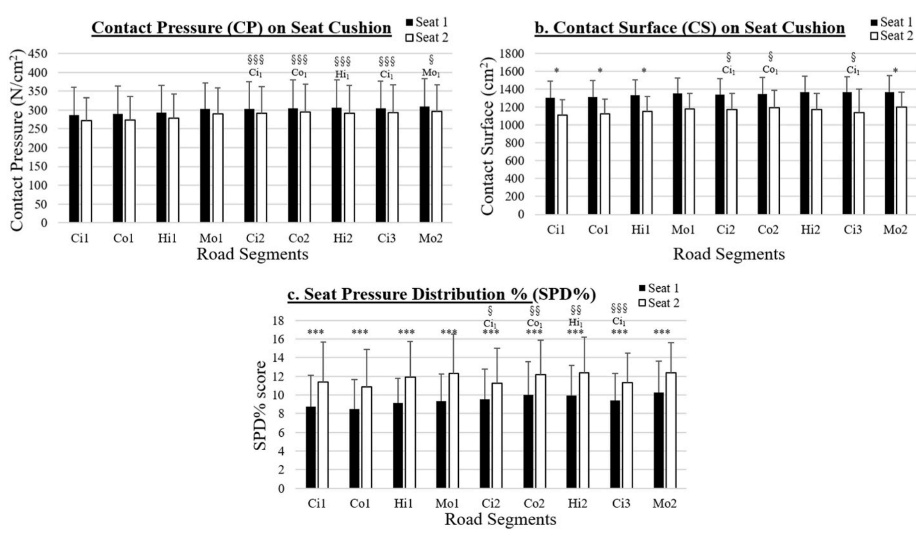


Fig. 6. Means and standard deviations exerted on cushion: contact pressure (5a), contact surface (5b) and seat pressure distribution percentage (5c). *: significant differences between seats for the same road segment (*: p < 0.05; **: p < 0.01; ***: p < 0.001). §: significant differences between segments for the same road type. Segments showing these significant differences are mentioned above § (§: p < 0.05; §§: p < 0.01; §§§: p < 0.001).

higher than for buttocks and bolsters. Thighs (CS-RTh + CS-LTh) represented respectively 41.64% of total CS for S1 and 41.26% for S2. Whatever the road segment, right bolster CS (CS-RBo) and left thigh CS (CS-LTh) were significantly greater for S1 than for S2 (p < 0.01). Post-hoc tests showed right buttock CS (CS-RBu) to be significantly smaller than left buttock CS (CS-LBu), whatever the seat (p < 0.05). Indeed, CS-LBu represented 17.02% of total CS for S1 and 17.24% for S2, while CS-RBu represented 14.68% of total CS for S1 and 14.92% for S2.

Moreover, at the beginning of the driving task (i.e. in Ci_1 and Co_1 segments), the CS for S_1 under the left buttock (CS_{-LBu}) and the left bolster (CS_{-LBo}) was significantly lower than in other road segments ($p < 0.05$). For S_2, significantly lower CS was also observed in Ci_1 and Co_1 segments, but for the left thigh (CS_{-LTh}) and the left bolster (CS_{-LBo}) ($p < 0.01$).

3.2. Backrest

3.2.1. Full backrest mat

Contrary to the seat cushion, backrest results revealed a main effect of type of *SEAT* on Contact Pressure (CP) ($F_{(1,18)} = 5.15$; $p < 0.05$;

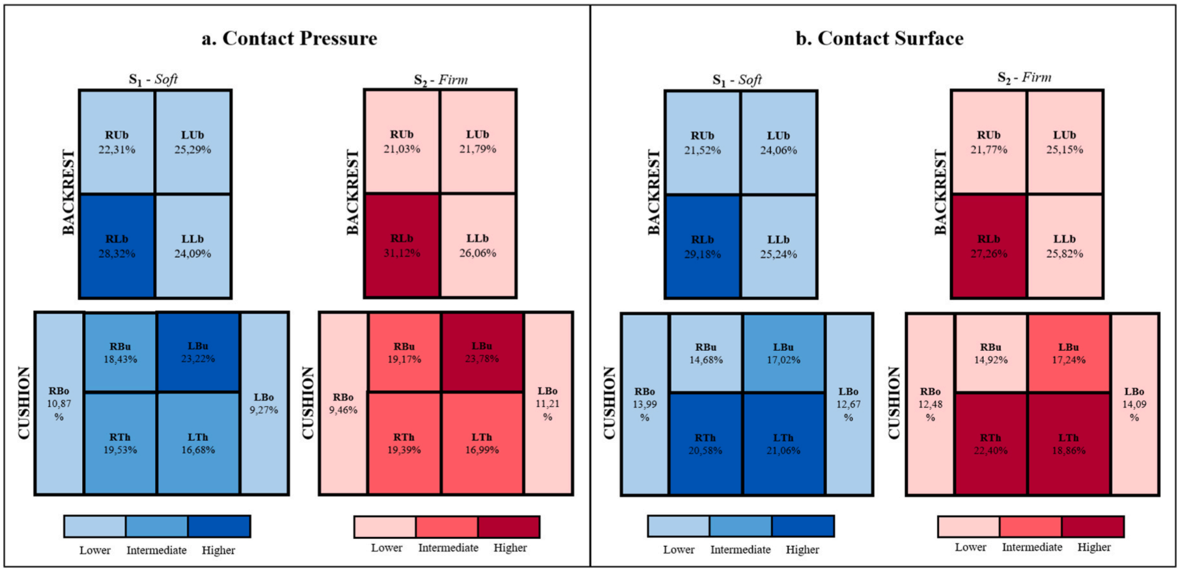


Fig. 7. Distribution of contact pressure (6a) and contact surface (6b) by area of the backrest and the cushion. Each shade of color represents a significant difference ($p < 0.05$).

partial $\eta^2 = 0.223$) and Contact Surface (CS) ($F_{(1,18)} = 18.78$; $p < 0.001$; partial $\eta^2 = 0.511$). S_1 showed higher CP and CS than S_2 throughout the driving sessions (Fig. 8).

No significant difference in CP and CS according to type of road segment was found for the backrest.

3.2.2. *Areas of backrest mat*

A main effect of *AREA* and an interaction effect of *SEGMENT*AREA* were observed for CP ($F_{(3,54)} = 5.96$; $p < 0.001$; partial $\eta^2 = 0.249$; $F_{(24,432)} = 6.46$; $p < 0.001$; partial $\eta^2 = 0.264$) and CS ($F_{(3,54)} = 4.78$; $p < 0.01$; partial $\eta^2 = 0.210$; $F_{(24,432)} = 7.91$; $p < 0.001$; partial $\eta^2 = 0.305$). Moreover, an interaction effect of *SEAT*AREA* was also observed ($F_{(3,54)} = 2.94$; $p < 0.05$; partial $\eta^2 = 0.141$). Regardless of seat, both CP and CS of the right lower back were significantly higher than those of the left ($p < 0.05$ for both parameters). These values represented 28.32% of total CP for S_1 and 31.12% for S_2; they represented 29.18% of total CS for S_1 and 27.26% for S_2 (Fig. 7).

3.3. *Discomfort*

Average whole-body discomfort scores increased throughout the driving time with both seats (*TIME* effect: $F_{(9,171)} = 61.36$; $p < 0.001$; partial $\eta^2 = 0.766$), but no difference between seats was observed from VAS ratings. (Fig. 9). Post-hoc analysis highlighted the precise time at which the discomfort score became significantly different from the initial score ($t_{start\text{-}0min}$). Each time interval from t_{20min} to $t_{end-180min}$ was compared with $t_{start-0min}$. For both seats, the whole-body discomfort score increased significantly from t_{40min}. ($p < 0.001$ for all).

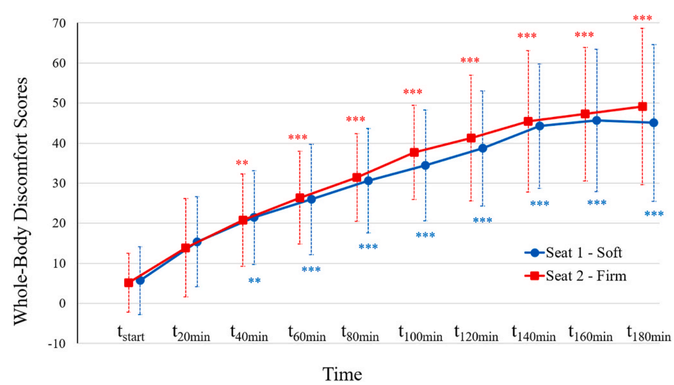


Fig. 9. Mean score for whole-body discomfort throughout driving session. Significant increases in discomfort level compared to the initial value are represented by * (**: $p < 0.01$; ***: $p < 0.001$).

There were similar results from the analysis of body-part discomfort. A main effect of *TIME* ($F_{(9,171)} = 26.46$; $p < 0.001$; partial $\eta^2 = 0.582$) and *BODY PART* ($F_{(12,228)} = 9.73$; $p < 0{,}001$; partial $\eta^2 = 0.339$) were observed, with each body-part discomfort score increasing as the driving session progressed. Post-hoc tests indicated significant differences between the first score ($t_{start\text{-}0min}$) and each of the other scores starting from the third score (t_{40min}), regardless of seat or body part. The highest body-part discomfort scores for both seats were for the neck, upper back, and lower back. Significant differences between sides appeared for legs and feet, with higher discomfort scores for the right side ($p < 0.05$ for

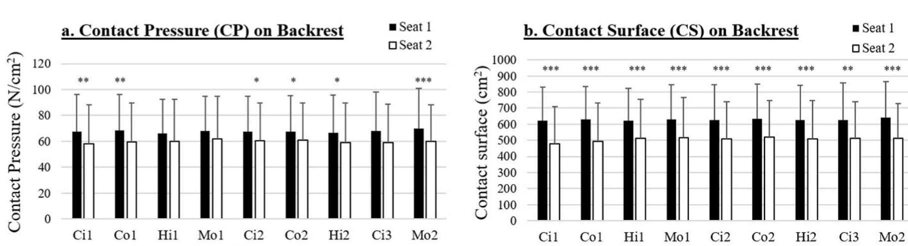


Fig. 8. Means and standard deviations of pressure parameters exerted on backrest: contact pressure (5a) and contact surface (5b). *: significant differences between seats for the same road segment (*: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$).

both) (Fig. 10).

4. Discussion

The main objective of this study was to investigate the effect of two different car seats (one soft - S1 and one firm - S2) on pressure distribution and perceived discomfort during a prolonged drive on a static simulator. Our protocol enabled us to analyze such parameters according to time and type of road, using a reproducible simulated driving task in a controlled environment. The overall results show that seat foam softness resulted in a different pressure distribution during driving, reflected in the pressure parameters, as already demonstrated by several authors (Khamis et al., 2019; Porter et al., 2003). The SPD% values found here show that S1 provided greater uniformity of pressure distribution by reducing pressure concentration under buttocks and thighs over a greater contact surface, as compared to S_2. Futhermore, regardless of seat type, the driving task involved higher asymmetric pressures on the left side both under the buttock and the lower back than on the right side. For both seat cushions, contact pressure and contact surface were lower at the beginning of the driving task and increased with time, as did perceived discomfort (Adler, 2007).

4.1. *Pressure analysis highlights seat differences and time effect*

In the automotive context, pressure mats are currently used to describe physical behavior at the interface between driver and car seat. Contact pressure and contact surface are repeatable and reliable measurements to assess the efficiency of different seats (Daruis et al., 2012). Comparing several seats, Milivojevich et al. (2000) concluded that a seat cushion should have a large contact surface and should induce the most uniform pressure distribution possible. Here, the softness of S_1 meant that it met these criteria, with a larger contact surface and a lower SPD% score, indicating a more homogeneous pressure distribution over the seat cushion compared to S_2. The higher SPD% score of S_2 points to excessive pressure on parts of the cushion, which could become uncomfortable or even painful. This is contrary to current seat design recommendations advising car manufacturers to avoid critical pressure points by adapting cushion foam hardness around ischial tuberosities (Kilincsoy et al., 2016).

However, the softness of the S_1 cushion may not prevent human soft tissue adaptations, and there may still be a risk of discomfort with prolonged contact (Hostens et al., 2001; Oomens et al., 2003). It has been demonstrated that pressure distribution becomes less homogeneous even during a short driving session of 1 h on a highway (Jagannath and Balasubramanian, 2014). Here, our results from prolonged driving showed that the evolution of seat cushion SPD% depended on the type of road segment. The SPD% score increased between highway segments ($Hi_1 < Hi_2$) and even between country roads ($Co_1 < Co_2$). Previous studies reported decreased attentional performance (increased response time and detection errors) when driving on monotonous roads

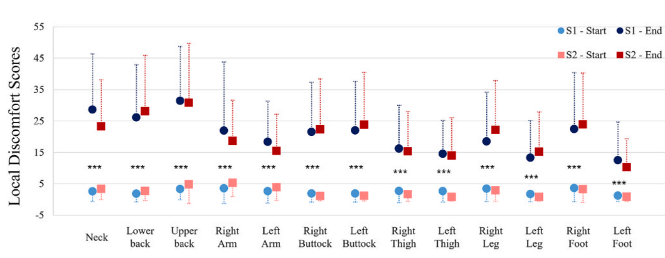


Fig. 10. Evolution of each body-part discomfort score between the first and the last evaluation for S_1 (in blue color) and S_2 (in red color). For each seat, the scores at the beginning of the drive are shown in light color and those at the end in dark color. *** represents all significant differences between the start and the end of the driving session for each body part ($p < 0.001$).

such as highways and country roads, due to lower cognitive demand from the environment (Ariën et al., 2013). This decline was accompanied by SPD% changes, indicating less uniform pressure distribution. In contrast, driving on city or mountain roads induces a higher cognitive workload because it requires more sustained attention and visual inspections (Oron-Gilad and Ronen, 2007; Liu and Wu, 2009). Thus, urban areas cause variability in driving dynamics, with successive accelerations and decelerations. Pressure variables observed during prolonged driving have previously been found to result from a combination of seat features, road type, and driving time. Previous investigations observed increased seat cushion contact pressure and contact surface starting from the beginning of test sessions and lasting until 45 min of driving (Adler, 2007; Vink, 2014). This is confirmed by our results, showing similar increases for the different road segments (Ci_1, Co_1, Hi_1). Then, these parameters rapidly stabilized until the end of the drive, generally leading to negative ratings on driving seat discomfort (Mansfield et al., 2015; Reed et al., 1999; Vink, 2014). Immediate cutaneous and proprioceptive reactions to the seats were not directly perceptible and reliable (Reed et al., 1999). Because of possible bias arising from expectations, and the so-called "feeling approach" or "cake-coating", this adaptation period of approximately 45 min is currently deemed necessary when conducting seating discomfort assessment (Vink, 2014; Mansfield et al., 2015, 2020). The idea is that participants need to drive long enough to be able to distinguish between seats based on objective criteria (Gyi and Porter, 1999; Mansfield et al., 2020).

In contrast, the pressure parameters of the backrest remained relatively unchanged throughout the driving task, showing no road segment effect. The pelvis kinematics and the lumbar and thoracic muscle system allow posture to be maintained even during a prolonged drive, which may be reflected by constant contact pressure on the backrest (Pau et al., 2016; Michida et al., 2001). Reed et al. (2002) confirmed this unchanged pressure on the backrest, with major limb changes but a relatively stable trunk position regardless of the driver's morphology. This result seems to be consistent with the postural fixity involved in driving.

Dividing the seat cushion into six parts (right & left buttocks/thighs/bolsters) and the backrest into four parts (right & left upper back/lower back) enabled us to determine precisely how pressure was distributed according to seat features (Kyung and Nussbaum, 2008). For both seat cushions, our results indicate uneven pressure distribution, with a greater contact surface under thighs than buttocks. This is likely related to the ergonomic characteristics of S_1 and S_2 cushions. Khamis et al. (2019) explained that seat pan length could alter pressure distribution between thighs and buttocks, which could affect blood circulation in the legs. Moreover for both seats, there was also asymmetry between the buttocks, with higher CP and greater CS under the left buttock. This is no doubt linked to the use of an automatic gearbox, only requiring use of the right leg and leaving the left leg free to move and to rest. Actually, automatic clutches favor an asymmetrical pressure interface, which was also observed for the backrest. Regardless of the seat, the right lower back area presented greater CP and CS than the other areas. However, no significant differences were observable between right and left upper back. This is probably due to compensation, where the driver adopts a stable position from the thoracic area to the head. This compensation is consistent with the need for the driver's trunk to be kept oriented towards the road and the fixity imposed by the driving posture (Grieco, 1986). Findings from Lecocq et al. (2020) using the same seats showed differences in muscular compensation strategies between S_1 and S_2. They found that the softness of the S_1 backrest forced drivers to apply higher muscle recuitment to maintain the trunk posture, while pressure asymmetry patterns appeared for both seats' backrests. Thus, although S_1 afforded greater CP and CS as recommended, it did not prevent asymmetry and muscle compensations.

4.2. *Perceived discomfort and driving posture*

An objective of this study was to identify seat features which may influence perceived whole-body and body-part discomfort. Previous studies (De Carvalho and Callaghan, 2011; Kyung et al., 2008; Sammonds et al., 2017) found that an increase in perceived whole-body discomfort appeared during the driving session and continued until the end of the experiment. Bazley et al. (2015) showed that perceived discomfort progressed throughout the day. To overcome the effect of time of day on discomfort level, we started each driving session at the same time of the day, which ensured that driving posture alone explained changes in perceived discomfort. The same evolution of discomfort was observed for both S_1 & S_2, consistent with Oudenhuijzen et al. (2003), who reported similar perceptions using two different seats, although pressure profiles differed for the cushion alone. Changes in perceived whole-body discomfort have previously been associated with an increase in each body-part discomfort score throughout driving, particularly in the lower back area (Mansfield et al., 2015). In our study, most body parts experienced discomfort after 40 min of driving. Neck, upper back and lower back were given the highest discomfort score, regardless of the seat, which confirms previous results indicating muscle fatigue in back and shoulders after 1 h of simulated driving (Jagannath and Balasubramanian, 2014). Seat S_2, despite firmer back support, did not prevent the onset of discomfort. This suggests that prolonged driving increases the risk of developing back pain symptoms while driving (Battié et al., 2002). Indeed, a recent review from De Carvalho et al. (2020) confirmed that immediate symptoms of lower-back pain appear during prolonged sitting. However, at present it is not known whether the pain experienced in response to sitting exposure is clinically relevant, predictive of future lower-back pain, or simply a momentary symptom. Thus, our results support current ergonomic recommendations to promote mobility by taking walking breaks (Sammonds et al., 2017) or by integrating systems that induce dynamic mobility to avoid the increase of perceived discomfort. The aim is to facilitate the driver's movements through spinal mobility, thereby alleviating the effects of sustained low contractions that could prevent blood flow, and thus ensure nutrition of the intervertebral disc (O'Sullivan et al., 2012). Another possibility might be to make the backrest movable so that it could be adjusted to fit different morphologies and to modify spine curvatures (Cardoso et al., 2017).

4.3. Limitations of the study

The main limitation of this static simulator study was the absence of vehicle dynamics. Only a visual simulation of the different road types was provided (Shechtman et al., 2009). However, a seat is defined by both static and dynamic properties (Ebe and Griffin, 2000; Mansfield et al., 2015). Dynamic road conditions like vibrations can modify the seat/driver relationship, thereby impacting pressure parameters. Here, although we did not consider mechanical perturbations to the seat/driver relationship, it can be assumed that the road types simulated visually influenced at least actions on the steering-wheel and pedals. Therefore, this experiment should be seen as a first approach exploring a prolonged driving task involving different road types visually simulated in a strictly controlled environment. Our main objective was to determine pressure distribution patterns and discomfort depending only on the seat and/or on the visual simulation of different road types during a prolonged driving task. While the simulator is a useful tool frequently used in driving studies, these first results not derived from real driving conditions simply provide a reliable database for future dynamic experiments to be performed with the same seats. Comparisons between static and dynamic conditions will highlight the effects of vibrations, lateral and longitudinal accelerations, greater cognitive attention, and higher interactions with commands, as suggested by Kyung and Nussbaum (2008).

Moreover, as suggested by Kolich (2003), seat designers need a better understanding both of physiological criteria, including pressure interface, and of anthropometric criteria, to improve designs. The two seats explored in our study are covered with different materials. The presence of leather in the S_2 covering could increase firmness, thereby influencing pressure distribution. Leather may produce a more rigid interface, which might play a role in the higher SPD% and lower CS found on the backrest for S_2. However, this difference in hardness between S_1 and S_2 was not perceptible by the drivers; general discomfort appeared only to be affected by increasing driving time. This is consistent with previous observations by Groenestjin et al. (2009) for office chairs. Various models indicate that individual factors such as BMI, weight or hip circumference may influence (dis)comfort evaluations and interface pressure (Hiemstra-van Mastrigt et al., 2016). In our study, these parameters were not analyzed and were collected only as sample descriptors, since our focus was on evaluating the effects of both seat hardness and road types, regardless of individual characteristics. Although our sample size was too small to study the effect of body mass, gender or stature on pressure parameters, it might be interesting to explore these factors further on a larger sample or on groups with different anthropometric characteristics. Hiemstra-van Mastrigt et al. (2016) highlighted, for instance, the importance of personal space on perceived discomfort during sitting exposure. Coupled with vehicle dynamics, considering such factors might reveal a greater influence of car seats on discomfort perception. In addition, to distinguish between car seats at this level of design quality, general and local comfort assessments could be added to discomfort assessments by drivers, since they seem to be processed through different neurological pathways (Kyung and Nussbaum, 2008; Vink and Hallbeck, 2012).

Finally, our discomfort assessment at 20-min intervals for easier comparison between participants did not reveal an effect from differing road types. It might be better to (i) assess comfort in parallel with discomfort and (ii) assess both at the end of each segment, even if this means unevenly distributing assessments over time. Moreover, a study of car passengers, who are not constrained by the fixity of the driving task, could shed light on how the seat and the task impact sitting behavior and the evolution of perceived discomfort.

5. Conclusion

Posture in car seats depends on a combination of many factors including driver characterics, the vehicle's specific cockpit dimensions, environment, and seat design. Our results confirm that pressure analysis is a viable means of comparing and defining sitting interface behavior between different seats during prolonged driving. The degree of hardness of the foam seems to have an impact on pressure patterns, with the soft seat offering greater contact surface and better pressure distribution. However, there were also asymmetries at the interface with both seats, probably due to the automatic gearbox requiring frequent mobilization of the right limb on gas and brake pedals. Furthermore, pressure patterns depended on driving time. The driver's pressure parameters were variable only for the seat cushion and at the beginning of the driving session, thereafter, remaining stable until the end of the driving session. On the seat cushion, however, the uniformity of pressure distribution is probably explained by cognitive demands and road segment characteristics. Yet despite these differences in uniformity of pressure exerted on the two seats' cushions, prolonged driving was found to trigger whole-body discomfort regardless of the seat. These observations suggest (i) that participants may not be able to perceive differences in their behavior at the interface with the seat, (ii) that changes observed in pressure distribution are too weak to be perceived regarding sitting discomfort during prolonged driving, (iii) that pressure distribution is not relevant for assessing the effect of driving tasks on perceived discomfort. Future research could usefully explore ways to improve the driving experience by optimizing seat design so as to raise the current threshold of 40 min of driving time before increased discomfort begins to be perceived. Seat design guidelines need to incorporate adaptive systems ensuring homogeneous distribution of pressure, encouraging movement while maintaining the driver's posture according to the demands of the type of road (Lecocq et al., 2020).

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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