Next-generation cars, secondary activities, and sitting configurations: In-line transmission of vertical vibration at seat cushion

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ABSTRACT

Next-generation cars will be electric, connected, autonomous, and shared. Aboard, primary activities such as driving or travelling will coexist with secondary activities such as (self-) entertaining, socialising, relaxing, sleeping, working, and eating. Although secondary activities have already been identified, related seating issues have only been touched. A three-factor mixed-design laboratory experimental study was conducted to test whether the concept of 'sitting configuration' (introduced and defined in this paper) is appropriate to characterise the seat–occupant system as a whole. Specifically, investigated were main effects and interaction effects of (biological) sex, vibration magnitude, and sitting configuration on in-line transmission of vertical vibration at seat cushion. With the Six-Axis Motion Simulator of the University of Southampton, six men and six women occupying a production reclining car seat were subjected to four vibration magnitudes in four sitting configurations corresponding to four pairs of primary and secondary activities. Transmissibility and coherence functions were calculated from acceleration measurements. An ANOVA model of first-resonance frequency of transmissibility showed an appreciable main effect of both vibration magnitude ($F(2.21, 22.11) = 369.54$, $p < 0.001$, $\eta^2 = 0.28$, $\eta_P^2 = 0.97$, $\eta_G^2 = 0.54$) and sitting configuration ($F(1.98, 19.80) = 82.27$, $p < 0.001$, $\eta^2 = 0.48$, $\eta_P^2 = 0.89$, $\eta_G^2 = 0.67$) but failed to show an appreciable main effect of sex ($F(1, 10) < 0.001$, $p > 0.99$, $\eta^2 < 0.001$, $\eta_P^2 = 0.001$, $\eta_G^2 < 0.001$) and any appreciable interaction effects ($p > 0.99$, $\eta^2 \leq 0.004$, $\eta_P^2 \leq 0.12$, $\eta_G^2 \leq 0.02$). Results suggest that the concept of sitting configuration is appropriate to characterise the seat–occupant system as a whole. Ultimately, in design and development of seats for next-generation cars, secondary activities and corresponding sitting configurations should be taken into consideration to optimise not only functionality, but also comfort and protection (and related affective/emotional attributes).

1 INTRODUCTION

The world of road transport has been rapidly metamorphosing in recent years. Indeed, both major advances and new challenges are expected within the automotive industry [1]. The four keywords of next-generation cars are *electrification*, *connection*, *automation*, and *sharing* [2]. It is still a matter of discussion whether such innovations will prove truly disruptive and revolutionary or just incremental and evolutionary [3]; in fact, it is even unclear whether they will be welcomed or not by the public [4]. However, at the very least, an automotive paradigm shift is a plausible development.

Should electric, connected, autonomous, and shared cars hit the road, important behavioural changes would spread amongst users [5]. Being more often passengers than drivers, users of next-generation cars might engage not only in *primary activities* such as *travelling* or *driving*, but also in *secondary activities* such as *(self-) entertaining*, *socialising*, *relaxing*, *sleeping*, *working*, and *eating* [6, 7, 8, 9, 10, 11, 12, 13]. In a similar automotive-industry scenario, when it comes to customer expectations and related product requirements, performance is likely to be outweighed not only by functionality, but also by comfort and protection (and related affective/emotional attributes [14]). In other words, *human factors and ergonomics (HFE)* is likely to become key.

We may know 'what' people will be doing in next-generation cars, and yet we do not know 'how'. To date, the (transport) HFE community has addressed the topic mainly within the *organisational* branch (*traffic management* [15] and *traffic safety* [16]) and the *cognitive* branch (*situational awareness* [17] and *human-machine interaction* [18]). Indeed, apart from *motion sickness* [19, 20], researchers have not probed deep into the *physical* branch (*comfort* and *protection*). In particular, *seating issues* specific to next-generation cars remain relatively unexplored from a 'static' point of view (*occupant packaging* [21, 22, 23, 24]) and barely approached from a 'dynamic' point of view (*vehicle safety* [25] and *human vibration* [26, 27, 28]).

As regards (whole-body) human vibration, many laboratory experimental studies have been designed to investigate *objective responses of seated human body to motion environment* [29, 30]. On the one hand, working closer to the 'basic' end of the basic–applied research continuum, investigators in *biodynamics* have used rigid or semirigid laboratory seats to characterise the occupant alone (mainly in terms of *apparent mass* [31, 32, 33]). On the other hand, working closer to the 'applied' end of the basic–applied research continuum, investigators in *seating dynamics* have used deformable factory seats to characterise both the seat alone (mainly in terms of *dynamic stiffness* [34, 35, 36]) and the seat–occupant system as a whole (mainly in terms of *transmissibility* [35, 37]). However, in many cases, attention has been paid to effects of specific factors considered in isolation. The most popular has been perhaps severity of motion environment (usually characterised in terms of *vibration magnitude*), which has shown unequivocal nonlinear effects [38, 39]. Other favourites are *seat-back reclination* [40], *footrest configuration* [41, 42], and *demographic and anthropometric characteristics* [43]; amongst these, only seat-back reclination has shown clear and consistent effects.

Now, three considerations are in order. First, although in real-life scenarios both seat-back reclination and footrest configuration contribute to determining the *overall arrangement of the seat–occupant system*, they have rarely been subjected to simultaneous experimental manipulation. Second, although women represent approximately half of the population, experimental studies have recurrently used samples composed only of men, and, if not, they have just sporadically included *(biological) sex* [1] as a factor. Third, although main effects are typically superseded by interaction effects (and, in turn, lower-order interaction effects are typically superseded by higher-order interaction effects), *interaction effects* of any kind have scarcely been investigated.

To meet habitability needs of next-generation cars, important advances in car interiors and specifically in car seats are to be pursued with targeted applied research. After adopting a conceptual framework in which the seat–occupant system is regarded as a whole [26], the natural step forward is deploying operational tools that facilitate addressing practical issues. Following this line of thought, the concept of *sitting configuration* is introduced and defined in this paper as *"activity-related overall arrangement of the seat–occupant system specified by position, orientation, body posture, body support, and body restraint"*.

In light of the above, a *laboratory experimental study* was conducted to test whether the concept of sitting configuration is appropriate to characterise the seat–occupant system as a whole. In particular, three *research questions* were formulated. On objective seat–occupant responses to motion environment, besides the well-known main effect of vibration magnitude:

- Is there an appreciable main effect of sitting configuration?
- Is there an appreciable main effect of sex?
- Are there any appreciable interaction effects between sex, vibration magnitude, and sitting configuration?

In what follows, objective seat–occupant responses to motion environment are related to *in-line transmission of vertical vibration at seat cushion*.

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[1] Within the context of this study, biologically rather than culturally determined characteristics are of interest. Accordingly, in this paper, the term 'sex' is used instead of the term 'gender'.

2 METHOD

Considering findings of published studies, four *sitting configurations* were identified and characterised, both qualitatively and quantitatively, to match one pair of primary activities [44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57] and three pairs of secondary activities [8, 22, 23, 24, 58, 59, 60]. Sitting configurations, shown in **Figure 1**, were labelled *(self-) entertaining/socialising (ES)*, *relaxing/sleeping (RS)*, *travelling/driving (TD)*, and *working/eating (WE)*. Qualitative characteristics of sitting configurations are shown in **Table 1**.

Figure 1 Sitting configurations. **Top left:** (self-) entertaining/socialising (ES). **Top right:** relaxing/sleeping (RS). **Bottom left:** travelling/driving (TD). **Bottom right:** working/eating (WE).

Table 1 Qualitative characteristics of sitting configurations

	ES	RS	TD	WE
Body posture	crouched	zero-gravity	regular	upright
Seat-back reclination	medium–high	high	medium–low	low
Footrest horizontal position	far	far	far	near
Footrest vertical position	high	medium–low	medium–high	low
Footrest inclination	high	medium	medium–high	zero

Four whole-body mechanical vibrations were used as *excitations/stimuli*. They were designed to perform an appropriate frequency-domain characterisation in the widest possible portion of the frequency band of interest for road-transport applications involving exposure to whole-body mechanical vibration (but not motion sickness) [29, 30]. In particular, chosen excitations/stimuli were intended to represent 'baseline' conditions with 'simple' direction, 'well-behaved' waveform, 'wide' frequency band, 'relatively modest' severity, and 'sufficiently long' duration. Even if it seems reasonable to expect passengers travelling aboard next-generation cars to be exposed to more complex motion environments [27, 28], baseline conditions were preferred to facilitate not only performing an appropriate frequency-domain characterisation, but also referencing to previous studies. Characteristics of excitations/stimuli are shown in **Table 2**.

Table 2 Characteristics of excitations/stimuli

Type	whole-body mechanical vibration
Direction	'vertical' (*z*-axis of laboratory geocentric coordinate system)
Waveform	low-crest-factor stationary pseudorandom with pseudo-white-noise power spectral density
Frequency band	between 0.5 Hz and 50 Hz
Severity [a]	{0.28 $m \cdot s^{-2}$, 0.45 $m \cdot s^{-2}$, 0.71 $m \cdot s^{-2}$, 1.12 $m \cdot s^{-2}$}
Duration	60 s

[a] Severity is expressed in terms of root-mean-square value of W_k-weighted acceleration [61] (approximately equal to root-mean-square value of W_b-weighted acceleration [62]).

Since the four excitations/stimuli differed only in severity, they were characterised in terms of *vibration magnitude*. In principle, vibration magnitude is a continuous quantity (whose four chosen values are equally spaced on a logarithmic scale). However, for the purposes of this study, it was conveniently considered as an (ordinal) categorical quantity assuming four values labelled *0d28w*, *0d45w*, *0d71w*, and *1d12w*. In terms of approximate indications of likely reactions, these four vibration magnitudes correspond respectively to the four verbal descriptors 'not uncomfortable', 'a little uncomfortable', 'fairly uncomfortable', and 'uncomfortable' [61, 62]. The four vibration magnitudes were chosen to cover the range of severity that may be expected in road-transport applications involving next-generation cars. The use of four values was decided to allow capturing possible non-monotonic trends with some detail.

2.1 Participants

This study was approved by the Faculty Ethics Committee of Engineering and the Environment at the University of Southampton (ERGO II submission reference 41143). A *sample* of 'adult' and 'healthy' men and women was selected amongst students and staff members of the University of Southampton to represent the target population of users of next-generation cars. To be regarded as 'adult', participants had to be eighteen years old or more. To be regarded as 'healthy' without further medical advice, participants had to be fit to travel in public transport without assistance and to accept the stress of a normal day's work, did not have to be suffering any serious illness or injury, did not have to be under medical treatment or suffering disability affecting their daily life, and did not have to have certain conditions (active disease of the respiratory system, active disease of the digestive system, active disease of the cardiovascular system, active disease of the genitourinary system, active disease of the musculoskeletal system, active or chronic disease or disorder of the nervous system, mental health problems, recent trauma, recent surgical procedures, prosthesis, pregnancy, and breastfeeding). For the formal assessment of eligibility, a health questionnaire was designed in compliance with International Standard ISO 13090-1:1998 [63].

Neither random nor systematic sampling plan was implemented, but equal numbers of men and women were sought to obtain *two independent groups* of the same size. The intended total *sample size* of *twelve participants* (*six men* and *six women*) was chosen, in the wake of the psychophysical tradition [64], with the aim of detecting 'large' effect sizes. Fourteen potential participants were reached haphazardly, either through direct approach (five men and four women) or through advertisement (one man and four women), and were preliminarily screened. Two directly approached women were excluded (one because of a refusal to participate and the other because of a scheduling conflict). Twelve potential participants (six men and six women) were formally assessed for eligibility and were recruited. They gave their informed consent to participate and received a reimbursement payment. Personal data collected or created about participants were pseudonymised and managed confidentially in compliance with the Data Protection Policy of the University of Southampton as well as with the Data Protection Act 2018 (for the purposes of which the University of Southampton is the data controller).

Major *demographic and anthropometric characteristics* of the two independent groups were as follows. The *male group* had age with median 28 y and interquartile range 3 y, body mass (weight) with median 78.6 kg and interquartile range 14.2 kg, stature (body height) with median 1797 mm and interquartile range 37 mm, and body mass index with median 23.8 $kg{\cdot}m^{-2}$ and interquartile range 2.8 $kg{\cdot}m^{-2}$. The *female group* had age with median 30 y and interquartile range 9 y, body mass (weight) with median 67.7 kg and interquartile range 11.0 kg, stature (body height) with median 1666 mm and interquartile range 57 mm, and body mass index with median 23.6 $kg{\cdot}m^{-2}$ and interquartile range 5.2 $kg{\cdot}m^{-2}$.

2.2 Measures

Objective seat–occupant responses to motion environment were measured within a laboratory experiment. Measurements of *rectilinear components of acceleration* were performed, by means of measuring instrumentation complying with International Standard ISO 8041-1:2017 [65], in the three perpendicular directions of each of *two coordinate systems*. The $\{x_t, y_t, z_t\}$ coordinate system was located at the *vibration table*, whereas the $\{x_c, y_c, z_c\}$ coordinate system was located at *the interface between seat cushion and occupant buttocks*. Experimental arrangement and coordinate systems are shown in **Figure 2**.

Figure 2 Experimental arrangement and coordinate systems. $\{x_t, y_t, z_t\}$: coordinate system at vibration table. $\{x_c, y_c, z_c\}$: coordinate system at interface between seat cushion and occupant buttocks.

At the seat–occupant interface, the non-zero value of the cushion angle led to the adoption of a *basicentric biodynamic coordinate system* [66]. Hence, unlike the axes of the $\{x_t, y_t, z_t\}$ coordinate system, the axes of the $\{x_c, y_c, z_c\}$ coordinate system were not exactly parallel to those of the geocentric coordinate system of the laboratory (having *z*-axis lying in the direction of the earth's gravity). The $\{x_c, y_c, z_c\}$ coordinate system seemed appropriate on the reasonable assumption that psychophysiological responses to vibration depend on motion components in the directions of the axes of biodynamic rather than geocentric coordinate systems [61, 62]. However, considering the parallelism tolerances specified in International Standard ISO 2631-1:1997 [61] and in British Standard BS 6841:1987 [62] (respectively up to 20° and up to 15°), the z_t axis and the z_c axis could be considered in-line to a first approximation.

The seat–occupant system had a longitudinal plane of symmetry passing through the centreline of the seat and coinciding with the sagittal plane of the occupant; besides, the excitations/stimuli were one-directional and vertical. Accordingly, relevant measurements of acceleration were in the directions z_t, x_c, and z_c; nevertheless, for verification purposes, they were also performed in the directions x_t, y_t, and y_c. In what follows, only the $\{z_t, z_c\}$ *input–output pair* is considered; this implies regarding the seat–occupant system as a single-input single-output (SISO) dynamic system.

For each test, *two response functions* and *one response variable* were obtained from the input acceleration in the direction z_t and from the output acceleration in the direction z_c. The response functions were the $\{z_t, z_c\}$ *transmissibility function* (complex-valued function) and the corresponding $\{z_t, z_c\}$ *coherence function* (real-valued function), both defined in International Standard ISO 2041:2018 [67]. For subsequent analyses, the complex-valued transmissibility function was decomposed into modulus and argument (also known as amplitude and phase angle respectively). Calculations of transmissibility function and coherence function were performed, as described in International Standard ISO 18431-1:2005 [68], starting from estimated power spectral density and cross-spectral density of input and output accelerations. In particular, the transmissibility function was calculated as a frequency-response function of the first type. For its theoretical and practical importance, *first-resonance frequency* of $\{z_t, z_c\}$ transmissibility function (real-valued scalar) was chosen as response variable for statistical analysis.

2.3 Research Design

Implemented was a *(balanced) three-factor mixed design* with *one two-level between-group factor* (*sex*) and *two four-level within-group factors* (*vibration magnitude* and *sitting configuration*). Accordingly, each of the six participants within each of the two independent groups received *sixteen treatments*. An effort was made to adopt all the three fundamental principles of experimental design attributed to the British statistician and geneticist Ronald Aylmer Fisher (1890–1962): replication, blocking, and randomisation. To control random measurement error and improve measurement precision, *replication* was systematically implemented: namely, each of the sixteen treatments was replicated three times with each of the twelve participants to obtain thirty-six tests per treatment. To control the effect of nuisance factors and improve statistical power, *blocking* was implemented at two levels: namely, independent groups were used as blocks with respect to between-group factor and participants were used as blocks with respect to within-group factors and replicate. To control systematic measurement error and improve measurement trueness, *randomisation* was completely implemented with respect to within-group factors and replicate: namely, a different random test sequence was used for the forty-eight tests of each participant.

For inferential statistical analysis, a *three-way mixed-design univariate analysis of variance (ANOVA)* was used. The *(nil) null hypothesis* was that experimental manipulation of sex, vibration magnitude, and sitting configuration had neither appreciable main effects nor appreciable interaction effects. Despite requiring more restrictive assumptions than those required by semiparametric and nonparametric counterparts, a parametric technique was preferred because of the greater statistical power; the legitimacy of this choice was assessed a posteriori by verifying the assumption of normality for the model residuals.

These authors are aware of the criticism of the procedure of *null hypothesis statistical significance testing* [69]. In fact, controversies about statistical inference are perennial. At a higher level, epistemological discussions about paradigms (frequentist vs Bayesian) [70], frameworks (parameter estimation vs hypothesis testing) [71], and even approaches within the same framework (Fisher's vs Neyman–Pearson's hypothesis testing) [72] have persisted for decades. At a lower level, the old frequentist dilemma between parametric and nonparametric techniques [73] has been flanked by a more recent debate about possible parametric substitutes for ANOVA [74, 75]. Pragmatically, a classic well-attested technique allowing the analysis of three-way interactions with a relatively easy implementation was deemed appropriate for the purposes of this study. However, considering both the many well-founded reservations about the procedure of null hypothesis statistical significance testing [69] and the latest recommendations of the American Statistical Association (ASA) [76], no declarations of ‘statistical significance’ are made in this paper. Instead, assessments of ‘practical significance’ of effects are made by complementing p-values with numerical measures of *effect size* (eta-squared η^2, partial eta-squared η_{P}^2, and generalised eta-squared η_{G}^2) [2] and point estimates with graphical representations of *interval estimates* (confidence intervals at 95 % confidence level). In this paper, to avoid using the worn word ‘significant’ altogether, an effect deemed practically significant is qualified as ‘appreciable’.

2.4 Experimental Manipulations

The *vibration generator system* (Six-Axis Motion Simulator of the University of Southampton) was composed of a hydraulic vibration generator with table and a digital control system. In order to reproduce realistic seat–occupant interactions, used was a *production reclining car seat* (NHK left-outboard front-row passenger seat for right-hand-drive Subaru Outback) rigidly mounted on the vibration table. A *four-piece configurable footrest* made of wood and carpet (handcrafted at the University of Southampton) was mounted on the vibration table in front of the seat.

Target acceleration signals for the four excitations/stimuli were generated in MATLAB software environment (version 8.5.1.959712) by means of the HVLab Human Response to Vibration Toolbox (version 2.0). The corresponding *drive displacement signals* were obtained through an iterative ‘equalisation’ process by means of the vibration generator system.

All *acceleration measurements* were performed according to International Standard ISO 10326-1:2016 [78]. At vibration table, used were three uniaxial accelerometers (Silicon Design 2260-005). At the interface between seat cushion and occupant buttocks, used was one special-purpose triaxial accelerometer (HVLab SITpad-3-10g). The instrumented seat is shown in **Figure 3**.

Figure 3 Instrumented seat. **Left:** front view. **Right:** side view.

[2] Interpretations of measures of effect size against arbitrary benchmarks are not recommended; accordingly, they are not provided in this paper. In principle, one can use eta-squared η^2 for comparisons of effects within a single study, partial eta-squared η_{P}^2 for power analyses and for comparisons of effects across studies with the same research design, and generalised eta-squared η_{G}^2 for meta-analyses and for comparisons of effects across studies with different research design [77].

Acquisition of acceleration signals was performed in MATLAB software environment via the HVLab Human Response to Vibration Toolbox at a sampling rate of 512 $S \cdot s^{-1}$. The multichannel data acquisition system was composed of a multifunction I/O device (National Instruments NI USB6211) and of a signal conditioning system, which in turn was composed of two eight-channel mobile Micro Analog 2 enclosures (Fylde FE-MM8), two power supply modules (Fylde FE-810-BPS DC), six two-channel bridge transducer amplifier modules (Fylde FE-366-TA), and two auto-zero modules (Fylde FE-366-AZ).

The forty-eight tests of each participant were performed at the University of Southampton within *two sessions* held on two different days, each including twenty-four tests and lasting between 2.5 h and 3 h. The long duration of each session was due to the randomisation with respect to sitting configuration, which required long breaks between consecutive tests. Within these breaks, seat-back reclination and footrest configuration would be adjusted by using respectively an inclinometer and a set of reference stickers on the vibration table. Special care was taken to ensure that sitting configurations were reproduced consistently across different tests, both with the same participant and with different participants. Each sitting configuration was visually checked and documented photographically with each participant.

In accordance with the approved *research protocol*, participants had their demographic data collected and their anthropometric data measured at the beginning of their first session. Before actual tests of each of their two sessions, participants read an instruction sheet and received preliminary training for a duration of 5 min. Before each test, participants were secured with a safety harness and were given ready access to an emergency stop control. Within each test, participants were exposed to an excitation/stimulus for a duration of 60 s whilst sitting relaxed but unmoving. As expected, participants did not suffer from motion sickness nor other malaise throughout their sessions.

3 RESULTS

Data processing was performed in MATLAB software environment at a frequency resolution of 0.25 Hz. *Statistical analysis* was performed in RStudio integrated development environment for R (version 1.2.5019) running against R software environment (version 3.6.1) [79]. There were no missing data nor deleted cases. Median and interquartile range of the response variable (first-resonance frequency of $\{z_t, z_c\}$ transmissibility) calculated across all tests were respectively 4.5 Hz and 1 Hz.

The *data set* used for inferential statistical analysis was composed of median values of the response variable calculated across all three replicates of each treatment with each participant. The corresponding interquartile range values were generally less than the frequency resolution value of 0.25 Hz. For each treatment with each participant, such interquartile range values provide numerical information about intra-participant variability. The data set was deemed robust enough to allow abstaining from further detection and treatment of outliers.

Graphical summaries of *frequency-domain analysis* for the response functions are provided in **Figure 4** and **Figure 5**, which show Bode plots and coherence plots of grand-median response functions ($\{z_t, z_c\}$ transmissibility modulus, $\{z_t, z_c\}$ transmissibility argument, and $\{z_t, z_c\}$ coherence) calculated across all thirty-six tests per treatment. Bode plots and coherence plots shown in **Figure 4** and **Figure 5** are equivalent, but they are parameterised and arranged differently for convenience.

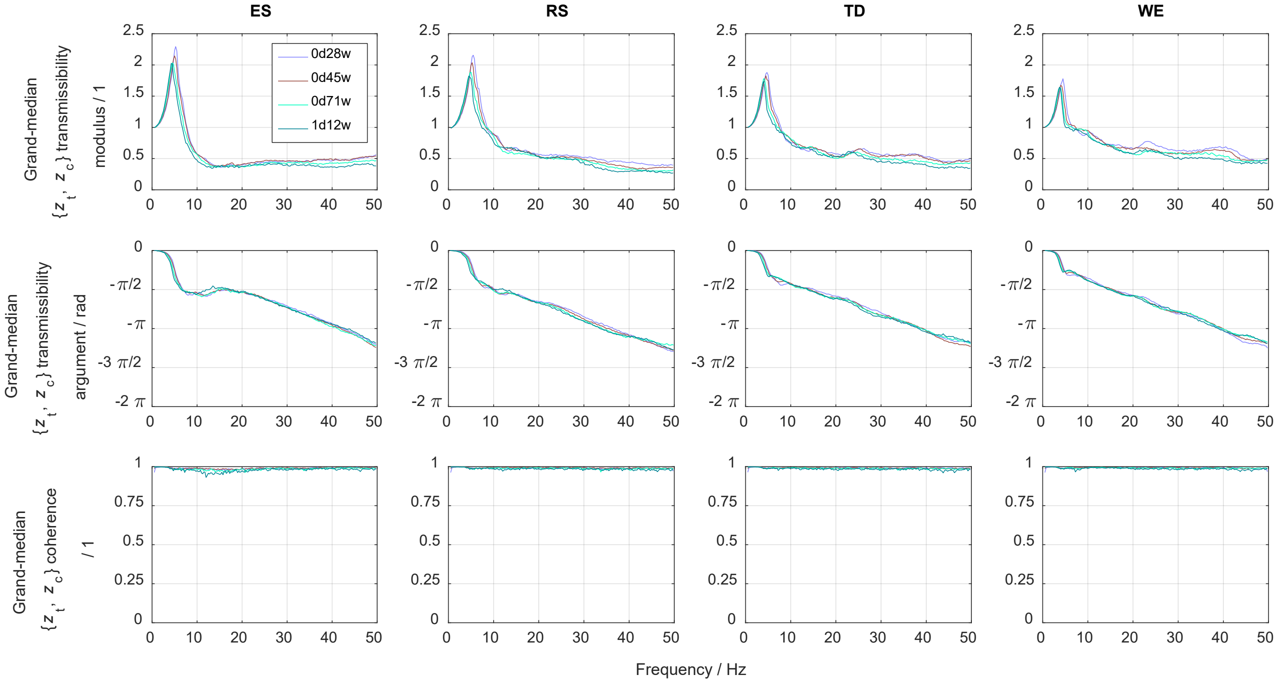

Figure 4 Bode plots and coherence plots of grand-median response functions ($\{z_t, z_c\}$ transmissibility modulus, $\{z_t, z_c\}$ transmissibility argument, and $\{z_t, z_c\}$ coherence) calculated across all thirty-six tests per treatment. Total sample: twelve participants (six men and six women). Vibration magnitude levels: {0d28w, 0d45w, 0d71w, 1d12w}. Sitting configuration levels: {ES, RS, TD, WE}. **Top row:** grand-median $\{z_t, z_c\}$ transmissibility modulus vs frequency. **Middle row:** grand-median $\{z_t, z_c\}$ transmissibility argument vs frequency. **Bottom row:** grand-median $\{z_t, z_c\}$ coherence vs frequency. (All graphs parameterised on vibration magnitude and arranged in columns by sitting configuration).

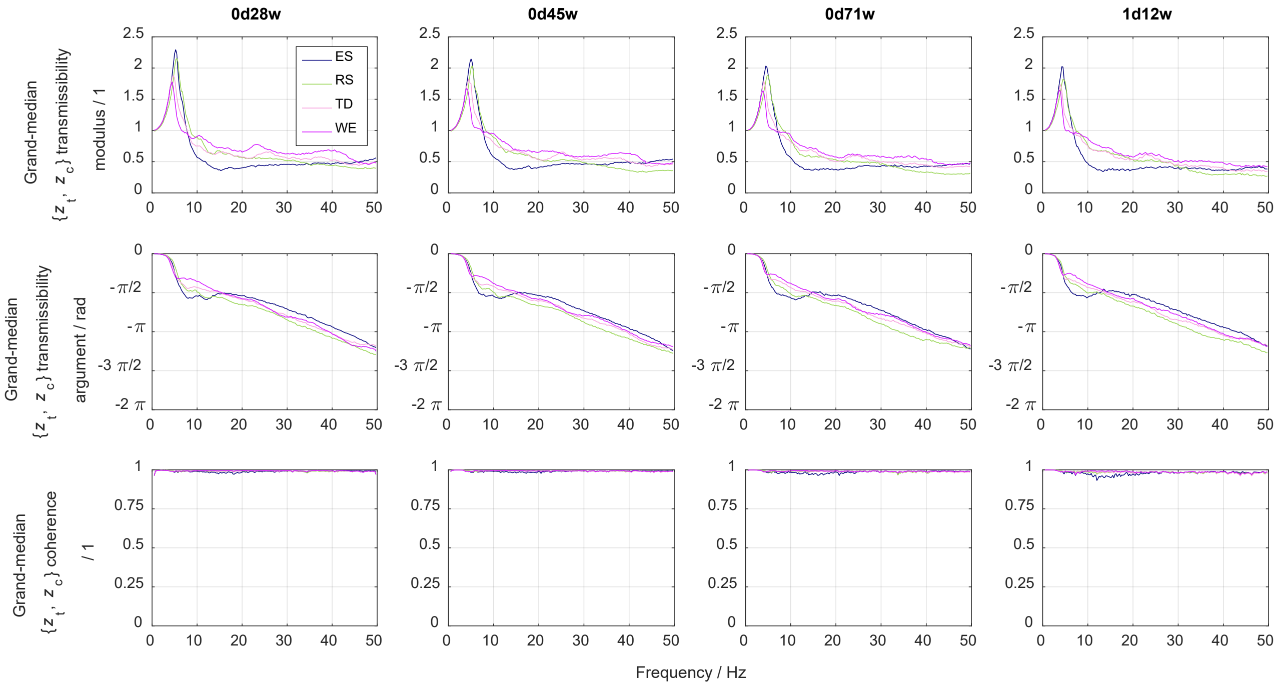

Figure 5 Bode plots and coherence plots of grand-median response functions ($\{z_t, z_c\}$ transmissibility modulus, $\{z_t, z_c\}$ transmissibility argument, and $\{z_t, z_c\}$ coherence) calculated across all thirty-six tests per treatment. Total sample: twelve participants (six men and six women). Vibration magnitude levels: {0d28w, 0d45w, 0d71w, 1d12w}. Sitting configuration levels: {ES, RS, TD, WE}. **Top row:** grand-median $\{z_t, z_c\}$ transmissibility modulus vs frequency. **Middle row:** grand-median $\{z_t, z_c\}$ transmissibility argument vs frequency. **Bottom row:** grand-median $\{z_t, z_c\}$ coherence vs frequency. (All graphs parameterised on sitting configuration and arranged in columns by vibration magnitude).

Graphical summaries of *descriptive statistical analysis* for the response variable are provided in **Figure 6**, which shows box plots of median response variable (first-resonance frequency of $\{z_t, z_c\}$ transmissibility) calculated across all three replicates. For each treatment with each independent group, such box plots provide graphical information about inter-participant variability. The bottom line of each box (lower hinge) corresponds to the lower quartile (also known as first quartile and coinciding with the 25th percentile). The middle line of each box corresponds to the median (also knowns as second quartile and coinciding with the 50th percentile). The top line of each box (upper hinge) corresponds to the upper quartile (also known as third quartile and coinciding with the 75th percentile). The difference between upper quartile and lower quartile is the interquartile range. The lower whisker extends from the lower hinge to the minimum value at or above the lower fence (value situated 1.5 times the interquartile range below the lower quartile). The upper whisker extends from the upper hinge to the maximum value at or below the upper fence (value situated 1.5 times the interquartile range above the upper quartile). Values beyond the lower fence and the upper fence are marked separately. Box plots shown on the left side and of the right side of **Figure 6** are equivalent, but they are parameterised and arranged differently for convenience.

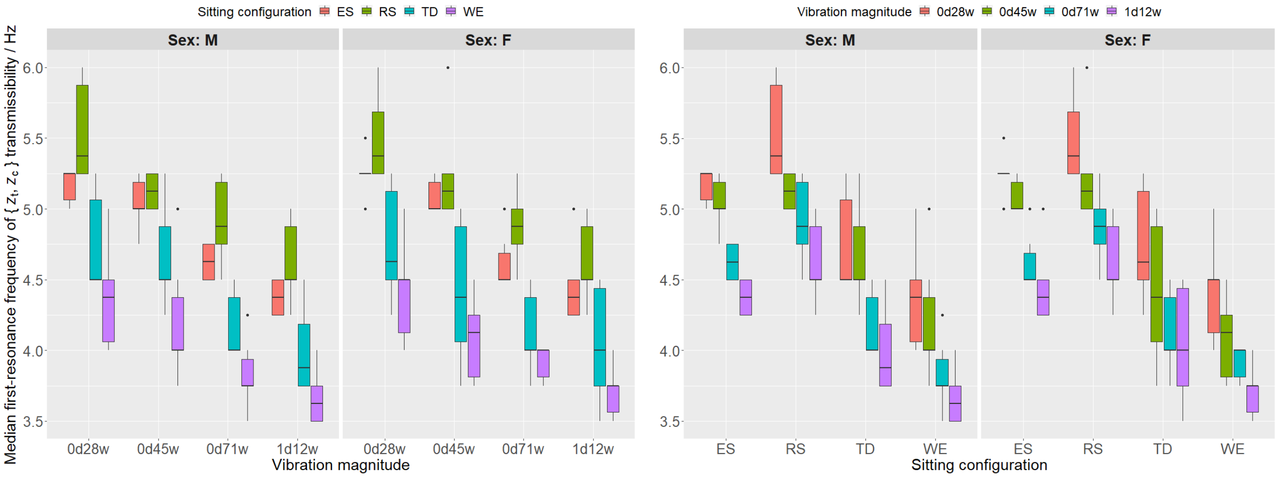

Figure 6 Box plots of median response variable (first-resonance frequency of $\{z_t, z_c\}$ transmissibility) calculated across all three replicates. Independent groups: male group (six participants) and female group (six participants). Sex levels: {M, F}. Vibration magnitude levels: {0d28w, 0d45w, 0d71w, 1d12w}. Sitting configuration levels: {ES, RS, TD, WE}. **Left:** median first-resonance frequency of $\{z_t, z_c\}$ transmissibility vs vibration magnitude (graphs parameterised on sitting configuration and arranged in columns by sex). **Right:** median first-resonance frequency of $\{z_t, z_c\}$ transmissibility vs sitting configuration (graphs parameterised on vibration magnitude and arranged in columns by sex).

A *three-way mixed-design univariate ANOVA model* of the response variable was fit by using the R package afex (version 0.25-1) [80]. To protect against possible violations of the sphericity assumption, conservative Greenhouse–Geisser corrections were applied to eligible statistical degrees of freedom. To mitigate the multiple-comparisons problem inherent in multiway ANOVA [81], *p*-values were adjusted using the Holm–Bonferroni method. The normality assumption for the model residuals was verified by means of diagnostic plots; the histogram of residuals, the residual–fitted plot, and the quantile–quantile plot of residuals indicated no obvious deviation from normality.

The ANOVA model of the response variable showed an appreciable main effect of both vibration magnitude ($F(2.21, 22.11) = 369.54$, $p < 0.001$, $\eta^2 = 0.28$, $\eta_P^2 = 0.97$, $\eta_G^2 = 0.54$) and sitting configuration ($F(1.98, 19.80) = 82.27$, $p < 0.001$, $\eta^2 = 0.48$, $\eta_P^2 = 0.89$, $\eta_G^2 = 0.67$) but failed to show an appreciable main effect of sex ($F(1, 10) < 0.001$, $p > 0.99$, $\eta^2 < 0.001$, $\eta_P^2 = 0.001$, $\eta_G^2 < 0.001$) and any appreciable interaction effects ($p > 0.99$, $\eta^2 \leq 0.004$, $\eta_P^2 \leq 0.12$, $\eta_G^2 \leq 0.02$). Graphical summaries of *inferential statistical analysis* for the response variable are provided in **Figure 7**, which shows three-way interaction-effect plots of ANOVA model of response variable (first-resonance frequency of $\{z_t, z_c\}$ transmissibility) with confidence-interval error bars at confidence level 95 % (not usable for comparisons across different levels of the between-group factor sex) [3]. Interaction-effect plots shown on the left side and of the right side of **Figure 7** are equivalent, but they are parameterised and arranged differently for convenience.

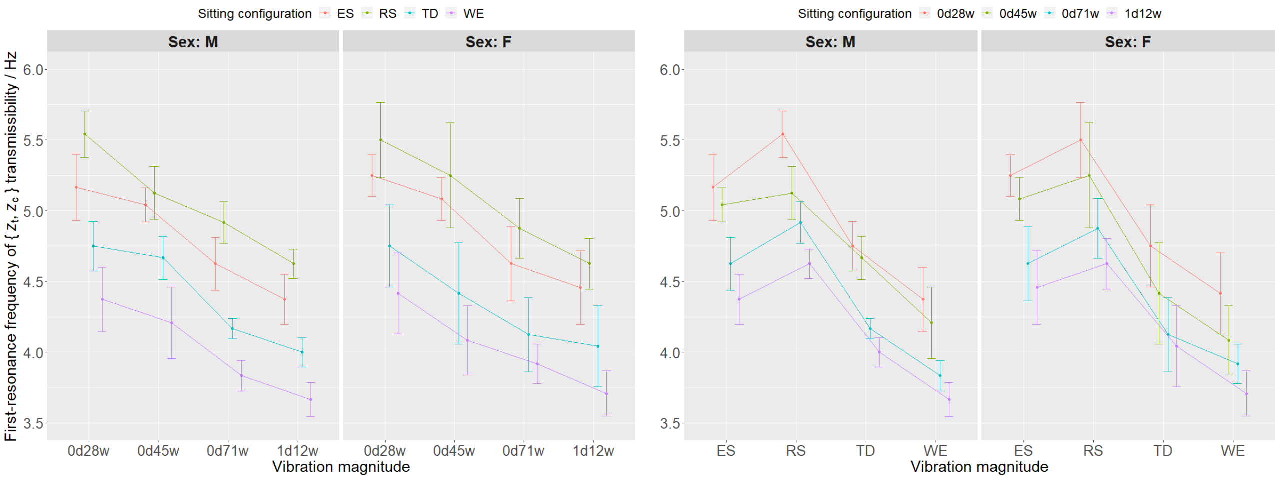

Figure 7 Three-way interaction-effect plots of ANOVA model of response variable (first-resonance frequency of $\{z_t, z_c\}$ transmissibility) with confidence-interval error bars at confidence level 95 % (not usable for comparisons across different levels of the between-group factor sex). Independent groups: male group (six participants) and female group (six participants). Sex levels: {M, F}. Vibration magnitude levels: {0d28w, 0d45w, 0d71w, 1d12w}. Sitting configuration levels: {ES, RS, TD, WE}. **Left:** first-resonance frequency of $\{z_t, z_c\}$ transmissibility vs vibration magnitude (graphs parameterised on sitting configuration and arranged in columns by sex, data points horizontally offset for clarity). **Right:** first-resonance frequency of $\{z_t, z_c\}$ transmissibility vs sitting configuration (graphs parameterised on vibration magnitude and arranged in columns by sex, data points horizontally offset for clarity).

4 DISCUSSION

In almost static conditions, near zero frequency, *transmissibility functions* are almost real-valued; in particular, modulus is almost equal to unity (by virtue of input and output axes being almost parallel), and argument is almost null (by virtue of input and output accelerations being in phase). Within the low end of the frequency band of interest, a one-degree-of-freedom-like first resonance is identifiable by means of a prominent peak in modulus and a corresponding drop in argument.

As can be seen in **Figure 4**, transmissibility functions are affected by vibration magnitude in terms of *shifting* and *scaling*. Indeed, with increasing vibration magnitude, a decrease both in first-resonance frequency of transmissibility and in first-resonance value of transmissibility modulus is observed. This nonlinear *softening effect*, well known from previous studies [38, 39], occurs not only locally, but also across the whole frequency band of interest; in particular, with increasing vibration magnitude, both transmissibility modulus curves and (less markedly) transmissibility argument curves shift to the left and scale down.

As can be seen in **Figure 5**, transmissibility functions are affected by sitting configuration in terms of *shaping*. Indeed, different behaviours can be observed at the two ends of the frequency band of interest; this allows identifying two *end zones* and one separating *transition zone*. The frequency

[3] It is worth emphasising that, when used for comparisons, overlapping confidence-interval error bars at confidence level $1 - \alpha$ do not preclude a 'statistically significant' difference between the means at a 'significance level' less than or equal to α. In fact, non-overlapping confidence-interval error bars at confidence level $1 - \alpha$ imply a 'statistically significant' difference between the means at a 'significance level' distinctly less than α [82].

boundaries of the three zones and the overall shape of transmissibility modulus and argument curves depend on the sitting configuration. By inspection, the transition zone appears to have lower bound approximately at the first-resonance frequency (having median value 4.5 Hz and interquartile range 1 Hz across all tests) and upper bound approximately at a frequency between 14 Hz and 16 Hz. In accordance with previously reported results, it can be hypothesised that response functions are controlled in the low-end zone by seat-back reclination [40] and in the high-end zone by footrest horizontal and vertical position [41, 42]. In turn, these parameters may exert their influence by affecting loading distribution and contact area at the interface between seat cushion and occupant buttocks and, through the latter, by affecting dynamic stiffness of the seat [34, 35, 36] and apparent mass of the occupant [31, 32]. In terms of the reference items defined in Surface Vehicle Recommended Practice SAE J1100:2009-11 [83], the most important role is probably played in the low-end zone by A40 (torso angle) and in the high-end zone by the difference between A57 (thigh angle) and A27 (cushion angle).

For all treatments, *coherence* is high across the whole frequency band of interest, which proves the *input–output relation* to be *linear* and *noiseless*. Nevertheless, with increasing vibration magnitude, a slight decrease in coherence can be observed across the whole frequency band of interest; this can be explained by the contact at the interface between seat cushion and occupant buttocks becoming less stable. In particular, approximately between 5 Hz and 25 Hz, coherence takes slightly (but consistently) lower values for the ES sitting configuration; this can be interpreted as an effect of *occupant (involuntary) muscular activity*, which is a confounder in the adopted research design.

Median and interquartile range of the *response variable* calculated across all tests (respectively 4.5 Hz and 1 Hz) are in agreement with previous observations [37]. Main effects and interaction effects of the three considered factors on the response variable offer a varied picture. On the one hand, whilst an *appreciable main effect of vibration magnitude* is unsurprising [38, 39], an *appreciable main effect of sitting configuration* is a new finding, which suggests that the concept of sitting configuration is appropriate to characterise the seat–occupant system as a whole. On the other hand, whilst *failure to observe an appreciable main effect of sex* is consistent with previous inconclusive observations [33, 42, 43], *failure to observe any appreciable interaction effects* cannot be compared with known previous findings; however, if confirmed by further studies, it will have relevant implications in product design and development.

5 CONCLUSION

This study allowed showing that the concept of sitting configuration is appropriate to characterise the seat–occupant system as a whole. Indeed, at least as regards in-line transmission of vertical vibration at seat cushion, possible sitting configurations for secondary activities in next-generation cars are associated with different objective seat–occupant responses to motion environment. Ultimately, in design and development of seats for next-generation cars, secondary activities and corresponding sitting configurations should be taken into consideration to optimise not only functionality, but also comfort and protection (and related affective/emotional attributes). In order to generalise these findings to the target population of users of next-generation cars, the main technical limitation of this study is the sample size. Future investigations should consider more realistic motion environments as well as a wider range of response functions and response variables. The effects of different seat designs should also be investigated.

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