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Fore-and-aft transmissibility of backrests: Variation with height above the seat surface and non-linearity

Nawal A. Abdul Jalil[1], Michael J. Griffin*

Human Factors Research Unit, Institute of Sound and Vibration Research, University of Southampton, Southampton SO17 1BJ, England

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Abstract

The transmissibility of a seat depends on the dynamic response of the human body (which varies between individuals, body locations, and vibration magnitudes) and the dynamic response of the seat (which varies according to seat design). In the fore-and-aft direction, the transmissibility of a seat backrest was therefore expected to vary with vertical position on the backrest. This experimental study with 12 subjects investigated how backrest transmissibility varied with both the vertical measurement position and the magnitude of vibration. The transmissibilities of the backrest of a car seat and a block of solid foam were measured at five heights above the seat surface with random fore-and-aft vibration at five magnitudes (0.1, 0.2, 0.4, 0.8 and 1.6 $\mathrm{ms^{-2}}$ rms) over the range 0.25–20 Hz. The median transmissibilities exhibited resonances in the range 4–5 Hz for the car seat and in the range 3–6 Hz for the foam. The backrests showed clear changes in transmissibility with vertical position, but there were minimal changes in the resonance frequencies. For both backrests, the transmissibilities were greatest at the middle of the backrest. The least transmissibility was measured at the top of the car seat but at the bottom of the foam backrest. At each measurement position on both backrests, the transmissibility was non-linear with vibration magnitude: the resonance frequencies and transmissibilities at resonance decreased with increasing vibration magnitude. The variations in backrest transmissibility with vertical position and with vibration magnitude were sufficiently great to affect assessments of backrest dynamic performance. The results suggest that the fore-and-aft transmissibilities of backrests should be evaluated from more than one measurement location.

1. Introduction

The vibration discomfort of seated persons in vehicles is often dominated by vertical vibration and so many studies have investigated the vertical transmissibility of seats [1–4]. However, fore-and-aft vibration is also present on the seats of vehicles and may contribute to discomfort [5]. An understanding of the transmission of fore-and-aft vibration through seats to the backrest may assist the reduction in discomfort caused by such vibration.

*Corresponding author. Tel.: +44 023 80592277; fax: +44 023 80592927.
E-mail addresses: M.J.Griffin@soton.ac.uk, , mjg@isvr.soton.ac.uk (M.J. Griffin).
[1]Now at: Department of Mechanical and Manufacturing, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM, Serdang, Selangor, Malaysia.

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According to the frequency weightings in current standards, if a seat is rigid, fore-and-aft vibration at the backrest will cause more discomfort than fore-and-aft vibration on the seat at frequencies greater than about 3.15 Hz (e.g., Ref. [6]). The frequency weightings show a human sensitivity to fore-and-aft acceleration that falls in inverse proportion to the vibration frequency at frequencies greater than 2 Hz on the seat and at frequencies greater than 8 Hz on the backrest. Consequently, fore-and-aft backrest vibration needs to be only half the magnitude of seat vibration at 4 Hz and only a quarter of the magnitude of seat vibration at 8 Hz to cause similar discomfort to fore-and-aft seat vibration. In practice, seats are not rigid and so, at these frequencies, there is often a greater magnitude of fore-and-aft vibration on the backrest than on the supporting seat surface.

The fore-and-aft vibration on backrests has been measured in some laboratory studies with single-axis excitation and, in a few field studies, with multiple-axis excitation. When excited with vertical vibration, a pronounced peak at 4–5 Hz has been reported in the fore-and-aft motion of a car seat backrest [7]. When a car seat was exposed to fore-and-aft vibration in the laboratory, three resonances (4–5, 25–30 and 45–50 Hz) were found [5], whereas a block of foam supported on a rigid flat backrest showed only one resonance (at 1.5–3 Hz) during fore-and-aft excitation [8].

In previous studies, the backrest vibration has been measured using an accelerometer contained within a mount (i.e., a seat interface transducer pad, 'SIT-pad') positioned near the middle of the backrest, although the location has differed between studies [5,7–8]. International Standard ISO 10326-2 [9] specifies that the vibration on the backrest should be measured by positioning the transducer '*in the area of principal support for the body*', although it is not clear how this position is to be found. British Standard 6841 (1987) [6] says that measurements at the backrest '*should be made at the position with the greatest effective vibration in contact with the body*'. This gives recognition to the potential for the vibration to vary with location on a backrest, but there are no known studies investigating how the position of measurement affects the vibration on backrests.

Recent studies have found that the transmission of vibration through backrests is non-linear, showing a reduction in the resonance frequency with an increase in vibration magnitude [5,8]. This is due, at least in part, to the non-linearity in the apparent mass of the back when subjects are exposed to fore-and-aft vibration [10,11].

The present study was conducted to investigate the variation in the fore-and-aft backrest transmissibility of a car seat and a block of foam supported on a rigid flat frame. It was hypothesised that the transmission of vibration through the backrests would vary with vertical position on both backrests. It was also hypothesized that, because the impedance of the human body is non-linear in the fore-and-aft direction, the fore-and-aft transmissibility would be non-linear with vibration magnitude.

2. Method

2.1. Subjects

Twelve healthy male subjects participated in the study (see Table 1). The experiment was approved by the Human Experimentation, Safety and Ethics Committee of the Institute of Sound and Vibration Research (ISVR), University of Southampton.

Table 1
Subject age, stature, weight, and seat-to-shoulder distance

	Age (years)	Stature (m)	Weight (kg)	Seat-to-shoulder height (m)
Minimum	20	1.65	58	0.58
Maximum	39	1.86	99	0.69
Median	24.5	1.75	72.3	0.62

2.2. Apparatus

2.2.1. Vibration generation

The experiment was conducted using a 1-m stroke horizontal electro-hydraulic vibrator in the Human Factors Research Unit at the ISVR, University of Southampton. The vibrator was designed to reproduce motions suitable and safe for the study of human responses to vibration.

2.2.2. Seat description

Two types of seat were used in the experiment: a car seat (from a popular current family car) and a rigid seat with a backrest containing of a block of foam.

The car seat weighed 19.3 kg and was constructed from a steel frame in which the backrest was connected to the seat-pan frame via a connecting-plate (Fig. 1). The contoured cloth covers of the seat cushion and backrest contained moulded foam supported by springs. The inclination of the backrest was set using a SAE H-point manikin [12] by rotating a knob so that the backrest was 17° from the vertical and the seat pan was 10° from the horizontal.

For measurements with the block of foam, subjects sat on a seat with a rigid frame and flat rigid horizontal and vertical wooden surfaces on the seat and backrest. The rectangular block of polyurethane foam (540 mm × 355 mm × 100 mm) had flat surfaces and was attached to the vertical backrest using Velcro. The lower edge of the foam block was 30 mm above the horizontal surface of the flat rigid seat. There was no cushion beneath the subjects.

2.2.3. Accelerometers

Vibration was measured using six Entran EGCS-Y 24-10-D accelerometers. Five accelerometers were attached to circular wooden plates of 50 mm diameter and 2 mm thickness. Each combined accelerometer and wooden plate weighed 14 g and is referred to as a 'mini SIT-pad'. These 'mini SIT-pads' were mounted to the

Fig. 1. Car seat.

surfaces of the backrests at five heights above the seat surface using Velcro. The flat surfaces of the plates faced the back of the body with the accelerometer on the side adjacent to the seat surfaces. One Entran EGCS-Y 24-10-D accelerometer was attached to the vibrator platform beneath the seats to measure the fore-and-aft excitation.

The five locations of the 'mini SIT-pads' on the backrests were obtained by dividing the 50th percentile seat-to-shoulder height of the British male population aged 19–45 years (approximately 595 mm [13]) into five equal bands of 120 mm, with an accelerometer at the centre of each band. For the car seat, the location of the central 'mini SIT-pad' was assumed to be 340 mm above the seat cushion surface, after the addition of 40 mm to compensate for seat compression [13]. For the foam backrest, the central 'mini SIT-pad' was 300 mm above the flat seat surface. Table 2 shows the height of each of the accelerometers above the supporting seat surface for both backrest types. Location 1 was nearest to the seat surface and location 5 was nearest to the top of the backrest (i.e., shoulder area).

The arrangement of the experimental equipment is shown in Fig. 2.

2.2.4. *Signal generation*

A Gaussian random signal having a duration of 60 s and a nominally flat constant-bandwidth acceleration power spectrum over the frequency range 0.25–20 Hz was generated using an *HVLab* Data Acquisition and Analysis system (version 3.81). Subjects were exposed to five vibration magnitudes (0.1, 0.2, 0.4, 0.8, 1.6 ms^{-2} rms) in independent random orders. All acceleration signals were conditioned and acquired directly into the *HVLab* Data Acquisition and Analysis system at 512 samples per second via 170 Hz anti-aliasing filters.

Table 2
Locations of the accelerometers on the surfaces of the backrests and the corresponding height above the seat surface

Location	Vertical distance from the seat surface (mm)	
	On foam secured to the rigid seat	On car seat (after the addition of 40 mm compensation)
1	60	100
2	180	220
3	300	340
4	420	460
5	600	640

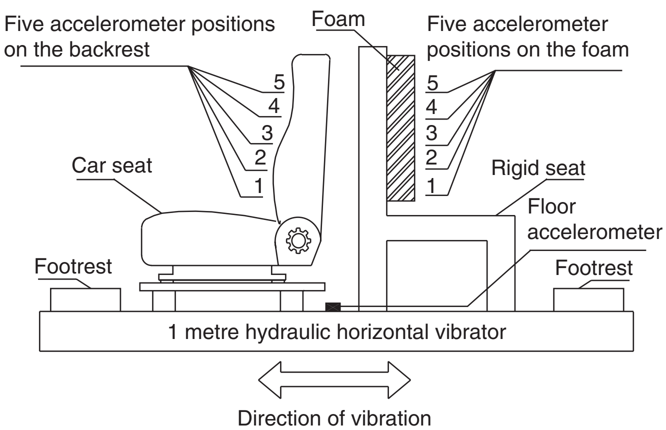

Fig. 2. Experimental set-up. Five accelerometers were attached to the surface of each backrest. The footrest was 300 mm forward from the front edge of each seat.

2.3. Analysis

The acquired acceleration data were normalised to remove any dc offsets before they were used to calculate the modulus, phase and coherency of the backrest transmissibility for each location. The transfer functions between the floor and all five accelerometers on the backrest surface were calculated using the cross-spectral density method.

The transfer function, $H(f)$, was determined as the ratio of cross-spectral density of the input and output acceleration, $G_{io}(f)$, to the power spectral density of the input acceleration, $G_{ii}(f)$:

$$H(f) = \frac{G_{io}(f)}{G_{ii}(f)}.$$

The coherencies between the acceleration at the platform and the accelerations on the backrest were also calculated:

$$\text{Coherency,} \quad \gamma_{io}^2(f) = \frac{\left|G_{io}(f)\right|^2}{G_{ii}(f)G_{oo}(f)},$$

where $G_{oo}(f)$ is the power spectral density of the output acceleration. A resolution of 0.25 Hz was used for the calculation, which gave 60 degrees-of-freedom.

3. Results

Individual results show high inter-subject variability in the fore-and-aft backrest transmissibilities at each height above the seat surface with both the car seat and the foam backrest (Fig. 3). The car seat showed resonances between 2.4 and 7.2 Hz, while the foam backrest showed resonances between 1.4 and 7.1 Hz. High coherencies (more than 0.9) were obtained at each height for all subjects and at all vibration magnitudes with both backrests.

Inspection of individual data showed that with the car seat, four subjects exhibited only one resonance frequency (in the range 2.5–5.7 Hz) at each height for all vibration magnitudes. Two resonances were visible for eight subjects (in the range 2.4–7.2 Hz): two resonances did not occur at all measurement locations—they were most visible at the middle part of the backrest. The lowest of the two resonance frequencies was in the frequency range 2.4–5.3 Hz, while the second resonance was evident in the range 3.3–7.2 Hz. For six subjects, the transmissibility at the first resonance was greater than the second resonance, while two subjects had greater transmissibilities at the second resonance.

With the foam backrest, a single resonance (in the frequency range 1.5–6.1 Hz) was clearly visible for eight subjects at all vibration magnitudes. Four subjects showed two resonances in the range 1.4–7.1 Hz, but again not at all locations and most visible at the middle part of the backrest. For these four subjects, the first and the second resonance frequencies were in the range 1.4–3.9 and 3.9–7.1 Hz, respectively. For two subjects the transmissibility at the first resonance was greater than at the second resonance, while the other two subjects gave the opposite response.

In general, the fore-and-aft vibration at the back–backrest interface was amplified relative to the vibrator platform at frequencies less than 7 Hz for both the car seat and the foam backrest. At frequencies greater than 7 Hz, the transmissibilities were progressively attenuated up to around 10 Hz, and remained less than 1.0 at frequencies between 10 and 20 Hz.

Prior to calculating the median results, an artefact in an individual result with the foam backrest (in subject 6) was removed. The 'mini SIT-pad' was 'detached' from its location by the belt of the subject. Five transmissibilities at all locations (at 0.1 $\mathrm{ms^{-2}}$ rms with foam backrest) were excluded from the median calculations (the artefact data are not shown in the figures or tables).

The median fore-and-aft backrest transmissibilities showed resonances in the range 4–5 Hz for the car seat, and in the range 3–6 Hz for the foam backrest (Fig. 4). With neither backrest was a second resonance evident in the median data as its influence was 'smeared' across the frequency range.

With all 12 subjects and both backrests, the fore-and-aft transmissibilities from the floor to the backrest show differences between measurement locations (Figs. 5 and 6). For both the car seat and the foam backrest,

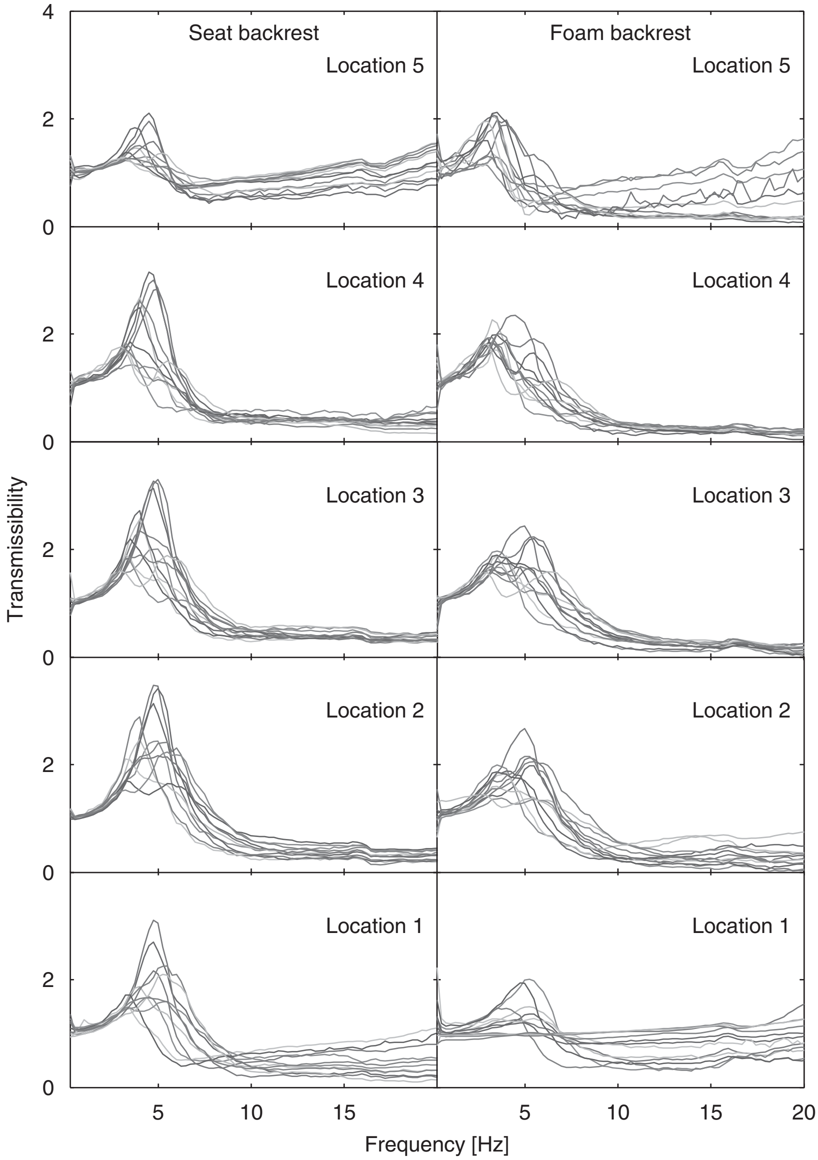

Fig. 3. Inter-subject variability in the fore-and-aft transmissibilities of a car backrest and foam backrest with 12 subjects at a vibration magnitude of 0.4 ms^{-2} rms. The figure shows transmissibilities at five locations (see Fig. 2).

the transmissibilities differed significantly over the five measurement locations at the centre frequency of each preferred $\frac{1}{3}$-octave from 2 to 10 Hz at all vibration magnitudes ($p<0.05$; Friedman).

A Wilcoxon matched-pairs signed ranks test was performed on the transmissibilities between measurement locations with both backrests. A total of 40 pairs were tested at each preferred $\frac{1}{3}$-octave centre frequency from 2 to 10 Hz and at all magnitudes (Table 3). With the car seat, the total number of significant differences (i.e., $p<0.05$, Wilcoxon) between locations 1 and 4, between locations 2 and 3, between locations 2 and 4, and between locations 3 and 4 was less than 50% of the possible differences. For other paired-locations, at least 65% of the transmissibilities differed significantly, with the transmissibilities between locations 2 and 5 having the greatest number of significant differences (90%). With the foam backrest, the number of significant differences in transmissibilities between locations 2 and 3, and between locations 2 and 5, was less than 50% of the possible differences. Between locations 3 and 5, and between locations 4 and 5, the number of statistically

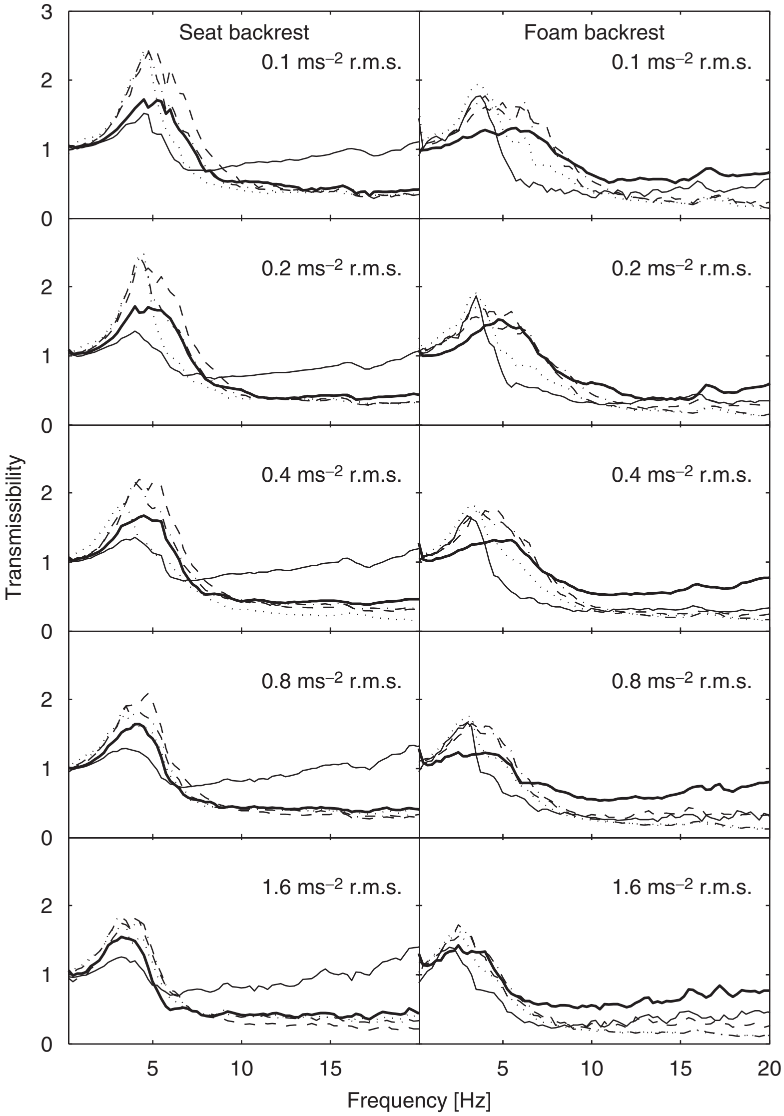

Fig. 4. Median fore-and-aft backrest transmissibilities with 12 subjects for both the car backrest and the foam backrest at five magnitudes. Location 1 (▬▬▬); Location 2 (- - - -); Location 3 (▬·▬·▬·▬); Location 4 (··········); Location 5 (———).

significant differences was 50–55%. For other paired-locations, at least 65% of the transmissibilities differed significantly, with the transmissibilities between locations 3 and 4 having the greatest number of significant differences (83%).

For both the car seat and the foam backrest, variations in the vertical position of the measurement location had little effect of the resonance frequencies shown in the median data, although the transmissibilities at resonance varied with measurement location.

With both the car seat and the foam backrest, the median transmissibilities were greater at the middle part (i.e., locations 2–4) than at the top (location 5) or bottom (location 1) of the backrest. The least transmissibility was measured at the top of the car seat (location 5), but at the bottom of the foam backrest (location 1). For six subjects, the transmissibilities of the foam backrest at location 1 sometimes showed 'unity transmissibility' with no evidence of a resonance (Fig. 6). This may have arisen from these subjects having little or no contact between the back and the backrest at this location.

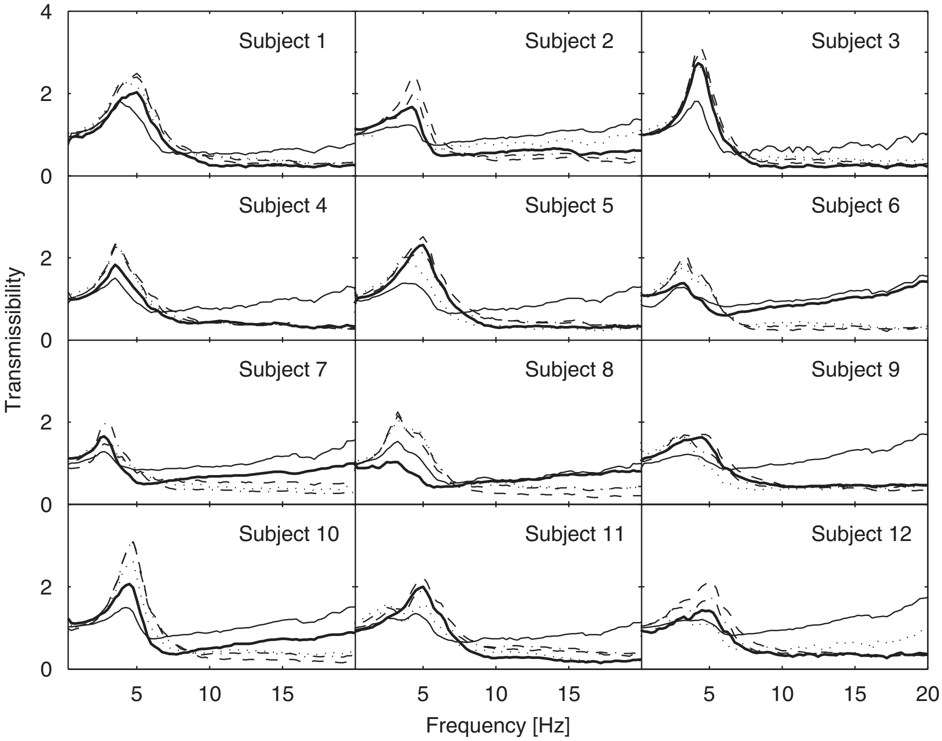

Fig. 5. Variation in car seat backrest transmissibility with location for 12 subjects at a vibration magnitude of 0.4 ms^{-2} rms. Key: Location 1 (▬▬▬); Location 2 (- - - -); Location 3 (▬·▬·▬·); Location 4 (··········); Location 5 (———).

There were no statistically significant correlations between subject characteristics (seat-to-shoulder measurements, stature, mass) and either the principal resonance frequencies or transmissibilities at resonance at any measurement location on either backrest ($p > 0.05$, Spearman).

The effect of the vibration magnitude on the individual and median backrest transmissibilities at different measurement locations is shown in Figs. 7–9. With the car seat, the transmissibilities at each measurement location from 2 to 10 Hz (at $\frac{1}{3}$-octave frequencies) showed significant changes with vibration magnitude ($p < 0.05$; Friedman), except at location 5 (at 2 Hz), at locations 3–5 (at 3.15 Hz), at locations 1–3 (at 4 Hz) and at locations 1, 3 and 4 (at 10 Hz). Significant differences were also found at each measurement location with the foam backrest ($p < 0.05$), except at location 1 (at 2 and 2.5 Hz), at locations 1–3 (at 3.15 and 4 Hz) and at locations 1–2 (at 10 Hz).

4. Discussion

Prior to commencing the study, the performance of the 'mini SIT-pad' was compared with a 'SIT-pad' conforming to ISO 10326-1 [14] with a built-in Entran EGCS-DO-10/V05/L5M accelerometer. The 'mini SIT-pad' was designed to be broadly similar to the mount described in ISO 10326-1, but sufficiently small to allow several 'mini SIT-pads' to be placed at different locations on the backrest and measure transmissibilities to different locations at the same time. The comparison involved measuring the fore-and-aft transmissibility of a foam block used as a backrest (similar to that in this experiment) at the same location in separate measurements. The location of both accelerometer mounts was the same. One subject was used and exposed to two vibration magnitudes (0.2 and 0.8 ms^{-2} rms). The results showed minimal differences in the backrest transmissibility measured using the two mounts with the relative percentage difference between the measurements less than 8% over the frequency range 0.25–20 Hz (Fig. 10). It was concluded that the transmissibilities measured using the 'mini SIT-pads' as in this experiment were similar to those that would have been measured using a full-sized 'SIT-pad' according to ISO 10326-1 [14].

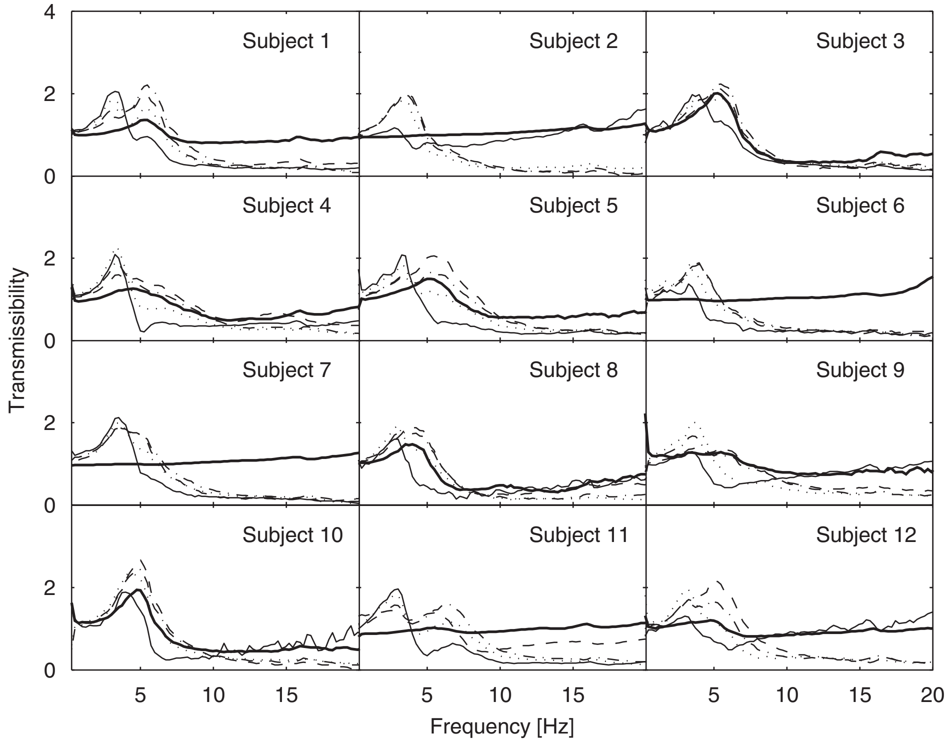

Fig. 6. Variation in foam backrest transmissibility with location for 12 subjects at a vibration magnitude of 0.4 ms^{-2} rms. Key: Location 1 (▬▬▬); Location 2 (- - - -); Location 3 (▬·▬·▬·▬); Location 4 (··········); Location 5 (———).

Table 3
Percentages of statistically significant differences (i.e. $p<0.05$, Wilcoxon) between the transmissibilities at pairs of locations for all vibration magnitudes at $\frac{1}{3}$-octave centre frequencies between 2 and 10 Hz

Paired-location	Number of statistically significant differences
(a) *Car seat*	
L1–L2	30/40
L1–L3	26/40
L1–L4	19/40
L1–L5	27/40
L2–L3	17/40
L2–L4	18/40
L2–L5	35/40
L3–L4	15/40
L3–L5	36/40
L4–L5	33/40
(b) *Foam backrest*	
L1–L2	30/40
L1–L3	30/40
L1–L4	30/40
L1–L5	32/40
L2–L3	8/40
L2–L4	26/40
L2–L5	15/40
L3–L4	33/40
L3–L5	20/40
L4–L5	22/40

The right-hand column presents the number of pairs showing a statistically significant difference, with a total of 40 pairs for each paired-locations and at all magnitudes.

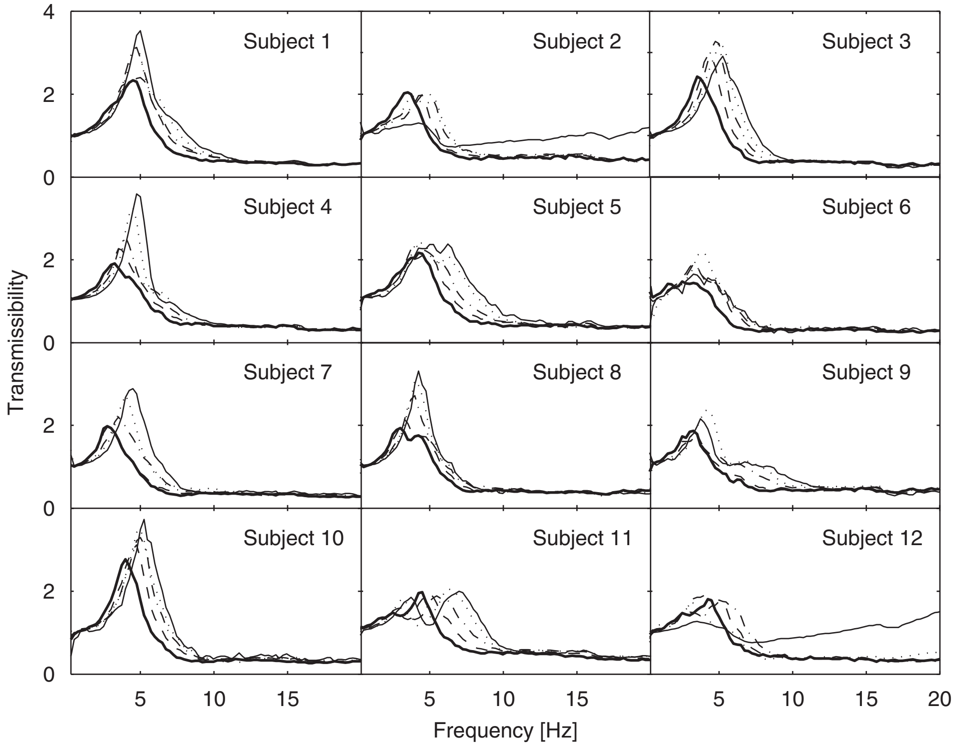

Fig. 7. Fore-and-aft backrest transmissibility for 12 subjects with the car seat at location 3 at 0.1 ms^{-2} rms (▬▬▬), 0.2 ms^{-2} rms (- - - -), 0.4 ms^{-2} rms (▬·▬·▬·▬), 0.8 ms^{-2} rms (··········) and 1.6 ms^{-2} rms (———).

In a car, the origin of the fore-and-aft vibration on the backrest may be complex: fore-and-aft, pitch and vertical vibration on the floor can all contribute to backrest vibration [5]. In the present laboratory study, the input vibration at the base of the seat was constrained to the fore-and-aft direction, even though this is often not the case in vehicles. If vertical and pitch vibration of a vehicle floor cause fore-and-aft vibration of a backrest, the variation in vibration with measurement position on the backrest may differ from that found here.

The median resonance frequencies of the backrest transmissibilities of the car seat found in this study (4–5 Hz) are similar with the results reported by Qiu and Griffin [5] who investigated the fore-and-aft transmissibility of the backrest of a car seat with both field and laboratory measurements.

Although the general trends in the transmissibilities for both backrests were similar, the foam backrest showed slightly broader resonances in the frequency range 3–6 Hz with lower transmissibilities at resonance than for the seat backrest. The difference is unlikely to be entirely due to different seat adjustment—the seat-pan and foam backrest were horizontal and vertical, respectively, compared with a 10° inclination of the seat-pan and a 17° inclination of the backrest angle of the car seat. A difference between the dynamic stiffnesses of the backrests are likely to have affected the transmissibilities [15–17].

The individual results showed that some subjects (four subjects with the car seat and eight subjects with the foam backrest) exhibited one principal resonance. However, other subjects (eight subjects with the car seat and four subjects with the foam backrest) showed a second resonance. The resonances can be associated with modes of the body during fore-and-aft excitation. Kitazaki and Griffin [18] found that when seated persons were exposed to vertical vibration, the resonance frequency at 4.9 Hz consisted of an entire body mode, including a bending of the upper thoracic spine and the cervical spine. They also observed modes at 5.6 and 8.1 Hz, consisting of bending and pitching modes. Matsumoto and Griffin [19] found that the pitch transmissibilities of the first thoracic vertebra (T1) and the head had clear peaks between 5 and 7 Hz when subjects were exposed to vertical excitation. It seems possible that the resonances found in this study are

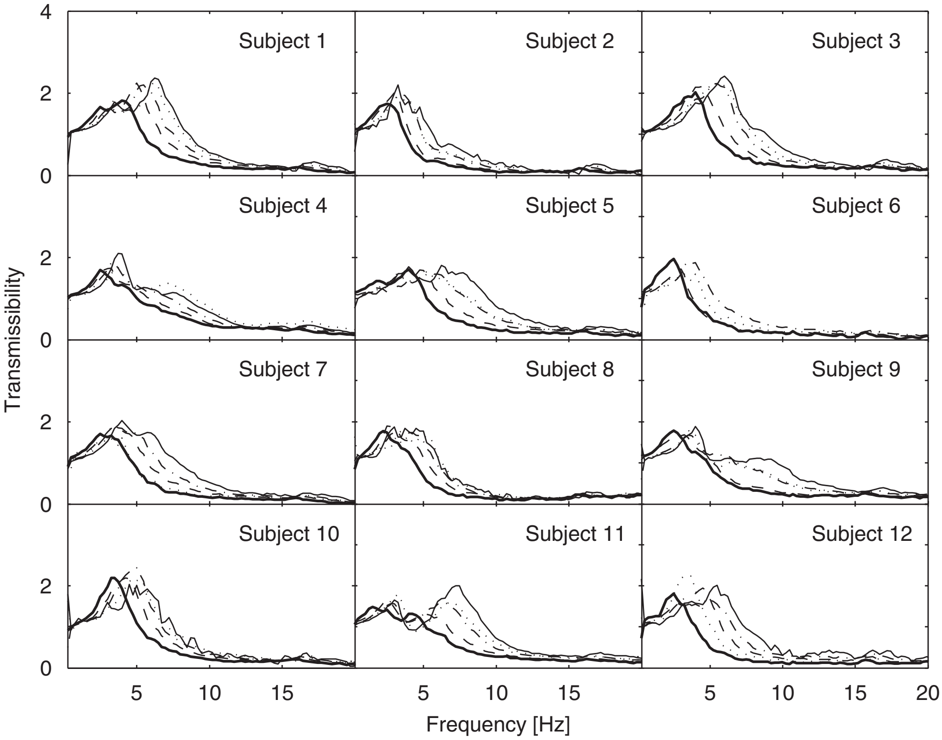

Fig. 8. Fore-and-aft backrest transmissibility for 12 subjects with the foam backrest at location 3 at 0.1 ms^{-2} rms (▬▬▬), 0.2 ms^{-2} rms (- - - -), 0.4 ms^{-2} rms (▬·▬·▬·), 0.8 ms^{-2} rms (·········) and 1.6 ms^{-2} rms (———).

related to the modes found by Kitazaki and Griffin [18] and Matsumoto and Griffin [19]. Measurement of the apparent mass of the back at various vertical positions are required to further understand the responses of the back in the fore-and-aft direction.

The unity transmissibility at location 1 for six subjects with the foam backrest is thought to have arisen because in these subjects at this location there was little or no contact between the back and the backrest. All six subjects had a stature greater than 1.73 m, which may have influenced their sitting posture so that the lower back made less contact with the flat surface of the foam block at this location. However, there were some subjects with a stature greater than 1.73 m who showed good results and clear resonances (Fig. 6; subjects 3 and 4). For a relatively short subject, the transmissibility at location 1 also showed a clear resonance (Fig. 6; subject 10). The statistical analysis showed no correlation between the resonance frequency and the stature of the subjects. The unity transmissibility at location 1 in this study may therefore be attributed to some unknown individual response. The unity transmissibility was not observed with the car backrest with the same six subjects. The lumbar support in the car seat encouraged greater contact between the lower back and the backrest than occurred with the flat foam block.

Models for predicting the vertical transmissibility of a seat have assumed one connecting-point representing the interface between the seat cushion and the seated human body (e.g., Refs. [2,4]). It may be reasonable to make this assumption when predicting vertical seat transmissibility because the principal load-bearing interface between the buttocks and a seat cushion is usually concentrated around the ischial tuberosities. The results of this study suggest that a backrest-back model may require more than one connecting point between the back and the backrest. The points might represent interfaces at the lower part of the backrest (e.g., location 1), the middle part of the backrest (locations 2–4) and the upper part of the backrest (e.g., location 5). The development of a model for predicting the transmissibility of a backrest may require information on both the seat dynamic stiffness and the body impedance at each of these locations, or over an area encompassing these locations.

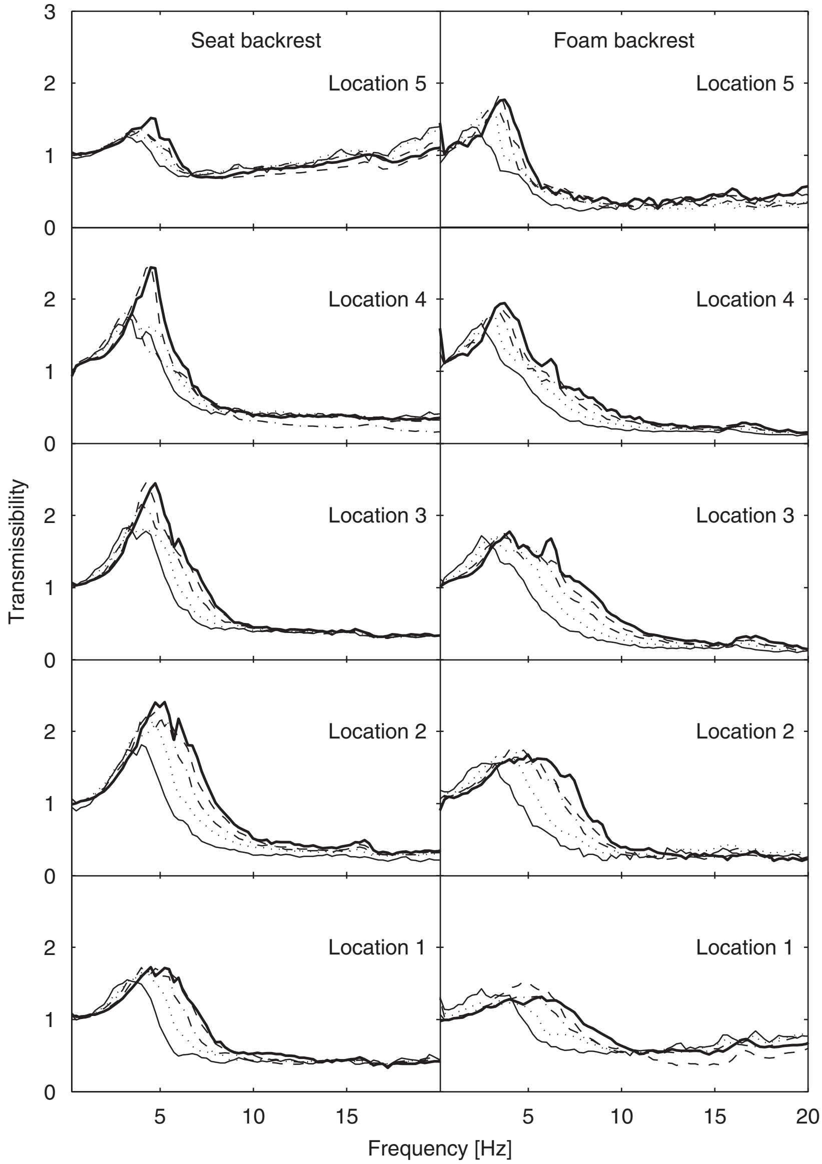

Fig. 9. Median fore-and-aft backrest transmissibilities with 12 subjects for both the car seat and the foam backrests at each of five locations at 0.1 ms^{-2} rms (▬▬▬), 0.2 ms^{-2} rms (- - - -), 0.4 ms^{-2} rms (▬·▬·▬·), 0.8 ms^{-2} rms (··········) and 1.6 ms^{-2} rms (———).

The non-linearity seen here in the backrest transmissibility will have been due, at least in part, to the non-linear response of the body during fore-and-aft excitation [10]. Further understanding of the variations in apparent mass of the back with measurement location, body posture and vibration magnitude will be required to develop dynamic models of the body needed to predict backrest transmissibility. An understanding of variations in the dynamic stiffnesses of backrests with location and vibration magnitude will also be required.

5. Conclusions

Laboratory measurements of the fore-and-aft transmissibilities of a car seat backrest and a foam backrest showed median resonance frequencies in the range 4–5 and 3–6 Hz, respectively.

There were large variations in the transmissibilities of both backrests at different vertical positions, although the resonance frequencies showed only small changes with position. With both seats, the median backrest

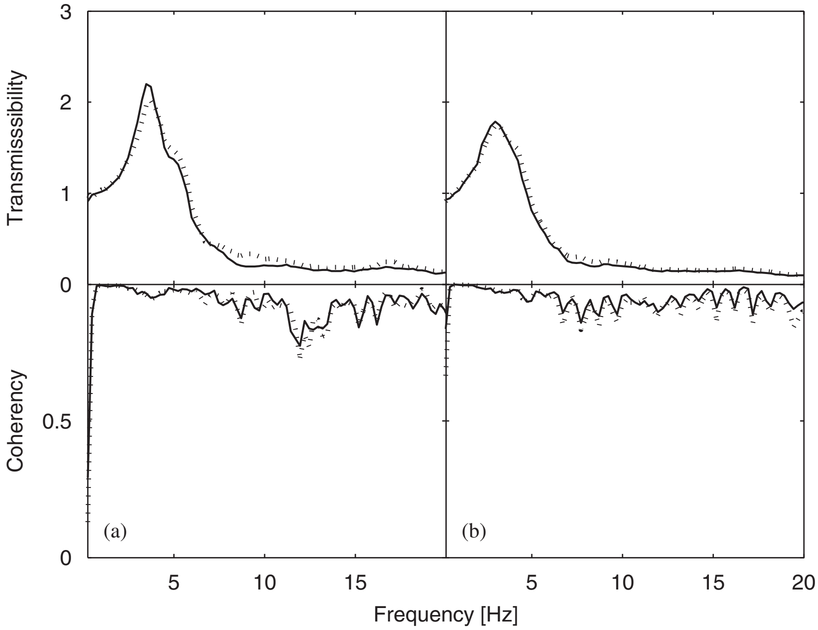

Fig. 10. Comparison of foam backrest transmissibility measured with the 'mini SIT-pad' used in this study (··········) and a 'SIT-pad', according to ISO 10326-1 [15] (———). Key: (a) at 0.2 ms^{-2} rms; and (b) at 0.8 ms^{-2} rms.

transmissibilities at resonance were greater at the middle than at the top or bottom of the backrest. The transmissibility was least at the top of the car backrest but least at the bottom of the foam backrest.

The backrest transmissibilities were non-linear at all measurement locations: the resonance frequencies and transmissibilities at resonance decreased with increasing vibration magnitude.

The variations in the fore-and-aft backrest transmissibility with vertical position on the backrests were sufficiently great to affect assessments of backrest dynamic performance. Dynamic models of the backrest–back system may therefore require more than one connecting point between the back and the backrest and should take into account the non-linearity in the transmissibility.

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