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# Fore-and-aft transmissibility of backrests: Effect of backrest inclination, seat-pan inclination, and measurement location

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## Abstract

Car seats have inclined backrests and inclined seat-pans, but there has been little study of how the inclinations of the surfaces of a seat influence the transmission of fore-and-aft vibration through the backrest. The effects of backrest inclination and seat-pan inclination on the fore-and-aft transmissibilities of two seats (a car seat and a rigid seat with solid foam backrest) have been investigated in the laboratory. With 12 subjects, each seat was exposed to random fore-and-aft vibration in the frequency range 0.25–20 Hz with a vibration magnitude of 0.4 $\mathrm{ms}^{-2}$ rms. At six vertical locations on each backrest, the fore-and-aft transmissibilities of the backrests were measured with four backrest inclinations (90° (i.e. vertical), 105°, 100°, and 105°) and up to four seat-pan inclinations (0° (i.e. horizontal), 5°, 10°, and 15°). At all six measurement locations, there was a resonance of both backrests at about 4 Hz, which increased in frequency with increasing backrest inclination for the car seat but showed little change with inclination for the foam backrest. The inclination of the backrest had more influence at the bottom that at the top of the backrest of the car seat, but showed little variation with position on the foam backrest. Variations in seat-pan inclination had little influence on the resonance frequencies of either backrest at any location. Inclining the backrest and the seat-pan increased the transmissibility at resonance with the car seat, but produced little change with the foam backrest. It is concluded that both the backrest inclination and the seat inclination can affect the fore-and-aft transmissibility of backrests but, with moderate changes of inclination, the effects are not large.

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## 1. Introduction

Exposures to whole-body vibration in a car involve a variety of sitting postures that partly depend on the seat design. Car seats have inclined seat-pans and inclined backrests. For example, in a study of the transmission of vibration to the backrest of a small car by Qiu and Griffin [1] the backrest was reclined at 15° to the vertical and the seat-pan was inclined at 12° to the horizontal, as measured with an SAE-manikin [2]. The seat-pan and backrest inclinations vary between cars and can often be adjusted by the driver.

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Laboratory studies of the vertical transmissibilities of seats have used both car seats (e.g. [3]) and rigid seats supporting foam cushions (e.g. [4]). In some studies, the angle between the seat and the backrest has been 90°, giving an upright posture. Rakheja et al. [5] suggested that the sitting postures adopted in automotive seats differed considerably from those used in laboratory studies. Both an inclined cushion and an inclined backrest were thought to contribute to the differences in the dynamic responses of subjects compared to a 90° seat-backrest angle. The authors reported that the apparent masses of subjects sitting in an automotive sitting posture showed higher fundamental resonance frequencies (i.e. 6.5–8.6 Hz) than those previously reported for subjects with either an upright sitting posture without a backrest or sitting on a seat with a 90° seat-backrest angle (i.e. 4.5–5 Hz).

Backrest inclination has been reported to have little effect on the vertical transmissibility of a seat [6]. In that study, with one subject, when the backrest was inclined from 90° to 115°, there was minimal change in the resonance frequency, but the transmissibility at resonance decreased when the backrest was inclined. Toward [7] also noticed a decrease in the vertical transmissibility at resonance of a seat when the backrest inclination increased from 90° to 110°. Houghton [8] found that the vertical transmissibility at resonance increased as the backrest inclination increased from 90° to 120°. In that study, subjects were exposed to vertical vibration and the transmissibilities of the seat and the backrest were measured in both the vertical and the fore-and-aft directions. The 'cross-axis' fore-and-aft backrest transmissibility (i.e. the fore-and-aft vibration of the backrest caused by the vertical excitation) showed a resonance around 4 Hz with the frequency increasing with increasing backrest inclination.

When subjects in a rigid seat with a foam cushion were exposed to random vertical vibration, there was a tendency towards increased vertical seat transmissibility at frequencies below the resonance frequency when seat-pan inclination increased from 0° to 20° [9]. However, the authors found that seat-pan inclination had little effect on the resonance frequency of vertical seat transmissibility and that the vertical transmissibility at resonance decreased with increasing seat-pan inclination.

A recent study has found that the fore-and-aft vibration transmitted from the floor to a backrest varied with height above the seat surface [10]. In that study, 12 subjects were exposed to fore-and-aft vibration in both a car seat and a rigid seat with a solid foam backrest: the fore-and-aft transmissibilities of the backrest measured at five locations showed median resonance frequencies around 4–5 Hz for the car seat and in the range of 3–6 Hz for the foam backrest. Although the transmissibilities varied with height on both backrests, the resonance frequencies showed minimal changes with height for both backrests. There is little knowledge of factors that influence the fore-and-aft transmissibilities of seat backrests. Recent studies have found that backrest transmissibility is nonlinear with vibration magnitude (e.g. Refs. [1,10]) and that the transmissibility of a foam backrest is affected by foam thickness, although in a complex manner [11]. There is no known study of the effect of the backrest inclination or seat-pan inclination on backrest transmissibility in the fore-and-aft direction.

Variations in the inclination of either the seat-pan or the backrest will change the lumbar curve, partly by rotation of the pelvis [12]. Rotation of the pelvis will alter sitting posture and the biodynamic responses of the body. If the variations in inclination result in large changes in the fore-and-aft impedance of the back, the transmissibility of the backrest is likely to change, since the backrest transmissibility is determined by the dynamic interaction between the back and the backrest.

The objective of this study was to investigate the effects of backrest inclination and seat-pan inclination on the fore-and-aft transmissibility of the backrest of a car seat and of a backrest consisting of a rectangular block of solid foam supported on a rigid flat vertical plate. It was hypothesized that changing the backrest inclination and changing the seat-pan inclination would change backrest transmissibility.

## 2. Method

### 2.1. Subjects

Twelve male subjects, with ages, weights, statures and seat-to-shoulder heights as shown in Table 1, participated in the study. The experiment was approved by the Human Experimentation, Safety and Ethics

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

| | Age (years) | Stature (m) | Weight (kg) | Seat-to-shoulder height (m) |
|---|---|---|---|---|
| Minimum | 20 | 1.64 | 50 | 0.58 |
| Maximum | 29 | 1.78 | 85 | 0.64 |
| Median | 23.8 | 1.72 | 67.7 | 0.62 |

Committee of the Institute of Sound and Vibration Research (ISVR), University of Southampton. Before vibration exposure, each subject completed a health questionnaire and an exposure consent form.

## 2.2. Apparatus

### 2.2.1. Vibration generation

The experiment was performed in the Human Factors Research Unit at ISVR, University of Southampton, using an electro-hydraulic vibrator capable of producing a 1-m peak-to-peak horizontal displacements. The motion of the vibrator was measured using an Entran EGCSY-240D*-10 accelerometer mounted on the moving platform.

### 2.2.2. Seating and transducers

Most of the apparatus (seat, accelerometers, etc.) used in this experiment was the same as that used previously [10]. The two seats were: (i) a car seat (from a popular current family car) and (ii) a rigid wooden seat with flat surfaces and adjustable backrest and seat-pan inclinations, with the backrest supporting of a block of polyurethane foam (540 mm × 355 mm by 100 mm).

The car seat had contoured surfaces on the cushion and backrest and weighed 19.3 kg. The inclination of the backrest could be changed through a built-in mechanism controlled by a rotating knob, located at the left side of the seat. The seat cushion inclination could be adjusted through a built-in gear mechanism via a rotating lever located beneath the seat pan.

A magnetic protractor, capable of measuring angle to the vertical and horizontal was used to measure the backrest and seat-pan angles. The protractor was attached at the left side of the backrest using double-sided adhesive tape when measuring the backrest inclination. For measuring the seat-pan inclination, the protractor was placed on the uncompressed surface of the seat cushion. For measurements with the block of foam, the angles of the wooden backrest and seat-pan were adjusted and then secured using bolts and clamps.

The fore-and-aft acceleration at the back-backrest interface was measured using six Entran EGA-125F*-10-D accelerometers attached to circular wooden plates (50 mm in diameter), similar to that used in a previous study [10]. The total weight of each accelerometer with the wooden block was approximately 5 g, and is referred to as a ‘mini SIT-pad’. The flat surface of the plate faced the backrest with the accelerometer on the side adjacent to the body.

The ‘mini SIT-pads’ were positioned at six locations on the backrest, corresponding to the locations of specific vertebrae for a 50th percentile male [13]. Table 2 lists the locations of the ‘mini SIT-pads’, measured vertically from the seat surface, and the corresponding vertebrae. The ‘mini SIT-pads’ were always normal to the surface of the backrest, and so the orientation of the accelerometer varied with backrest inclination.

The experimental set-up is shown in Fig. 1.

### 2.2.3. Subject posture and experimental conditions

Subjects adopted a ‘normal’ upright posture throughout the experiment. The posture was defined as: *‘upper body leaning on the backrest with hands placed on the lap and feet resting on the wooden footrest’*. The upper and lower legs of subjects were perpendicular to each other throughout the experiment.

Two conditions were studied: the first investigating the effect of backrest inclination and the second investigating the effect of seat-pan inclination (Table 3). In both conditions, the backrest transmissibilities were measured in an independent random order of backrest and seat-pan inclination.

Table 2
Height of the 'mini SIT-pads' on the backrests and their approximate locations relative to spinal vertebrae (from Singley and Haley [13])

| Location | Vertical distance, measured to the centre of the mini SIT-pad from the seat surface (mm) | Corresponding spinal position or vertebrae |
|---|---|---|
| 1 | 200 | Pelvis |
| 2 | 300 | Lumbar 1 |
| 3 | 350 | Thoracic 12 |
| 4 | 400 | Thoracic 11 |
| 5 | 450 | Thoracic 9 |
| 6 | 500 | Thoracic 7 |

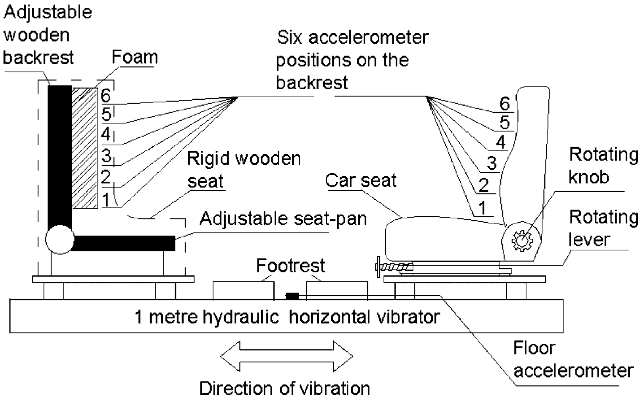

Fig. 1. Experimental set-up.

Table 3
Experimental conditions

| | Car seat | Foam backrest |
|---|---|---|
| Condition (i): effect of backrest inclination | 90°, 95°, 100°, and 105° with 10° of seat-pan inclination | 90°, 95°, 100°, and 105° with 0° of seat-pan inclination |
| Condition (ii): effect of seat-pan inclination | 10° and 15° with 95° of backrest inclination | 0°, 5°, 10°, and 15° with 90° of backrest inclination |

Note: All inclinations measured from the horizontal.

The footrest height was adjusted at each seat inclination to maintain the same leg posture: upper and lower legs perpendicular to each other at all seat-pan inclinations.

### 2.2.4. *Signal generation*

All 12 subjects were exposed to $0.4\,\mathrm{ms}^{-2}$ rms of Gaussian random vibration having a duration of 60 s with a nominally flat constant bandwidth acceleration spectrum over the frequency range 0.25–20 Hz. The vibration stimuli were generated using a *HVLab* version 3.81 Data Acquisition and Analysis system. All acceleration signals were conditioned and acquired directly into the *HVLab* Data Acquisition system at 512 samples per second via 170 Hz anti-aliasing filters.

## 2.3. *Analysis*

The transfer functions between the floor and the backrest surface at each backrest angle and each seat angle were calculated using the 'cross-spectral density function method'. Before the calculation of the backrest transmissibility, the coherency and the phase, all acquired signals were normalized to remove any dc offset from the time histories using the *HVLab* data acquisition system.

The transfer function, $H(f)$, was determined as the ratio of the 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 coherency between the acceleration at the platform and the acceleration on the backrest was also calculated:

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

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

### 3.1. Effect of the backrest angle

Individual results suggested that the resonance frequencies of the fore-and-aft transmissibility of the car seat backrest at all locations tended to increase with increasing backrest inclination from 90° to 105°, but only showed minimal changes with the foam backrest (figures are not shown here). There was also an increase in the transmissibilities at frequencies between 4 and 8 Hz with increasing backrest inclination, more obvious with the car seat backrest. The transmissibilities at resonance with the car seat backrest increased with increasing backrest inclination, but only showed little change with the foam backrest (figures are not shown here).

Fig. 2 shows the median fore-and-aft backrest transmissibilities over the 12 subjects with both the car seat and the foam backrest at all six locations with varying backrest inclination. There was a resonance around 4 Hz for both backrests at all six locations. The median resonance frequencies increased as the backrest inclination increased from 90° to 105° with the car seat, more obviously at the bottom of the backrest (location 1) than at the top of the backrest (location 5). The increase in the resonance frequency of the car seat with increasing backrest inclination was statistically significant at locations 1–2 ($p<0.05$, Friedman). However, varying the inclination of the foam backrest had no significant effect on the median resonance frequency at any measurement location ($p>0.05$; Fig. 2).

For the car seat backrest, the median transmissibilities at resonance increased with increasing backrest inclination from 90° to 105°, with the influence most obvious at location 1. Statistical analysis with the data from the car seat showed significant increases in the transmissibility at resonance at all locations ($p<0.05$, Friedman), except at location 6 ($p>0.05$). With the foam backrest, increasing the backrest inclination resulted in a significant reduction in the transmissibility at resonance at the top of the backrest (i.e. locations 5 and 6, $p<0.05$), but no significant change at other locations on the backrest ($p>0.05$).

### 3.2. Effect of seat-pan inclination

Individual results suggest that increasing the inclination of the seat pan from 10° to 15° in the car seat and from 0° to 15° in the foam seat tended to decrease the resonance frequency in the fore-and-aft transmissibility of both backrests (figures are not shown). The transmissibility at resonance increased with increasing seat inclination from 10° to 15° in the car seat but there were only small changes with the foam backrest when the seat inclination increased from 0° to 15° (figures not shown).

The median results appear to show a consistent trend with increasing seat-pan inclination: the resonance frequency tended to decrease with a more inclined seat pan with both backrests (Fig. 3). However, the influence of the seat-pan inclination on the fore-and-aft transmissibility was not statistically significant with either backrest ($p>0.05$, Friedman). With increases in seat-pan inclination from 10° to 15°, the median

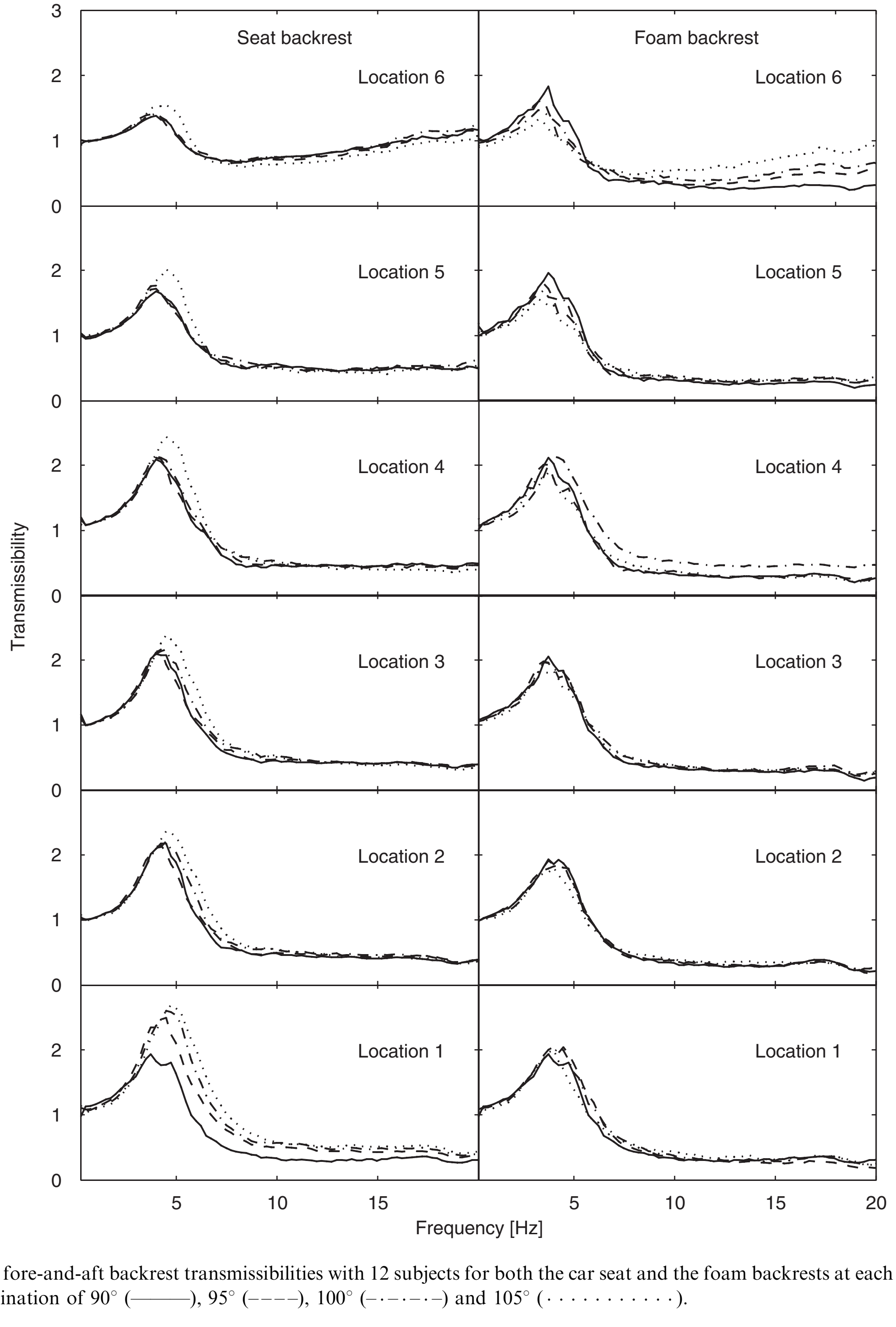

Fig. 2. Median fore-and-aft backrest transmissibilities with 12 subjects for both the car seat and the foam backrests at each of six locations at backrest inclination of 90° (———), 95° (– – –), 100° (–·–·–) and 105° (· · · · · · · · · · ·).

fore-and-aft transmissibilities of the car seat backrest tended to increase at frequencies close to, and below, the resonance frequency, but decrease at frequencies greater than the resonance frequency. With variations in seat-pan inclination between 0° and 15°, the median transmissibilities of the foam backrest showed little change at any frequency between 0.25 and 20 Hz.

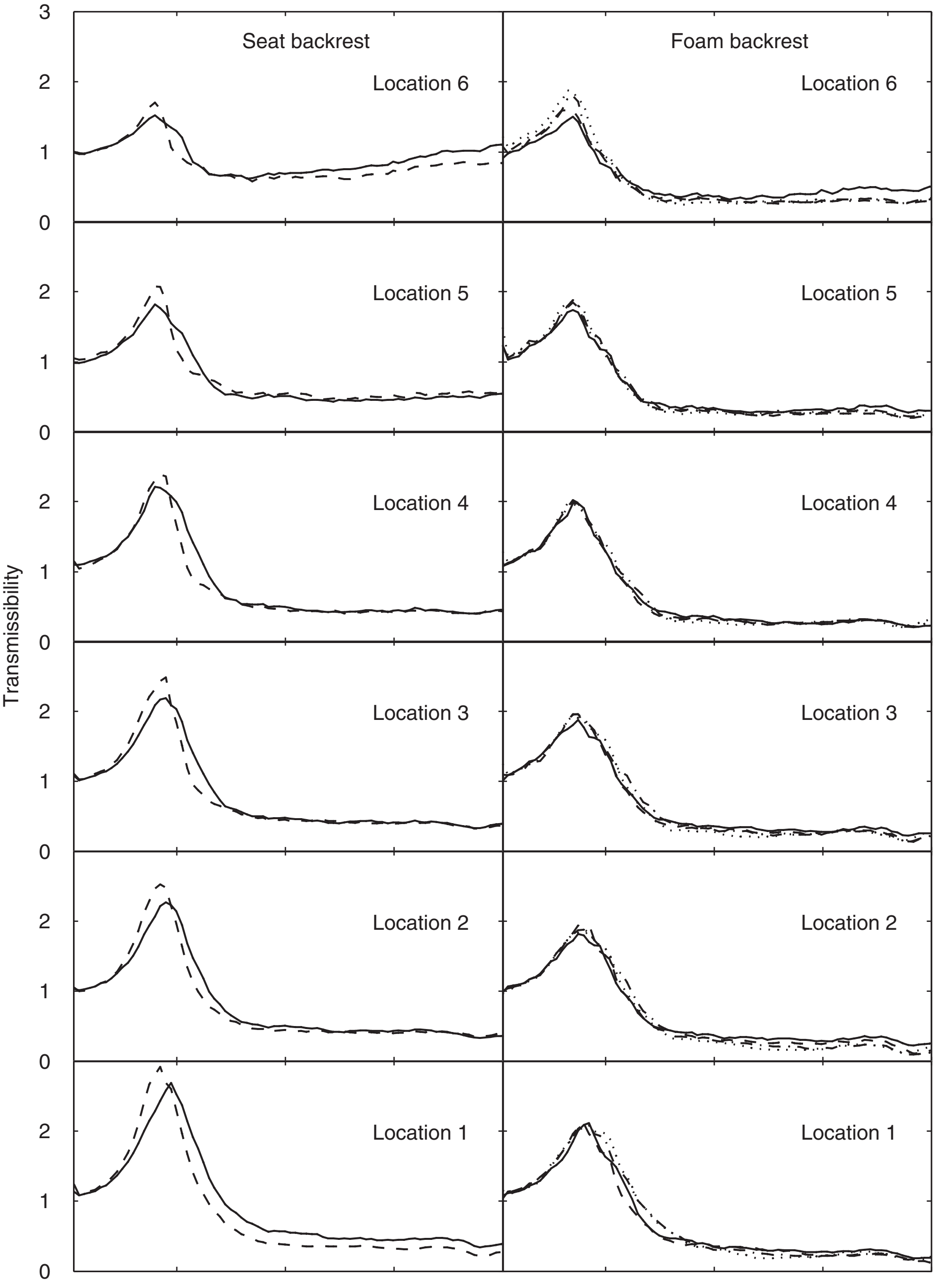

Fig. 3. Median fore-and-aft backrest transmissibilities with twelve subjects at each of six locations for both backrests at different seat-pan angle. Car seat-pan angle: 10° (———) and 15° (– – – –). Foam backrest seat-pan angle: 0° (———), 95° (– – – –), 100° (– · – · – · –) and 105° (· · · · · · · · · · · ·).

At all measurement locations, there was a significant increase in the median transmissibility at resonance when the inclination of the seat pan of the car seat increased from 10° to 15° ($p<0.05$, Wilcoxon). However, increasing the seat-pan inclination from 0° to 15° had no significant influence on the median transmissibilities at resonance of the foam backrest at any location ($p>0.05$, Friedman), except at location 6 ($p<0.05$).

## 4. Discussion

In this experimental study, consideration has been restricted to fore-and-aft excitation of the seats and the fore-and-aft vibration in the seats (i.e. at the back-backrest interface). In vehicles, the vibration entering the seat and the vibration in the seat is more complex. In a car, the fore-and-aft vibration on the backrest can arise from fore-and-aft, pitch and vertical vibration on the floor [1,14]. The effects of these vibration inputs on backrest vibration may differ from the effects of pure fore-and-aft excitation found in this study.

### *4.1. Effect of backrest inclination*

The resonance frequencies and transmissibilities at resonance of the car seat increased with increasing backrest inclination. This is consistent with the results of Houghton [8] who exposed subjects to vertical vibration and measured vertical backrest transmissibility and 'cross-axis' fore-and-aft backrest transmissibility with various backrest angles using a similar car seat. The seat was exposed to vertical vibration and the 'cross-axis' fore-and-aft backrest transmissibility was calculated by computing the transfer function between the vertical acceleration at the vibrator platform and the fore-and-aft acceleration measured on the backrest. The 'cross-axis' fore-and-aft transmissibility of the backrest showed a resonance frequency at 4–5 Hz, and a transmissibility at resonance that increased with increasing backrest angle.

The vibration measured on the backrest in this study was always normal (i.e. perpendicular) to the backrest and therefore not always horizontal. This is the method used when measuring vibration at this location in vehicles according to current standards. With more inclined backrests, the 'fore-and-aft' (i.e. $x$-axis) component normal to the seat surface will tend to be reduced in proportion to the cosine of the angle between the backrest and the vertical. However, the 'vertical' (i.e. $z$-axis) component parallel to the seat surface will tend to increase in proportion to the sine of the angle between the backrest and the vertical. The $z$-axis vibration will tend to become increasingly important as the backrest inclination increases since the sine of the angle increases rapidly with increasing angle.

The vibration measured at backrests could be resolved into horizontal and vertical components. Both fore-and-aft seat transmissibilities and human responses to the seat vibration could be calculated from the resolved horizontal components. However, because the reduction in the $x$-axis vibration is not great with small deviations from 90°, there would have been only a small effect on the 'fore-and-aft' backrest transmissibility measured in this experiment with backrest inclinations up to 105°. It is anticipated that other effects (e.g., a change in the impedance of the body, a change in pressure on the backrest, and a nonlinear coupling between 'vertical' and 'fore-and-aft' vibration of the body) will have had a greater effect on the fore-and-aft transmissibility.

An increase in the dynamic stiffness of the backrest cushion might partly explain the observed increase in the resonance frequency with increased inclination of the car seat backrest. Previous studies have found that the dynamic stiffnesses of foam blocks and seat cushions increase with increasing pre-load force [4]. There may have been a change in the dynamic stiffness of the car seat backrest due the increased load supported by the backrest with the more reclined postures. However, the foam backrest showed no significant change in resonance frequency with variations in inclination from 90° to 105°, suggesting little change in foam dynamic stiffness associated with the difference in load at these inclinations.

When exposed to a single axis of vibration, the upper body moves in two axes and so there are forces at the back in both the fore-and-aft and the vertical directions [15]. Some of the forces on the backrest cushion in the present experiment will have arisen from cross-axis movements of the upper body: fore-and-aft excitation producing 'cross-axis' vertical movement. With variations in backrest inclination, these cross-axis motions will have had a varying influence on the vibration measured normal to the backrest surface.

The increase in the resonance frequencies and the increase in the transmissibilities at the resonance of the fore-and-aft backrest transmissibilities with increasing backrest inclination for both backrests may be attributed to a combination of several factors: a change in the biodynamic response of the body with changing posture, a change in the mechanical properties of the backrest cushion due increased dynamic stiffness of the backrests when supporting more weight of the body, and components of acceleration in the 'fore-and-aft' direction due to the inclined orientation of the accelerometers on the backrest.

Even if the vibration at the back–backrest interface was unchanged with variations in backrest inclination it would not imply that human response to the vibration was unaffected by backrest inclination. Studies are required to determine whether the evaluation method in current standards is appropriate with inclined seats: possibly the frequency weighting should be adjusted to allow for variations in sensitivity as the measured 'fore-aft vibration' becomes more vertical in an inclined seat.

### 4.2. *Effect of seat-pan inclination*

In comparison with the increases in the resonance frequency and transmissibility at resonance with increasing backrest inclination, the effects of seat-pan inclination on the fore-and-aft transmissibility of the car seat backrest were less substantial. There was no statistically significant influence of seat-pan angle on the resonance frequencies of the car seat backrest and only a small increase in the median transmissibilities at resonance as the seat-pan inclination increased. With the foam backrest, the seat-pan inclination also showed little influence on the resonance frequency and transmissibility at resonance.

The results suggest that there were only small changes in the dynamic stiffnesses of the backrests with increased seat-pan inclination and only small change in the mechanical impedance of the back. However, investigation of vertical and fore-and-aft forces at the backs of seated subjects exposed to whole-body fore-and-aft vibration with varying seat-pan inclination may show changes, especially with greater inclinations than investigated here.

## 5. Conclusions

Increasing the backrest inclination of a car seat from 90° to 105° increased both the fore-and-aft backrest resonance frequency and the backrest transmissibility at resonance. There was little influence of such changes on the resonance frequency of a foam backrest, but the transmissibility at resonance increased with the more inclined backrest.

Inclination of the seat-pan had little effect on the resonance frequencies in the fore-and-aft backrest transmissibility with either backrest. There was a significant increase in the backrest transmissibility at resonance with the car seat with a more inclined seat-pan angle, but the foam backrest showed little change.

It is concluded that common variations in backrest inclination are likely to have a greater effect on the fore-and-aft transmissibility of backrests than common changes in seat-pan inclination.

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