# Apparent mass of the human body in the vertical direction: Effect of seat backrest

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## ARTICLE INFO

## ABSTRACT

The transmission of vibration through a seat depends on various characteristics of the seat and the dynamic response of the human body. The dynamic response of the body can be represented by its apparent mass, but the effect of the seat on the apparent mass of the body is not well understood. This study was designed to quantify the effect of foam and rigid backrests on the vertical apparent mass of the human measured at the seat surface supporting the body. The apparent masses of 12 subjects were measured during exposure to random vertical vibration ($1.0\,\mathrm{ms}^{-2}$ rms from 0.125 to 40 Hz) in a seat with a rigid backrest, in the same rigid seat with three thicknesses of foam backrest (50, 100 and 150 mm), and in the same seat with no backrest. The backrests were inclined at various angles: $0°, 5°, 10°, 15°, 20°, 25°$ and $30°$ for the rigid and 100 mm foam backrests, and $0°, 10°, 20°$ and $30°$ for the 50 and 150 mm foam backrests. With all vertical backrests (i.e., $0°$ inclination), there were resonances in the apparent mass of the body around 5 and 10 Hz. With no backrest, the apparent mass was increased at frequencies less than the resonance frequency but decreased at frequencies between 8 and 20 Hz, relative to the apparent mass with the vertical rigid and foam backrests. With the rigid backrest, the primary resonance frequencies in the apparent mass increased with increasing backrest inclination. With the foam backrests, the resonance frequencies decreased with increasing backrest inclination. At frequencies less than the primary resonance, the apparent mass decreased with increasing backrest inclination, particularly with the rigid backrest. Between 8 and 15 Hz, the apparent mass decreased with increasing inclination, most notably with the foam backrests. At inclinations less than $30°$, there was little effect of foam thickness on the apparent mass, but at $30°$ an increase in the thickness of the foam decreased the frequency of the first resonances. Since contact with backrests and the characteristics of backrests influence the vertical apparent mass of the seated body, backrests should be expected to influence the transmission of vertical vibration through a supporting seat cushion.

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## 1. Introduction

The biodynamic responses of the human body provide information on how the body moves and how it will interact with motions causing body movement. For example, the transmission of vibration through a seat is influenced by the dynamic response of the body and not only the dynamic characteristics of the seat (e.g. Refs. [1,2]). Understanding of the biodynamic

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responses can be used to develop mechanical and mathematical models of the body used to predict seat transmissibility and assist in the optimisation of passenger comfort.

The biodynamic responses of the body have been characterised from measurements of apparent mass, driving point mechanical impedance, and seat-to-head transmissibility. When exposed to vertical vibration, the seated human body exhibits various resonances, the principal of these being around 5 Hz. However, the biodynamic responses of the body are influenced by many factors, especially inter-subject variability (e.g. Refs. [3,4]), intra-subject variability (e.g. Refs. [3,5]), and the input vibration (due to non-linearities in the response (e.g. Refs. [3,6,7]).

The apparent mass of the human body has often been measured with subjects sitting on a flat rigid seat with no back support (e.g. Refs. [3,4]). Sitting in a car seat involves contact with a backrest, with the backrest varying greatly from one car to another and presenting different contact conditions from those in most laboratory studies of apparent mass.

Some of the mass of a seated body can be supported by a backrest, so even with a rigid vertical backrest the apparent mass at low frequencies can be reduced by a backrest [7]. Some studies have found that the resonance frequency and the apparent mass between 5 and 18 Hz tend to be increased by a backrest (e.g. Refs. [7,8]). When a backrest is reclined, a greater proportion of the body mass is supported by the backrest (approximately 30 percent with a backrest reclined to 24° [9]. Compared with an upright backrest, the resonance frequency, and the apparent mass at frequencies greater than the resonance frequency, have been reported to increase when subjects are supported by a rigid backrest inclined to 12° [8]. With the upper-body supported by a rigid backrest inclined by 24°, the apparent mass normal to the backrest has been reported to have peaks with a magnitude similar to those measured at the seat surface [10]. The apparent masses of subjects supported in an 'automotive posture' (rigid backrest inclined by 24°, seat pan inclined by 13°) showed peaks between 6.5 and 8.6 Hz, compared to 4.5–5.5 Hz in studies where the back was unsupported or supported by an upright backrest [10]. With subjects fully reclined to the supine position, the dominant resonance frequency in the apparent mass has been reported to reduce from 10.4 to 7.3 Hz as the vibration magnitude increased from 0.125 to 1.0 ms$^{-2}$ rms [11].

Reduced seat transmissibility has been reported at resonance when the back is supported by a foam backrest than when it is supported by a rigid backrest, with the transmissibility at resonance decreasing less when reclining a foam backrest than when reclining a rigid backrest [12]. It seems likely that some of the reported variations in seat transmissibility can be explained by the dynamic properties of seat cushions and variations in the biodynamic responses of the body. The thickness of foam used in a seat has a systematic effect on seat transmissibility and the frequency of the primary seat resonance, consistent with increased hysteretic damping with increased foam thickness [13]. The effect of foam at a backrest on the vertical apparent mass of the body measured at the seat surface has not previously been reported.

The objectives of this study were to investigate the effects of backrest contact, backrest inclination, and backrest foam thickness on the vertical apparent mass measured at the seat surface. It was anticipated that reclining the backrest would reduce the mass supported on the seat surface and, with increased support for the upper-body, the frequency of the primary resonance would increase. It was further hypothesised that the addition of foam to the backrest would reduce the magnitude of the primary resonance in the apparent mass measured at the seat surface, and that the apparent mass at resonance would decrease further with increasing inclination of the backrest as a greater proportion of the mass of the body was supported by the backrest.

## 2. Methods and procedures

### 2.1. Apparatus

The vertical apparent mass of the human body was measured on the surface of a rigid seat with an adjustable backrest. The seat was mounted to a 1 m stroke electro-hydraulic vertical vibrator. Foam squabs of uniform thickness were attached to the backrest of the seat and adjustments made so that with 50, 100 and 150 mm thick foam backrests and a rigid backrest the subject posture remained unchanged. The dynamic properties of the 100 mm foam had been previously measured using a SIT-bar shaped indenter with a 100 N preload. Over the range of frequencies studied here, the foam stiffness was found to be approximately 21 kN/m and the damping approximately 109 Ns/m. Subjects sat with their feet supported on a footrest inclined at 35° to the horizontal. The angle of the footrest and its vertical position relative to the seat were chosen to create a posture representative of a car driver. Subjects were instructed to adjust the fore-and-aft position of the footrest to obtain a posture similar to their normal driving posture. A loose lap strap was fastened around the subjects for safety purposes. The general arrangement of the apparatus is illustrated in Fig. 1.

The vertical force on the seat surface was measured using a Kistler 9821B force platform consisting of four single-axis piezo-electric force cells located beneath each corner of a top-plate. The charge output from the four force cells was summed and conditioned using a Kistler 5001 charge amplifier. An *HVLab* SIT-pad containing an Entran EGCSDO-10 piezo-resistive accelerometer was used to measure the vertical acceleration on the seat surface.

### 2.2. Backrest conditions

The vertical apparent masses of seated subjects were measured with different backrest conditions to investigate the effects of: (i) an upright rigid backrest and three thicknesses of upright foam backrest (50, 100 and 150 mm); (ii) the angle
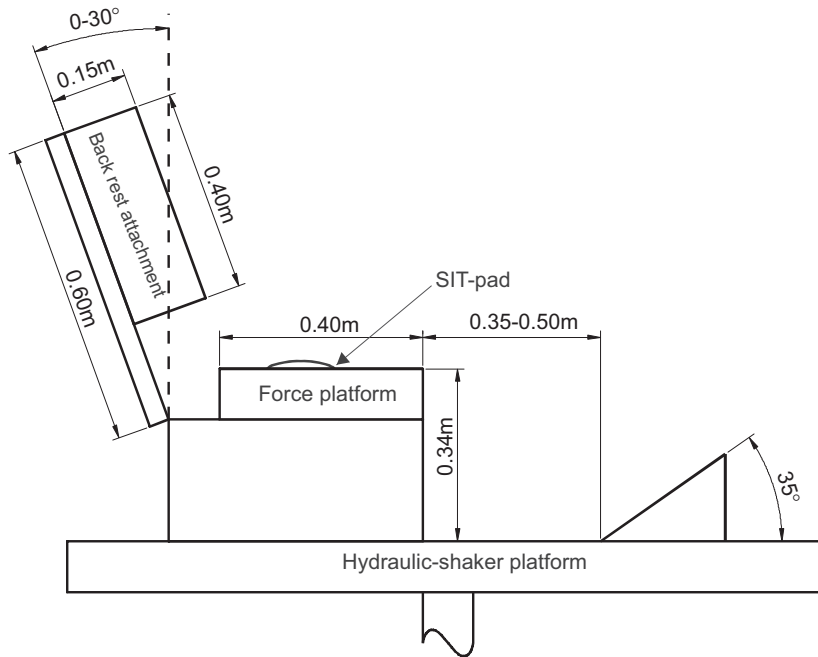
**Fig. 1.** General arrangement of the seat, footrest, and transducers on the vibrator platform.

of inclination with rigid and 100 mm thick foam backrests (from 0° to 30° in 5° increments); (iii) the angle of inclination with 50 and 150 mm foam backrests (from 0° to 30° in 10° increments). Additionally, the vertical apparent mass of each subject was measured in an upright posture with no backrest contact. In all conditions, the subjects were asked to maintain a relaxed posture without slouching. They placed their hands in their laps and looked straight ahead.

Subjects were exposed to the 23 conditions in a single session lasting approximately 1 h. The conditions were presented to subjects in independent random orders to minimise the influence of order effects.

### 2.3. Vibration

The platform was excited using 60 s periods of Gaussian random vibration at $1.0\,\mathrm{ms}^{-2}$ rms band-limited by 8-pole Butterworth filters between 0.125 and 40 Hz. Over this frequency range the constant bandwidth acceleration spectrum was approximately flat. Signals were generated and analysed using an *HVLab* data acquisition and analysis system (version 3.81). Different random signals were generated for each subject and equalised for the response of the vibrator. Signals from the force platform and the accelerometer were sampled at 500 samples per second via 167 Hz anti-aliasing filters.

### 2.4. Subjects

Twelve healthy male subjects (aged 21–48 years mean 28.1 years) participated in the study. Their statures ranged between 1.69 and 1.86 m (mean 1.81 m) and their weights between 64 and 93 kg (mean 74.4 kg).

The experiment was approved by the Human Experimentation, Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton.

### 2.5. Analysis

Mass cancellation was performed to remove the influence of the mass of the top-plate of the force platform (33.0 kg) from the measured force. Mass cancellation was performed in the time domain: the acceleration time-history on the seat surface was multiplied by the mass of the force platform, and then subtracted from the measured force response.

Transfer functions were calculated between the vertical seat acceleration and the vertical force at the seat surface after mass cancellation, to give the apparent masses of the subjects. The apparent mass, $H_{io}(f)$, was calculated from the cross spectral density between the acceleration and the force at the seat, $G_{io}(f)$, and the power spectral density of the acceleration at the seat, $G_{ii}(f)$, using a resolution of 0.195 Hz:

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

The coherency between the force and acceleration was calculated after mass cancellation in the time domain and found to be greater than 0.9 over the frequency range 0.20–30 Hz; above 30 Hz the coherency tended to decrease slightly but was still generally over 0.8.

Data analysis was performed using non-parametric statistical methods using SPSS (version 14). Non-parametric tests (Friedman test for $k$-related samples and the Wilcoxon matched-pairs signed-ranks test for two-related samples) were employed in the statistical analysis. Non-parametric statistics were used to avoid assuming a normal distribution in the data.

## 3. Results

### 3.1. Effect of backrest contact

The vertical apparent masses of the 12 subjects with no backrest, with a rigid vertical backrest, and with a vertical 100 mm foam backrest are compared in Fig. 2. With all three backrest conditions, the apparent mass increased to a peak around 5 Hz and decreased at higher frequencies. Some subjects exhibited a second resonance, with the frequency varying between subjects over the range 7–14 Hz. At frequencies between 15 and 40 Hz there was no evidence of major resonances of the body. The phase lag between the vertical acceleration and the vertical force increased to 1.5 rad around the resonance and then remained approximately constant to higher frequencies. For some subjects the phase response decreased or increased slightly from 15 to 40 Hz. The phase can be very much influenced by imperfect mass cancellation—the response at 40 Hz may have been influenced by small errors in the mass cancellation for some subjects. The median apparent masses for these three conditions are shown in Fig. 3.
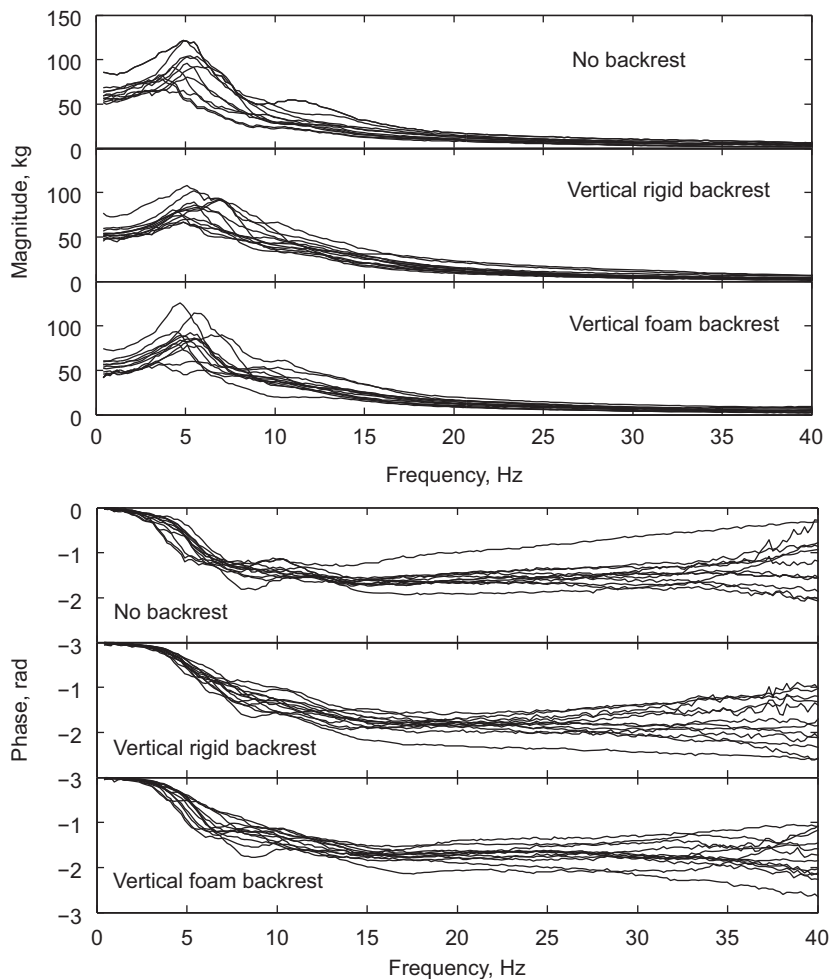


Fig. 2. Moduli and phases of the vertical apparent masses of the 12 subjects with no backrest, a vertical rigid backrest, and a vertical foam (100 mm) backrest.
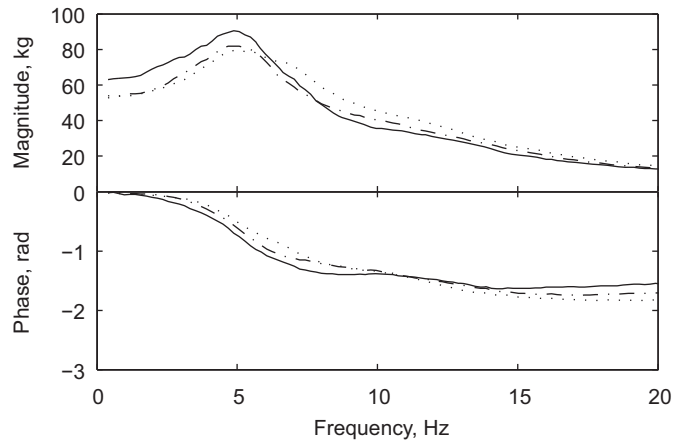
**Fig. 3.** Effect of backrest contact and backrest type on the modulus and phase of the median apparent mass (median vertical apparent mass of 12 subjects measured on the seat): —————, no backrest; · · · · · ·, rigid backrest at 0°; ·–·–·–·,100 mm foam backrest at 0°.

**Table 1**
Median resonance frequencies in the apparent mass moduli for the 23 backrest conditions.

| Angle (deg.) | Frequency (Hz) | | | | |
|---|---|---|---|---|---|
| | No backrest | Rigid backrest | 50 mm foam backrest | 100 mm foam backrest | 150 mm foam backrest |
| 0 | 4.98 | 5.47 | 5.57 | 5.18 | 5.27 |
| 5 | | 5.47 | | 5.37 | |
| 10 | | 5.57 | 4.88 | 4.98 | 4.88 |
| 15 | | 6.25 | | 4.88 | |
| 20 | | 6.25 | 4.79 | 4.69 | 4.59 |
| 25 | | 5.76 | | 4.59 | |
| 30 | | 6.35 | 4.88 | 4.49 | 4.20 |

**Table 2**
Median apparent masses at the primary resonances for the 23 backrest conditions.

| Angle (deg.) | Apparent mass (kg) | | | | |
|---|---|---|---|---|---|
| | No backrest | Rigid backrest | 50 mm foam backrest | 100 mm foam backrest | 150 mm foam backrest |
| 0 | 94.1 | 83.8 | 86.1 | 87.3 | 83.6 |
| 5 | | 82.0 | | 85.5 | |
| 10 | | 78.4 | 89.0 | 87.2 | 88.1 |
| 15 | | 76.3 | | 89.6 | |
| 20 | | 75.1 | 86.4 | 85.8 | 90.8 |
| 25 | | 73.2 | | 84.7 | |
| 30 | | 70.3 | 75.8 | 79.3 | 76.3 |

The medians of the resonance frequencies of the 12 subjects with each of the 23 backrest conditions are given in Table 1 and the medians of the individual apparent masses at each subject's resonance frequency are shown in Table 2. There was no significant difference between no backrest, a vertical rigid backrest, and a vertical 100 mm foam backrest in either the frequency of the primary resonance or the apparent mass at resonance ($p = 0.12$ and 0.17, respectively; Friedman).

Further statistical analysis was conducted to investigate whether backrest contact affected the proportion of the subject mass supported on the seat surface. At very low frequencies the measured apparent mass of a subject is approximately equal to the static mass supported on the seat surface, because the body is almost rigid. Significant differences in apparent mass were found between the three backrest conditions (no backrest, a vertical rigid backrest, and a vertical 100 mm foam backrest) at 0.4 Hz (Friedman, $p = 0.01$). The apparent mass at 0.4 Hz reduced by approximately 10 kg with a rigid and a foam backrest compared to no backrest ($p < 0.01$; Wilcoxon). There was no significant difference in the mass supported on the seat surface with the rigid and the foam backrests ($p = 0.35$).

At frequencies between 7 and 15 Hz, the apparent mass in the three conditions was influenced by the backrest (Friedman, $p < 0.01$). The apparent mass increased when there was contact with the rigid backrest compared to no backrest (at 12 Hz, $p = 0.02$; Wilcoxon), and between the foam backrest and the no backrest conditions ($p = 0.01$; Wilcoxon). There was no significant difference in apparent mass between the no backrest and the foam backrest conditions ($p = 0.27$).

A comparison of apparent masses at 40 Hz produced significant differences between pairs of conditions similar to those at 12 Hz. The influences of other backrest variables (angle, foam thickness) on apparent mass were also statistically significant at 40 Hz if they were significant at 12 Hz. Consequently, subsequent figures and analysis are only presented for frequencies less than 20 Hz.

### 3.2. Effect of inclination of the rigid backrest

The median apparent masses of the 12 subjects measured with each inclination of the rigid backrest are shown in Fig. 4. The frequency of the primary resonance tended to increase as the backrest was reclined from 0° to 25°, although only when the backrest was reclined to 15° and 20° was the resonance frequency significantly greater than with the upright backrest ($p < 0.05$). The resonance frequency with the backrest inclined to 30° was significantly greater than when the backrest was inclined to 0°, 5°, 10° and 25° ($p < 0.05$) but was not significantly greater than with 15° and 20° inclination ($p > 0.05$, Table 3).

At frequencies less than 8 Hz, the apparent mass tended to reduce as the backrest was reclined. A similar but lesser effect is apparent between 10 and 15 Hz. At frequencies greater than 15 Hz, the apparent mass was unaffected by backrest inclination. The apparent mass at the primary resonance tended to decrease with increasing backrest inclination, with significant differences between 14 of the 21 pairs of backrest inclinations ($p < 0.05$; Table 3).

The median 'static mass' supported on the platform (i.e., the apparent mass at 0.4 Hz) decreased from 51.7 to 43.9 kg as the backrest was reclined from 0° to 30°. The apparent mass at 0.4 Hz was unaffected by variations in backrest inclinations up to 15°, but was significantly reduced with the backrest inclined at 20°, 25°, and 30° ($p < 0.05$; Table 3).

### 3.3. Effect of inclination of the 100 mm foam backrest

Fig. 5 shows the effect of reclining the 100 mm foam backrest on the median apparent mass; statistical analysis is given in Table 4. With inclinations greater than 5°, the resonance frequency tended to decrease with increasing backrest angle. This differs from the effect of reclining the rigid backrest where the resonance frequency tended to increase with increasing backrest inclination. There were significant differences between the resonance frequencies with 14 of the 21 backrest pairs ($p < 0.05$). However, the resonance frequencies with the backrest reclined to 5°, 10°, and 15° ($p > 0.05$) did not differ from that with the upright backrest.

The static mass supported on the seat surface (the apparent mass at 0.4 Hz) was unaffected by inclinations of the 100 mm foam backrest up to 25° ($p > 0.05$; Friedman). As the inclination increased from 25° to 30°, the apparent mass reduced from 51.7 to 48.8 kg. There were statistically significant differences in the apparent mass at 0.4 Hz between 5° and 30°, between 15° and 30°, and between 20° and 30° ($p < 0.05$). Similarly, the apparent mass at resonance was broadly unchanged with backrest angles up to 25° but decreased at 30°. The apparent mass between 8 and 20 Hz tended to decrease with increasing backrest inclination, with significant differences between 15 of the 21 pairs of backrest inclinations for the response at 12 Hz ($p < 0.05$).
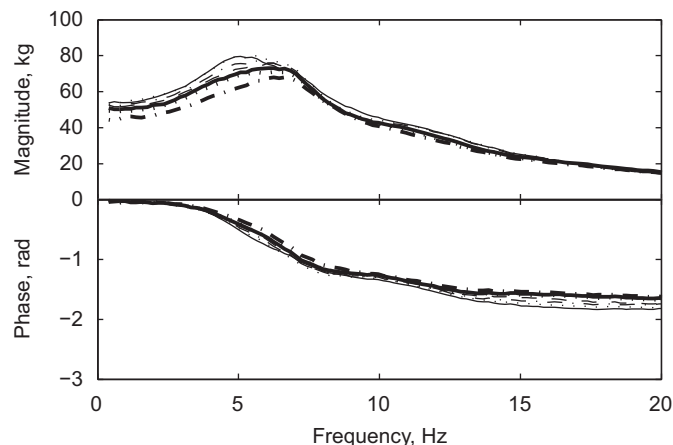


Fig. 4. Effect of inclination of a rigid backrest on the median vertical apparent masses of 12 subjects measured on the seat: —————, 0°; · · · · · · · , 5°; · - · - · -10°; - - - - -, 15°; ▬▬▬▬, 20°; ▪ ▪ ▪ ▪ ▪, 25°; · ▬ · ▬ · , 30°.

**Table 3**
Effect of inclination of the rigid backrest: results of Wilcoxon matched-pairs signed-ranks tests and directions of change for differences in the apparent mass resonance frequency and apparent mass at resonance, at 0.4 Hz, and at 12 Hz.

| Backrest inclination (deg.) | 0 | 5 | 10 | 15 | 20 | 25 | 30 |
|---|---|---|---|---|---|---|---|
| (a) Resonance frequency | | | | | | | |
| 0 | | ns − | ns ↑ | * ↑ | * ↑ | ns ↑ | ** ↑ |
| 5 | | | ns ↑ | ns ↑ | ns ↑ | ns ↑ | * ↑ |
| 10 | | | | ns ↑ | ns ↑ | ns ↑ | * ↑ |
| 15 | | | | | ns ↑ | ns ↑ | ns ↑ |
| 20 | | | | | | ns ↑ | ns ↑ |
| 25 | | | | | | | * ↑ |
| 30 | | | | | | | |
| (b) Apparent mass at resonance | | | | | | | |
| 0 | | ns ↓ | ns ↓ | ns ↓ | * ↓ | * ↓ | ** ↓ |
| 5 | | | * ↓ | ** ↓ | ** ↓ | ** ↓ | ** ↓ |
| 10 | | | | ns ↓ | * ↓ | * ↓ | ** ↓ |
| 15 | | | | | ns ↓ | ns ↓ | ** ↓ |
| 20 | | | | | | ns ↓ | ** ↓ |
| 25 | | | | | | | * ↓ |
| 30 | | | | | | | |
| (c) Apparent mass at 0.4 Hz | | | | | | | |
| 0 | | ns ↑ | ns ↓ | ns ↑ | ** ↓ | ** ↓ | ** ↓ |
| 5 | | | ns ↑ | * ↓ | * ↓ | * ↓ | ** ↓ |
| 10 | | | | ns ↑ | * ↓ | ** ↓ | ** ↓ |
| 15 | | | | | ** ↓ | ** ↓ | ** ↓ |
| 20 | | | | | | ** ↓ | ** ↓ |
| 25 | | | | | | | ** ↓ |
| 30 | | | | | | | |
| (d) Apparent mass at 12 Hz | | | | | | | |
| 0 | | ns ↑ | ns ↓ | ns ↓ | ns ↓ | * ↓ | ** ↓ |
| 5 | | | ns ↓ | ns ↓ | ns ↓ | * ↓ | ** ↓ |
| 10 | | | | ns ↓ | ns ↓ | ** ↓ | ** ↓ |
| 15 | | | | | ns ↑ | ns ↓ | * ↓ |
| 20 | | | | | | ns ↓ | * ↓ |
| 25 | | | | | | | ns ↓ |
| 30 | | | | | | | |

ns = not significant; $p > 0.05$; $^*p < 0.05$; $^{**}p < 0.01$.
↑ median higher with greater backrest angle, ↓ median lower with greater backrest angle, − median same with both backrest angles.
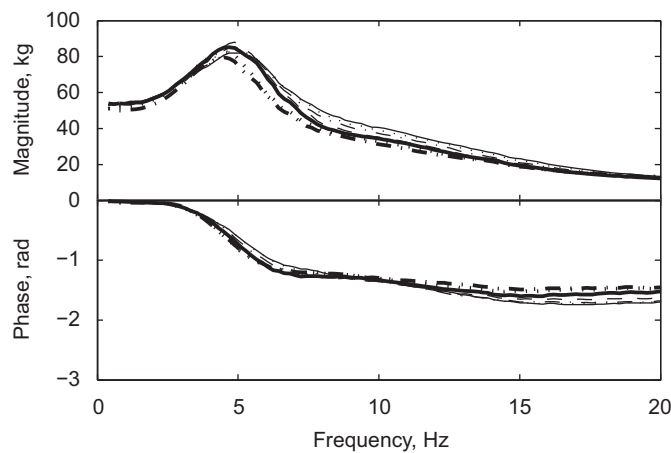


**Fig. 5.** Effect of inclination of a 100 mm foam backrest on the median vertical apparent masses of 12 subjects measured on the seat: ———, 0°; · · · · · · , 5°; ·—·—·—, 10°; − − − −, 15°; ▬▬▬, 20°; ▪ ▪ ▪ ▪ ▪, 25°; · ▬ · ▬ ·, 30°.

### 3.4. Effect of backrest foam thickness at different backrest inclinations

The effect on apparent mass of increasing the thickness of the foam on the backrest at different angles of backrest inclination is shown in Fig. 6. With the upright backrest, the apparent masses with the three foam thicknesses were similar at frequencies less than 8 Hz, with no significant differences in either the apparent mass at 0.4 Hz or the apparent mass at

**Table 4**
Effect of inclination of the 100 mm foam backrest: results of Wilcoxon matched-pairs signed-ranks test and directions of change for differences in the apparent mass resonance frequency and apparent mass at resonance, at 0.4 Hz and at 12 Hz.

| Backrest inclination (deg.) | 0 | 5 | 10 | 15 | 20 | 25 | 30 |
|---|---|---|---|---|---|---|---|
| (a) Resonance frequency | | | | | | | |
| 0 | | ns ↑ | ns ↓ | ns ↓ | ns ↓ | * ↓ | * ↓ |
| 5 | | | * ↓ | * ↓ | ** ↓ | ** ↓ | ** ↓ |
| 10 | | | | ns | * ↓ | ** ↓ | ** ↓ |
| 15 | | | | | ns ↓ | * ↓ | * ↓ |
| 20 | | | | | | * ↓ | * ↓ |
| 25 | | | | | | | ns |
| 30 | | | | | | | |
| (b) Apparent mass at resonance | | | | | | | |
| 0 | | ns ↓ | ns ↓ | ns ↑ | ns ↓ | ns ↓ | ns ↓ |
| 5 | | | ns ↑ | ns ↑ | ns ↑ | ns ↓ | ns ↓ |
| 10 | | | | ns ↑ | ns ↓ | ns ↓ | * ↓ |
| 15 | | | | | ns ↓ | ** ↓ | ** ↓ |
| 20 | | | | | | * ↓ | ** ↓ |
| 25 | | | | | | | ns ↓ |
| 30 | | | | | | | |
| (c) Apparent mass at 0.4 Hz | | | | | | | |
| 0 | | ns ↓ | ns – | ns ↓ | ns ↓ | ns ↓ | ns ↓ |
| 5 | | | ns ↑ | ns ↓ | ns ↓ | ns ↑ | * ↓ |
| 10 | | | | ns ↓ | ns ↓ | ns ↓ | ns ↓ |
| 15 | | | | | ns ↑ | ns ↑ | * ↓ |
| 20 | | | | | | ns ↑ | ** ↓ |
| 25 | | | | | | | ns ↓ |
| 30 | | | | | | | |
| (d) Apparent mass at 12 Hz | | | | | | | |
| 0 | | ns – | ns ↓ | * ↓ | * ↓ | ** ↓ | ** ↓ |
| 5 | | | ns ↓ | * ↓ | * ↓ | ** ↓ | ** ↓ |
| 10 | | | | ns ↓ | * ↓ | ** ↓ | ** ↓ |
| 15 | | | | | ns ↓ | * ↓ | * ↓ |
| 20 | | | | | | * ↓ | ** ↓ |
| 25 | | | | | | | ns ↓ |
| 30 | | | | | | | |

ns = not significant; $p > 0.05$; $^{*}p < 0.05$; $^{**}p < 0.01$.
↑ median higher with greater backrest angle, ↓ median lower with greater backrest angle, − median same with both backrest angles.

resonance ($p > 0.1$, Friedman). At frequencies between 8 and 20 Hz, the rigid backrest resulted in slightly greater apparent mass compared to the foam backrests. There were significant differences in apparent mass between the rigid backrest and the three thicknesses of foam backrest at 12 Hz, but no significant difference in apparent mass between the three foam backrests at this frequency (Table 5).

With the backrest inclined to 10°, the apparent mass was unaffected by the thickness of the three foam backrests, but the apparent mass was greater with the rigid backrest at frequencies between 7 and 30 Hz ($p < 0.05$ at 12 Hz).

With the backrest inclined to 20°, a difference between the rigid backrest and the three thicknesses of foam backrest was more evident. With the rigid backrest, the apparent mass was reduced at frequencies less than 8 Hz but increased at higher frequencies than with the three foam backrests. There were significant differences in the apparent mass between the rigid backrest and all three thicknesses of foam backrest at resonance and at 12 Hz. At 0.4 Hz there were significant differences in the apparent mass between the rigid and the two thicker foam backrests ($p < 0.05$) and also between the 50 mm foam backrest and the other two foam backrests ($p < 0.05$). The resonance frequency of the apparent mass was significantly higher with the rigid backrest than with each of the three thickness of foam backrest ($p < 0.05$).

With the backrest inclined to 30°, the apparent mass with the 50 mm foam backrest was lower at 0.4 Hz and higher at 12 Hz compared to the apparent mass with the 100 and 150 mm foam backrests ($p < 0.05$). The apparent mass resonance frequency with the rigid backrest, was 6.35 Hz, and significantly higher than with the 150 mm foam backrest, at 4.20 Hz ($p < 0.01$). The resonance frequency was also higher with the 50 mm foam backrest than with the other two thicker backrests ($p < 0.05$; Table 1).

### 3.5. Effect of backrest angle with different thicknesses of foam backrest

The effect of backrest angle on apparent mass with the rigid backrest and the three thicknesses of foam backrest is shown in Fig. 7. At low frequencies (i.e., <1 Hz) and at resonance there is a small but consistent reduction in the apparent mass as the backrest angle increases with the rigid backrest, but this is less noticeable with the foam backrests. This was
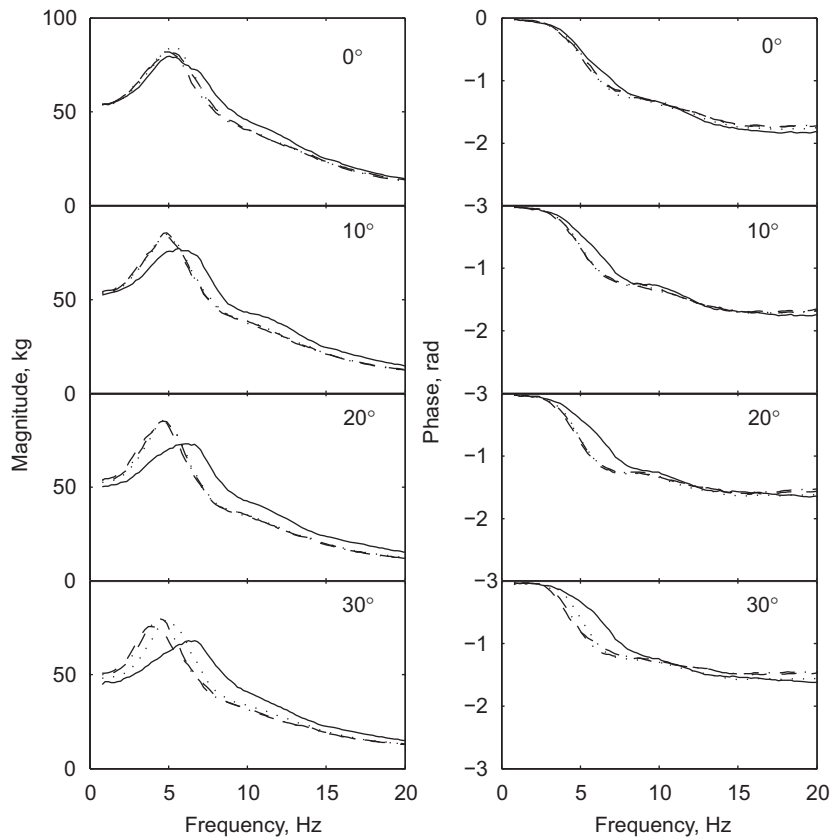
**Fig. 6.** Effect of backrest foam thickness at different backrest inclinations on the median vertical apparent masses of 12 subjects measured on the seat: ————, rigid backrest; · · · · · · , 50 mm foam; ·—·—·—·, 100 mm foam; - - - - -, 150 mm foam.

borne out in the statistical analysis which showed that, at 0.4 Hz and at resonance, the number of significant differences between apparent masses at pairs of backrest angles was less for each of the foam backrests than the rigid backrest (Table 6). From 8 to 20 Hz, the variation in apparent mass with backrest inclination tended to increase with increasing foam thickness, with the apparent mass generally decreasing as the backrest was reclined. At 12 Hz, the differences in apparent mass were significant between five of the six backrest angle pairs for both the 100 and the 150 mm foam backrests compared to only three of the six for the rigid backrest.

With the rigid backrest, as the backrest angle increased the frequency of the first resonance increased. With the foam backrests, the resonance frequency tended to decrease as the backrest angle increased. Statistical analysis shows that this effect was more pronounced with greater thickness of foam (Table 5).

With the 50 mm foam backrest, the greatest apparent mass at resonance occurred when the backrest was reclined to 10° and the lowest apparent mass at resonance occurred when the backrest was reclined to 30° (Table 2). A similar trend occurred with the 100 and 150 mm foam backrests, except that the greatest apparent mass at resonance occurred when the seat was reclined to 15° and 20°, respectively.

## 4. Discussion

### 4.1. Effect of backrest contact

The moduli and phases of the vertical apparent masses of the subjects with no backrest contact were similar to those previously reported (e.g. Refs. [3,14,15]). Subjects showed a principal resonance in the 5 Hz region and some subjects showed a second resonance in the 7–14 Hz range.

Contact with the rigid vertical backrest generally decreased the apparent mass at frequencies less than the resonance frequency and increased the apparent mass in the frequency range 7–14 Hz, consistent with the findings of Fairley and Griffin [3] and Nawayseh and Griffin [16]. Although Wang et al. [8] found a similar increase in the apparent mass at frequencies greater than the primary resonance with an upright backrest, they found the apparent mass at frequencies less than the resonance frequency was largely unaffected by backrest contact, contrary to the findings of this study. Although the seat heights differed between the studies (0.34 m above the foot support in this study and 0.46 m in the previous

**Table 5**
Statistically significant different (i.e. $p < 0.05$) pairs of backrest foam thicknesses with different backrest inclinations. 0: rigid backrest; 50: 50 mm foam backrest; 100: 100 mm foam backrest; 150: 150 mm foam backrest.

| | Resonance frequency | Apparent mass at resonance | Apparent mass at 0.4 Hz | Apparent mass at 12 Hz | Total out of 24 possible combinations |
|---|---|---|---|---|---|
| Backrest at 0° | | | | 0/50 ↓<br>0/100 ↓<br>0/150 ↓ | 3 |
| Backrest at 10° | | | | 0/50 ↓<br>0/100 ↓<br>0/150 ↓ | 3 |
| Backrest at 20° | 0/50 ↓<br>0/100 ↓<br>0/150 ↓<br>100/150 ↓ | 0/50 ↑<br>0/100 ↑<br>0/150 ↑ | 0/100 ↑<br>0/150 ↑<br>50/100 ↑<br>50/150 ↑ | 0/50 ↓<br>0/100 ↓<br>0/150 ↓ | 14 |
| Backrest at 30° | 0/50 ↓<br>0/100 ↓<br>0/150 ↓<br>50/100 ↓<br>50/150 ↓ | 0/50 ↑<br>0/100 ↑<br>0/150 ↑ | 0/50 ↑<br>0/100 ↑<br>0/150 ↑<br>50/100 ↑<br>50/150 ↑ | 0/50 ↓<br>0/100 ↓<br>0/150 ↓<br>50/100 ↓<br>50/150 ↓ | 18 |

Comparisons shown where $p < 0.05$; Wilcoxon matched-pairs signed ranks test.
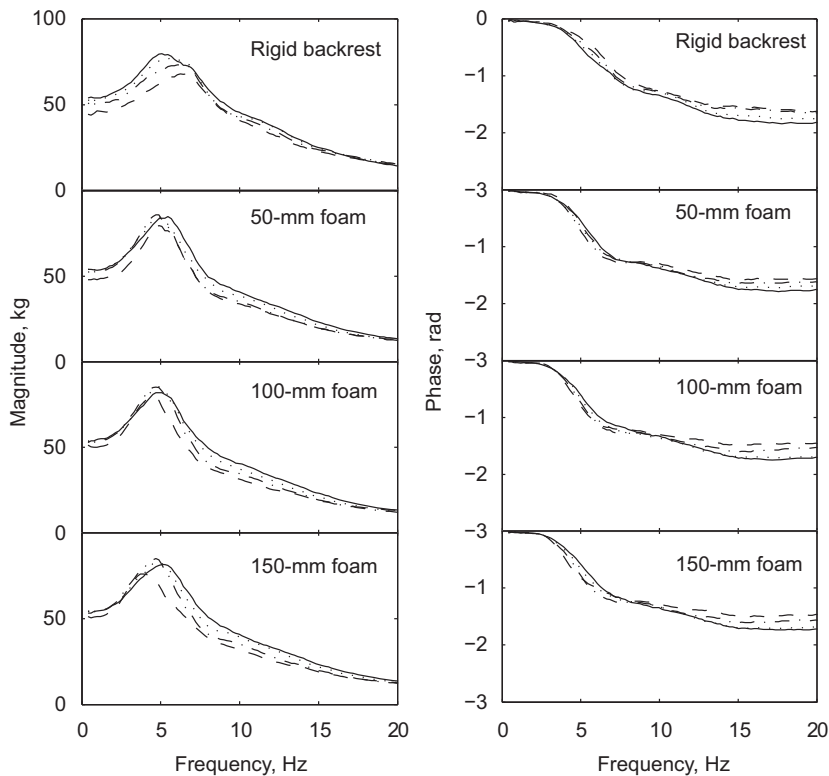↑ median higher with greater foam thickness, ↓ median lower with greater foam thickness.



**Fig. 7.** Effect of backrest inclination with different thicknesses of foam backrest on the median vertical apparent masses of 12 subjects measured on the seat: ————, 0°; · · · · · · · ·, 10°; ·–·–·–, 20°; – – – –, 30°.

study), this is unlikely to explain the difference: Nawayseh and Griffin [7] found that backrest contact decreased the apparent mass at frequencies less than the resonance frequency irrespective of the height of the feet relative to the seat surface. The increase in the apparent mass between 7 and 14 Hz with backrest contact is consistent with an increase in damping of the primary resonance.

**Table 6**
Statistically significant different (i.e. $p<0.05$) pairs of backrest inclinations with different thickness of foam backrest. 0: upright backrest; 10: backrest reclined to 10°; 20: backrest reclined to 20°; 30: backrest reclined to 30°.

| | Resonance frequency | Apparent mass at resonance | Apparent mass at 0.4 Hz | Apparent mass at 12 Hz | Total out of 24 possible combinations |
|---|---|---|---|---|---|
| Rigid backrest | 0/20 ↑<br>0/30 ↑<br>10/30 ↑ | 0/20 ↓<br>0/30 ↓<br>10/20 ↓<br>10/30 ↓<br>20/30 ↓ | 0/20 ↓<br>0/30 ↓<br>10/20 ↓<br>10/30 ↓<br>20/30 ↓ | 0/30 ↓<br>10/30 ↓<br>20/30 ↓ | 16 |
| 50 mm foam | 0/20 ↓ | 0/30 ↓<br>10/30 ↓<br>20/30 ↓ | 0/30 ↓<br>10/20 ↓<br>10/30 ↓<br>20/30 ↓ | 0/20 ↓<br>0/30 ↓<br>10/20 ↓<br>10/30 ↓ | 12 |
| 100 mm foam | 0/30 ↓<br>10/20 ↓<br>10/30 ↓<br>20/30 ↓ | 10/30 ↓<br>20/30 ↓ | 20/30 ↓ | 0/20 ↓<br>0/30 ↓<br>10/20 ↓<br>10/30 ↓<br>20/30 ↓ | 12 |
| 150 mm foam | 0/10 ↓<br>0/20 ↓<br>0/30 ↓<br>10/30 ↓<br>20/30 ↓ | 10/30 ↓<br>20/30 ↓ | 0/30 ↓<br>10/30 ↓<br>20/30 ↓ | 0/20 ↓<br>0/30 ↓<br>10/20 ↓<br>10/30 ↓<br>20/30 ↓ | 15 |

Comparisons shown where $p<0.05$; Wilcoxon matched-pairs signed ranks test.
↑ median higher with greater backrest angle, ↓ median lower with greater backrest angle.

There was a small but statistically significant increase in the resonance frequency when subjects were supported by a rigid backrest compared to no backrest. This is consistent with Nawayseh and Griffin [7] but contrary to Nawayseh and Griffin [16] and the findings of Wang et al. [8] in which there were no significant effects of a rigid backrest on the resonance frequency. The difference might be explained by the backrest employed: in this study and the earlier study by Nawayseh and Griffin [7] the lumbar spine and pelvis were not in contact with the backrest whereas in the later study by Nawayseh and Griffin [16] and the study by Wang et al. [8] there was contact with the full length of the back. Previous studies (e.g. Ref. [3]) have found that when subjects vary between an 'erect' and 'tensed' posture there is a corresponding change in their apparent mass resonance frequency. Where the lumbar region was not supported, the subjects may have exerted greater muscle tension or maintained a more upright posture than with no backrest or a full backrest support, resulting in an increased resonance frequency.

In this study the apparent mass at 0.4 Hz decreased by approximately 10 kg when there was contact with a rigid flat vertical backrest. This indicates that either this was supported by the backrest or the feet supported a greater proportion of the body weight when this backrest was present. Nawayseh and Griffin [15] measured the vertical apparent mass at both the seat and the backrest and found that when subjects were in contact with an upright backrest the apparent mass at the seat was reduced at low frequencies, consistent with the findings of this study. They also found that the vertical forces on a seat with no backrest were the same as the vector addition of the vertical forces at the seat surface and the backrest. This indicates that a proportion of subject body weight was supported by shear forces at the backrest.

With the 100 mm foam backrest, the apparent mass at frequencies less than the resonance frequency was similar to that with the rigid backrest, indicating that at low frequencies a similar proportion of subject mass was supported in shear by the 100 mm foam backrest and the rigid backrest. At frequencies between 7 and 15 Hz, the apparent mass was lower with the foam backrest than with no backrest, possibly due to the second resonance being less evident in some subjects when there was no backrest. The origin of the second resonance is not certain, but a biodynamic model developed by Matsumoto and Griffin [17] indicated that the resonance could be caused by a rotational mode of the pelvis and the lower upper-body. This mode may have been more damped by the foam backrest than the rigid backrest.

### 4.2. Effect of backrest inclination

The resonance frequency in the vertical apparent mass at the seat surface increased from 5.47 Hz with a vertical rigid backrest to 6.35 Hz when this backrest was reclined to 30°. Rakheja et al. [10] measured the vertical apparent mass on the surface of a seat with a backrest reclined to 24° and found the mean resonance of the subjects at 7.8 Hz. The present study used an input magnitude of 1.0 ms$^{-2}$ rms whereas Rakhekja et al. [10] used 0.5 ms$^{-2}$ rms over a similar frequency range (0.5–40 Hz). It is has been widely reported that the response of the body is nonlinear with input magnitude: the resonance frequency decreasing with increasing vibration magnitude (e.g. Ref. [6]). The differences in resonance frequency between

the two studies may be a result of the different excitation magnitudes. There were also postural differences between the two studies: in this experiment a flat rigid seat pan was used but Rakheja et al. [10] employed a seat pan inclined to 13°. However, both Nawayseh and Griffin [16] and Wang et al. [8] have found that the inclination of a seat pan had a negligible effect on the vertical apparent mass. The resonance frequency of the apparent mass of the body (not legs) of supine subjects measured with an input magnitude of $1.0\,\mathrm{ms}^{-2}$ rms, as in this study, has been reported as 7.32 Hz (e.g. Ref. [11]). This is higher than the resonance frequencies measured in this study and consistent with increased resonance frequency with increased inclination. The findings of these studies suggest that the changes in the apparent mass of the body caused by contact with an inclined rigid backrest may be reflected by increasing the stiffness in an apparent mass model, although the actual changes in the body will be more complex. This increase in stiffness could be a result of the rigid backrest constraining the motions of the upper-body. At higher backrest inclinations, more mass of the body is supported on the backrest this may further constrain the motions of the upper-body.

With no backrest, excitation of the body occurs primarily through the supporting seat surface. When subjects are also supported by a backrest, there is an additional source of excitation, which is in the *z*-axis of the back when the backrest is vertical but increasingly in the *x*-axis of the back as the backrest is reclined. The two inputs will be in-phase with a rigid seat but there will be phase differences between the inputs when either the backrest or the seat surface are not rigid. Clearly, the dynamic response of the body under these circumstances is not simple, although it may be possible to provide simple representations of the apparent mass of the body that are sufficient to assist the optimisation of the dynamic responses of seats.

The apparent mass resonance frequency and also the response between 5 and 15 Hz tended to decrease as the foam backrests were reclined; this is consistent with a decrease in the 'stiffness' of the combined response of the body and the backrest. This decrease in stiffness might be explained by the foam being more compliant when there was more of the subject's weight supported normal to the backrest and consequently greater compression forces acting on the foam. That this decrease became more pronounced as the thickness of foam increased, is consistent with the compressive stiffness of the foam decreasing as the thickness was increased.

The apparent mass reduced at low frequencies as the rigid backrest and the 50 mm foam backrest were reclined, indicating that a reduced proportion of the subject body mass was supported on the seat surface. With the 100 and 150 mm foam backrests, the static mass supported on the seat surface increased as the backrest was reclined from 0° to 10° but then decreased as the backrest was reclined from 10° to 30°. At 30°, the static mass on the seat surface with the rigid backrest was 43.9 kg, while the median static mass at this inclination with the foam backrests varied between 47.0 and 48.7 kg. The difference in static mass supported on the seat surface between the reclined rigid and reclined foam backrests might be explained by postural differences. With the reclined rigid backrest, subjects were likely to maintain a straight back whereas with the foam backrests subjects may have adopted a kyphotic posture in which the centre of gravity was brought forward, reducing the mass supported on the backrest.

### 4.3. Effect of the thickness of foam on the backrest

The thickness of foam on the backrest had the greatest effect on the measured apparent mass when the backrest was inclined to 30°, with the resonance frequency decreasing with increasing thickness of foam, consistent with a lowering of the stiffness of the body-backrest system.

There was evidence of increased damping of the primary resonance in the apparent mass (a broadening of the resonance peak with increased apparent mass at frequencies greater than the resonance frequency) with the foam backrest compared to the rigid backrest. However, there was no evidence in the apparent mass of further increases in damping with increasing foam thickness. The mass supported on the seat surface increased with increasing thickness of foam, consistent with the thicker foam being more compliant and supporting less of the subject weight on the backrest.

### 4.4. Implications for seat testing and biodynamic models

This study shows that contact with a backrest, and the inclination and compliance of a backrest, influence the vertical apparent mass of the human body measured at a seat surface. As the vibration transmitted through a seat is dependent on the apparent mass of the body, contact with a backrest and the inclination and compliance of a backrest will also affect seat transmissibility (e.g. Ref. [12]). When measuring seat transmissibility it therefore seems advisable to use an appropriate backrest set to an angle appropriate for the vehicle, or to measure seat transmissibility with a range of backrest inclinations.

Biodynamic models of the dynamic responses of the body have not generally been developed to consider interactions with a backrest (e.g. Refs. [17,18]). Wei and Griffin [18] showed that a simple two dof model could accurately reflect the apparent mass of subject sitting upright with no backrest contact. This model was combined with measurements of the dynamic stiffness and damping of foam to provide useful predictions of seat transmissibility for subjects sitting with no backrest [19]. The principal effect of contact with a backrest in the current study was a shifting of the resonances in the apparent mass as opposed to the addition of new resonances. This suggests it may be appropriate for the effect of backrest contact on the apparent mass at the seat surface to be approximated by adjustments to the parameters of a two dof model

(e.g. Ref. [18]). Different types and inclinations of backrest might be represented by different values for the variables within the model. An alternative to this approach is to include backrest interaction within a mechanistic model. The vertical transmissibility of a car seat with subjects supported by a backrest reclined to 20° can be represented by a four dof lumped parameter model with vertical stiffness and damping elements representing the total compliance of the back and the backrest [20]. This model did not attempt to separate out the compliance of the backrest or reflect the effects of backrest inclination. To represent these factors, a mechanistic model requires rotational or cross-axis components. It has been found that a three dof model with vertical, fore-and-aft and rotational (i.e., pitch) dof can be optimised to represent the vertical apparent mass and the fore-and-aft cross-axis apparent mass of the human body with no backrest support [21]. The dynamic properties of a reclined compliant backrest has been taken into account in a nine dof model representing the transmission of vertical vibration to the hip and head and also the fore–aft transmissibility to the back, with the human body represented by three rigid bodies connected by rotational spring and damper elements [22]. A similar model could represent the dynamic response of the body and the backrests in the conditions investigated in this study.

## 5. Conclusions

Contact with an upright rigid backrest or upright foam backrests reduces the body mass supported on the seat surface, indicating backrests support a proportion of the body mass in shear. Reclining a backrest reduces the proportion of subject mass supported on the seat surface, although the reduction is less apparent when the compliance of foam in a backrest reduces the proportion of the body mass supported by the backrest.

The apparent mass resonance frequency is little affected by contact with either a vertical flat rigid backrest or a vertical foam backrest. Whereas reclining a rigid backrest increases the resonance frequency, reclining a foam backrest decreases the resonance frequency: with a backrest inclined to 30°, the resonance frequency was 6.35 Hz with a rigid backrest compared to 4.49 Hz with a 100 mm foam backrest.

The thickness of foam on the backrest had the greatest effect on the vertical apparent mass measured at the seat when the backrest was maximally inclined to 30°, with the resonance frequency and the apparent mass between 5 and 15 Hz greater, and the mass supported on the seat less, with 50 mm foam than with 100 and 150 mm foam.

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