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VERTICAL VIBRATION TRANSMISSION THROUGH THE LUMBAR SPINE OF THE SEATED SUBJECT—FIRST RESULTS

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Seven fresh, not embalmed, cadavers (58·1 ± 6·6 years, 73 ± 10·3 kg, 170·7 ± 6·5 cm) were submitted, in the week following their death (7·1 ± 3·1 days), to a whole-body vertical broad-band white random vibration in the bandwidth 0·8 to 25 Hz of about 1·5 m/s^2 r.m.s. Two postures were tested using the same rigid seat, each one with and without a lumbar support: seated erect and seated as in a car. Vibration was monitored on the floor, the seating in the vertical direction (buttocks-to-head), the five lumbar vertebrae and the sternum: vertical (buttocks-to-head) and longitudinal (back-to-chest). Biaxial accelerometers were mounted rigidly on the anterior face of the vertebral body, after the removal of the abdominal viscera. Analogue recordings of each channel were passed through an antialising filter (Fc = 40 Hz) then sampled at 80 Hz (4096 samples/channel). The inclination of each accelerometer (α) was measured on the lateral X-ray taken for every trial, then the data were set in order to be in the same reference ($Z = z/\cos\alpha$, $X = x\cos\alpha$). Spectral analysis was performed with a frequency resolution of 0·3 Hz, on the basis of Welch's method. Thirty one overlapping sections (256 samples per section using a Hanning window with an overlap rate of 128 samples) of the estimated periodograms were averaged. Transfer and coherence functions were then estimated between the vertical seating acceleration and the measured accelerations at the upper levels. The first results showed that the vertical vibration transmission was constant throughout the lumbar spine. Inter-subject variability was the major source of disparity. Resonance phenomena were observed between 4 and 9 Hz and depended on posture.

1. INTRODUCTION

Whole-body vibration exposure has been identified as a possible risk factor for low back pain and pathological changes in the spine (see, e.g., reference [1]). The mechanical exposure of the spine resulted from the increased forces at resonance at different parts of the body (see, e.g., reference [2]). The exposure depended on many factors: some of them were quantitative like the vibration energy or its duration [3], and others were qualitative like posture [2], anthropometric variables [4, 5], and the main frequency of the vibration. Improving the protection of workers who are submitted to whole-body vibration depends on controlling these factors. As a result, their effects on the spinal behaviour were investigated. Standards were largely based on the results of studies of body kinematics and subjective perception of volunteers exposed to vibration. Biomechanical behaviour of isolated spinal units was also investigated, leading to many mechanical models (e.g., that of Langrana *et al*. [6]).

Human biodynamics may be assessed by measuring different parts of the body (e.g., head, trunk and pelvis). This data enabled the understanding of vibration transmission, especially motion and resonance characteristics. Hence, the principal resonance was

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observed between 4 Hz and 6 Hz, and a secondary one between 8 Hz and 12 Hz [7, 8]. These results were proved by modelling (5 Hz and 8 Hz respectively) which underlined the importance of pelvic tilting in the second mode [9]. But these data gave no indication of the relative motion in the lumbar spine (see, e.g., reference [1]). Direct measures were therefore necessary in this region.

Panjabi *et al*. [8] measured vibration transmission in the seated erect posture at the third lumbar level (L3) and found a resonance frequency at 4·5 Hz. Pope *et al*. [10] found lower values of the resonance frequency, at the same level. They showed that it depended on the seat (or cushion) and on the subject [11]. Changing posture (e.g., erect or relaxed, leaning forward or backward, back off or back on, etc.) influenced the resonance frequency in several ways [7, 12, 13]. Vibration transmission through the spine of primates was monitored at different vertebral levels by Quandieu and Pellieux [14]. They showed that the intervertebral disc behaved like a very linear low-pass filter for exposures of 4 m/s^2.

In this work, the authors have contributed to the study of the biodynamics of the seated subject by conducting experiments on human cadavers. Vibration was monitored at all lumbar levels in different postures. The effects of subject, vertebral level, and posture on the axial seat-to-vertebrae transmissibility and resonance were examined.

The main hypotheses one sought to investigate were as follows: (1) the intervertebral discs modified vibration transmission through the lumbar spine from the lower vertebra (L5) to the upper one (L1); (2) the lumbar support altered vibration transmission in the lumbar spine.

2. MATERIALS AND METHODS

Seven cadavers (one female and six males) from the Corpses Donation Department of Paris, were tested in the week following their death (see Table 1). During this period, they were stored at 4°C. They were selected on the basis of the absence of any known infectious diseases or spinal deformities or disorders. The instrumentation method was developed by

TABLE 1

Subjects' characteristics

Subject	Sex	Age (years)	Cause of death	Post-mortem days before test (days)	Weight (kg)	Weight abd. visc. (kg)	Height (cm)
1	Female	63	Asthma—cardiac crisis	3	77·5	Not measured	169
2	Male	66	Myocardial infarction	3	77·4	9·8	164
3	Male	63	Road accident—skull trauma	6	85·4	9·4	178
4	Male	49	Septicemia—oesophagus carcinoma	10	69·5	8·5	160
5	Male	50	Cardiac arrest	11	82	7·5	179
6	Male	63	Kidney carcinoma	7	53	7·3	171
7	Male	53	Suicide by barbiturate	10	66	6·5	174
Mean		58·1		7·1	73	8·2	170·7
Standard deviation		6·6		3·1	10·3	1·2	6·5

Guillon [15]. The preparation consisted in fixing accelerometers on the anterior wall of each lumbar vertebral body. These were $\pm 5\,\boldsymbol{g}$ damped biaxial accelerometers (Entran, EGAS2-CM*-5VC) with a bandwidth of $\pm 5\%$ from 0–60 Hz, and a resonance frequency superior to 250 Hz. The errors due to non-linearity and hysteresis were about $\pm 1\%$ of the scale. The abdominal wall was opened and the abdominal viscera were removed and weighted. Each accelerometer was mounted on a support specifically designed to fit to the vertebral corpse, using a screw-bolt system. The support was rigidly fixed to the vertebra by two screws, one on each side of the mid-sagittal plane. Another biaxial accelerometer was mounted on the sternum, to measure the trunk acceleration. The sensitive axes of the accelerometers were oriented in the vertical (buttocks-to-head) and longitudinal (back-to-chest) directions. The vertical axes were aligned in the frontal plane. The abdominal wall was reconstituted and the subject was dressed in a tightly fitting thin suit. The subject was then positioned on an experimental rigid seat and restrained by using a lap belt and a thoracic belt, the head was attached to the head-rest and the feet to the foot-rest. The purpose of these attachments was to maintain the subject's position throughout the experiments. Four postures were tested seated erect without a lumbar support, seated erect with a lumbar support, seated as in a car (backrest tilted backward at 25° from vertical and seating tilted upward at 7° from horizontal) without a lumbar support, and seated like in a car with a lumbar support. The lumbar support consisted of a semi-cylindrical wooden bar. It was positioned opposite the third lumbar vertebra (L3) and adjusted in order to create a real hyper-lordosis. The first position test (seated erect or seated like in a car) was randomly chosen. However, a pilot test showed that it was more difficult for a passive corpse to adjust from a posture with a lumbar support to one without. Because of these, it was then necessary to introduce some kind of order in the experimentation design so that variability due to bad positioning was prevented. Consequently, the situation without a lumbar support was always tested first. Vibration was also monitored on the floor and the seating in the vertical direction, by using $\pm 5\,\boldsymbol{g}$ monoaxial accelerometers (Entran, EGAS-FT*-5VC) with the same physical characteristics as the vertebral accelerometers. A standardized semi-rigid interface device [16] was used for measuring the vibration at the body–seat interface. The floor accelerometer was positioned with reference to the same standard. The vibration exposure was given by using a servo-hydraulic simulator of 100 mm stroke. The excitation was a whole-body vertical broad-band white random vibration in the bandwidth 0·8–25 Hz, of about 1·5 $\mathrm{m/s^2}$ r.m.s. (root-mean-square). The signals were conditioned (Entran MC 402) and then stored on an analogue tape recorder (Teac XR-9000, Signal/Noise = 40 dB). Lateral X-rays (36 × 43 cm) of the lumbar spine of the seated subject were taken for each posture, before the vibration exposure. Each vibration lasted about five mins, followed by a resting period of approximately twenty mins after changing posture, in order to allow joint recovery and to make sure that the new position was stabilized. Only 51·2 s of the original signal were digitized. Analogue recordings of each channel were passed through an antialiasing filter (Kemo VBF 8, 48 dB/octave) at a cut-off frequency of 40 Hz then sampled at 80 Hz (4096 samples/channel). Because the curvature of the lumbar spine (lumbar lordosis) and its variation depending on posture, the lumbar vertebrae were not aligned in the sagittal plane. Consequently, the inclination of the vertebral accelerometers varied from one level to another. The lateral X-rays were examined in order to measure the inclination (α) of each accelerometer relatively to the absolute vertical direction. It was then possible to set all vertebral acceleration measurements to the same reference. Since the trunk accelerometer was out of the range of the radiograph, its inclination was computed using the static analogue values measured before the vibration exposure: if x_s was the static longitudinal acceleration and z_s the vertical one, then the angle was $\alpha = \tan^{-1}(x_s/z_s)$. For each accelerometer, the vertical acceleration was $Z = z/\cos\alpha$ and the longitudinal acceleration $X = x\cos\alpha$, where z and x were the measured vertical and longitudinal accelerations, respectively. Spectral analysis was performed with a frequency resolution of 0·3 Hz, on the basis of Welch's method. Thirty-one overlapping sections (256 samples per section using a Hanning window with an overlap rate of 128 samples) of the estimated periodograms were averaged. Transfer and coherence functions were estimated between the seating vertical acceleration and the vertical accelerations measured at the upper levels (vertebrae and sternum), assuming a linear, time invariant system. The transfer function ($H(f)$) was defined as the ratio between the cross-spectral density function of the input (i) and output (o) ($G_{i,o}(f)$) to the spectral density function of the input ($G_{i,i}(f)$): $H(f) = G_{i,o}(f)/G_{i,i}(f)$. The coherence function ($\gamma^2_{i,o}(f)$) was defined as the ratio of the square of the absolute value of the cross-spectral density function to the product of the spectral density functions of the input and output ($G_{o,o}(f)$): $\gamma^2_{i,o}(f) = |G_{i,o}(f)|^2/G_{i,i}(f)G_{o,o}(f)$ [17].

One-way analysis of variance (ANOVA) was performed at 0·3 Hz intervals from 0–25 Hz, to study the effect of individual, vertebral level, and posture, on the vertical seat-to-vertebrae transmissibility (modulus of the transfer functions). The null hypothesis H_0 was that the means would be equal, and the alternative hypothesis H_1 that they were, in fact, different.

3. RESULTS

Vertical seat-to-vertebrae transmissibility data were analyzed in the seated erect posture without a lumbar support, to determine the biodynamics of the lumbar spine of the seated subject (see Figure 1). On average, for frequencies above 4 Hz, vertical seat-to-vertebrae transmissibility increased and showed a first resonance peak around 6·3 Hz and a transmissibility factor of 1·3. The vibration was attenuated for frequencies above 8·2 Hz, but increased again from 10·7 Hz, exhibiting a hardly noticeable second peak around 13·6 Hz of 0·9. As expected, inter-subject variability was highly significant from 2·8–25 Hz, as shown by the analysis of variance ($p = 0$). Below this frequency, differences were not significant up to 1·9 Hz ($0{\cdot}12 \leqslant p \leqslant 0{\cdot}33$).

One important result concerned the vertebral level effect. An assumption was made concerning an amplification of the vibration transmission throughout the lumbar spine, from the fifth lumbar vertebra (L5) to the first one (L1). The analysis of variance did not show any significant effect of the vertebral level on the vibration transmission, and this was true for all tested postures and at all frequencies. On the contrary, it even suggested a quite identical exposure between 4·4 Hz and 10·6 Hz ($0{\cdot}8 \leqslant p \leqslant 1$), in the seated erect posture without a lumbar support. Only subject 3, and to a lesser degree, subject 5, could have satisfied this assumption. Finally, it should be noticed that subject 6 had different vertical seat-to-vertebrae transmissibility shapes than the others. This may be due to degenerated discs which will be examined later when NMR, discography and macroscopic grading of the intervertebral discs will be practised, in completion of the X-rays.

Changing posture did not affect these results relative to the inter-subject variability ($p \leqslant 0{\cdot}1$ or $p = 0$ in most cases, at all frequencies), or to the vertebral level effect ($p > 0{\cdot}11$ or $0{\cdot}8 \leqslant p \leqslant 0{\cdot}98$ at most frequencies).

The lumbar support had a significant effect on the vertical seat-to-vertebrae transmissibility for frequencies above 3·8 Hz ($p \leqslant 0{\cdot}01$). The whole curve slipped slightly towards higher frequencies as shown in Figure 2. On average, the first resonance peak was observed at 6·9 Hz and a second peak at 13·8 Hz. It displayed approximately a 5% decrease for the first peak, and a 10·4% amplification for the second peak, compared to the reference posture (seated erect without a lumbar support).

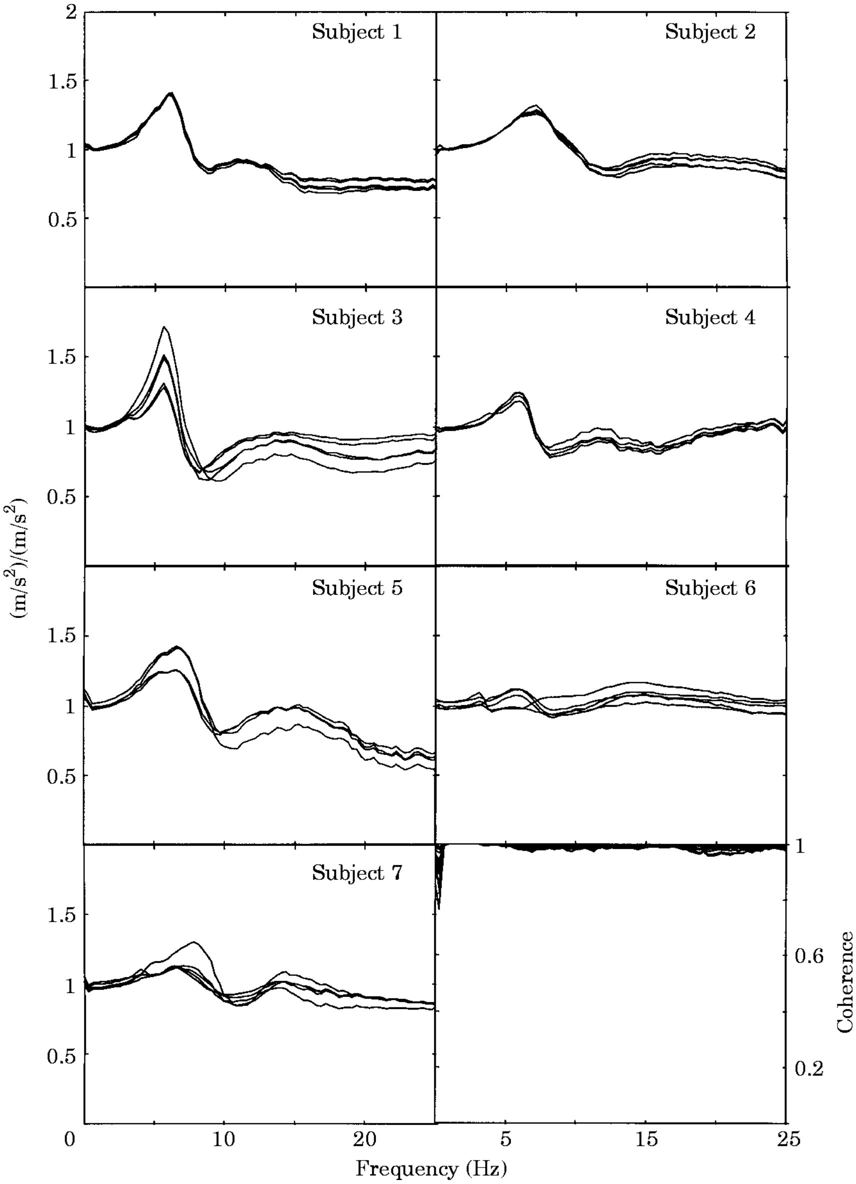

Figure 1. Vertical seat-to-vertebrae transmissibility in the seated erect posture without a lumbar support and their corresponding coherence functions.

The seated as in a car without a lumbar support posture was significantly different from the seated erect posture without a lumbar support, between 4·4 Hz and 9·1 Hz ($p \leqslant 0{\cdot}05$, mostly $p = 0$), except between 5·6 Hz and 6·9 Hz. The differences were also significant from 14·7–16·9 Hz ($p \leqslant 0{\cdot}04$). These variations occurred in the first and second resonance peak bandwidths. Vibration was about 10% and 4·7% higher at the first and the second resonance frequencies, respectively, compared to those for the seated erect posture without a lumbar support. Resonance frequencies were also higher: 6·9 Hz and 15·2 Hz for the first and second peaks, respectively. The lumbar support did not have a significant effect on the vertical seat-to-vertebrae transmissibility below 9·4 Hz; however, the transmissibility at the first resonance frequency (7·6 Hz) was about 4·3% greater than the same posture without a lumbar support, and 13% greater than the seated erect posture without a lumbar support.

The vertical seat-to-trunk transmissibility differed from the vertical seat-to-vertebrae transmissibility in many respects (see Figure 3). The first peak generally occurred at a higher frequency than the vertical seat-to-vertebrae transmissibility, the mean difference was about 0·3 Hz (which was the frequency resolution) with a standard deviation of 0·4 Hz. The first transmissibility peak was at least 40% higher than that of the first peak of the

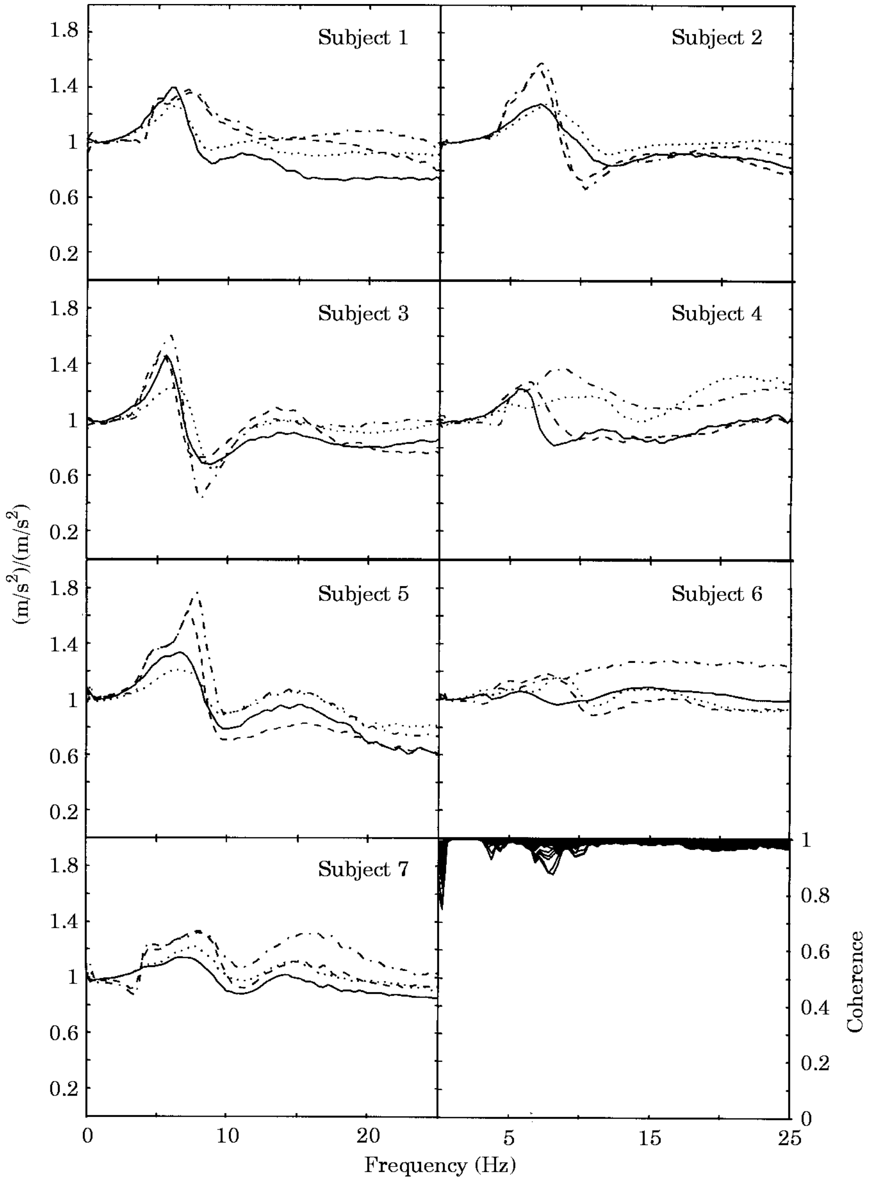

Figure 2. Vertical seat-to-vertebrae transmissibility in the four postures (mean for five lumbar levels): —, seated erect without a lumbar support; . . . . , seated erect with a lumbar support; – – – , seated as in a car without a lumbar support; – · – , seated as in a car with a lumbar support; and their corresponding coherence functions: 7 subjects × 5 lumbar vertebrae × 4 postures.

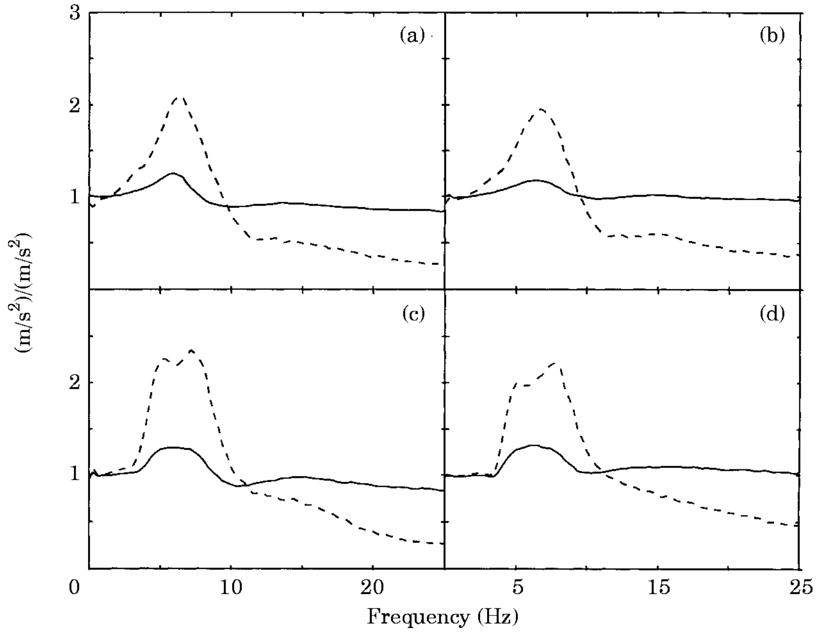

Figure 3. —, Vertical seat-to-vertebrae transmissibility (mean for five lumbar vertebrae and seven subjects), and – – –, vertical seat-to-trunk transmissibility (mean for seven subjects), in the four postures: (a), seated erect without a lumbar support; (b), seated erect with a lumbar support; (c), seated as in a car without a lumbar support; (d), seated as in a car with a lumbar support.

vertical seat-to-vertebrae transmissibility. The attenuation was much more important and rapid than for the vertebrae whose transmissibility remained around 1 after the first resonance. It occurred above 9·2 Hz in the seated erect posture and above 11·3 Hz in the seated as in a car posture. In all cases, the resonance frequencies at all levels (vertebrae and trunk) depended on the subject ($p \leqslant 0{\cdot}01$). The mean resonance frequency at the vertebral level was correlated to the trunk resonance frequency (correlation coefficient = 0·86).

4. DISCUSSION

One original aspect of this research was the use of human cadavers as substitutes for living volunteers. A better understanding of how the whole-body vibration exposure could be a possible risk factor for low-back pain was required. Since pathological changes in the spine could be involved, it was necessary for the data to be recorded directly on the spinal column. Many workers tried to investigate the lumbar spine exposure on volunteers. Some of this work consisted of acceleration measures on the skin, opposite the spinous processes [18, 19]. Others used invasive measurements realized under local anaesthesia [8, 10, 20]. The conditions of these experiments limited the various test possibilities due to ethical and safety considerations. Using cadavers had many advantages: for example, taking X-rays of the spinal column in all tested postures. The cadaver could be compared to a relaxed subject, once the cadaver rigidity was broken. The body positioning was improved as there could not be any uncontrolled reaction to the exposure, motion or fatigue. Consequently, the inter-individual variability was probably reduced. However, Hein-Sorensen *et al.* [21] and Guillon [15], using intranuclear pressure measurements, showed that the discal axial load was smaller in para- and tetraplegic patients or cadavers than in normal subjects, a consequence of the absence of muscle function. Quandieu [22] studied the discal transfer function in primates. He showed that their intervertebral discs behaved like a low-pass filter whose characteristics shifted toward higher frequencies when administrating curare (myo-relaxant). The effect of the corpse temperature ($<37^\circ$C) was unfortunately uncontrolled. The removal of the abdominal viscera (about 8 kg), even though modifying the total body weight and the trunk centre of gravity, allowed a direct approach to the mechanical behaviour of the ligamentous lumbar spine in its physiological environment. The decrease of the total body weight probably had an effect on vibration transmission characteristics, which will be discussed hereafter. Finally, electromyographic data or subjective scaling could not be assessed simultaneously with other mechanical parameters when using cadavers.

The mean value of the seat-to-trunk resonance frequency was 7·2 Hz (range 5·6–8·4 Hz). These values slightly exceeded those reported by other workers, for the seat-to-head vibration transmission. Seidel *et al.* [23] found the first resonance peak to occur between 3·9 Hz and 5·7 Hz while Paddan and Griffin [24] observed the same resonance around 7 Hz. Donati and Bonthoux [25] showed that the seat-to-trunk exceeded the seat-to-head resonance frequency. However, these values are lower than those the authors observed. This may be due to differences in the vibration magnitude, considering the non-linearity of the human body. Fairley and Griffin [7] and Hinz and Seidel [19] noticed that increasing the vibration magnitude resulted in lower resonance frequencies. Nevertheless, Holmlund *et al.* [26] reported resonance frequencies similar to our results for females (4–8 Hz) and lower frequencies for males (4–5 Hz), for exposures of 0·5 $\mathrm{m/s^2}$ to 1·5 $\mathrm{m/s^2}$. The authors believe that the differences of weight between the two populations may explain this variation. Our cohort consisted of one female and six males, with relative low weights (see Table 1). Furthermore, the abdominal viscera were removed, which reduced the total body weight and modified the masses distribution. The mean value of the Body Mass Index [27] was 22. For this population, the Body Mass Index was 20 and fell to 18 for the same population without the abdominal viscera. This was probably the reason for the observed higher resonance frequencies as anthropometric characteristics were a possible source of inter-subject variability at some frequencies [19, 24, 26, 28].

The resonance frequency did not depend on the spinal level, in all cases. Sandover and Dupuis [20] showed similar results with measurements realized at the twelfth thoracic vertebra (T12), the second (L2) and the fourth (L4) lumbar levels. The mean value of the seat-to-vertebrae resonance frequency was 6·8 Hz, with a standard deviation of 0·9 Hz (range 4·4–9·1 Hz). These values were in agreement with those found in the literature, either for skin measurements (4·5–6·5 Hz, [13]), or invasive measurements: Pope *et al.* [11] found a resonance frequency of 5 Hz at the third lumbar level (L3), Panjabi *et al.* [8] at 4 Hz, Broman *et al.* [29] between 4·5 Hz and 7·5 Hz.

The axial seat-to-trunk resonance frequency generally exceeded that of the seat-to-vertebrae. However, the mean difference was of 0·3 Hz, which happened to be the frequency resolution, with a standard deviation of 0·4 Hz. Pope *et al.* [11] also reported a small difference between the seat-to-head and the seat-to-vertebrae resonance frequencies.

As expected, the resonance frequency was subject dependent, in agreement with the significant inter-individual variability observed by Paddan and Griffin [5] on the seat-to-head vertical transfer functions. However, they showed a satisfying repeatability of the intra-individual measurements. This variability may result from some physical characteristics of the subjects [7]. Wilder *et al.* [30] examined the role of the muscle function in this regard. They reported little increase of the resonance frequency, when a Valsalva manoeuvre was accomplished, especially for females, but did not show a significant effect of muscle fatigue. Fairley and Griffin [7] reported an increase of the resonance frequency in particular with an increased muscle tension, but there was considerable variability in the changes between individuals. Anyhow, the differences here observed may not be explained by muscle function. Further work should be done to study the effect of the anthropometric variables and other spinal parameters (as suggested by Messenger [28]) by using measurements from the lateral X-rays, on our own seat-to-vertebrae and seat-to-trunk transmissibility, and to examine the effect of the trunk centre of gravity, in this respect.

The resonance frequency depended on posture. Moving from a seated erect posture to a seated posture as in a car, as for the lumbar support, increased this frequency. Broman *et al*. [29] reported an increase of the resonance frequency, when moving from a relaxed posture to an erect posture with more lordosis.

The axial seat-to-trunk was at least 40% greater than the axial seat-to-vertebrae first peak, which was similar at all lumbar levels (except one subject). The mean value, in the seated erect posture without a lumbar support, of the first vertebral peak, was about 1·3, in agreement with the results of Pope *et al*. [10] (1·4), and Broman *et al*. [29] (1·55), for the third lumbar level. Sandover and Dupuis [20] made the same observation, for measures at the twelfth thoracic level, the second and the fourth lumbar levels. They suggested that the dynamic compressive load of the spinal column was small and the discal compression did not exceed 1 mm. In the same way, Quandieu [22] observed that the primate lumbar intervertebral discs behaved like a low-pass filter, with unity vertical discal transmissibility. There were significant differences in the seat-to-vertebrae magnitude amongst subjects, at all frequencies. Further analysis of their anthropometric and morphologic characteristics may explain these variations [5].

Changing posture also had consistent effects on seat-to-vertebrae transmissibility, at some frequencies. The biggest variation was a 14% increase of the resonance peak between the seated erect posture without a lumbar support and the seated like in a car posture with a lumbar support. This was probably due to the increase of the lumbar lordosis generally observed in this case [4]. However, the lumbar support did not have the same effect when we considered the seated erect posture or the seated as in a car posture. In the first case, the lumbar support induced a 5% decrease of the first peak while it produced a 10% increase of the same peak in the second case. Thus, the probable increase of the lumbar lordosis was not the single factor responsible for these differences. Zimmermann and Cook [13], Pope *et al*., [31] and Messenger and Griffin [4] all supported that the pelvic tilting was a possible cause of changes in the vibration magnitude. This one was reduced at 4 Hz but increased above 6 Hz as a consequence of the anterior tilting of the pelvis [4].

5. CONCLUSION

In this work, the original contribution consisted of making simultaneous measures of the vertical vibration transmission from the seat to the trunk and throughout the lumbar spine. The results showed that vibration monitoring at the trunk was not sufficient to determine completely the level of spinal exposure. The first lumbar transmissibility peak was observed around 6·3 Hz (versus 7 Hz for the thorax) and was about 40% lower than the trunk. Attenuation was much larger at the trunk after resonance. In the tested frequency range, the human lumbar discs behaved like very rigid material in the vertical direction, with unity transmissibility, though rejecting the first hypothesis. The lumbar support did not have the same effect in the seated erect posture, or in the seated as in a car posture (backrest tilted backward, and seating upward), on a hard seat. However, in both cases, it induced an increase of the first resonance frequency, even though this frequency shift remained small. In the seated erect posture, the lumbar support induced a very slight decrease of the first resonance peak, which increased in the seated as in a car posture, relatively to the same postures without a lumbar support. Therefore, it could not be stated that the lumbar support provoked a decrease of the vibration transmission at the lumbar vertebrae, regarding the axial seat-to-vertebrae transmissibility. Inter-individual variability was significant. Therefore, additional analysis of the effects of anthropometric characteristics (weight, height, lumbar lordosis, etc.) would be of interest.

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