Journal of Sound and Vibration (1998) **215**(4), 801–812
Article No. sv981593

MECHANICAL IMPEDANCE OF THE HUMAN BODY IN THE HORIZONTAL DIRECTION

P. Holmlund and R. Lundström

National Institute for Working Life, Department of Technical Hygiene, S-90713 Umeå, Sweden

(*Accepted* 16 *March* 1998)

The mechanical impedance of the seated human body in horizontal directions (fore-and-aft and lateral) was measured during different experimental conditions, such as vibration level (0·25–1·4 m/s^2 r.m.s.), frequency (1·13–80 Hz), body weight (54–93 kg), upper body posture (relaxed and erect) and gender. The outcome showed that impedance, normalized by the sitting weight, varies with direction, level, posture and gender. Generally the impedance spectra show one peak for the fore-and-aft (X) direction while two peaks are found in the lateral (Y) direction. Males showed a lower normalized impedance than females. Increasing fore-and-aft vibration decreases the frequency at which maximum impedance occurs but also reduces the overall magnitude. For the lateral direction a more complex pattern was found. The frequency of impedance peaks are constant with increasing vibration level. The magnitude of the seocnd peak decreases when changing posture from erect to relaxed. Males showed a higher impedance magnitude than females and a greater dip between the two peaks. The impedance spectra for the two horizontal directions have different shapes. This supports the idea of treating them differently; such as with respect to risk assessments and development of preventative measures.

1. INTRODUCTION

A large number of people are exposed to whole-body vibration (WBV) in their occupational life. This is especially the case for drivers of various vehicles, such as dumpers, excavators, scrapers, buses and trucks. The main categories of human response to WBV are perception, degraded comfort, interference with activities, impaired health and occurrence of motion sickness. Many scientific papers, reports and other documents have been published which address these types of response. Some of them present comprehensive surveys of current knowledge on the effects of WBV: e.g., references [1–9]. On the basis of the information given in this, as well as all other related literature, it can be concluded that human response to WBV is a very complex phenomenon. In some cases combinations of effects may occur simultaneously. One effect may also promote the onset of another effect. During exposure to WBV there are many different physiological, psychophysical and physical factors which are relevant for the development of unwanted effects, such as individual susceptibility, body constitution and posture together with the frequency, direction, magnitude and duration of the vibration.

Knowledge of how vibration is transmitted to and through the human body can provide an important input to our understanding of human response to WBV. For instance, biodynamic studies in the vertical direction (Z) have identified critical frequency ranges, i.e., resonant frequencies, for different parts of the body, such as the eyes, head, shoulders, neck and spine (see e.g., references [2, 3, 8]). It is possible that some types of detrimental effects are closely related to WBV exposures which contain frequencies leading to a

0022–460X/98/340801 + 12 $30.00/0

resonant behaviour of the body or parts of the body. Fairley and Griffin [10] studied the apparent mass of the sitting human and found that the human body has two resonances at low frequencies at about 0·7 and 2–2·5 Hz in the horizontal direction. The authors also found that the apparent mass increased at frequencies above 0·8 Hz when subjects used a backrest. This was due to stiffening of the upper body. It has been shown that the spine has a resonant frequency of about 5 Hz in the vertical direction [2, 3, 11]: i.e., a frequency which is produced in many types of vehicles and earth-moving machinery [1]. This might be either a causal or a contributing factor for the development of low back pain among professional drivers. Understanding whole-body dynamics is also necessary for proper design of protective measures, such as suspension seats.

The mechanical driving point impedance is sometimes used to describe the biodynamical properties of the human body. It specifies the complex ratio between the dynamic force to which the subject is exposed and the resulting body motion in terms of velocity. The international standard, ISO 5982 [12], presents diagrams showing the modulus and phase of the driving point impedance of the human body in the Z direction for a sitting upright posture. The ISO-standard is restricted to males. This is unfortunate since the proportion of female drivers is steadily increasing in most countries. Since there are differences in average anthropometric measures between females and males, it seems plausible to assume differences in biodynamic behaviour.

A study for the Z direction has been conducted previously [13]. The study focused on the relation between the mechanical impedance and frequency, exposure level, upper body posture and gender. The purpose of the present study is, against this background, to investigate the mechanical impedance of the human body in the horizontal direction using the same conditions.

2. THEORY

The mechanical impedance (Z) is defined by the dynamic force (F) to which a structure is exposed, divided by the resulting velocity (v), such that:

$$Z = F/v \text{ (Ns/m)}. \tag{1}$$

As the impedance is a complex unit it can be divided into two components, real (Re) and imaginary (Im), such that:

$$Z = Z_{\mathrm{Re}} + Z_{\mathrm{Im}} = (F/v)(\cos(\Phi_{F,v}) + \mathrm{i}\sin(\Phi_{F,v})) \text{ (Ns/m)}. \tag{2}$$

Z_{Re} corresponds to the part of the vibration energy that is absorbed by the system. Z_{Im} corresponds to the part of the energy that is returned to the vibration source: i.e., the energy that is not absorbed by the system. This implies that the magnitude of the impedance not only depends on the force (F) and the velocity (v) but also on the phase difference between them. The maximum absorption of energy by the system occurs when F and v are in phase: i.e., $\Phi = 0^\circ$. No energy is consequently absorbed when the phase between F and v is 90°.

The mechanical impedance (Z_M) for a solid mass (M) at a certain frequency (f) and acceleration (a) is

$$Z_M(f) = F_M(f)/v_M(f) = Ma/(a/2\pi f) = 2\pi f M \text{ (Ns/m)}. \tag{3}$$

TABLE 1

Mean (M), *standard deviation* (SD), *maximum* (max) *and minimum* (min) *values for the subjects' age*, *body weight* (kg) *and height* (cm), $n = 15$ *for each group*

	Female	Male	All
	M (SD, max, min)	M (SD, max, min)	M (SD, max, min)
Age	24 (11, 51, 22)	39 (12, 59, 24)	37 (11, 59, 22)
Weight	63 (7, 76, 54)	75 (10, 93, 55)	69 (10, 93, 54)
Height	167 (4, 173, 160)	177 (6, 188, 167)	172 (7, 188, 160)

3. METHOD

3.1. SUBJECTS

The study group consisted of 15 females and 15 males. Basic information about their age, work assignment, years at work, general state of health, previous or present exposure to whole-body vibration etc., were ascertained through a questionnaire. All subjects were considered to be healthy and with no signs or symptoms of disorders of the musculo-skeletal system, such as lower back pain and lumbago. Averaged anthropometric data, measured by the experimenter, for the subjects are shown in Table 1.

3.2. APPARATUS

Sinusoidal vibration was generated by using a signal generator (Brüel & Kjær 1049), an electrodynamic shaker (Ling Dynamic System, Mod. 712 + ILS 712) and a power amplifier (Ling Dynamic System, MPA 1). The force and acceleration was collected with piezo-electric transducers (Acceleration: Brüel & Kjær 4231, Force: Kistler 9251A) mounted in a seat plate. Signals were amplified and low-pass filtered (LP < 300 Hz) by identical charge amplifiers (Rion UV-06) and Bessel-filters. After A/D-conversion of the signals ($f_s = 1000$ Hz), the values were continuously stored on disk for later analysis. As can be seen in Figure 1 no backrest was used and the feet were stationary on the floor.

To calibrate the force channel dynamically, the seat plate was loaded with solid masses weighing from 5–25 kg. An accelerometer calibrator (Brüel & Kjær 4291) was used for the acceleration channel. Before the experiments the "no load impedance" of the measuring

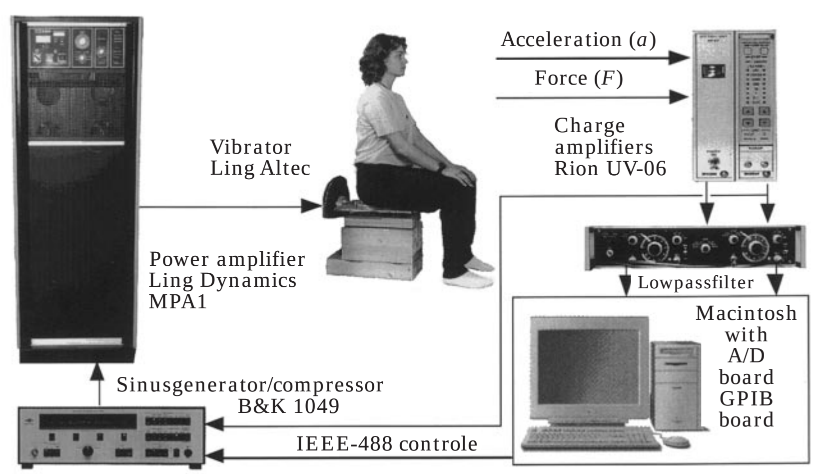

Figure 1. The experimental set-up.

system was tested. This was to ensure that the system's impedance would not affect the results and to determine the signal-to-noise ratio.

3.3. EXPERIMENTAL PROCEDURE

Prior to the first occasion, each subject was given written information about the experiment which included the purpose of the study, possible risk for acute or chronic injuries, ethical committee approval (University of Umeå, Dnr 94-255) and their right to either interrupt an on-going test run or refrain from further tests. Informed prior consent was signed by each subject.

The experimental procedure for all test runs followed a predetermined protocol. All subjects wore T-shirts and loose cotton sports pants (see Figure 1). After being weighed in a standing position the subjects sat down on the seat plate and positioned their feet on the floor. The static sitting weight on the seat plate (M_S) and the floor was then determined. At each occasion the subject was exposed to one of six acceleration levels (0·25, 0·35, 0·5, 0·7, 1·0 or 1·4 m/s^2 r.m.s.) with both erect (E) and relaxed (R) upper body postures. The posture was visually checked by the experimenter during each test run. If a correction to the posture was required it was made during measurement pauses. The measurement period for each frequency was 20 sinusoidal cycles with a 5 s pause between frequencies. The frequency was increased from 1·13–2·5 Hz to 31·5–80 Hz, depending on exposure level, in steps of 1/6 octaves. In the range of 25–80 Hz the steps were 1/3 octaves. To limit the risk of posture fatigue the frequencies were presented for all subjects in increasing order since a random procedure would have increased the total exposure time. Each subject attended on twelve different days, one for each acceleration level in the fore-and-aft (X) and lateral (Y) directions.

3.4. ANALYSIS

LabView computer software was used for data acquisition and analysis. For each test frequency the acquired acceleration signal was integrated to velocity. This was followed by calculating the root mean square (r.m.s.) value for the measured time period. The r.m.s. value for the force was determined after vectorial compensation for the load that the seat plate generated (1·6 kg) on the force transducers; a procedure usually denoted as "mass cancelation". On the basis of these results, the absolute and normalized mechanical impedance was calculated. The impedance is obtained by the quotient of the force and velocity together with their phase difference. Normalized mechanical impedance (NMI) constitutes the quotient between the impedance at each frequency and the seated body mass (M_S) such that

$$Z_{\mathrm{Norm}}(f) = Z(f)/M_S. \tag{4}$$

The purpose for this was two-fold: firstly, to get a standard measure for the impedance independent of the subjects' static weight, and secondly, to facilitate estimation of the impedance for any given person. The phase difference between the force and the acceleration was calculated by measuring the time difference between zero crossings for the force and velocity signals.

Some limitations in the experimental set-up caused problems in the analysis of the data. It was not possible to generate sinusoidal motion below 2·5 Hz for all vibration levels. A further limitation, on this occasion, was that the computer did not consistently measure vibration frequency up to 80 Hz at all magnitudes. As a result it was not possible to run the statistical analysis for the whole frequency range.

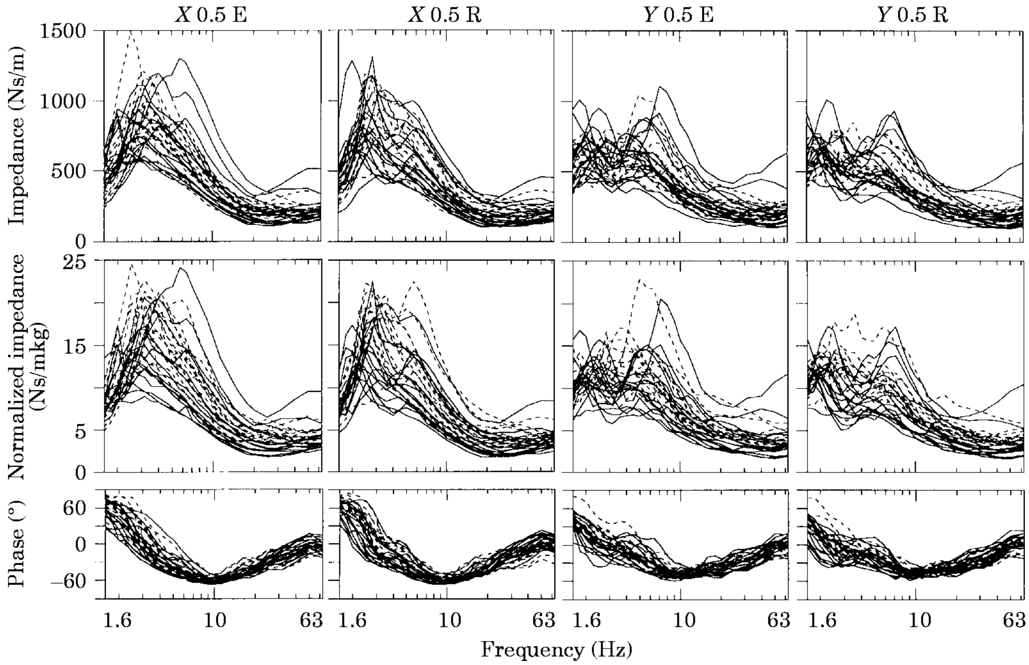

Figure 2. Impedance, normalized impedance and phase spectra for 15 female (- - -) and 15 male (—) subjects. The left and right parts of the figure show fore-and-aft (X) and lateral (Y) vibration directions. For each direction both erect (E) and relaxed (R) upper body postures are shown.

4. RESULTS

A general finding for both X and Y directions, was that the *NMI* increased with frequency up to a first peak in the range 2–5 Hz. For most test subjects a second peak in the range of 5–7 Hz was also observed in the Y direction. The frequency at which the first *NMI* peak occurred was dependent upon each subject. There were also relatively large inter-individual differences for both females and males. Differences between the female and male groups in *NMI* peaks and magnitude were also observed. To illustrate the individual variation in the obtained data, the impedance magnitude, *NMI* magnitude and phase at $0{\cdot}5\ \mathrm{m/s^2}$ in both erect and relaxed upper body postures are shown in Figure 2.

Averaged *NMI* results for female and male groups are shown in Figure 3 for the different directions, acceleration levels and postures. It appeared that the lowest vibration level caused the highest *NMI* magnitudes. As the vibration level increased the *NMI* magnitude and frequency of peak *NMI* magnitude decreased. This *NMI* magnitude reduction is, in principal, valid for the whole frequency range following the first *NMI* peak. The phase is shown as a function of frequency below each *NMI* spectrum (see Figure 3). The phase angle spectra for the six levels of acceleration were similar for both females and males in the X direction while some differences were discernible in the Y direction. Generally, the phase decreased from about 80° at 1·6 Hz to between $-60^\circ - 40^\circ$ at 10 Hz, after which it increased.

NMI spectra for the X direction showed in principal one peak at about 3–5 Hz. At low vibration levels and in a relaxed posture there was an indication of two defuse peaks at about 3 and 6–7 Hz. At higher vibration levels only one peak was discernible. The male group showed a lower *NMI* magnitude than the female group. Corresponding spectra for the Y direction showed two peaks at about 2 and 6 Hz at low vibration levels for both postures. However, the second peak diminished with increasing vibration level. The erect posture showed a clearer level dependency while the relaxed posture showed a more complex pattern. For the male group in the erect posture, two peaks with about the same magnitude were found. In the relaxed posture the second peak decreased in magnitude and was always lower than the first. In the erect posture for females, the second peak was higher at low vibration levels. Two peaks of equal magnitude were found at low levels in the relaxed posture for the females.

In Tables 2 and 3 the mean values and standard deviations for the *NMI* and related phase angles at different frequencies for the 0·5 m/s^2 r.m.s. acceleration level in the relaxed upper body posture are shown. Mean values are shown for females, males and all subjects.

The *NMI* data, $Z_{\mathrm{Norm}}(f)$, presented in Figure 3, Tables 2 and 3, together with the total body mass (M_T), can be used for an estimation of a person's impedance at different frequencies for any of the shown levels, postures and genders. The impedance for a sitting person can thus be calculated from the formula

$$Z(f) = kM_T Z_{\mathrm{Norm}}(f)\ (\mathrm{Ns/m}). \tag{5}$$

The constant k equals 0·77 and is quotient between the seated body mass (M_S) and the total body mass (M_T) found in this study.

An ANOVA test, run on the *NMI*, showed significant differences with respect to gender (see Table 4). Significant differences were found between 2 and 6·3 Hz and between 18 and 31·5 Hz. These significant differences, however, were not observed at the highest level of

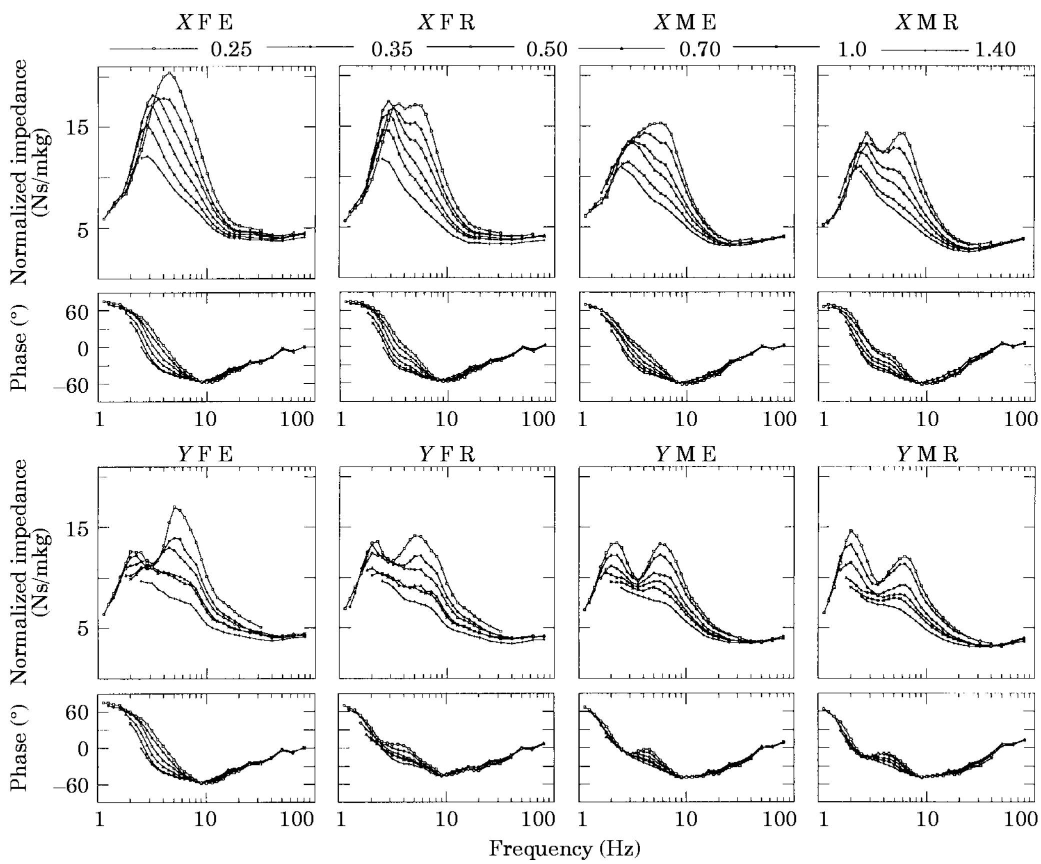

Figure 3. Mean values for each acceleration level and upper body posture, erect (E) or relaxed (R), separated into males (M) and females (F) for both directions (X) and (Y).

TABLE 2

Mean values and standard deviations (within parentheses) for the normalized impedance and phase angles at different frequencies for 0·5 m/s² in the X direction with relaxed upper body posture

Frequency (Hz)	Normalized impedance						Phase angle (°)					
	Female $n=15$		Male $n=15$		All $n=30$		Female $n=15$		Male $n=15$		All $n=30$	
1·6	7·62	(1·20)	7·99	(2·00)	7·80	(1·63)	64	(13)	57	(14)	62	(13)
1·8	9·03	(1·51)	9·72	(3·01)	9·38	(2·37)	66	(10)	49	(19)	56	(18)
2	11·06	(1·85)	11·04	(2·78)	11·05	(2·32)	58	(14)	36	(24)	47	(22)
2·26	14·23	(3·02)	12·29	(1·96)	13·26	(2·69)	47	(15)	24	(29)	36	(26)
2·5	16·53	(3·50)	13·28	(2·88)	14·90	(3·56)	32	(18)	9	(29)	21	(26)
2·83	17·47	(3·30)	13·28	(4·01)	15·37	(4·19)	11	(21)	−6	(25)	3	(24)
3·15	16·91	(3·25)	12·34	(3·70)	14·63	(4·14)	−3	(20)	−16	(20)	−10	(20)
3·56	15·52	(3·54)	11·37	(3·54)	13·44	(4·07)	−14	(18)	−21	(16)	−17	(17)
4	14·30	(3·13)	10·91	(3·36)	12·60	(3·62)	−19	(15)	−25	(15)	−22	(15)
4·5	13·67	(3·26)	10·78	(3·07)	12·22	(3·44)	−23	(16)	−28	(16)	−25	(16)
5	13·55	(3·55)	10·73	(3·21)	12·14	(3·62)	−30	(14)	−34	(16)	−32	(15)
5·7	12·79	(3·76)	10·43	(3·54)	11·61	(3·79)	−40	(11)	−44	(12)	−42	(12)
6·3	11·83	(3·64)	9·88	(3·46)	10·86	(3·63)	−45	(9)	−49	(10)	−47	(10)
7·1	10·57	(3·37)	8·87	(3·19)	9·72	(3·34)	−51	(8)	−56	(8)	−53	(8)
8	9·35	(2·86)	7·91	(2·83)	8·63	(2·89)	−55	(5)	−59	(6)	−57	(6)
9	8·20	(2·43)	6·96	(2·52)	7·58	(2·51)	−57	(5)	−62	(5)	−59	(5)
10	7·32	(2·14)	6·20	(2·26)	6·76	(2·24)	−56	(5)	−60	(5)	−58	(5)
11·3	6·28	(1·83)	5·43	(1·97)	5·85	(1·92)	−54	(5)	−60	(5)	−57	(5)
12·5	5·67	(1·67)	4·90	(1·77)	5·28	(1·73)	−51	(6)	−58	(4)	−54	(6)
14·3	5·04	(1·49)	4·21	(1·50)	4·63	(1·53)	−47	(8)	−55	(5)	−51	(8)
16	4·63	(1·36)	3·78	(1·34)	4·20	(1·39)	−38	(10)	−48	(7)	−43	(10)
18	4·40	(1·18)	3·41	(1·25)	3·90	(1·29)	−36	(10)	−45	(7)	−40	(10)
20	4·34	(1·04)	3·20	(1·23)	3·77	(1·26)	−33	(9)	−41	(8)	−37	(9)
25	4·24	(1·02)	2·92	(1·18)	3·58	(1·27)	−23	(10)	−24	(8)	−24	(9)
31·5	4·13	(0·91)	3·06	(1·32)	3·60	(1·24)	−21	(11)	−15	(11)	−18	(11)
40	4·14	(0·80)	3·27	(1·48)	3·70	(1·25)	−14	(12)	−6	(11)	−10	(12)
50	4·17	(0·76)	3·51	(1·53)	3·84	(1·23)	−2	(10)	5	(10)	1	(11)
63	4·33	(0·64)	3·71	(1·42)	4·02	(1·13)	−8	(10)	0	(10)	−4	(11)

vibration, 1·4 m/s². A Wilcoxon matched pairs signed rank sum test was performed on the posture dependent data. The test showed a clear posture dependency (see Table 5). Generally, significant differences were found throughout the whole frequency range above 3–4 Hz. An exception occurred at 1·0 m/s² r.m.s. for males in the *Y* direction where the only significance was found at 2·5 Hz. The rank test showed that the erect posture in most cases had a higher *NMI* than the relaxed posture.

5. DISCUSSION

The results from this study show that the mechanical impedance of the human body is dependent on a number of factors, such as frequency, vibration level, body weight and gender. Generally, it applies for both directions that the *NMI* increases with frequency up to a first peak around 2–4 Hz; this is probably strongly related to the biomechanical characteristics of the spine and upper body. For the *Y* direction one additional peak, in the range 5–7 Hz, is in most cases discernible. This peak is probably caused by other body parts such as the head, shoulder and arm, chest and abdomen. One interesting finding in the Y direction is that the first peak is more distinct for male subjects than for females, who have their highest impedance magnitude at the second peak. This was also the case for an earlier study in the Z direction [13].

NMI magnitude has a clear vibration level dependency at low frequencies. One interesting observation is that the human body seems to respond as a two-mass system at lower vibration levels but as a one-mass system at higher levels, especially for the Y direction. This may be due to the muscle activity in the abdomen and along the spine. It has been shown that there is a difference in the reaction time for the muscles along the spine [14], which can therefore alter the biomechanical response of the human body. Statistical analysis indicates that there are significant differences with respect to gender (see Table 4) and posture (see Table 5). It is also obvious that the *NM*I spectra for the X and Y directions have different shapes. The direction differences found support the idea of treating the two directions differently, for instance, with respect to risk assessments and

TABLE 3

Mean values and standard deviations (within parentheses) for the normalized impedance and phase angles at different frequencies for $0{\cdot}5\,m/s^2$ in the Y-direction with relaxed upper body posture

Frequency (Hz)	Normalized impedance: Female $n = 15$		Normalized impedance: Male $n = 15$		Normalized impedance: All $n = 30$		Phase angle (°): Female $n = 15$		Phase angle (°): Male $n = 15$		Phase angle (°): All $n = 30$	
1·6	10·37	(1·25)	10·74	(1·98)	10·55	(1·64)	41	(13)	28	(22)	35	(19)
1·8	11·67	(1·69)	11·26	(1·47)	11·47	(1·57)	31	(16)	14	(22)	22	(21)
2	12·41	(1·65)	11·49	(1·94)	11·95	(1·83)	23	(16)	1	(21)	12	(21)
2·26	12·18	(1·76)	10·78	(2·77)	11·48	(2·39)	13	(16)	−9	(19)	2	(20)
2·5	12·14	(2·47)	10·09	(2·96)	11·12	(2·87)	6	(15)	−15	(18)	−5	(20)
2·83	11·91	(2·86)	9·01	(2·74)	10·46	(3·12)	−2	(15)	−18	(16)	−10	(17)
3·15	11·31	(2·88)	8·59	(2·28)	9·95	(2·90)	−7	(14)	−18	(15)	−12	(15)
3·56	11·18	(2·89)	8·28	(1·81)	9·73	(2·79)	−9	(12)	−16	(14)	−13	(13)
4	10·90	(2·14)	8·51	(1·81)	9·71	(2·30)	−14	(12)	−17	(13)	−15	(12)
4·5	10·86	(1·92)	8·76	(2·00)	9·81	(2·20)	−16	(11)	−19	(14)	−18	(12)
5	10·77	(1·92)	8·90	(2·21)	9·84	(2·25)	−20	(11)	−22	(15)	−21	(13)
5·7	10·77	(2·29)	9·23	(2·87)	10·00	(2·67)	−28	(11)	−29	(15)	−28	(13)
6·3	10·23	(2·35)	9·27	(3·41)	9·75	(2·92)	−31	(9)	−34	(13)	−32	(11)
7·1	9·89	(1·93)	8·86	(3·71)	9·38	(2·95)	−35	(9)	−42	(9)	−38	(10)
8	9·22	(1·93)	7·90	(3·22)	8·56	(2·69)	−41	(9)	−46	(6)	−44	(8)
9	8·26	(1·82)	7·05	(2·73)	7·65	(2·36)	−46	(8)	−49	(5)	−48	(7)
10	7·32	(1·63)	6·42	(2·39)	6·87	(2·06)	−45	(7)	−47	(5)	−46	(6)
11·3	6·58	(1·43)	5·83	(2·07)	6·20	(1·79)	−44	(5)	−46	(4)	−45	(5)
12·5	6·04	(1·00)	5·45	(1·77)	5·75	(1·44)	−40	(5)	−45	(5)	−43	(5)
14·3	5·78	(1·02)	4·89	(1·59)	5·33	(1·39)	−38	(5)	−45	(7)	−41	(7)
16	5·51	(1·24)	4·46	(1·50)	4·98	(1·45)	−34	(4)	−41	(6)	−37	(6)
18	5·20	(1·19)	4·11	(1·38)	4·65	(1·38)	−35	(5)	−40	(8)	−38	(7)
20	4·91	(1·05)	3·92	(1·37)	4·41	(1·30)	−35	(6)	−40	(9)	−37	(8)
25	4·52	(1·01)	3·52	(1·41)	4·02	(1·31)	−26	(8)	−29	(11)	−27	(10)
31·5	4·20	(0·94)	3·28	(1·56)	3·74	(1·35)	−24	(9)	−24	(11)	−24	(10)
40	4·01	(0·81)	3·20	(1·80)	3·60	(1·43)	−14	(10)	−13	(11)	−13	(10)
50	4·05	(0·77)	3·28	(2·06)	3·66	(1·58)	−2	(9)	4	(11)	1	(10)
63	4·22	(0·71)	3·63	(2·08)	3·93	(1·56)	−3	(8)	6	(12)	1	(11)

TABLE 4

ANOVA *results from a gender dependency test*; *the data are separated into erect and relaxed postures in the X and Y directions*; 0·25, 0·35, 0·50, 0·70, 1·0 *and* 1·4 *denote acceleration levels in* m/s^2 r.m.s. *the numbers in the table indicate p-values* ($- = p > 0{\cdot}05$, $1 = p < 0{\cdot}05$, $2 = p < 0{\cdot}01$ *and* $3 = p < 0{\cdot}001$)

	Erect posture												Relaxed posture											
	X						*Y*						*X*						*Y*					
Frequency (Hz)	0·25	0·35	0·50	0·70	1·0	1·4	0·25	0·35	0·50	0·70	1·0	1·4	0·25	0·35	0·50	0·70	1·0	1·4	0·25	0·35	0·50	0·70	1·0	1·4
1·13	–						–						–						–					
1·25	–	–					–	–					–	1					–	–				
1·4	–	–					–	–					–	–					–	–				
1·6	–	–	–				–	–	–				–	–	–				–	–	–			
1·8	–	–	–	–			–	–	–	–			–	–	–	–			–	–	–	–		
2	–	–	–	–	1		–	–	–	–	–		–	1	–	–	–		–	–	–	1	–	
2·26	–	–	–	–	2		–	–	–	–	–		–	–	1	–	1		–	–	–	–	1	
2·5	–	–	1	2	3	–	–	–	–	–	1	–	–	2	2	2	2	–	–	–	1	1	1	1
2·83	–	1	3	2	2	–	–	–	–	–	2	–	–	1	2	2	3	–	–	–	2	–	1	1
3·15	2	2	3	2	2	–	–	–	1	–	2	–	1	2	2	2	3	–	–	1	2	–	1	–
3·56	2	2	3	1	1	–	1	1	2	1	1	–	2	1	2	2	2	–	1	1	2	–	–	–
4	3	1	2	1	–	–	2	2	3	–	–	–	2	1	2	2	2	–	2	–	2	–	–	–
4·5	3	1	1	–	–	–	3	2	2	–	–	–	2	–	1	1	1	–	2	–	2	–	–	–
5	2	–	1	–	–	–	3	1	1	–	–	–	1	–	1	1	1	–	2	–	1	–	–	–
5·7	–	–	–	–	–	–	1	–	–	–	–	–	–	–	–	–	1	–	–	–	–	–	–	–
6·3	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
7·1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
8	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
9	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
10	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
11·3	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
12·5	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
14·3	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
16	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	–	–	–
18	–	–	–	–	–	–	1	–	–	–	–	–	–	–	1	1	1	1	–	–	1	–	–	–
20	1	–	1	1	–	1	1	–	–	–	–	–	1	1	1	2	2	2	1	–	1	–	–	–
25	2	1	2	2	–	–	1	–	–	–	–	–	1	–	2	2	2	2	1	–	1	–	–	–
31·5	1	–	1	1	–	–	–	–	–	–	–	–	1	–	1	2	1	1	–	–	–	–	–	–
40		–	–	–	–	–		–	–	–	–	–		–	–	2	–	–		–	–	–	–	–
50			–	–	–	–			–	–	–	–			–	–	–	–			–	–	–	–
63			–	–	–	–			–	–	–	–			–	–	–	–			–	–	–	–
80				–	–	–				–	–	–				–	–	–				–	–	–

TABLE 5

Wilcoxon matched pairs signed rank sum test results from a posture dependency test; the data are separated in the X and Y directions for females and males; 0·25, 0·35, 0·50, 0·70, 1·0 *and* 1·4 *denote acceleration levels in* m/s^2 r.m.s.; *the numbers in the table indicate p-values* ($- = p > 0·05$, $1 = p < 0·05$, $2 = p < 0·01$ *and* $3 = p < 0·001$).

	X direction												Y direction											
	Females						Males						Females						Males					
Frequency (Hz)	0·25	0·35	0·50	0·70	1·0	1·4	0·25	0·35	0·50	0·70	1·0	1·4	0·25	0·35	0·50	0·70	1·0	1·4	0·25	0·35	0·50	0·70	1·0	1·4
1·13	–						1						1						–					
1·25	–	–					–	1					1	–					–	–				
1·4	–	–					–	1					1	1					–	–				
1·6	–	–	–				–	–	–				–	2	–				–	2	1			
1·8	–	–	–	–			–	–	–	–			1	1	–	–			1	1	–	–		
2	–	–	–	–	–		–	–	–	–	–		–	1	–	–	–		1	–	–	–	–	
2·26	–	1	–	–	–		–	–	–	–	–		–	–	–	–	–		–	–	–	–	–	
2·5	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	–	1
2·83	–	–	–	–	–	–	–	–	–	1	1	–	–	–	–	–	2	–	–	–	–	–	1	1
3·15	–	–	1	2	–	2	–	–	2	2	2	2	–	–	–	2	2	–	–	–	–	–	–	2
3·56	1	1	2	3	–	2	1	1	2	3	2	3	–	–	–	3	2	–	–	–	1	–	–	2
4	3	2	3	3	2	2	2	2	3	3	2	3	–	2	2	3	2	2	–	–	2	1	–	2
4·5	3	1	3	3	1	3	2	2	2	2	2	2	2	3	3	3	2	2	–	–	2	1	–	2
5	3	–	1	2	–	2	2	1	2	2	2	2	2	3	3	2	2	1	2	1	2	2	–	2
5·7	–	–	–	2	–	2	–	–	1	2	2	2	3	2	3	3	3	1	1	1	2	2	–	3
6·3	–	1	–	2	–	2	–	1	2	2	2	3	3	2	2	3	2	–	1	–	2	2	–	3
7·1	–	1	–	2	1	3	1	1	2	3	2	2	3	2	2	2	3	2	1	–	2	2	–	3
8	1	1	2	3	1	3	1	1	2	3	3	3	2	1	2	2	2	2	1	1	2	2	–	3
9	2	1	2	3	2	3	–	1	2	3	3	3	2	1	2	3	2	2	2	1	2	3	–	3
10	2	1	1	3	2	3	1	2	2	3	3	3	2	–	2	3	2	1	2	1	2	2	–	3
11·3	2	1	1	3	2	3	1	2	2	3	2	3	1	–	1	2	2	1	2	1	3	2	–	3
12·5	1	1	1	3	2	2	1	2	2	3	2	3	1	–	1	2	1	1	1	–	2	1	–	2
14·3	1	1	1	3	1	3	1	1	2	3	3	3	2	–	–	2	1	1	1	–	2	1	–	2
16	1	1	1	3	1	3	1	2	2	3	2	3	2	–	–	1	–	1	–	–	1	1	–	3
18	1	1	1	2	1	3	1	2	2	3	2	3	1	–	–	2	–	1	–	–	3	1	–	3
20	1	1	1	2	2	3	1	1	2	3	2	3	2	–	1	2	–	2	–	–	3	2	–	3
25	1	1	1	3	2	3	–	–	2	2	1	3	2	1	2	2	2	2	1	–	2	2	–	3
31·5	1	1	1	2	2	2	1	1	2	2	1	2	1	–	2	1	2	3	1	–	3	2	–	3
40		2	–	2	2	3		1	1	2	2	1		1	1	–	1	2		–	2	2	–	2
50			–	–	1	2			–	1	1	–			–	–	–	2			2	2	–	1
63			1	2	2	3			–	1	1	1			–	–	2	2			–	1	–	–
80				2	3	3				2	–	–				–	1	1				1	–	–

the development of preventative measures. The difference between X and Y directions become even more obvious when adding a backrest [10].

To the authors' knowledge only a few studies have addressed the mechanical impedance and its relation to posture, particularly in the horizontal direction. In ISO 5982 [12] only the Z direction mechanical impedance is described in the sitting posture. Some investigations have shown a variety of effects due to posture in the Z direction [15–17]. One reason for this might be the problem with posture control for subjects, as discussed by Sandover [18]. A situation which has not been included here is sitting with the back supported by a backrest. Fairley and Griffin [10] have shown that there are differences in the responses (apparent mass) to X direction vibration with and without a backrest. This difference is larger than any other change in posture. The two postures used here can be called extremes of sitting and might be the reason for the significant differences found in this study. With a smaller change in posture such differences might not be so obvious. Postures such as twisting and looking over the shoulder are also of great interest because with such postures the muscles and joints are at their maximum stretch so that movement beyond this point might cause injury [19].

One reason for the gender difference might be the differences in body structure and fat distribution between females and males. Another factor could be the difference in muscle strength capacity, in which females on average are "weaker" compared to males with the same total body weight. It has been pointed out that breast support might influence the mechanical impedance of the female subjects. Therefore, a pilot study was performed testing a few female subjects with and without breast support. The outcome did not show any significant differences.

The results indicate that the mean *NMI* decreased with increasing vibration level in the whole frequency range. Exceptions occurred for the female group at 0·7 and 1·0 m/s^2 in the Y direction (see Figure 3). The impedance increased in dependency on the biodynamical characteristics of body parts adjacent to the vibrating source with increasing frequency. As the level of vibration increases so the impedance peaks decrease in magnitude. Furthermore, peaks are consequently shifted towards lower frequencies within the impedance spectra.

In Figure 3 the phase between the force and velocity is shown as a function of frequency. The phase decreases in the range of 2–12 Hz, after which it increases again. In the range of 4–12·5 Hz the phase is affected by the vibration level in a similar way to the impedance magnitude; i.e., an increasing vibration level leads to a decreasing phase value.

In order not only to simplify comparisons of results from different studies, but also to increase the usefulness of impedance data, it is recommended that impedance data should be presented as normalized values with respect to the static weight. For a seated person it is suggested that the static weight measured at the interface between the seat and person is used. Another possibility is to use a measure of the upper body structure including the sitting height; e.g., normalization with the quotient of sitting weight and square of sitting height. Because of the similarity with the body mass index (*BMI*) it could be denoted as the upper body mass index (*UBMI*). One advantage would be that a 0·75 m and 50 kg (index = 89) person is separated from a 1·00 m and 50 kg (index = 50) person. The difference in upper body height would be likely to cause differences in mechanical impedance. Due to the fact that the sitting height was not measured in this study, it was not possible to test this normalization method.

The human body is in most cases supported by a backrest and in many cases also an arm rest, when driving a vehicle. Moreover, the body is also subjected to multi-directional vibration. Therefore, it is planned to investigate the effects of these factors on the mechanical impedance in forthcoming experiments. The aim is to explore the possibility of calculating an estimate of the mechanical impedance during driving based on laboratory data.

ACKNOWLEDGMENTS

The financial support by the Swedish Council for Work Life Research is gratefully acknowledged (Project: 94-0026). We would also like to thank Research Engineer Lennart Lindberg for his assistance in the laboratory.

REFERENCES

1. E. CHRIST, H. BRUSL, P. DONATI, M. GRIFFIN, B. HOHMANN, R. LUNDSTRÖM, J. MEYER and H. STRAATSMA 1989 *International Section "Research", Institut National de Recherche et de Securité (INRS)*, Paris. Vibration at work.
2. H. DUPUIS and G. ZERLETT 1986 *The effects of whole-body vibration*. Berlin: Springer-Verlag.
3. M. J. GRIFFIN 1990 *Handbook of human vibration*. London: Academic Press.
4. C. HULSHOF and v. B. V. ZANTEN 1987 *International Archives of Occupational and Environmental Health* **59**, 205–220. Whole-body vibration and low-back pain—a review of epidemiological studies.
5. A. KJELLBERG, B. O. WIKSTRÖM and U. LANDSTRÖM 1994 *Arbete och Hälsa* **41**, 1–63. Injuries and other adverse effects of occupational exposure to whole-body vibration.
6. M. L. MAGNUSSON 1991 *Doctoral dissertation from the Division of Occupational Orthopaedics, Department of Orthopaedics, University of Göteborg and Sahlgrenska Hospital, Gothenburg, Sweden*. Effects of seated whole body vibrations on the spine.
7. M. H. POPE, M. I. V. JAYSON, A. D. BLANN, A. M. KAIGLE, J. N. WEINSTEIN and D. G. WILDER 1994 *European Spine Journal* **3**, 143–145. The effect of vibration on back discomfort and serum levels of von Willebrand factor antigen: a preliminary communication.
8. J. SANDOVER 1988 *Clinical Biomechanics* **3**, 249–256. Behaviour of the spine under shock and vibration: a review.
9. H. SEIDEL and R. HEIDE 1986 *International Archives of Occupational and Environmental Health* **58**, 1–26. Long-term effects of whole-body vibration: a critical survey of the literature.
10. T. E. FAIRLEY and M. J. GRIFFIN 1990 *Journal of Sound and Vibration* **139**, 299–306. The apparent mass of the seated human body in the fore-and-aft and lateral directions.
11. M. H. POPE and J. E. NOVOTNY 1993 *Journal of Biomechanical Engineering* **115**(4B), 569–574. Spinal biomechanics.
12. ISO 5982 1991 *International Standardization Organization*, Geneva. Human exposure to mechanical vibration and shock.
13. P. HOLMLUND, R. LUNDSTRÖM and L. LINDBERG 1997 Mechanical impedance of the human body in the vertical direction. (submitted for publication).
14. D. G. WILDER, A. R. ALEKSIEV, M. L. MAGNUSSON, M. H. POPE, K. F. SPRATT and V. K. GOEL 1996 *Spine* **22**, 2628–2639. Muscle activity during sudden load.
15. R. R. COERMAN 1962 *Human Factors* **4**, 227–253. The mechanical impedance of the human body in sitting and standing position at low frequencies.
16. T. MIWA 1975 *Industrial Health* **13**(1–2), 1–22. Mechanical impedance of human body in various postures.
17. T. E. FAIRLEY and M. J. GRIFFIN 1989 *Journal of Biomechanics* **22**, 81–94. The apparent mass of the seated human body: vertical vibration.
18. J. SANDOVER 1982 *Ph.D. thesis at Loughborough University of technology*. Measurement of the frequency response characteristics of man exposed to vibration.
19. M. A. ADAMS and W. C. HUTTON 1981 *Spine* **6**, 241–247. The relevance of torsion to the mechanical derangement of the lumbar spine.