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A study of vibration characteristics on a luxury wheelchair and a new prototype wheelchair

I. Hostens[a,*], Y. Papaioannou[b], A. Spaepen[b], H. Ramon[a]

[a] *Laboratory for Agro-Machinery and Processing, Katholieke Universiteit Leuven, Kasteelpark Arenberg 30, 3001 Leuven, Belgium*

[b] *Laboratory of Ergonomics and Occupational Biomechanics, Katholieke Universiteit Leuven, Tervuursevest 101, 3001 Leuven, Belgium*

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Abstract

The transmission of wheelchair vibrations to the body will influence comfort, performance and the long-term health of the user. Improved knowledge of vibration transmissibility and its variability enhances our understanding of various human responses to vibration. In this study, an outdoor experiment and an experiment with vibration simulation using two wheelchairs (high-quality models of a new prototype wheelchair taken from two different stages of the iterative production procedure) were performed. The study confirms that the human body is very sensitive to the frequency range of 0.5–10 Hz, as found in the literature. Both wheelchairs equipped with passive suspension system did not perform adequately in this frequency range and even amplified the input signal at the resonance frequency (3–4.5 Hz). As the risk of physical damage is not likely to improve with these wheelchair suspension systems, the future depends on new designs with higher low-frequency comfort and affordable additional costs.

1. Introduction

All on- and off-road vehicles are exposed to vibrations caused by unevenness of the road or soil profile and by moving elements within the machine. The consequences are reduction in vehicle lifetime, driving precision and driving comfort. This trend is also noticeable for wheelchair systems and assisting technology vehicles. There exist over 700 different types of wheelchair today [1]. The overall wheelchair market in Europe today is estimated in 400 000 pieces per annum,

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*Corresponding author. Tel.: +32-16-32-14-44; fax: +32-16-32-19-94.

E-mail address: ivo.hostens@agr.kuleuven.ac.be (I. Hostens).

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whereas the relevant US Market is around 250 000 pieces per annum, 10% of which are electric ones [2]. However, most of the above are based on a standard set of technical specifications, trying to enhance the speed, autonomy, comfort and aesthetic elements while keeping the price low. As long as no further insight is gained into the wheelchair–human relationship, there will be no real need to develop any new methodology, as development within this field of specifications has been established for decades now.

The transmission of vibration to the human body will have a large influence on comfort, performance and health. Many factors influence the transmission of vibration to and through the body. Being a dynamic system, the transmission associated with it will depend on the frequency and direction of the input motion. Transmissibility of vibration will differ between individuals. The transmissibility will also depend on the characteristics of the seat from which the vibration exposure is received. Vibration within the frequency range up to 12 Hz affects the whole human organism, while the vibrations above 12 Hz have only a local effect. Low-frequency (4–6 Hz) cyclic motions like those caused by a vehicle's tyres rolling over an uneven road can put the body into resonance. Just one hour of seated vibration exposure can cause muscle fatigue, weaken the soft tissues and make a user more susceptible to back injury. Vibration attenuating seats and correct ergonomic layout of vehicle interior may reduce the risk of recurrence [3].

There are some studies that suggest that unexpected load is etiologic for low back pain [4–6]. When a sudden load is applied, the muscles respond rapidly to stabilize the body, which leads to overcompensation of the muscles. It was hypothesized that subjects who had been exposed to whole-body vibration would show a larger latency of response and a greater response amplitude [7]. When the motion of a vehicle includes "shocks" or impulsive velocity changes, root mean square (r.m.s.) acceleration has no relation to crew comfort or injury. Existing (r.m.s.g) methods of ride assessment can show lethal accelerations as being perfectly safe, and vice versa. It follows that r.m.s. acceleration is not meaningful for non-sinusoidal "random" vibration either [8].

Wheelchairs suitable for outdoor use are exposed to vibration coming from a variety of different road surfaces. Knowing better these different vibration inputs and the human response is useful in defining the vibration problem and in initiating the finding of solutions.

2. Test set-up

2.1. Outdoor vibration experiment

In this study, a high-quality prototype wheelchair (TRANSWHEEL: DE3013 an EU sponsored and partly funded project (DGXIII, Technology Initiative for Elderly and Disabled)), suitable for outdoor use is tested for vibration characteristics while driving on asphalt and uneven paved road surfaces with the maximum allowable speed of 6.5 km/h. The propulsion comes from the electric motor of the wheelchair. The wheelchair is equipped with a suspension system consisting of four springs, one above each wheel. They are positioned in the vertical position. The wheels are 30 cm in diameter with full rubber tyres. Vertical and fore and aft vibration acceleration data were taken under the suspension next to the wheelbase, immediately above the suspension on the left and right sides, directly under the seat cushion where the vibrations enter the human body and on the chest of the driver. To optimize the measurement of vibrations transmitted to the chest a rubber plate, with dimensions $15 \times 15 \times 0.4\ \text{cm}^3$ and firmly attached to the chest with wide tape (going all around the upper body), with the accelerometers secured on top, was applied. Capacitive sensors (Kistler type K.-beam No. 8303A2, sensitivity: 0.5 V/g, frequency range: 0–150 Hz) were used. The raw data were amplified and analogue filtered with cutoff frequency 100 Hz and sampled at 200 Hz. Two road types were used for the tests: a smooth asphalt road and a rough paved road. Two subjects of different body anthropometry volunteered for the tests. This pilot study assesses suitable vibration characteristics for subject and road surface comparison. Another purpose will be served by investigating the transmission of vibration within specific frequency bands from under the suspension to the seat and to the subject. The performance of the wheelchair suspension in relation to frequencies of interest can be evaluated.

2.2. *Simulated vibration experiment*

In the framework of the TRANSWHEEL project, a new prototype wheelchair was developed, suitable for outdoor use and with a crash-proof anchoring system to fix the wheelchair in a car. For this latter, specific adaptations had to be made as there are smaller wheels (diameter 15 cm), lightweight and a single passive suspension system for the whole wheelchair. The suspension system consists of an airspring and a hydraulic damper and is placed under the seat. The relative motion is restricted with a scissor system. As it was not possible to make outdoor measurements with this prototype, vibrations were simulated on an electro-hydraulic vibration platform. A sweptsine with linear increasing frequency (0.7–20 Hz) with an approximately constant acceleration of $0.5\boldsymbol{g}$, was enforced to the wheelchair in the vertical direction. Although not completely representative for the real inputs on the road, it gives useful information on the system performance. The same capacitive accelerometers as for the outdoor experiment are used for vertical vibration data acquisition on the wheelchair. For safety reasons, a car crash dummy (standard 50 percentile male) is used as sitting object. With only the wheelchair wheels tied down to the vibration platform, the transfer of vibration to the driver is examined. With the wheelchair entirely strapped down to the platform with safety belts, the transportation of the wheelchair in car, bus or train is simulated. The purpose is to investigate vibration transmission from the vibration source to the point of entering the body. The measurement of vibration at a body–seat interface requires that transducers are located between body and seat. The accelerometers must move with the interface, they must not alter the dynamic properties of either the seat or the body and they must offer little impedance to movement over the frequency range of interest. The rigid device used is the seat interface for transducers indicating body acceleration received (SIT-BAR). It is contoured such that it will compress the seat in a similar way, as do human buttocks [9]. It is mostly used in fundamental studies of human response to vibration. This SIT-BAR was not used in the outdoor measurements with the old prototype because the very rigid foam cushion used would not change the transmission of vibration much. In the new wheelchair, a 10 cm thick air-based cushion with low stiffness was used, having a larger attenuating effect.

3. Data processing

3.1. Outdoor vibration experiment

No ISO 2631/1 standard r.m.s. values [10] and BS 6841 vibration dose value (VDV) [11] are calculated.

The data are processed both in the time and frequency domains. In the time domain, a histogram is made of the raw vibration data consisting of gravity classes (**g**) and their respective percentage distribution to find useful characteristics. A Gauss curve is fitted on the normally distributed histogram. One characteristic extracted is the standard deviation as a measure of the percentage of occurrence of vibration inputs with higher magnitudes. Another characteristic is the surface under the histogram as a measure that correlates to the total of the accelerations experienced per unit of time by the human subject. Due to the percentage distribution, these Gauss characteristics can be considered as averages for certain vibration inputs and are not influenced by the parameter time as seen in Fig. 1. For frequency domain representation the power spectral densities (PSDs) S_{xx} and S_{xy} (with x input and y output) are calculated.

3.2. Simulated vibration experiment

The input data are the 0.7–20 Hz sweptsine and the output data are the response of the wheelchair frame immediately above the suspension and the SIT-BAR information. The PSDs (S_{xx} and S_{xy}) are calculated and are compared between points of measurement for the vertical direction. Also extracted are the transfer function $H(j\omega)$ and coherence function $\gamma(j\omega)$ for

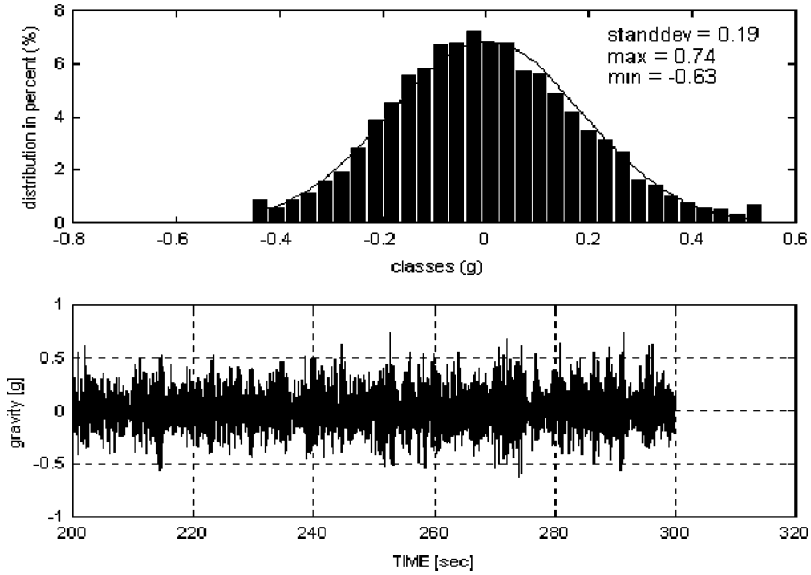

Fig. 1. Top: Gauss curve fitted on time-independent histogram of vertical acceleration data; below: original vibration signal, taken in the vertical direction on the wheel base of the wheelchair.

single-input systems using the following non-parametric formulae:

$$H(\mathrm{j}\omega) = \frac{S_{xy}(\mathrm{j}\omega)}{S_{xx}(\omega)} \tag{1}$$

with $S_{xy}(\mathrm{j}\omega)$ the cross-spectral density with x the input and y the output vibration acceleration:

$$\gamma(\mathrm{j}\omega) = \frac{abs(S_{xy}(\mathrm{j}\omega))}{S_{xx}(\omega)}. \tag{2}$$

4. Results

4.1. Outdoor vibration experiment

Comparing the Gauss characteristics for the rough road surface, the suspension appears to be effective in attenuating the vibration inputs in general but not so effective in attenuating the vibrations responsible for the high energy content of the chest. In Fig. 2, driving on the smooth road surface the suspension seems highly ineffective in attenuating the vibrations going to the chest. To investigate this further in Fig. 3 the differences, seen from the histogram characteristics, for the rough and smooth road surface are shown again on the power spectra, calculated for both road surfaces. The unit is 20 log 10 (W/Hz), which means that the value of 0 in the power spectrum stands for 1 W/Hz.

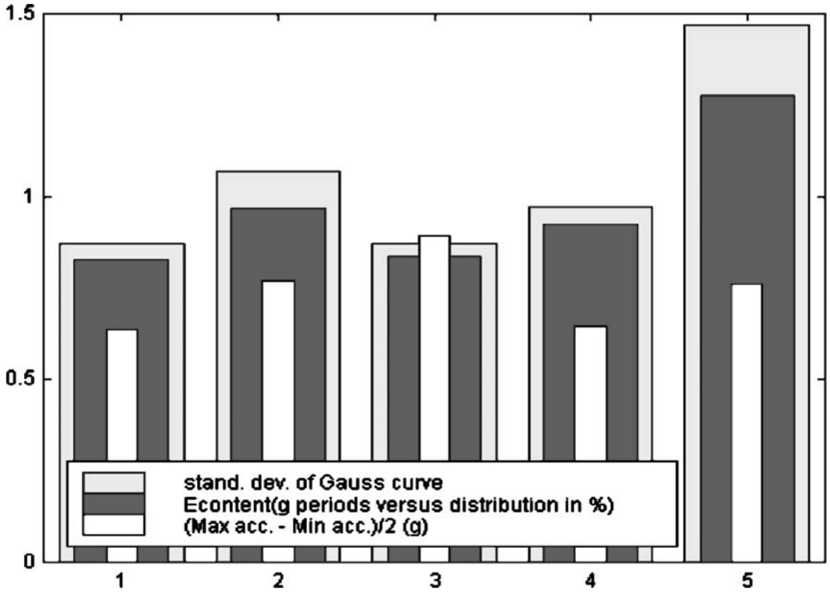

Fig. 2. Gauss characteristics (standard deviation, energy content, min–max range) of vibration histogram vertical acceleration data taken on a smooth road surface: (1) under the suspension; (2) above suspension (left side); (3) above suspension (right side); (4) under the seat; (5) on the chest.

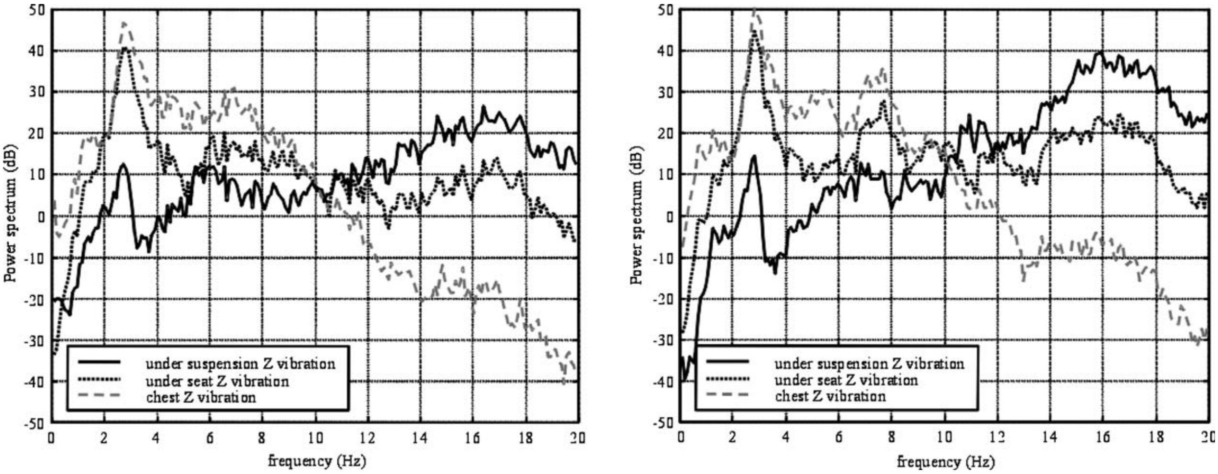

Fig. 3. Power spectra of vertical vibration data measured under the suspension, above the suspension before entering the human body and on the chest while driving a wheelchair on a smooth surface (left plot) and a rough surface (right plot). Differences between the plots are mainly observed for frequencies above 10 Hz.

Comparing the two spectral plots it is clear that the vibration input above 10 Hz is higher for the rough road surface. On the other hand, this has no effect on the response of the chest for these frequencies. Because the histogram characteristics are taken for the whole frequency range (0–20 Hz) the frequencies above 10 Hz gloss over the real influence of the suspension system. The human body and especially the backbone are sensitive to the frequency range of 0.5–10 Hz for severe physical damage after long-term vibration exposure [12,13]. The attenuation of the vibration inputs in this frequency range (0.5–10 Hz) is poor irrespective of the road condition. The spectra demonstrate that the suspension system is very effective in attenuating the vibration inputs above 10 Hz, but amplifies the vibration under 10 Hz with a resonance frequency at 3 Hz. The chest, however, not only follows the input signal but even amplifies it at 2.5–8 Hz.

The transmission of horizontal vibration may be expected to vary with frequency in a manner different from the transmission of vertical vibration. Lewis and Griffin [14] found that, without a backrest, the transmission of fore and aft and lateral seat vibration to the head was mainly restricted to low frequencies. The addition of a backrest greatly increased translational and rotational head motion at all frequencies with both axes of translational seat vibration. The entering vibration inputs for the fore and aft direction in Fig. 4 shows higher amplitudes until 14 Hz for the smooth road surface.

The chest spectrum for the rough surface peaks higher in the 2 Hz area, although vibration input is lower and suspension attenuation is similar. This confirms a study of Paddan and Griffin [15,16] which concluded that seat-to-head transmissibilities associated with vertical seat vibration were presented at frequencies up to 25 Hz for all six axes of head vibration both with and without a backrest. The study performed here is a methodological introduction to vibration characteristics of wheelchairs. The two male subjects participating in the tests are chosen to have similar anthropometry trends towards the mesomorph. More test population is required for statistical significance of the above findings.

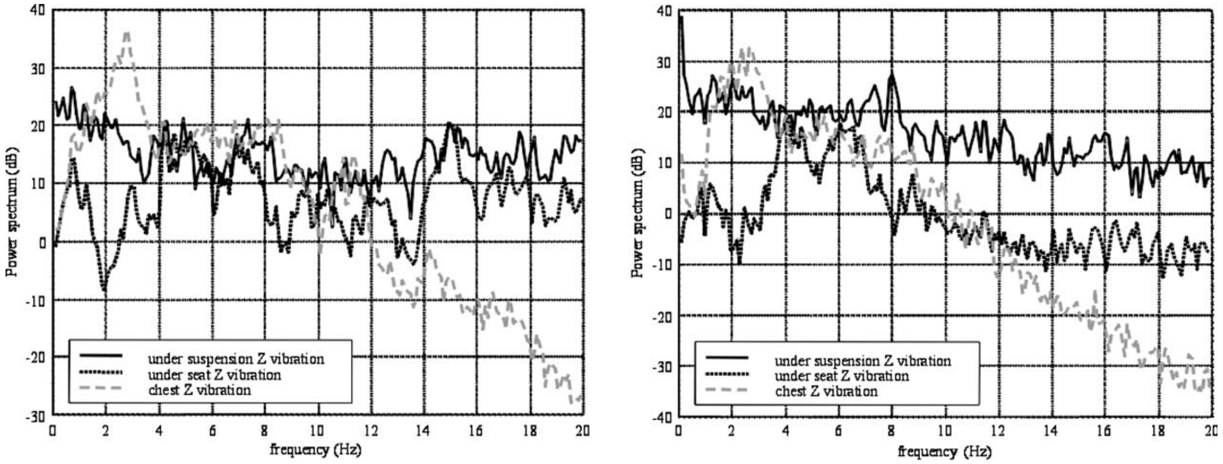

Fig. 4. Power spectra of fore and aft vibration data measured under the suspension, above the suspension before entering the human body and on the chest while driving a wheelchair on a smooth surface (left plot) and a rough surface (right plot). Differences are mainly observed around 2 Hz.

4.2. Simulated vibration experiment

Because of the very controlled input of vibration using the electro-hydraulic platform, the transfer function for the enforced 0.7–20 Hz sweptsine is very reliable. The coherence function shows a linear relationship between input (vertical accelerations of platform) and output (vertical accelerations of wheelchair above the suspension and on the seat using the SIT-BAR). This stands for frequencies above 2.5–3.5 Hz with coherence values higher than 0.85 and for both different tie down methods used here. This can be seen in Fig. 5. Contributions of the lower frequencies are less present in the sweptsine and this lower energy input is partly responsible for the lower reliability of the transfer function in these frequency bands.

Vibration spectra of the wheelchair above the suspension system and on the seat–human interface (SIT-BAR) can be plotted against the spectrum of the input vibration (20 Hz sweptsine). Under 3.5 Hz, no reliable information was drawn. If the output signal is taken from the wheelchair frame the resonance frequency of the suspension is clearly noticeable at 4.5 Hz with a higher magnitude than the input. Other frequencies where the system is weaker in attenuation can be seen at 7.8 and 12 Hz, but can be correlated with the resonance frequencies of the dummy. In general, vibration attenuation "sets in" from 8 Hz onwards. The spectra of the entirely tied down wheelchair (belts) show the same result indicating that the suspension, even restricted, still performs well. With the SIT-BAR data as output signal an extra attenuation at the second peak of the wheelchair system (7.5 Hz) can be seen in Fig. 6 and an amplitude rise in the third (12 Hz). Above 16 Hz, there is a larger attenuation than that at the suspension system.

The transfer function shows almost the same result in Fig. 7. The larger attenuation at the SIT-BAR in the frequency band 6–10 Hz is clearly visible. It is possible that the air cushion is responsible for the attenuation and not the seat–human (dummy) dynamics due to the very low stiffness.

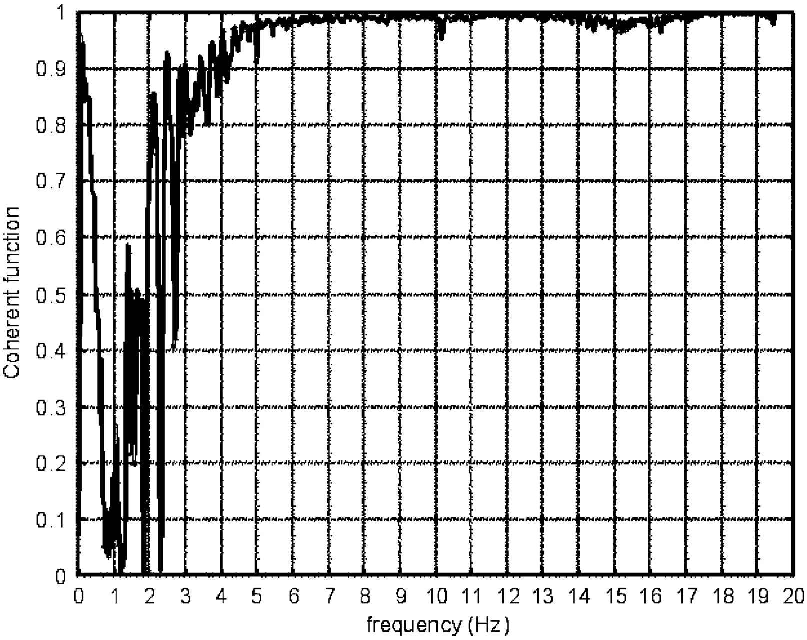

Fig. 5. Coherence function with input 20 Hz sweptsine on the platform and output above the suspension on the wheelchair. From 2.5 Hz onwards there is an almost perfect linear relationship between input and output.

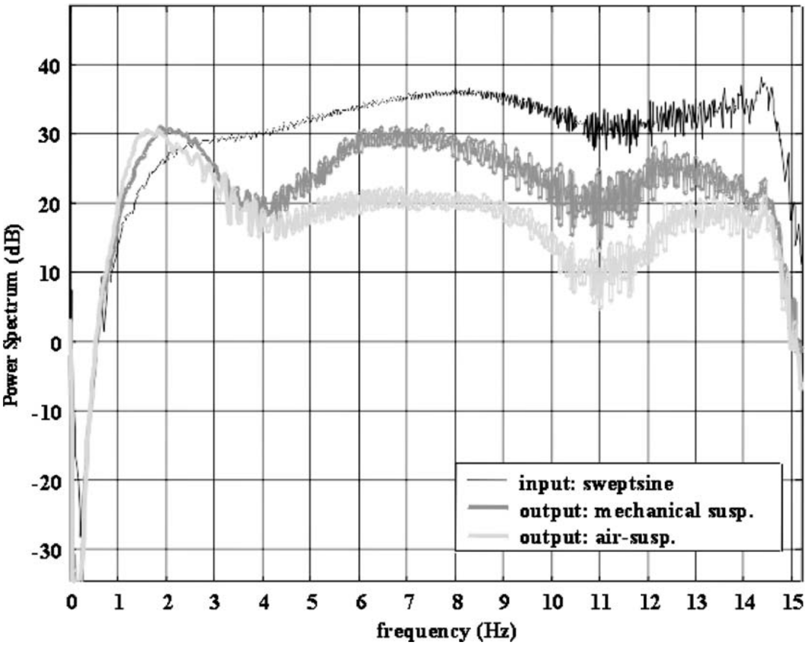

Fig. 6. PSDs for 20 Hz sweptsine (input), for acceleration of wheelchair frame above suspension (output 1) and for the acceleration of the SIT-BAR.

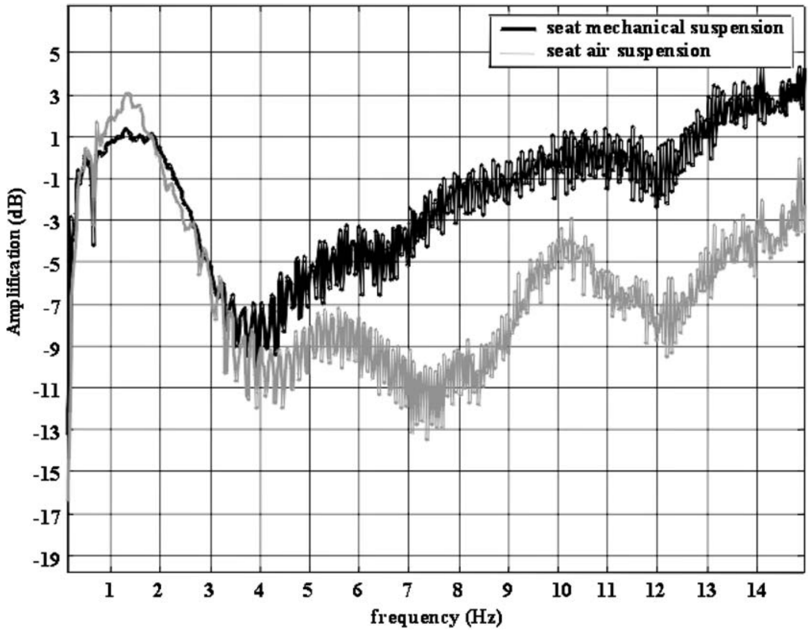

Fig. 7. Transfer function for 20 Hz sweptsine (input), for acceleration of wheelchair frame above suspension (output 1) and for the acceleration of the SIT-BAR.

5. Conclusions

Outdoor wheelchair vibration measurements show clearly that the range of frequencies for which humans are most vulnerable (0.8–10 Hz) are highly present. The chest signal of the subjects amplifies the vibration input in this frequency range. Both passive suspension systems that are used, have their resonance frequency in the range of 3–4.5 Hz. This study points out that current suspension systems may not be adequate in filtering off vibration levels responsible for back pain and discomfort in general. As the risk of physical damage is not likely to improve with these wheelchair suspension systems, the future depends on new designs with higher low-frequency comfort and affordable additional costs.

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