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A Novel Method for Whole Body Vibration Platform Characterization for Clinical Applications

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***Abstract* – In the last decades, many studies have been conducted on the biological effects resulting from Whole-Body Vibration (WBV) platforms, even if benefits or side effects resulting from exposure to whole-body vibrations in sport and rehabilitation applications are often conflicting. These discrepancies are likely due also to different operating conditions such as load, unload, load position on footboard, etc. Since acceleration differences could affect the biological response of the person it would be suitable to verify the actual vibrations. Nevertheless a standard and widespread accepted method for measuring and verifying the actual vibrations provided by a WBV device has not been established yet. The authors performed a characterization of a novel WBV platform by developing a method reported in section II. The tests carried out in different conditions show that the footboard doesn't provide quite uniform vibrations along the vertical direction over the platform. Furthermore, transversal accelerations have been detected and in some cases they reached the 25% of the vertical ones. Currently, very few studies have investigated whether a WBV platform produces comparable accelerations in at least two points of the footboard. This paper proposes a method for the characterization of WBV platforms and the comparison of their performances.**

Keywords* – *Whole Body Vibration, vibration, acceleration measurement, platform, characterization

I. INTRODUCTION

Many studies are currently ongoing on the improvement of neuromuscular performance by Whole Body Vibration (WBV) exercises. Generally, a WBV platform performs vertical or tilting vibration. Parameters such as type of vibration (vertical, side-alternating, etc), vibration frequency, peak-to-peak displacement, type of exercise (duration, number of repetitions, rest period, etc.) have to be detailed when an exercise is prescribed [1]. Currently, in the market there are many devices and some of them allow the final user to set the vibration frequency and the peak-to-peak displacement. Sometimes the manufacturers do not report the ranges of variability of these parameters, but only allow some settings, such as ”vibration speed” or ”low/high amplitude”, that usually cannot be used for comparison with the data of experimental measurements [2]. Aiming at overcoming this problem, the authors of this contribution have designed, developed and characterized a novel WBV platform prototype, where the amplitude of oscillation can be modified independently from the frequency [3, 4]. The prototype provides amplitudes between 0.1 - 0.9 mm at a frequency range of 20 – 50 Hz and bears from 70 kg up to 90 kg bodyweight. As described in Section III, significant differences in vertical accelerations at two points of the footboard may come out after characterizing the WBV platform: this means that since the lower limbs of the subject receive different accelerations, the biological response of the subject may be altered [1, 5]. The lack of detailed studies on WBV platform characterization has led the authors to investigate these phenomena on the developed prototype; in the following sections an easy-to-use and repeatable method to measure the actual performances of a WBV platform is proposed.

II. MATERIALS AND METHOD

Accelerometers are widely used in the assessment of WBV platforms: many researchers use one or more accelerometers to measure footboard acceleration on the three axes [1-3, 6] and displacements. The WBV prototype here used provides vibration through a connecting rod-crank mechanism previously described in [3, 4] with a rubber damping element to get smoother oscillation. Currently, a variable crank mechanism allows the amplitude of oscillation to be set in the range 0.1 mm – 0.9 mm.

A. Measurement procedure

During a WBV platform characterization many elements must be taken into account and the following quantities should be evaluated:

1. Vertical accelerations in proximity of the feet and the footboard interface or nearby to it. Indeed it is important to detect the actual accelerations transmitted to the subject's feet, as they should be related to the biological effects. Since there is no certainty that vertical acceleration is the same in terms of amplitude and shape on each footboard point, an accelerometer should be placed for each contact area. Thereby, the motion nature (vertical or tilting) could be identified from the acceleration signal phase.
2. Displacement. A position sensor may be placed next to the feet in order to evaluate their displacement. Alternatively, a double integration of the acceleration data could be used [3, 4, 8, 9].
3. Frequency can be evaluated through a Fast Fourier Transform of the acceleration signal. Other significant parameters that help to assess the platform motion and its dynamic behavior are the SINAD and the Total Harmonic Distortion (THD), as they measure the likelihood of the motion to a sinusoidal one by evaluating the power contributions of the primary and secondary harmonics [10]. This is important because the clinical effects are waveform dependent, i.e. squared and sinusoidal waves may produce different effects. The THD is evaluated as:

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} y_h^2}}{y_1}. \quad (1)$$

   In (1) y_h is its amplitude. SINAD is the ratio of the RMS signal amplitude to the mean value of the root-sum-square (RSS) of all other spectral components, including harmonics, apart from DC [11, 21].
4. Transversal accelerations should be evaluated because they can affect the biological response, also by providing a crosstalk of two different acceleration types.

In the next paragraphs some applications of the above procedure will be described and the corresponding results discussed.

B. Experimental setup

In analogy with other studies in literature [3, 4, 12-17] two piezoelectric I.C.P. monoaxial accelerometers (*Piezotronics PCB 338B35*) are placed on the footboard, near to the toes, to detect vertical accelerations. In addition, two micro I.C.P. accelerometers (*Piezotronics PCB 352A56)* are placed in proximity of the longitudinal axes of the footboard to measure transversal accelerations. All accelerometers have a 10.2 mV·m^{-1}·s^{-2} sensitivity, ±490 m^{-1}·s^{-2} pk measurement range and ≤1% non-linearity; all sensors are placed using PCB wax. The signal from each transducer has been acquired by an I.C.P. accelerometer power supply (*Piezotronics 482A05*) and a data acquisition card (*National Instruments NI USB 6251*) collected and stored simultaneously. Each test has been conducted for 20 *s* at 10 kS/s sampling rate and processed by LabVIEW software (National Instruments). As in other works on dynamic performances of biomedical systems [18-20] in order to evaluate the vibration of the prototype, the authors performed FFT of the data for each test. The displacement time evolution at the measuring points has been evaluated through a double integration in LabVIEW. Some researchers used optical or laser sensors to assess the displacement amplitude [5] others calculated it from the acceleration assuming a sinusoidal motion of the platform [6, 11, 21]. The use of appropriate sensors for measuring the platform displacement is here suggested because the hypothesis of sinusoidal motion is not always confirmed, as reported in many studies [5, 7, 8, 25]: the dynamic behavior of a real electro-mechanical system is usually complex and requires the evaluation of signal distortions due to its frequency response [3,10, 22, 23].

Otherwise, the displacement could be calculated by means of the double integration of the acceleration signal [3, 4, 8, 9]. The acceleration and displacement distortion analysis has been performed calculating the SINAD (Signal-to-Noise and Distortion ratio in dB) through a LabVIEW subroutine.

A preliminary study on the measurement chain uncertainty was carried out by the authors and such an experimental setup is affected by a 4% error in the evaluation of acceleration and displacement [4].

III. RESULTS AND DISCUSSIONS

The purpose of prototype characterization is to verify the actual vibrations provided by the device. In Fig. 1a, 1b, and 1c the FFT of the four accelerations are reported (2 near the toes, 2 for transversal acceleration measurements) for three tests performed at three different frequencies (20 Hz, 30 Hz, 40 Hz), 70 kg bodymass and the same setup of the slider crank mechanism (same displacement amplitude). Moreover, Fig. 1d represents the vertical accelerations spectrum (FFT) of the signals from the two sensors placed in other footboard points: one accelerometer was installed next to the right foot and the other in the middle of the plate (the subject and mechanism setup are the same of Fig. 1a, 1b and 1c). The spectrums of the vertical accelerations close to the right foot and in the center of the plate (Fig. 1d) show a significant variability, when the measuring point changes, although the test setup is the same of Fig. 1c. The FFT processing of the acceleration introduces a very low error if compared to measurement chain uncertainty [24]. Fig. 1a shows the accelerations spectrum for a 20 Hz solicitation. The vertical accelerations are quite identical while X-axis and Y-axis (transversal) accelerations have amplitudes up to 21% of the vertical ones (Table 1). From Fig. 1b the right and left foot accelerations have almost the same values at 30 Hz, while the Y axis and X axis accelerations are 30% and 10% of the vertical accelerations respectively. In Fig. 1c the acceleration spectrum at 40 Hz solicitation confirms the good uniformity of the vertical feet accelerations, while the magnitude of transversal accelerations is stable (up to 25% of vertical accelerations) compared to the 30 Hz test. Moreover the FFT data analysis of the feet acceleration reveals that the second harmonic of vertical accelerations is 10-20% of the fundamental, while the third harmonic does not exceed 10-15% of the fundamental. The results obtained from the FFT analysis of Fig. 1 are summarized in Table 1 and 2, where the accelerations are reported as fundamental amplitude. From the tables it can be observed that Y-axis acceleration is usually greater than X-axis one; besides Y-axis acceleration increases proportionally with the frequency and its magnitude can be up to 30% of the vertical acceleration. Moreover in our test the vertical feet accelerations do not significantly differ.

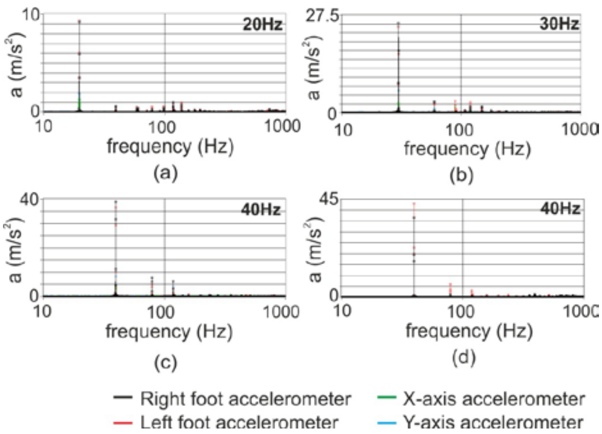

Fig. 1. Acceleration FFT of the four accelerometers signal for 70 kg bodyweight at (a) 20 Hz solicitation and 0.6 mm nominal displacement, (b) 30 Hz and 0.7 mm nominal displacement (c) 40 Hz, 0.6 mm nominal displacement. (d) FFT of the acceleration signals from two accelerometers placed in the middle of the footboard and near the right foot for 70 kg bodyweight at 40 Hz solicitation and 0.6 mm nominal displacement

On the other hand it is clear that there is a considerable difference in accelerations and displacements measured in the two cases of Table 1c (both transducers close to the foot) and 2 (one transducer close to the foot, the other in the center of the footboard). Focusing on the displacement detected by the accelerometer placed in the center of the plate and comparing it to the values of the accelerometers in Table 1c, it is clear that the footboard center has been submitted to a lower vibratory motion both for acceleration and displacement. This behavior is likely due to the prototype operating conditions: in fact, the subject's mass, the center of pressure position on the footboard and the coupling between the frame and the floor affects the dynamic response of the prototype. Under the same frequency, nominal amplitude and subject's mass, the data show an average variability of 25%. The above results seem to confirm the importance of measuring these quantities not only in the center of the platform, but also near the feet of the subject in order to establish whether the device actually supplies a homogeneous vibratory solicitation across the footboard. Moreover a feedback control of the patient posture on the footboard should be considered to reduce variability due to the subject's loss of balance [14, 26].

Table 1. Acceleration a, displacement s and SINAD measurements with repeatability and measurement uncertainty to 22%.

20 Hz and 0.6 mm (Fig. 1a)				
	R. foot	L. foot	X-Axis	Y-Axis
a (m s^{-2})	9.2	9.4	1.32	1.92
s (mm)	0.60	0.61	0.09	0.121
SINAD (dB)	9	9	4	3
30 Hz and 0.7 mm (Fig. 1b)				
a (m s^{-2})	25	24	2.7	8.2
s (mm)	0.72	0.69	0.07	0.23
SINAD (dB)	12	11	1	5
40 Hz and 0.6 mm (Fig. 1c)				
a (m s^{-2})	39	36	3.9	10.2
s (mm)	0.63	0.59	0.06	0.16
SINAD (dB)	10	12	2	4

Table 2. Acceleration a, displacement s and SINAD measurements for the test at 40 Hz and 0.6 mm repeatability and measurement uncertainty to 22% (Fig. 1d).

	R. foot	Footboard center
a (m s^{-2})	32	26
s (mm)	0.50	0.41
SINAD (dB)	13	12

Table 3 shows the differences between the commonly used method and the authors' proposed protocol to characterize a WBV platform performance: the main differences are in the number of measurement points and in how the acceleration is assessed. A sinusoidal behavior is usually assumed but it should be verified, as a large error may occurs in evaluating the displacement amplitude from dividing the acceleration (max or peak-to-peak value) by $(2\pi f)^2$ when the solicitation is not a perfect sinusoid. The inconsistency of results obtained by adopting a common method has been pointed out in [6], and the protocol proposed in the current work could be considered as a contribution to solve this issue. Moreover, the distortion measurement on accelerations provided by a WBV device and their FFT analysis would allow the researcher to understand with more detail the actual vibrations produced by the platform and transmitted to the subject.

Table 3. Comparison between the commonly used method and the authors' proposed protocol to characterize a WBV platform.

	Common method	Proposed protocol
Frequency (Hz)	Calculated from FFT.	Calculated from FFT.
Acceleration	Peak-to-peak, amplitude or max value of acceleration (under the assumption of a sinusoidal motion) [6].	Fundamental's amplitude of the acceleration FFT (only if the other harmonics are equal to or less than 20% of fundamental).
Displacement	Measured or calculated from acceleration dividing by $(2\pi f)^2$. In this way the actual waveform's shape is not taken into account and a large variability in the result could be introduced depending on the acceleration's parameter used to calculate the displacement [6]	Measured or expressed as amplitude of the signal deriving from double integration of acceleration data.
Measuring points	Most of the time only one sensor is used and it is placed in the middle of the footboard.	At least two points, preferably near the feet, in the case of triaxial sensors. Otherwise four monoaxial sensors could be used as well to assess two vertical accelerations (near the feet) and two longitudinal accelerations.
Distortion measurement	-	SINAD.

IV. CONCLUSIONS

Several works in literature have shown that a significant difference between nominal and actual accelerations produced by commercial WBV platforms could exist. This variability has not been studied yet, as well as a golden standard has not been well established in the characterization of these devices. The first aim of this study is to propose a method to characterize the performance of a WBV platform. To this regard, a specific experimental setup has been tested and used to measure the actual vibrations provided by a WBV platform prototype along the three axes. The vertical accelerations observed close the foot show similar values. On the other hand the accelerations away from the subject-footboard contact zone have shown differences up to 20%. Moreover transversal accelerations are predominantly along Y axis and are up to 30% of the vertical ones, with the highest magnitude between 30 and 35 Hz. Results suggest to measure vibrations at least in two points, preferably near the feet, and to assess the transverse acceleration components, in order to relate the actual solicitation transmitted to the subject (displacement amplitude, frequency and signal waveform) with the biological response that has occurred. It might also be interesting to use a stereophotogrammetric system [27] to evaluate the actual vibrations induced on some muscle to better understand the relationship between the mechanical vibration load (displacement amplitude, frequency) and the biological response. More sophisticated analysis of signals recorded from accelerometers could be hypothesized as a future improvement by using techniques already experimented in different application fields and based on time-frequency approaches [28-30].

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