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Review Article

Reporting whole-body vibration intervention studies: Recommendations of the International Society of Musculoskeletal and Neuronal Interactions

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Abstract

Whole-body vibration (WBV) is receiving increasing interest as a therapeutic modality to improve neuromuscular performance or to increase bone mass or density. In order to help improve the quality of reports about WBV treatment studies, the International Society of Musculoskeletal and Neuronal Interactions (ISMNI) invited experts in the field to provide suggestions on how the intervention should be described in such reports. The recommendations are presented here.

Keywords: Mechanical Oscillation, Musculoskeletal, Osteoporosis, Physical Medicine, Rehabilitation, Whole-body Vibration

Introduction

During the past decade there has been increasing interest in the use of whole-body vibration (WBV) as a therapeutic modality. Many WBV treatment studies aim at improving some aspect of neuromuscular performance or at increasing bone mass or density (for recent reviews see [1-7]).

However, a scientific study can lead to scientific progress only if the resulting study report can be understood by others. This requires a common language and consistent use of well-defined terminology. It is also critical that the methodology of the study is described accurately and with sufficient detail for others to replicate the study. However, as recently highlighted by Lorenzen et al., published study reports on the therapeutic effects of WBV have not always met these requirements[8].

In order to help improve the quality of reports about WBV treatment studies, the International Society of Musculoskeletal and Neuronal Interactions invited experts in the field to provide suggestions on how the intervention should be described in such reports. The recommendations are presented here.

The present recommendations only deal with issues that are specific to the reporting of WBV treatment interventions. For a general checklist of items that need to be addressed in clinical trial reports, readers should refer to the CONSORT (Consolidated Standards of Reporting Trials) statement[9,10] (also available at the CONSORT website (http://www.consort-statement.org/). Most of the leading journals that publish clinical trials have endorsed the CONSORT statement[11]. The extension of the CONSORT statement to non-pharmacologic treatment trials is of particular relevance for the reporting of WBV treatment trials[12].

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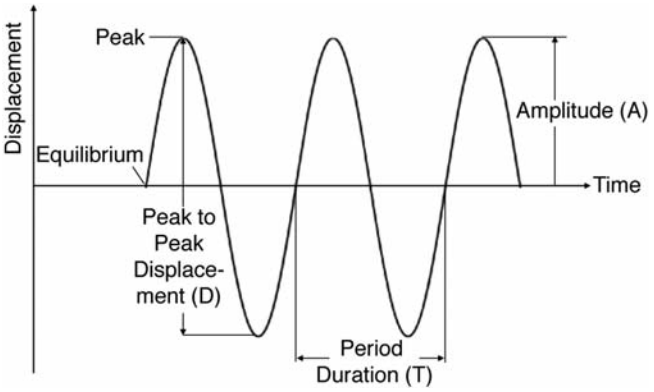

Figure 1. A plot of displacement against time in sinusoidal vibration. The definitions of the terms amplitude (A), peak-to-peak displacement (D) and period duration (T) are given in Table 1. The frequency (f) corresponding to the period duration is equal to: f = 1 / T.

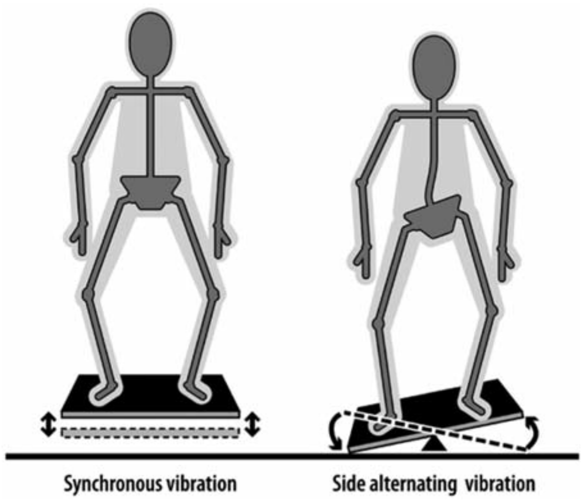

Figure 2. Direction of vibration movement in synchronous and in side-alternating vibration. Adapted from Rittweger[3].

Physical Principles and Recommended Terminology to Describe WBV

The physical principles of WBV have recently been summarized in more detail by Rittweger[3]. Vibration is oscillatory motion about an equilibrium point. Several types of vibration can be distinguished but only sinusoidal vibrations are considered here, as this is the type of vibration that currently available WBV devices aim to provide (Figure 1).

WBV is applied through a vibrating surface that supports the study subject. WBV treatment studies are usually performed with the user standing on a motor-driven vibrating plate. The vibration transmitted to the body via the plate constitutes the vibration exposure to the user.

Terms that are commonly used to describe vibrations are defined and explained in Table 1. To describe a sinusoidal vibration, it is necessary to provide information on both the frequency and the extent of the vibration. The extent of the vibration can be given as the displacement from the lowest to the highest point (=peak-to-peak displacement) or the maximum displacement from equilibrium (=amplitude)[13]. In the WBV treatment literature, the term 'amplitude' has sometimes been confused with 'peak-to-peak amplitude'[8]. However, peak-to-peak amplitude is synonymous with peak-to-peak displacement and thus differs from the amplitude by a factor of 2 (Table 1). Therefore, in order to avoid future confusion, it is preferable to use the term 'peak-to-peak displacement' to indicate the extent of the vibration.

The commonly used descriptor of vibration, peak acceleration, can be mathematically derived from the frequency and the peak-to-peak displacement and therefore does not provide additional information once frequency and peak-to-peak displacement are known (Table 1). However, to facilitate comparisons between studies it is recommended to provide acceleration levels associated with the vibration, preferably as the peak acceleration (a_{Peak}) in multiples of Earth's gravity (symbol: g; 1 g = 9.81 ms^{-2}). Alternatively, root-mean-squared acceleration (a_{RMS}) can also be reported. The root-mean-squared acceleration is the preferred descriptor if the WBV device produces vibrations that do not follow a pure sine wave pattern[14]. For a pure sinusoidal wave, a_{RMS} is obtained by dividing a_{Peak} by $\sqrt{2}$.

It should be noted that the actual oscillations generated by WBV devices may significantly deviate from a pure sine waveform. It is also possible that the frequency and amplitude generated by a device differ from the preset values, or from the values provided by the manufacturer, in particular when the participant is moving on the vibration plate and/or is using additional weights (e.g. barbells and dumbbells)[15]. The displacement and acceleration generated by a device also depend on the rigidity of the plate, which may differ between brands and between devices. These considerations highlight the need to evaluate the vibrations produced by a WBV device in a given study setting.

It is therefore recommended to measure the actually generated vibration parameters (frequency, amplitude, acceleration) in a pilot test which is appropriate for the target group and WBV protocol of the planned intervention study. See Appendix 1 for a description of how the accuracy of a vibration plate can be tested. It is also recommended that manufacturers provide relevant information about the performance of their device under different body weights.

Depending on the vibration parameters, it is possible that the acceleration transmitted to the body does not follow the acceleration waveform of the plate but can be substantially distorted and attenuated[16]. The acceleration transmitted to the body can also be assessed, similar to the measurement of the acceleration produced by the WBV device, as described in Appendix 1. However, assessing vibration transmission in human subjects

	Unit	Definition	Symbol	Formula	Comments
Period duration	s	Duration of one oscillation cycle	T		
Frequency	Hz, s^{-1}	Repetition rate of the cycles of oscillation	f	$f = 1/T$	$1\ Hz = 1\ s^{-1}$
Peak-to-Peak Displacement	mm	Displacement from the lowest to the highest point of the total vibration excursion	D	$D = a_{Peak}/(2 \times \pi^2 \times f^2)$	Synonymous to 'Peak-to-Peak Amplitude'
Amplitude	mm	Maximal displacement from equilibrium position	A	$A = D/2$	Synonymous to 'Peak Amplitude'
Peak Acceleration	ms^{-2}	Maximal rate of change in velocity during an oscillation cycle	a_{Peak}	$a_{Peak} = 2 \times \pi^2 \times f^2 \times D$ $a_{Peak} \approx 20 \times f^2 \times D$	Often expressed as multiples of Earth's gravity*
Root Mean Squared Acceleration	ms^{-2}	Average rate of change in velocity during an oscillation cycle	a_{RMS}	$a_{RMS} = a_{Peak} / \sqrt{2}$	

* Earth's gravity (commonly used symbol: g) is a constant (9.81 ms^{-2}) that denotes the nominal acceleration due to gravity at the Earth's surface at sea level.

Example for calculating peak acceleration when vibration with a frequency of 20 Hz and a peak-to-peak displacement of 4 mm is used: Peak acceleration = $2 \times \pi^2 \times 400\ s^{-2} \times 0.004\ m = 31.6\ ms^{-2}$. Expressed as a multiple of standard gravity, peak acceleration in this example is $31.6/9.81\ g \approx 3.2\ g$. The root-mean-squared acceleration is $31.6\ ms^{-2}/\sqrt{2} = 22.3\ ms^{-2}$.

Table 1. Terms used to describe sinusoidal vibration.

requires more experience and expertise than determining the vibration parameters of a vibration plate and therefore is recommended only where such special expertise is available.

Vibration devices do not only differ with regard to the frequency and peak-to-peak displacement that they generate. Some models apply the vibration to the right and the left foot in a side-alternating way (Figure 2). On other vibration plates, the right and the left foot move up and down at the same time. These latter devices are said to operate in a synchronous way[3]. It is recommended that the type of device (synchronous, side-alternating or other) be specified.

For synchronous WBV, the peak-to-peak displacement and peak acceleration are identical for the entire surface of the plate, if the force transmission from the motor to the plate is rigid. However, springs attached to the vibrating plate (e.g., to the corners) may affect the local acceleration. For side-alternating WBV, the vibrating plate typically oscillates about a horizontal anteroposterior central axis. The peak-to-peak displacement and thus peak acceleration of a given point on the surface of such a vibration plate depends on the distance of this point from the central axis, while the rigidity of the plate accounts for the actual displacements and accelerations at the given point. At least some inter-device variation in the flexural rigidity of the plate can be expected, which underpins the importance of measuring the actual performance of the given vibration device, as recommended above.

Description of the Intervention Protocol

Apart from details about the vibration settings, WBV study reports should include a precise description of how WBV was applied. It is recommended that authors prepare their reports by following the 22-item CONSORT checklist for reporting trials of nonpharmacologic treatments[12]. The recommendations of this CONSORT statement pertaining to the description of the intervention are:

- Item 4: "Precise details of the interventions intended for each group and how and when they were actually administered. Precise details of both the experimental treatment and comparator".
- Item 4 A: "Description of the different components of the interventions and, when applicable, descriptions of the procedure for tailoring the interventions to individual participants".

The text elaborating on this CONSORT checklist further points out that "authors should report qualitative and quantitative data. Qualitative data describe the content of each session, how it is delivered (individual or group), whether the treatment is supervised, the content of the information exchanged with participants, and the instruments used to give information. Quantitative data describe the number of sessions, timing of each session, duration of each session, duration of each main component of each session, and overall duration of the intervention. It is also essential to report how the intervention was tailored to patients' comorbid conditions, tolerance, and clinical course.“

To apply these general CONSORT recommendations, a report of a WBV treatment study should contain a number of key WBV-specific elements, as listed in Table 2.

If a commercially available device was used, the manufacturer and the brand name of the device should be given in the study report. Nevertheless, the vibration produced by the device should still be described with sufficient detail, so that

Items related to the WBV device
1. For commercial devices, brand name and type 2. Type of vibration: Synchronous; side-alternating; other? 3. Vibration frequency (or frequencies) in Hz 4. Peak-to-peak displacement of the vibration in mm. For side-alternating vibration, give this information for a specific landmark, e.g. the second toe 5. Peak (or RMS) acceleration, preferably in multiples of g (9.81 ms^{-2}) 6. Accuracy of vibration parameters, preferably based on the results from own pilot test of an appropriate study group or reference to literature 7. If applicable, whether skidding of the feet was evaluated 8. Changes of the vibration settings during the course of the study 9. Rationale for choosing specific vibration settings: Based on literature; pilot studies; or biological considerations?
Items related to study participants
10. Support devices during WBV: e.g, none when standing freely; holding on to a railing; lying on a tilt table; other 11. Type of footwear: barefoot; socks; shoes; other 12. Body position/posture of the participant when standing on the plate (e.g. knee and hip angle, standing on one or two legs, leaning on toes or heels, trunk upright or tilted forward) 13. If applicable, describe exercise performed on the plate (e.g. static or dynamic exercises)

Table 2. Checklist of items that should be addressed in reports on WBV treatment studies.

readers can appreciate the applied vibration without consulting the user manual of the device. It is essential to indicate the type of vibration plate used (synchronous, side-alternating, other), as well as its frequency, peak-to-peak displacement and measured peak acceleration in different vibration settings appropriate for the study.

For side-alternating devices, it is critical to indicate the peak-to-peak displacement for the precise foot position that was used in a study. The recommended landmark for indicating peak-to-peak displacement is the second toe, which is at about mid-distance between the contact points of the forefoot.

The study report should further indicate whether the accuracy of these vibration parameters was tested and if so, how this was done. It should also be described whether the possibility of skidding of the feet was evaluated (See Appendix 2). The vibration settings may change during the study interval (e.g., in order to provide progressive training). If so, these changes should be listed. If changes in vibration settings were dependent on some characteristic of the study participants then this should be clearly stated. Whatever vibration settings were selected, the authors should provide a rationale for their choices.

Apart from these device-oriented descriptors, the force and acceleration produced by the vibration in the body depend on how the device is used. It is essential to describe whether study participants were standing freely on the device, were holding on to some support or whether the vibration plate was combined with some other device, such as a tilt table. The type of footwear, if any, also has an obvious influence on the vibration transmitted to the study participant[17]. Another critical element is the description of the body position and posture of the study participant on the plate[3]. The relevant information in this respect includes knee and hip angle, whether the participants is standing on one or two legs, leaning on toes or heels, and whether the trunk is upright or tilted forward.

Study participants may perform exercises while using the WBV device. If so, the exercise should be described in sufficient detail so other investigators can replicate it. For dynamic exercises the speed of the movement and the range of motion should be indicated. For further recommendations on how to describe other aspects of the treatment protocol and the general study design, readers are referred to the CONSORT statement for reporting trials of nonpharmacologic treatments[12].

It is hoped that the use of the checklist shown in Table 2 will improve the quality of reporting WBV treatment trials.

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Appendix 1:
Ascertaining vibration parameters by using accelerometers

Various companies offer easy-to-use accelerometers in the price range of a few hundred dollars/euros that can be used to verify the settings of a vibration plate. Many commercially available accelerometers measure acceleration in all three dimensions (and are therefore called tri-axial accelerometers), but a two-axial or even a one-axial accelerometer could still be used for verifying WBV parameters.

The accelerometer needs to be firmly affixed to the plate. This could be done with a machine screw, which however requires a corresponding threaded hole in the plate, and may not be generally feasible. Alternatively, the accelerometer could be glued to the vibration plate or attached to it with double-sided sticky tape from a local hardware store. It is important that the accelerometer is affixed exactly at the location on the plate for which vibration parameters are to be determined. This is particularly relevant for side-alternating systems. It is also important to affix the accelerometer in a position that allows measuring the vertical component of the acceleration correctly.

The remainder of the testing setup depends on the type of accelerometer that is used. For accelerometers that are equipped with an amplifier, the signal needs to be fed into some kind of recording device, either an oscilloscope, an A/D board or a physiological recording system. The manual of the accelerometer needs to be consulted about the recommended recording device. This approach generally requires engineering expertise. Therefore, the simplest solution is probably to use an accelerometer that stores vibration data without the need for additional equipment, as was used for the experiments described in Figure 1.

Good accelerometers are calibrated by the manufacturer. One can verify the calibration by assessing the signal when the accelerometer is placed upright (+1g) and when it is turned upside-down (-1g). Once the accelerometer is calibrated and solidly affixed to the vibration plate, the WBV system can be switched on and the accelerometer signal can be recorded. The WBV system will usually take a few seconds to get to speed, so the analysis should include only recordings that were obtained after acceleration readings have stabilized.

It first should be verified whether the vibration signal is sinusoidal. This could be done by simple visual inspection of the graphical read-out of the recording device (e.g., an oscilloscope). Alternatively, the recorded vibration measurements could be imported into a software that evaluates how much of the signal power is within the fundamental frequency of oscillation. Figure 1 shows a step-by-step example of how an accelerometer read-out can be analyzed with the software package Sigview.

In synchronous systems, there should normally be no or only very little acceleration in directions other than the vertical. For side-alternating systems, a small acceleration in a lateral direction is expected. In either type of vibration plate, if there is considerable acceleration in planes other than the vertical, then the fixation of the accelerometer to the vibration plate probably needs to be improved. However, if the accelerometer fixation is solid and the vibration signal is still not sinusoidal, then it is likely that the WBV system does not produce sinusoidal vibration and registration of the two other orthogonal acceleration axes are useful.

Next, the frequency of the vibration should be evaluated on the basis of the accelerometer read-out. One way to do this is to count a given number of vibration cycles (e.g. from one peak to the next) and to divide that number by the time (in seconds)

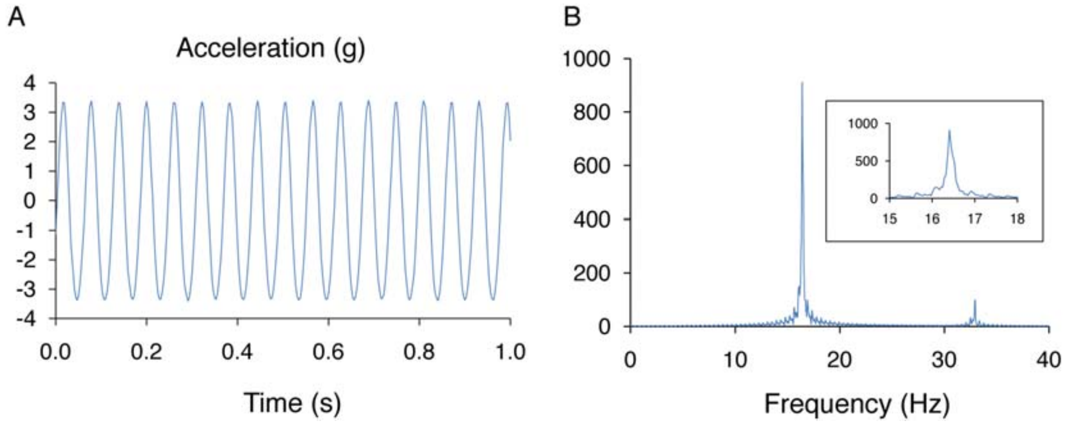

Figure 1. Practical example of an accelerometer test of a vibration plate. The plate was set to vibrate at a frequency of 16 Hz. **A.** Accelerometer read-out during a 1 second measurement interval. On inspection, the signal appears approximately sinusoidal. The average peak acceleration is at 33 ms^{-2}, corresponding to 3.36 units of g (1 g = 9.81 ms^{-2}). The total harmonic distortion of a 20-second interval of the same measurement run was 3.2%, confirming the visual impression that the signal was close to a sine wave. **B.** Fast Fourier transform analysis of a 20 second interval of the same measurement run. The main peak appears at approximately 16 Hz to 17 Hz and a smaller peak at about 32 Hz to 33 Hz. The inset shows that the main peak is at a frequency of approximately 16.4 Hz. **Methods:** A USB accelerometer X6-2 (Gulf Coast Data Concepts Inc; Waveland, MS; USA) was glued to a side-alternating vibration plate (Vibraflex Home Edition II®, Orthometrix Inc, White Plains, NY; USA) at a position where peak-to-peak displacement was expected to be 6 mm. The accelerometer was set at a sampling rate of 320 Hz. The accelerometer measurements were stored automatically on a microSD® chip inside the accelerometer. After completion of a 60-second measurement run, the CSV (comma separated values) data files containing the accelerometer readings were copied to a computer via the USB connection of the accelerometer. The results of the accelerometer measurements were analyzed using Sigview software (downloaded from http://www.sigview.com/download.htm) as follows: The CSV file containing the accelerometer reading was imported into Sigview (File>ASCII files>Import Signal). The results for a 1-second interval obtained in the middle of the measurement run is shown in Figure 1A. Peak acceleration was determined by averaging the maximal accelerations during the vibration cycles shown in Figure 1A. The Fast Fourier transform analysis of a 20 second interval (Figure 1B; obtained in the middle of the 60-second measurement run) was performed using the ‘FFT spectrum analysis’ tool in Sigview. Total harmonic distortion (a measure for how much the vibration signal departs from a pure sine wave), was determined using the ‘Total Harmonic Distortion’ tool of Sigview. It is proposed that a total harmonic distortion value below 10% corresponds sufficiently to sine wave in whole-body vibration applications. **Interpretation:** The actual vibration frequency is slightly higher than the vibration frequency indicated by the display of the vibration plate (16.4 Hz vs 16.0 Hz, difference 2.5%). The measured peak acceleration (3.36 units of g) is approximately 9% higher than expected for the nominal settings of the device (at the selected vibration frequency of 16 Hz and a peak-to-peak displacement of 6 mm, the formula given in Table 1 of the main text predicts a peak acceleration of $2 \times \pi^2 \times 16\ s^{-1} \times 16\ s^{-1} \times 0.006\ m = 30.3\ ms^{-2}$, corresponding to 30.3 / 9.81 = 3.09 units of g). It is also possible to interpret results in terms of peak-to-peak displacement, which can be derived from the measured values of peak acceleration (3.36 g) and frequency (16.4 Hz = 16.4 s^{-1}) as follows (Table 1): $D = (3.36 \times 9.81\ ms^{-2}) / (2 \times \pi^2 \times 16.4\ s^{-1} \times 16.4\ s^{-1}) = 6.2\ mm$. Thus calculated, the measured results indicate that the actual peak-to-peak displacement is about 3% higher than the nominal peak-to-peak displacement.

interval between the peaks. The resulting ratio is the frequency in Hz. The frequency of the vibration can also be determined using a software program (see Figure 1 for an example).

Finally, one should assess peak acceleration. It should be possible to obtain peak acceleration directly from the accelerometer readings. Figure 1 provides an example for the determination of peak acceleration.

Appendix 2: Test for ‘Skidding’

It becomes increasingly difficult with increasing acceleration levels for the feet to follow the vibrating foot plate on its way down (for an explanation see the review by Rittweger [ref 1 of this Appendix]). This results in a loss of contact between the subject’s feet and the vibration plate. Such loss of contact is called ‘skidding‘. When skidding occurs, the parameters of vibration that the study participant is subjected to are no longer defined. A test to exclude such loss of contact would be to insert a sheet of paper between the foot and the WBV plate and to pull at the sheet while the participant is performing the exercise. If the sheet can be pulled out, then the contact is likely to be insufficient.

Reference for Appendix 2

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