Original Research

Is There an Optimal Whole-Body Vibration Exposure 'Dosage' for Performance Improvement?

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ABSTRACT

International Journal of Exercise Science 7(3) : 169-178, 2014. Whole-body vibration exposure has been shown to improve performance in vertical jumping and knee extensions. Some studies have addressed the question of dose optimality, but are inconclusive and inappropriately designed. Our purpose was to more thoroughly seek an optimum combination of duration, amplitude and frequency of exposure to side-alternating whole-body vibration. We used experimental designs constructed for response surface fitting and optimisation, using both blocked and unblocked second order central composite designs with 12 participants. Immediately after each exposure a discomfort index was recorded, then peak and average torque, peak and average jump height, together with peak and average jump power were recorded over three trials both pre- and post-exposure at each treatment combination. ANOVA revealed that all performance measures improved after vibration exposure. However, no successful response surface fits could be achieved for any of the performance measures, except weakly for average jump height and average jump power for a single subject. Conversely, the discomfort index increased linearly with both vibration amplitude and frequency, more steeply as exposure duration increased. We conclude that although vibration exposure has a significant positive effect on performance, its effect is so variable both between and within individuals that no real optimum can be discerned; and that high amplitudes, frequencies and durations lead to excessive discomfort.

KEY WORDS: Amplitude, counter movement jump, displacement, duration, frequency, isometric knee extension

INTRODUCTION

Whole-body vibration (WBV) is enjoying popularity as an alternative exercise modality. It is being prescribed by exercise specialists in the belief that it is a safe and effective method of providing a neurogenic potentiation to enhance muscle performance compared to traditional exercise techniques. Acute WBV has been reported to increase lower limb muscle performance in various populations (4,10,13) and is dependent on WBV parameters such as; frequency (Hz), amplitude (mm, also known as displacement), exposure duration and rest interval (min or sec) between the conclusion of WBV and ensuing performance. Bosco et al. (4) revealed that when one leg received acute WBV (26 Hz) it was effective in enhancing single leg press performance by shifting force-velocity and power-force relationship to the right, and enhanced average force, velocity and power compared to the control leg. Furthermore, 26 Hz has also been shown to increase vertical jump (VJ) height by 8% compared to control and stationary cycling interventions (10). Given the dependence on frequency, amplitude and duration, it is natural to enquire whether variation in one or more of these can modulate the effect of WBV.

A variety of studies have sought to determine optimum exposure by varying one or more of the dependant factors involved. In terms of muscle activity, Cardinale and Lim (8) reported that electromyography (EMG) of the vastus lateralis was significantly higher after exposure at 30 Hz compared to 40 Hz, and 50 Hz. Likewise, amplitude (*A*) has been shown to have a positive influence on EMG activity; Delecluse et al. (15) reporting that 2.5-5 mm amplitude (*f*=35-40 Hz) significantly increased EMG_{rms} of the rectus femoris and medial gastrocnemius compared to negligible amplitude (*f*=35-40 Hz). Single or multiple bouts (30-60 sec) of acute WBV have been used to enhance muscle performance, for example single vibration exposures of 30 sec and 45 sec (*f*=30 & 40 Hz, *A*=2-4 mm) recorded a 0.6% and 9% improvement in VJ height (2,13). Ten sets of 60 sec of WBV interspersed with 60 sec rest (*f* =26 Hz, *A*=4 mm) produced an increase in VJ height of 4% (5). Stewart et al. (27) reported that 2 min of continuous WBV (*f*=26 Hz, *A*=4 mm) increased isometric peak torque by 3.8%, compared to decrements in peak torque after 4 and 6 min exposure. The time course of muscle performance after acute WBV shows that the transient increase can remain elevated at least up to 5 min post-treatment (1,2) but declines below significant levels at 10 min (1).

It is clear from this mixed collection of studies that there are numerous permutations to selecting WBV parameters, and that the various experimental protocols have included different ranges of exposure duration (from a single 30 sec bout to ten sets of 60 sec); vibration frequency (from 25-40 Hz); and amplitude (from 2-6 mm). Consequently, a number of studies have focussed on finding the optimal 'dosage' of WBV exposure for performance improvement, by varying one or more of the three exposure characteristics, together in some cases with other factors such as the participant's stance. Some studies vary only one, keeping the other two fixed. Gerodimos et al. (18) report on one study in which 25 females undertook three protocols of 6 min duration at 25 Hz and amplitudes of 4, 6, and 8 mm; and on a second study in which 18 females undertook three protocols of 6 min duration at 6 mm and frequencies of 15, 20 and 30 Hz. Squat jump (SJ) performance was not significantly affected by either amplitude or frequency, though flexibility was. Da Silva-Grigoletto et al. (14) report on one study in which 30 men were exposed to vibrations of 30 Hz and 4 mm for 30, 60 or 90 sec, and a second of 27 men exposed for three, six or nine sets of 60 sec, also at 30 Hz and 4 mm. These authors conclude firstly that 60 sec was the best duration and secondly, that six 60-sec sets lead to 'optimal' muscle performance as measured by SJ, counter movement jump (CMJ) and power output. In a cross-over design that investigated WBV parameters of frequency (5, 10, 15, 20, 25, 30 Hz), knee angles (10, 30, 60°), stance (forefoot or normal), load (body weight & additional one-third of body weight) and type of machine (side-alternating & synchronous vibration), (23), the authors report that at a fixed duration (10 sec) and amplitude (2 mm), higher vibration frequencies (25 & 30 Hz) with additional load (one-third of body weight) increased EMG activity of lower limb muscles with slightly less pronounced EMG activity in thigh muscles.

Several studies vary two of the factors simultaneously. Bazett-Jones et al. (2) considered four different accelerations (amplitude/frequency combinations) for a fixed 45 sec duration, finding that in a sample of 33 men, no significant effects on CMJ were evident; whereas in a sample of 11 women, only those two trials with higher frequencies (40 Hz, 2-4 mm and 50 Hz, 4-6 mm) had a significant positive effect. Bedient et al. (3) report on a study involving 40 male and female participants, utilising a factorial experiment design with eight combinations of frequencies (30, 35, 40 and 50 Hz) amplitudes (2-4 and 4-6 mm), all for a fixed duration of 30 sec. These authors found that only frequency had a significant effect on peak CMJ power. No significant interactions were reported, and their analysis suggests only that 30 Hz appears to be optimal. Petit et al. (20) report on a study of male participants exposed three times per week for six weeks to either high-frequency/high peak-to-peak displacement (n=12) or low-frequency/low peak-to-peak displacement (n=10) for a fixed duration of 10 min. The high/high combination was found to be the most effective in enhancing knee extensor strength and jump performance. We can find only one study which simultaneously varied all three exposure characteristics. Adams et al., (1) detail a study of 11 men and 9 women involving 24 combinations of amplitude (2-4 or 4-6 mm), frequency (30, 35, 40 or 50 Hz) and duration (30, 45 or 60 sec) in a full factorial design. They found that duration of exposure had no effect on CMJ peak power normalised to initial power. On the other hand high frequencies combined with high amplitudes, and the converse, were more effective. It is of interest to note that in none of the above studies has any analytic attempt been made to determine a real global optimal combination over any or all three factors simultaneously, as distinct from some locally best combination.

We therefore regard it as axiomatic that any attempt to find a true global optimum combination across all three factors, must: a) involve experimentation which varies all three simultaneously; and b) utilise a design which allows the optimum to be determined analytically. Only one of the above studies satisfies the first condition, and none satisfies the second. We have therefore designed and carried out a study which satisfies both conditions in order to ascertain whether a real global optimal combination of frequency, amplitude and duration of WBV exposure for muscle performance improvement can be discerned.

METHODS

Participants

Twelve healthy males (26.6 ± 1.2 yrs.; height 179 ± 7.5 cm; body mass 84 ±10.0 kg), volunteered to participate in this study. All were games players (hockey, football, basketball) playing competitively or training at least three times per week. Informed written consent was obtained from all participants and ethical approval was granted by the University Human Ethics Committee.

Protocol

We employed a two-pronged approach to the optimality determination, and both experimental designs employed model building and response surface fitting (6), using appropriately constructed designs. The first design was an orthogonally blocked, rotatable, 3-factor (duration, amplitude and frequency), second order central composite design (CCD), (6); comprising four replicates of three blocks each, one participant per block, detailed below and in Table 1, and requiring 12 participants in total. The second was three replicates of the full (unblocked) CCD; each one of three participants completing all the remaining treatment combinations to make up the full replicate (17). CCD's are relatively small-sized designs, with good statistical properties and are specifically structured for optimality determination (6). They are often used in industrial processes, and have previously been used in human biology (19).

In the first experiment the 3 block design specified one block per participant, which was allocated in a randomised order and consisted of short duration exposures of 30, 54, 90, 126, 150 sec, at frequencies of 6, 11, 18, 25, 30 Hz, and at amplitudes of 4, 5.6, 8, 10.4, 12 mm (Table 1). These ranges were selected according to values permitted by the physical limitations of the vibration platform and its operation, and the specific values in accordance with the rotatable property of the CCD. In accordance with the design structure, Blocks 1 and 2 are the two half-fractions of the 2^3 factorial part of the CCD with an added centre-point, whilst Block 3 comprises the six star points of the CCD with another added centre-point. In the second experiment, all fifteen exposures were completed (centre points were not repeated) by each of the three participants completing the whole design.

Table 1. Experimental design for WBV optimization.

Block 1

Frequency (Hz)	Duration (s)	Amplitude (mm)
11	54	5.6
11	126	10.4
18	90	8
25	54	10.4
25	126	5.6

Block 2

Frequency (Hz)	Duration (s)	Amplitude (mm)
11	126	5.6
11	54	10.4
25	54	5.6
18	90	8
25	126	10.4

Block 3

Frequency (Hz)	Duration (s)	Amplitude (mm)
6	90	8
18	90	4
18	90	12
18	30	8
18	90	8
18	150	8
30	90	8

Prior to the study (at least 24 hr) all participants were familiarized with the equipment and correct technique of CMJ and isometric knee extension (ISO). The settings of chair and lever positions for ISO were recorded and used for subsequent trials. To account for daily biorhythms all trials were conducted at the same time of day, participants were instructed to refrain from physical training at least 12 hr before testing, and a warm-up was prohibited prior to the testing to reduce the possibility of influencing the outcome of the study. To reduce the time lag of lacing up shoes between WBV exposure and outcome measures, participants performed all CMJ, ISO and WBV trials in bare feet.

Participants were randomly assigned to one of the four replicates of three WBV exposure blocks (first design), consisting of either 5 or 7 vibration exposures each with at least 24 hours rest between each exposure. The exposure order within each block was also randomly allocated. Participants in the second design completed the remaining treatment combinations in random order also, totaling 15 exposures each. Participants performed three pre-measures of CMJ and ISO immediately followed by WBV with post measures of CMJ occurring at 1 min (post WBV) and ISO occurring 2 min post WBV.

Isometric knee extension tests were performed on the dominant leg using an isokinetic dynamometer (Biodex system 3, Biodex Medical Systems, New York, USA). Participants were seated in an adjustable chair where they were secured with thigh, waist, and shoulder straps to minimize body movements. A device that emitted an infra-red beam was magnetically attached to the rotational axis of the dynamometer to align the lateral femoral epicondyle, and the lower limb was attached to the dynamometer lever arm above the medial malleolus via a cushioned pad that was firmly secured by a Velcro strap. Every participant performed three maximal efforts of ISO for 3 sec at a knee angle of 75°, separated by a rest period of 10 sec. Mean and peak torque (Nm) were recorded and used for subsequent analysis.

Three CMJ separated by 10 sec of rest were performed on a contact-timing jump mat (SmartSpeed, Fusion Sport, Queensland, Australia), which was connected to a wireless interface handheld pocket computer (iPAQ, Hewlett Packard, Palo Alto, CA, USA). Participants stood with feet at shoulder width apart with hands on hips to negate any influence of the upper body and performed a maximal CMJ to a self-selected knee depth. CMJ height (cm) and peak power (W) was computed by SmartSpeed software; jump height was calculated from flight time and power was computed using the Sayers et al. (25) equation. Peak and mean jump height, and peak and mean power were recorded and used for further analysis.

WBV was performed on a commercial machine (Galileo Sport, Novotec, Pforzheim, Germany), which had a motorised teeterboard that produced side-alternating vertical sinusoidal vibrations (up to 30 Hz and a maximum amplitude of 12 mm). For this particular machine, the amplitude was dependent upon the foot position; the further the feet were on either side of the central oscillating axis the larger the amplitude. Therefore, a single axis accelerometer (Imems®, ADXL250, Analog Devices, Norwood, MA, USA) was fixed to the edge of the vibrating platform to assess the amplitudes (peak-to-peak displacement) of the different foot positions. To ensure the correct location and identification of the different amplitudes, longitudinal strips of reflective adhesive tape were applied to the plate. This provided a visual cue for participants to place their second toe and heel midpoint in line with the tape, which enabled the feet to remain in the correct position during the trials. This positioning was constantly checked by the investigator, as any movement of the feet laterally or medially could affect the amplitude setting.

Participants maintained a static squat stance with 40° of knee flexion, (knee fully extended = 0°), which was measured by a manual goniometer. The rationale of selecting a static squat at 40° was that it elicits postactivation potentiation (11), which is suggestive of WBV enhancing neurogenic factors. Participants were also instructed to placed their hands on their hips, maintain an upright torso, with head and eyes facing forward and to evenly distribute their body weight through the mid-foot of both feet.

Immediately post-WBV (within 5 sec) and before post-testing, every participant rated the vibration exposure using a 5-point Likert (very comfortable/very uncomfortable) scale (26).

Statistical Analysis
All data was checked for normality using the Shapiro-Wilk test; with $p > 0.3$ in all cases. Thereafter, exploratory analysis of all measured variables in experiment one was carried out using 3-way (amplitude, A; duration, D; and frequency, F) analysis of variance (general linear model) with repeated measures, in which replicates were considered as a component of, and block effects were completely confounded with, the between subject differences. The 3-factor second order response surface model subsequently fitted to the pre-post increments in all performance variables, taking the form:

$$Y = c_1 + c_2A + c_3F + c_4D + c_5AF + c_6AD + c_7FD + c_8A^2 + c_9F^2 + c_{10}D^2$$

was fitted as a multiple regression by ordinary least squares, using backward elimination. The same response surface model was fitted in the same way to the corresponding data from experiment two. Minitab software (Minitab Inc, State College PA) was used throughout, and statistical significance of all factor effects and regression coefficients was set at $p < 0.05$.

RESULTS

Exploratory analysis of the data from experiment one revealed that differences in pre versus post measures in all performance variables were significant. Peak torque increased from 326.4 to 334.1 Nm (+2.4%), $p < 0.01$, SEM = 6.6; average torque from 315.1 to 325.2 Nm (3.2%), $p < 0.001$, SEM = 6.6; peak jump height from 38.9 to 39.8 cm (2.3%), $p < 0.001$, SEM = 0.5; average jump height from 37.8 to 38.6 cm (2.1%), $p < 0.001$, SEM = 0.5; peak jump power from 4138 to 4193 W (1.3%), $p < 0.001$, SEM = 69; and average jump power from 4076 to 4125 W (1.2%), $p < 0.001$, SEM = 68. Discomfort scores were significantly affected by all of frequency, amplitude and duration, $p < 0.001$ in all cases. As the pre-post differences in average measures give a more appropriate indication of the effects of vibration exposure, only these differences (as single values determined by subtraction) in the corresponding three performance measures, together with the discomfort index were modelled using response surface methodology.

No acceptable response surface fits were achieved for any of the six performance variables in experiment one. More specifically no regression coefficients in any of the six models even approached

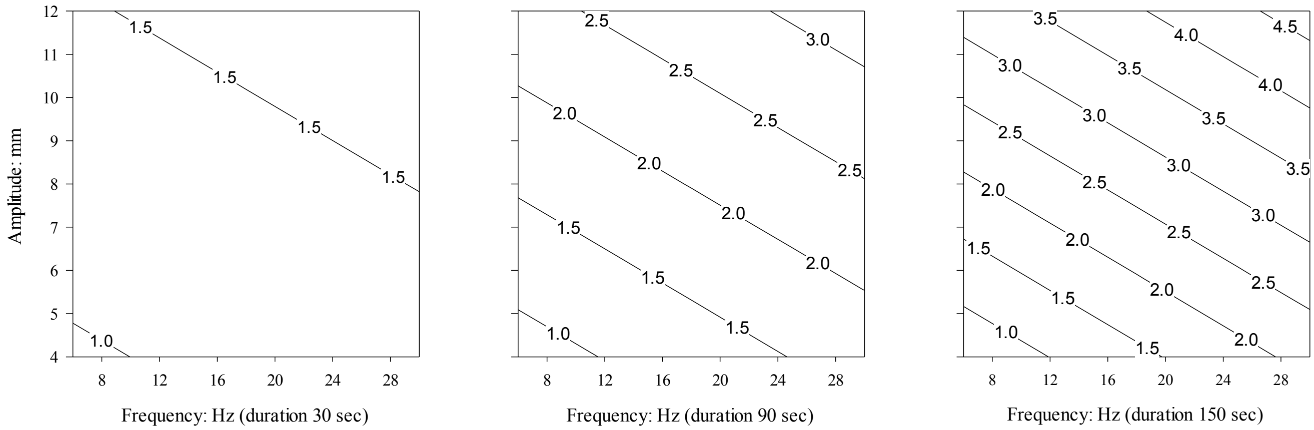

Figure 1. Contour plots of the discomfort scale.

significance below the $p = 0.1$ level, and no R^2 value exceeded 11.7%. In effect, random (block, and between and within subject) differences completely dominate the performance variation in all measures, and so no optimal combination of factor levels was obtainable, analytically or otherwise. This can be contrasted with analysis of the discomfort index (Y) which resulted in a response surface model of form:

$Y = 1.03 – 0.0138D + 0.000423FD + 0.00214AD$ which takes the form of an inclined plane in three dimensions, rising linearly with all three factors. Significance levels of the three regression coefficients are respectively $p = 0.015$, .0009 and < 0.001, and the intercept is not significantly different from 1.0 ($p = 0.78$), the lowest score on the index scale. Contour plots of this surface are shown in the three panels of Figure 1, and being a plane, the notion of a maximum or minimum is vacuous.

Experiment two, in which each of three participants completed a full replicate of the central composite design rather than a single block as a means of eliminating block and between subject differences, was an attempt to reach satisfactory response surface fits for the three performance variable averages. Similarly to the above result, not one of the nine (3 participants by 3 performance responses) attempts to obtain a fit was successful, and even when the significance level was relaxed to 0.10, only one was successful ($R^2 = 0.60$, adjusted $R^2 = 0.38$, and $p=0.09$).

DISCUSSION

From the current results the increases in peak and average CMJ height (~2%) and peak and average power (~1.3%) are in agreement with previous findings that acute WBV causes small transient effects in jump height and power (3, 14, 28). Likewise, the post-WBV increase of ~2% and 3% for peak and average ISO torque was comparable to that of Stewart et al. (27) and Torvinen et al. (28). Although the increase in CMJ and ISO was small it provides additional support that acute WBV enhances muscle performance. However, the mechanism of how WBV elicits this potentiation remains widely debated. One proposal is that acute WBV evokes a stretch reflex that increases muscle activation (9, 21, 24). However, other mechanisms such as the roles of muscle tuning, postural control, muscle temperature, and central motor command should not be discounted in explaining muscle performance changes (9, 22, 29).

It was beyond the scope of the present study to investigate the two types of vibration machines; namely side-alternating and synchronous vibration. However, it is important to note that the side-alternating machine used in this present study has a central axis that produces unilateral vibration to the left and right foot, which relies on foot placement to determine the amplitude; so when the feet are further from the central oscillating axis the amplitude will be larger. This differs from synchronous vibration where both legs are vibrated predominately in the vertical plane and amplitude is not dependent on foot placement. To ensure that the correct amplitude was maintained in the present study, the foot placement and position of the participant's body was carefully monitored by the researchers. However, it cannot be excluded that at very high frequencies and/or amplitudes the weight distribution of participants may have slightly changed, which may have influenced the outcome resulting in failure to locate optima.

Another explanation of why we failed to find a global optimal combination of frequency, amplitude and duration of WBV exposure could lie with the principle of individuality, this is; every participant may have an optimal or individualised resonance frequency, amplitude and duration for enhancing muscle performance. Di Giminiani et al. found that individualising vibration frequency maximises muscle activity to increasing muscle performance (16). Therefore, the lack of significant results in our first experiment could be due to the participants' individual sensitivity to frequency, amplitude and duration. Indeed this was the reason for extending the study to include experiment two. Nevertheless this issue remains problematic because in experiment two a surface fit was successfully found for just one performance variable in just one of the three participants, and then only when the significance level was relaxed to 0.10.

To further investigate the high variability evidenced in this study, we sought information on the repeatability of performance measures after vibration exposures. A number of studies report on test/retest reliability. For example, intraclass correlations of 0.93 for isometric strength and 0.98 for dynamic strength (15) and of 0.92 for countermovement jump and 0.80 for handgrip strength (10) are quoted. We are unable to find any studies reporting repeatability over more than simply the test/retest situation. It is our view therefore that these values are optimistic when applied to a higher number of tests such as in our and other experiments. Within subject variation cannot therefore be excluded as a contributor.

It is possible that each investigated WBV parameter may have interacted differently with each other (positively or negatively or no change) or modified the effect of another parameter. Recently, it has been documented that knee angle and stance are those most relevant parameters to increasing muscle activity (23), therefore it is conceivable that side-alternating WBV parameters of knee and hip angle, and body stance maybe the key characteristics to determining muscle performance enhancement. However, further research is required to validate this claim.

In conclusion these experiments are the first specifically designed to elicit a true optimal WBV exposure prescription, if indeed it exists. Our conclusions are that whilst vibration exposure does on average have a significant positive effect on muscle performance, its effect is so variable both between and within individuals that no real optimum can be discerned, either in general or for a given individual; and that excessive amplitudes, frequencies and durations lead to excessive discomfort.

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