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Determining the Optimal Whole-Body Vibration Dose–response Relationship for Muscle Performance

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Abstract

Da Silva-Grigoletto, ME, de Hoyo Lora, M, Corrales, BS, Páez, LC, and García-Manso, JM. Determining the optimal whole-body vibration dose–response relationship for muscle performance. *J Strength Cond Res* 25(X): 000–000, 2011—The aim of this investigation was twofold: first, to determine the optimal duration of a single whole-body vibration (WBV) exposure (phase 1) and second to find out the ideal number of sets per intervention to maximize muscle performance (phase 2). All participants were young (age: 19.4 ± 1.6 years), healthy, physically active men. In both studies, a 30-Hz frequency and a 4-mm peak-to-peak displacement were used. In phase 1, subjects ($n = 30$) underwent 3 sets of different durations (30, 60, and 90 seconds), whereas in phase 2, subjects ($n = 27$) AU4 undergo 3 interventions where the duration remained fixed at 60 seconds, and the number of sets performed (3, 6, or 9) was modified. The recovery time between sets was set at 2 minutes. In all interventions, each set consisted of 1 isometric repetition in a squat position with knees flexed at 100°. Before and after each session, jump height (countermovement jump [CMJ] and AU5 SJ) and power output in half squat (90° knee flexion) were assessed. In phase 1, an improvement in jump ability and power output was observed after the 30- and 60-second intervention AU6 ($p < 0.01$), whereas the 90-second participants just experienced an increase in SJ and CMJ ($p < 0.05$). When comparing the different protocols, the greatest response was achieved using 60 seconds ($p < 0.05$), which was therefore considered as the optimal duration to be used in phase 2. In the second phase, improvements in jump ability and power output were found with 3 and 6 sets ($p < 0.05$), whereas with 9 sets, participants actually experienced a decrease in these variables. Intergroup comparison showed a greater effect for the program of 6 sets ($p < 0.05$). In conclusion, a WBV intervention consisting of six 60-second sets produces improved muscle performance measured by SJ, CMJ, and power output.

Key Words vibration training, jump ability, muscular power

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Introduction

Whole-body vibration (WBV) has appeared increasingly in scientific journals and is being incorporated into regular training programs aiming to improve physical fitness (27). Several studies have looked at the effects of WBV on muscle performance. However, the results are not clear and are sometimes contradictory (9,13–15,17,21,22,25,35,38,39). The AU7 variability in the protocols used by different authors may explain the inconsistency of the results presented in published studies (13). These variations are related to the characteristics of the vibration used (i.e., frequency and amplitude), the movements on the platform, the duration and number of sets, recovery time after each stimulus, and the time between the end of stimulus and subsequent measurements. Thus, research has focused on finding the optimal combination of these variables to reach maximal muscular response. For this purpose, frequency, amplitude, and duration were the main parameters analyzed (1,4,20,23,35,37).

To determine the optimal training frequency, several studies used frequencies ranging from 15 to 90 Hz (24), although Cardinale and Bosco (12) suggested that beneficial effects could be obtained by using moderate frequencies (between 15 and 44 Hz). In a previous study, our working group assessed the effects of 3 different frequencies (20, 30, and 40 Hz), with a fixed amplitude of 4 mm, on jumping ability and power in the lower limbs; we concluded that 30 Hz yields the greatest increase in muscle performance (19).

With regard to the amplitude or peak-to-peak displacement, authors such as Cardinale and Bosco (12) note that most of the studies have shown positive results after the use of mechanical vibrations using low amplitudes, which varied between 3 and 10 mm. However, other authors such as AU8 Luo et al. (29) have concluded that there is no clearly defined, optimum range of training, although it appears that very small amplitudes may be insufficient to achieve an optimal AU9 effect in improving muscle response. In this line, Adams et al. (1) have analyzed different combinations of frequencies and amplitudes, showing that with a frequency of 30–35 Hz, the best results in countermovement jump (CMJ) are obtained with amplitudes of 2–4 mm, whereas, with frequencies in the 40- to 50-Hz range, the greatest improvements are achieved with amplitudes of 4–6 mm.

The duration of the exposure is also another factor to be considered when examining the effect of vibration training, because it too can affect muscle function. It appears that when the duration of exposure is excessive, muscle fatigue occurs (7,32). Bongiovanni and Hagbarth (5) observed increased muscular fatigue when the exposure is prolonged in time, corroborating this phenomenon with a decrease in the electromyographic (EMG) activity of the dorsiflexors. This effect could be because of an activation of the inhibitory feedback (e.g., Golgi tendon organs) or the reduced sensitivity of muscle spindles, such as the depletion of neurotransmitters or presynaptic inhibition (12). Adams et al. (1) found no difference in power output in a CMJ by varying the set time in the range of 30–60 seconds, although in all cases a single set was applied.

Focusing on this variable, Bazett-Jones et al. (2) suggested that although an exposure of short duration might elicit increased neural potentiation (postactivation potentiation [PAP]), a long-term stimulus would cause fatigue, resulting in a reduction of muscle strength. Similarly, if the stimulus is not enough to produce PAP, significant neuromuscular activation will not occur, so there will not be any improvement in muscle performance (3,28). Thus, most of the studies that have shown positive short-term effects of vibration exposure have not exceeded 10 minutes of total exposure (between 3 and 10 minutes), divided into 30- to 90-second sets (2,4,9,13,14,27,33,34,39).

Based on the aforementioned results, it seems that the best combination of these parameters is still unknown, and although the optimal frequency and peak-to-peak displacement have been studied in detail, evidence regarding the duration of the stimulus and the number of sets to be performed is more scarce. Therefore, the aim of this study was twofold: first, to determine the optimal duration of a single WBV exposure and second, to find out the ideal number of sets per intervention to maximize muscle performance. So, protocols were used in which the duration and number of sets were modified. To this aim, the study was conducted in 2 phases: phase 1 consisted of 6 isometric actions held for 30, 60, or 90 seconds, to determine the optimal duration; phase 2 comprised 3, 6, or 9 sets of the previously determined duration to determine the optimal dose–response relationship for muscle performance.

Methods

Experimental Approach to the Problem

Subjects performed 2 different WBV protocols with a week-long washout period between them. The parameters employed were the same for both protocols except for the variable that was assessed (exposure time in phase 1 and number of sets in phase 2). In each protocol, participants maintained an isometric squat position where the number of sets and their duration were modified.

In phase 1, the length of exposure was the variable studied to determine optimal set duration; for such a purpose, the subjects were randomly divided and allocated into 1 of 3 groups (30, 60, and 90 seconds); for all trials, the number of exposures was set at 6. All subjects performed all of the trials (30, 60, and 90 seconds), but the order in which they performed the trials was randomized. For phase 2, the best exposure time obtained in phase 1 was used, and the number of exposures varied (3, 6, and 9 exposures). As in phase 1, subjects were randomly allocated to one of the experimental conditions and performed all 3 protocols in a randomized order. The rest period between each experimental condition was a minimum of 72 hours to avoid carryover effects from previous sessions (Figure 1). F1 To summarize, phase 1 consisted of 6 isometric actions held for 30, 60, or 90 seconds, whereas phase 2 comprised sets of 3, 6, or 9 sets of a 60-second duration.

To avoid bruising, all subjects wore sport shoes for the vibration exercises. To avoid variations in vibration transmission, subjects were asked to wear the same footwear at all training sessions. Vibration was applied 10 minutes after the warm-up, and tests described earlier were performed by the subjects; 5 minutes after finishing the vibration condition, postvibration tests were also performed.

Subjects

Young, healthy male subjects volunteered to participate in the study (30 in phase 1 and 27 in phase 2). The mean (*SD*) characteristics of the subjects are shown in Table 1. T1 Participants' medical histories were reviewed by a doctor to assess their suitability for the study, and each subject completed a questionnaire on his physical activity (18). Subjects with osteoarticular conditions (including fracture or injury) were excluded. The study was conducted according

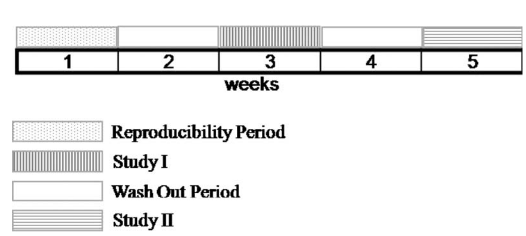


Figure 1. General layout and timing of studies.

Table 1. Descriptive data of participants.*†

	Weight (kg)	Height (cm)	Age	BMI
Phase 1 ($n = 30$)	71.88 ± 10.82	176.59 ± 5.41	19.50 ± 1.53	23.02 ± 3.08
Phase 2 ($n = 27$)	70.27 ± 9.81	175.55 ± 4.69	19.41 ± 1.55	22.77 ± 2.83

*BMI = body mass index.
†Values are given as mean ± *SD.*

to the Declaration of Helsinki, and the protocol was fully approved by the clinical research ethics committee before the assessments. After a detailed explanation about the aims, benefits, and risks involved in this investigation, all participants gave written informed consent. All subjects were physically active and played in intramural sports leagues at the university but had not participated in regular resistance or jump-training programs during the last 12 months. All subjects had a very similar training volume (minimum 3 per week and maximum 4 per week), broken up into 1-hour sessions. They were engaged in sports activities such as indoor soccer, basketball, volleyball, and paddle tennis. None of the selected subjects performed specific physical preparation exercises because, given the category they play in and the small amount of time they train, training was focused on game exercises. All research was done during a period (between February and March) in which the participants were competing in their respective intramural leagues. In addition, tests were always performed at the same time of the day to minimize any adverse effect on testing. All subjects had a typical Spanish breakfast (19); water intake was ad libitum.

Procedures

Warm-Up. All tests were preceded by a 5-minute warm-up (3 minutes 25 W + 2 minutes 50 W) on a cycloergometer (Ergoline 900, Ergometrics, Bitz, Germany) followed by 5 minutes of joint mobility in the upper normal range of motion (5–10 seconds) for femoral quadriceps, hamstrings, and triceps surae.

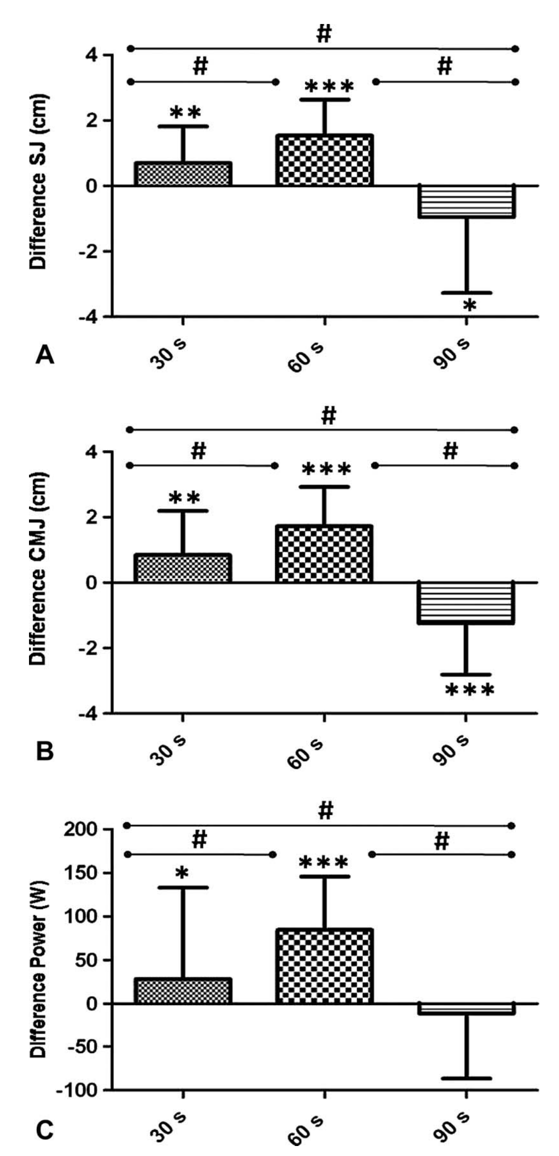
Jump Tests. Lower-body explosive strength characteristics, expressed as elevation of the body's center of gravity (vertical jump), were assessed using an infrared-ray platform (A.F.R technology) built into the MuscleLab system (Model PFMA 3010e, Ergotest, Langesund, Norway). AU10

Two different vertical jumps were used for data recording: SJ and CMJ (10). The SJ is a test used to assess lower-body power and the ability to recruit motor units. It is performed from the half-squat position with a knee angle of 90°; after a brief pause, the subject performing the test jumps upward

Table 2. Mean and *SD* to SJ, CMJ, and power tests before and after WBV intervention with 3 different times of exposure.*

		Mean (*SD*)				IC to 95%	
Time (s)	Test	Pretest†	Posttest	Sig. (p)‡	Effect size (d)§	Lower	Upper
30	SJ (cm)	36.31 (3.91)	37.01 (3.66)	0.002	0.18	0.284	1.123
	CMJ (cm)	40.04 (4.61)	40.88 (4.96)	0.002	0.17	0.336	1.344
	Power (W)	1,337.95 (194.13)	1,375.14 (197.98)	0.030	0.19	3.92	70.46
60	SJ (cm)	36.00 (4.20)	37.54 (4.14)	<0.001	0.37	1.132	1.955
	CMJ (cm)	39.61 (4.99)	41.33 (5.04)	<0.001	0.34	1.295	2.138
	Power (W)	1,336.45 (178.60)	1,407.66 (207.25)	<0.001	0.37	45.77	96.65
90	SJ (cm)	36.98 (4.01)	36.03 (4.21)	0.032	0.23	−1.820	−0.087
	CMJ (cm)	40.07 (4.07)	38.87 (5.15)	<0.001	0.26	−2.615	−0.925
	Power (W)	1,360.66 (183.56)	1,350.24 (195.90)	0.526	0.05	−43.63	22.79

AU18 *CMJ = countermovement jump; WBV = whole-body vibration.
†No significant differences between mean values.
‡Level intragroup significance.
§Effect size (Cohen's *d*).



AU17

Figure 2. Differences between pre and posttest in SJ (A), countermovement jump (B), and power output (C) using 3 different times of exposure to whole-body vibration. *Difference of means intragroup significant to the 0.05 level. **Difference of means intragroup significant to the 0.01 level. ***Difference in means intragroup significant to the 0.001 level. #Difference of means intergroup significant to the 0.05 level.

as high as possible. The CMJ is a test used to assess explosive strength with reuse of elastic energy and takes advantage of the myotatic reflex (10). The test starts with a preparatory movement of knee extension going down to a 90° knee flexion and, without pausing, jumping upward as high as possible. Both jumps were performed without the use of the arms; subjects were asked to keep their hands on their hips. Elevation of the center of gravity (height in meters) above ground level was calculated for both tests as flight time (t_v) in seconds, applying the laws of ballistics:

$$H = t_v^2 \cdot g \cdot 8^{-1}(\mathrm{m}),$$

where H is the height and g is the gravitational acceleration (9.81 m·s^{-2}).

The subjects performed 3 jumps of each type; the best result was used for statistical analysis. Participants conducted 3 SJs followed by 3 CMJs, leaving a recovery time of 30 seconds between each of the 3 SJ and CMJ actions. A recovery time of 1 minute was given between the end of the SJ actions and the beginning of CMJ actions.

Muscle Power. Although subjects had already performed the jump tests, they performed a set of 8 repetitions at loads of 30–40% of the perceived maximum as a specific warm-up. Lower-body maximal power was assessed using the MuscleLab system. The subjects were placed in a half-squat position, with shoulders touching the bar; the starting knee angle for movement execution was set at 90°. When told to do so, subjects extended their legs (extensors of hip, knee, and ankle) from the flexed knee position to reaching full extension at 180°. This movement was used for estimating maximum power, subjects were asked to perform the movement as quickly as possible (36). All tests were performed using a Multipower machine (GervaSport, Madrid, Spain), designed for doing squat exercises in which linear bearings only allow the bar to be displaced vertically. Four different loads added to body weight were used for estimating both maximal and mean power: 25, 45, 65, and 85 kg. Three trials were performed for each load, and the best result (maximum average speed) was used for subsequent analysis. A recovery time of 30 seconds was allowed in between the 3 actions of the same load in power testing, and a recovery time of 180 seconds was provided between the end of the 3 actions of the same load and the beginning of the following 3 actions at a higher load in power testing. During the test, maximum average speed (m·s^{-1}) and average power (watts) were collected using the lineal encoder built into the MuscleLab system, whose internal microprocessor works at a resolution of 10 microseconds. As the load is moved, the optical transducer signal interrupts the microprocessor at every 0.07-mm displacement. Power calculations were performed as previously described (36). Average power across the full range of motion of a repetition was calculated using a linear dynamometer.

Whole-Body Vibration Protocol. We used the combination of parameters determined to be the most effective by previous studies: a frequency of 30 Hz (14,19) and a recovery time of 2 minutes between sets for both studies (20). Because of the mechanical characteristics of the machine used, peak-to-peak displacement was fixed as 4 mm; greater muscle activity and strength were attained when this displacement was combined with the aforementioned frequency (1,19,20). Vibration

Table 3. Mean and *SD* to SJ, CMJ, and power tests before and after WBV intervention with 3 different numbers of sets.*

		Mean (*SD*)				IC to 95%	
No of sets	Test	Pretest†	Posttest	Sig. (p)‡	Effect size (d)§	Lower	Upper
3	SJ (cm)	37.64 (3.79)	38.44 (3.79)	0.018	0.21	0.32	1.27
	CMJ (cm)	40.62 (4.47)	42.28 (4.54)	<0.001	0.37	1.199	2.119
	Power (W)	1,295.64 (195.07)	1,311.11 (174.51)	0.017	0.09	8.66	79.14
6	SJ (cm)	37.09 (3.77)	38.95 (3.50)	<0.001	0.55	1.43	2.28
	CMJ (cm)	40.61 (5.04)	42.68 (5.37)	<0.001	0.40	1.458	2.688
	Power (W)	1,299.17 (201.08)	1,309.75 (180.81)	<0.001	0.05	33.86	90.09
9	SJ (cm)	37.50 (3.90)	37.72 (4.18)	0.060	0.05	−0.13	0.60
	CMJ (cm)	40.78 (5.02)	41.11 (5.06)	0.088	0.06	0.053	0.712
	Power (W)	1,301.19 (189.41)	1,313.77 (202.38)	0.477	0.06	−23.23	48.40

*CMJ = countermovement jump; WBV = whole-body vibration.
†No significant differences between mean values.
‡Level intragroup significance.
§Effect size (Cohen's *d*).

was applied using a vibrating platform producing sinusoidal oscillations (Nemes, Ergotest, Rome, Italy). The subjects adopted an isometric squat position during all exposures, with knees flexed at 100°, as measured by a manual goniometer. Hands were placed lightly on the machine handlebar during the intervention.

Reproducibility of Variables

Tests were repeated on 3 different days (Monday, Wednesday, and Friday) during the week before training. The intraclass correlation values (interday) were SJ = 0.93, CMJ = 0.96, and power = 0.95.

Statistical Analyses

Traditional statistical methods were used to calculate the means and *SD*. Sample normality was calculated using the Shapiro–Wilk test. An analysis of variance and the Bonferroni adjustment for multiple comparisons were used to compare mean values. The significance level was set at $p \leq 0.05$; the SPSS 17.0 package for Windows (Chicago, IL, USA) was used for all statistical tests. Effect size was calculated for paired variables (16). Rhea's scale was used to interpret the magnitude of effects in strength training: magnitude was thus classified as trivial (<0.50), small (0.50–1.25), moderate (1.25–1.9), or large (≥2) (31).

Results

Phase 1

The values obtained from tests of SJ, CMJ, and power output in half squat before and after exposure of subjects to a single session of WBV are shown in Table 2 and Figure 2. T2 F2

When analyzing the results after the SJ test, significant increases with 30 seconds (2.07%, $p < 0.05$) and 60 seconds (4.41%, $p < 0.01$) were observed. Additionally, there was a significant decrease (2.64%, $p < 0.05$) when the set time was increased 90 seconds. In any case, significant intergroup differences were found ($p < 0.05$).

For the CMJ test, there was a significant increase with the 60-second set (4.44%, $p < 0.01$). At the same time, there was a significant decrease (3.09%, $p < 0.01$) by using 90 seconds. There was no significant difference after the application of 30 seconds, despite a small increase (2.06%). Moreover, significant post hoc differences were found ($p < 0.05$).

Finally, considering the values obtained with the maximum power test significant increases were observed for set times of 30 seconds (2.28%, $p < 0.05$) and 60 seconds (5.33%, $p < 0.001$). However, there was a slight but not significant decrease when the subjects were exposed to 90-second WBV (0.77%). Again, for this variable, post hoc analysis did reach statistical significance ($p < 0.05$).

Phase 2

The results obtained from tests of SJ, CMJ, and power output in half squat before and after a single exposure to WBV are shown in Table 3 and Figure 3. T3 F3

Leer fonéticamenteA significant increase after 3 (2.08%, $p < 0.05$) and 6 (4.77%, $p < 0.001$) sets was found for SJ, whereas participants experienced a nonsignificant increase (0.58%) with 9 sets. Significant intergroup differences were found between the protocols used ($p < 0.05$). AU11

As forEscucha\As forA the CMJ test after the application of WBV training, significant increases were observed with 3 (4.17%, $p < 0.05$) and 6 sets (5.12%, $p < 0.01$) but not for 9 (0.77%). The post hoc comparison also showed significant differences between the protocols used ($p < 0.05$). AU12

Finally, the peak power test showed a significant increase after the applications of 3 (4.69%, $p < 0.05$) and 6 sets (4.91%, $p < 0.01$), whereas the intervention of 9 sets showed no

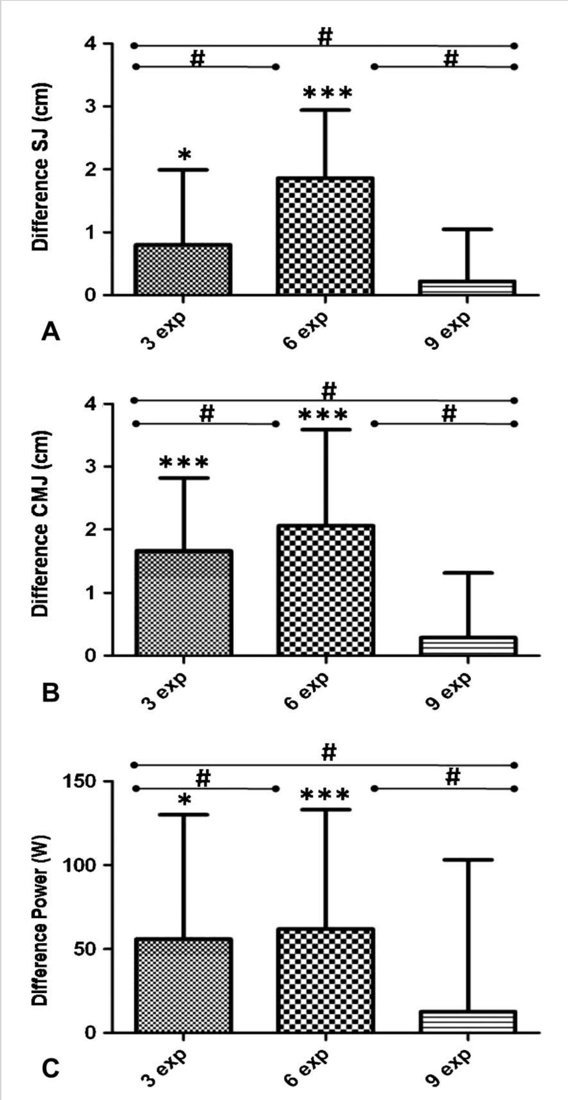


Figure 3. Differences between pre and posttest in SJ (A), countermovement jump (B), and power output (C) using 3 different numbers of sets to whole-body vibration. *Difference of means intragroup significant to the 0.05 level. **Difference of means intragroup significant to the 0.01 level. ***Difference in means intragroup significant to the 0.001 level. #Difference of means intergroup significant to the 0.05 level.

significant increments (1.01%). The post hoc comparison showed again significant differences between the protocols used ($p < 0.05$).

Discussion

The aim of this study was, first, to determine the most appropriate duration of vibratory stimuli (30, 60, or 90 seconds) and, second, once that variable had been established, determine the optimal number of sets (3, 6, or 9) to obtain greater muscular response, considering a fixed frequency and amplitude (30 Hz and 4 mm).

After the test significant improvements in jump ability (SJ and CMJ), and the power generated by the lower limbs muscles were found when applying exposures of 30 and 60 seconds, whereas with 90 seconds, participants even experienced a decrement in the performance. These changes have a trivial effect size for all exposure times.

Regarding the second phase of the experiment, and once 60 seconds was established as the optimal duration, improvements were achieved in all tests by using different numbers of exposures, although, these changes were only significant for 3 and 6 sets. Again, the effect size analysis showed a trivial effect for all protocols. Six sets, however, had a greater effect on the CMJ test.

These responses are in line with those previously reported by authors such as Bosco et al. (8), who used 10sets of 60 seconds (26 Hz, 10 mm) with a 60-second recovery between them and reported increments in both mean power and peak power in volleyball players. Using the aforementioned protocol, but with a lower amplitude (4 mm), this research group found a significant increase in CMJ in physically active men (9). However, one may consider that the number of exposures used in both studies (10 sets) can be excessive to achieve a better muscle response. On the other hand, our data differ with those reported by Bullock et al. (11), who used a duration of 60 seconds and also found no changes in jump height (SJ and CMJ) in a group of 7 elite skeleton athletes. In the study, authors used a recovery time of 3 minutes between sets, which has been deemed excessive (20).

Using a shorter exposure time, Bedient et al. (4) analyzed the effects of different intervention protocols on muscle strength. They combined a frequency of 30, 35, 40, and 45 Hz with amplitudes of 2 and 5 mm during a single exposure of 30 seconds. The greater response in power output (CMJ) was found with 30 Hz (2–3 mm) and 50 Hz (5–6 mm). These data contrast with the results of Bazett-Jones et al. (3) who found no significant changes with a frequency of 30 Hz (2–4 mm) after a single application of 45 seconds. However, significant changes were observed using exposures of 40 Hz (2–4 mm) and 50 Hz (4–6 mm).

Adams et al. (1) also analyzed the effect of different WBV frequencies, amplitudes, and durations, although no significant differences were observed when the duration of the stimulus changed (30, 45, and 60 seconds). It seems that the use of a protocol in which amplitude, frequency, and duration are changed together does not allow the optimal combination to be determined.

In their work to determine the optimal stimulation frequency, authors such as Cardinale and Lim (14) reported that the highest EMG root-mean-square signal (EMGrms) was found at 30 Hz, as compared with 40 or 50 Hz. The authors suggested that 30 Hz may elicit the highest reflex response in the vastus lateralis muscle during WBV in the half-squat position–but again, as in our case, this response was obtained with 60 seconds. Similarly, Da Silva et al. (19) with a protocol consisting of 6 sets of 60 seconds observed that the combination of parameters resulting in increased muscle response occurred with 30 Hz and 4 mm when compared to 20 and 40 Hz.

There is evidence that prolonged WBV exposure leads to AU13 a decrease in muscle response. In this sense, Rittweger et al. (32) observed a decrease in power output after a WBV exposure to fatigue (200–475 seconds) with a frequency of 26 Hz and an amplitude of 11 mm but using an additional load between 35 and 40% of the total body weight.

Similarly, Torvinen et al. (38) found no significant improvement in CMJ after the application of durations >1 minute (4 minutes). According to the authors, it seems that the amplitude of 2 mm used in this study was not enough to induce positive neuromuscular responses. Using the same AU19 exposure time, but with greater amplitude (10 mm), the same authors observed significant changes in CMJ (39). It is noteworthy that, despite the slight increase observed by the authors in the CMJ test (only 0.6 cm), the gastrocnemius muscles revealed a significant decrease in the EMG Mean Power Frequency signal (EMGmpf) and a significant increase in the EMGrms from the first minute, which can be taken as evidence of a state of muscle fatigue.

AU14 In addition, Stewart et al. (37) analyzed the WBV effects on maximum isometric strength after 2, 4, and 6 minutes (26 Hz and 4 mm on a rotational platform). The results showed a significant increase only after the 2-minute protocol, whereas with 4 and 6 minutes, there was a significant decrease. However, a comparison with this study is difficult, because both the platform used and the outcomes assessed differ from those of this study.

A possible explanation for the acute response observed in the explosive strength when the duration of exposure is prolonged may be related to the fatigue levels reached. Bongiovanni et al. (6) indicated that during a voluntary isometric contraction, which characterizes many of the protocols used in studies with WBV, fatigue seems to be low at the beginning and start to increase when the duration of exposure does, as can be seen by an increase in EMG response.

All this leads us to believe that, in moderately active subjects, exposures for >1 minute may not only elicit AU15 neuromuscular fatigue that limits explosive strength but also, if the number of sets exceeds 6, the above-mentioned response may be apparent. This phenomenon seems similar to the PAP experienced after the application of electrical stimulation or exercises of short duration and high load. Thus, PAP may be considered an increase of muscle contractile capacity after stimulation (30). However, if fatigue arises, neural potentiation may not occur (3).

Cardinale and Bosco (12) also suggested that although short-term exposure (time and number of sets) may cause an increase in neuromuscular potentiation (i.e., PAP), a long-term stimulus would elicit fatigue and therefore a decrease in muscle strength. Similarly, if the stimulus is not enough to induce PAP, the neuromuscular activation is not relevant, and therefore improvements in muscle performance are not apparent (3,28).

In conclusion, sets of 60 seconds had the greatest effect on different manifestations of explosive strength. Accordingly, for a frequency of 30 Hz and a peak-to-peak displacement of 4 mm, 6 sets of 60 seconds seem to be the optimal WBV protocol necessary to reach the greatest muscle response in the lower limbs.

Practical Applications

Whole-body vibration training is recommended for activities involving explosive motions, such as jumping as a warm-up activity. However the optimal dose–response relationship with this method remains unclear. The results of this study contribute to our understanding of effective training prescription during WBV. Several studies have focused on short-term effects of WBV based on the frequency and the peak-to-peak displacement to increase muscle response. However, The optimal duration and number of sets for achieving this aim remain unknown. Our results show that 6 sets of 60 seconds are effective in improving power performance and jump ability. Although the effect of WBV on performance is likely variable and minimal for most athletes, coaches might consider using it because of the potential benefit it may achieve when the WBV time is optimized.

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References

1. Adams, JB, Edwards, D, Serviette, D, Bedient, AM, Huntsman, E, Jacobs, KA, Del Rossi, G, Roos, BA, and Signorile, JF. Optimal frequency, displacement, duration, and recovery patterns to maximize power output following acute whole-body vibration. *J Strength Cond Res* 23: 237–245, 2010.
2. Bazett-Jones, DM, Finch, HW, and Dugan, EL. Comparing the effects of various whole-body vibration accelerations on counter-movement jump performance. *J Sports Sci Med* 7: 144–150, 2008.
3. Bazett-Jones, DM, Winchester, JB, and McBride, JM. Effect of potentiation and stretching on maximal force, rate of force development, and range of motion. *J Strength Cond Res* 19: 421–426, 2005.
4. Bedient, AM, Adams, JB, Edwards, DA, Serravite, DH, Huntsman, E, Mow, SE, Roos, BA, and Signorile, JF. Displacement and frequency for maximizing power output resulting from a bout of whole-body vibration. *J Strength Cond Res* 23: 1683–1687, 2009.
5. Bongiovanni, LG and Hagbarth, KE. Tonic vibration reflexes elicited during fatigue from maximal voluntary contractions in man. *J Physiol* 423: 1–14, 1990.
6. Bongiovanni, LG, Hagbarth, KE, and Stjernberg, L. Prolonged muscle vibration reducing motor output in maximal voluntary contractions in man. *J Physiol* 423: 15–26, 1990.
7. Bosco, C, Cardinale, M, and Tsarpela, O. Influence of vibration on mechanical power and electromyogram activity in human arm flexors muscles. *Eur J Appl Physiol* 79: 306–311, 1999.
8. Bosco, C, Colli, R, Introini, E, Cardinale, M, Tsarpela, O, Madella, A, Tihanyi, J, and Viru, A. Adaptive responses of human skeletal muscle to vibration exposure. *Clin Physiol* 19: 183–187, 1999.

9. Bosco, C, Iaconvell, M, Tsarpela, O, Cardinale, M, Bonifazi, M, Tihanyi, J, Viru, M, De Lorenzo, A, and Viru, A. Hormonal response to whole-body vibration in men. *Eur J Appl Physiol* 81: 449–454, 2000.
10. Bosco, C, Luhtanen, P, and Komi, PV. A simple method for measurement of mechanical power in jumping. *Eur J Appl Physiol* 50: 273–282, 1983.
11. Bullock, N, Martin, DT, Ross, A, Rosemond, CD, Jordan, MJ, and Marino, FE. Acute effect of whole-body vibration on sprint and jumping performance in elite skeleton athletes. *J Strength Cond Res* 22: 1371–1374, 2008.
12. Cardinale, M and Bosco, C. The use of vibration as an exercise intervention. *Exerc Sports Sci Rev* 31: 3–7, 2003.
13. Cardinale, M and Lim, J. The acute effects of two different whole body vibration frequencies on vertical jump performance. *Med Sports* 56: 287–292, 2003.
14. Cardinale, M and Lim, J. Electromyography activity of vastus lateralis muscle during whole-body vibrations of different frequencies. *J Strength Cond Res* 17: 621–624, 2003.
15. Cohen, J. *Statistical Power Analysis for the Behavioral Sciences* (2nd ed.).Hillsdale, NJ: L. Erlbaum Associates, 1998.
16. Cormie, P, Russell, S, Deane, N, and McBride, JM. Acute effects of whole-body vibration on muscle activity, strength and power. *J Strength Cond Res* 20: 257–261, 2006.
17. Craig, CL, Marshall, AL, Sjöström, M, Bauman, AE, Booth, ML, Ainsworth, BE, Pratt, M, Ekelund, U, Yngve, A, Sallis, JF, and Oja, P. International physical activity questionnaire: 12-country reliability and validity. *Med Sci Sports Exerc* 35: 1381–1395, 2003.
18. Da Silva, ME, Nuñez, VM, Vaamonde, D, Fernández, JM, Poblador, MS, Garcia-Manso, JM, and Lancho, JL. Effects of different frequencies of whole body vibration on muscular performance. *Biol Sport* 23: 1–14, 2006.
19. Da Silva, ME, Vaamonde, D, Castillo, E, Poblador, MS, García-Manso, JM, and Lancho, JL. Acute and cumulative effects of different times of recovery from whole body vibration exposure on muscle performance. *J Strength Cond Res* 23: 2073–2082, 2009.
20. De Ruiter, CJ, Van der Linden, RM, Van Der Zijden, MJ, Hollander, AP, and de Haan, A. Short-term effects of whole body vibration on maximal voluntary isometric knee extensor force and rate of force rise. *Eur J Appl Physiol* 88: 472–475, 2003.
21. Erskine, J, Smilie, I, Leiper, J, Ball, D, and Cardinale, M. Neuromuscular and hormonal responses to a single session of whole body vibration exercise in healthy young men. *Clin Physiol Funct Imaging* 27: 242–248, 2007.
22. Gerodimos, V, Zafeiridis, A, Karatrantou, K, Vasilopoulou, T, Chanou, K, and Pispirikou, E. The acute effects of different whole-body vibration amplitudes and frequencies on flexibility and vertical jumping performance. *J Sci Med Sport* 13: 438–443, 2009.
23. Issurin, BV. Vibrations and their applications in sport. *J Sports Med Phys Fitness* 45: 324–336, 2005.
24. Jordan, M, Norris, S, Smith, D, and Herzog, W. Acute effects of whole-body vibration on peak isometric torque, muscle twitch torque and voluntary muscle activation of the knee extensors. *Scand J Med Sci Sports* 20: 535–540, 2009.
25. Jordan, MJ, Norris, SR, Smith, DJ, and Herzog, W. Vibration training: An overview of the area, training consequences, and future considerations. *J Strength Cond Res* 19: 459–466, 2005.
26. Kerschan-Schindl, K, Grampp, S, Henk, C, Resch, H, Preisinger, E, Fialka-Moser, V, and Imhof, H. Whole-body vibration exercise leads to alterations in muscle blood volume. *Clin Physiol* 21: 377–382, 2001. AU16
27. Koch, AJ, O'Bryant, HS, Stone, ME, Sanborn, K, Proulx, C, Hruby, J, Shannonhouse, E, Boros, R, and Stone, MH. Effect of warm-up on the standing broad jump in trained and untrained men and women. *J Strength Cond Res* 17: 810–816, 2003.
28. Luo, J, McNamara, B, and Moran, K. The use of vibration training to enhance muscle strength and power. *Sports Med* 35: 23–41, 2005.
29. McBride, JM, Porcari, JP, and Scheunke, MD. Effect of vibration during fatiguing resistance exercise on subsequent muscle activity during maximal voluntary isometric contractions. *J Strength Cond Res* 18: 777–781, 2004.
30. Rhea, MR. Determining the magnitude of treatment effects in strength training research through the use of the effect size. *J Strength Cond Res* 18: 918–920, 2004.
31. Rittweger, J, Beller, G, and Felsenberg, D. Acute physiological effects of exhaustive whole-body vibration exercise in man. *Clin Physiol* 20: 134–142, 2000.
32. Rittweger, J, Hans, S, and Felsenberg, D. Oxygen uptake during whole-body vibration exercise: Comparison with squatting as a slow voluntary movement. *Eur J Appl Physiol* 86: 169–173, 2001.
33. Rittweger, J, Just, K, Kautzsch, K, Reeg, P, and Felsenberg, D. Treatment of chronic lower back pain with lumbar extension and whole-body vibration exercise. *Spine* 27: 1829–1834, 2002.
34. Rønnestad, BR. Acute effects of various whole body vibration frequencies on 1RM in trained and untrained subjects. *J Strength Cond Res* 23: 2068–2072, 2009.
35. Sahaly, R, Vandewalle, H, Driss, T, and Monod, H. Maximal voluntary force and rate of force development in humans importance of instruction. *Eur J Appl Physiol* 85: 345–350, 2001.
36. Stewart, JA, Cochrane, DJ, and Morton, RH. Differential effects of whole body vibration durations on knee extensor strength. *J Sci Med Sport* 12: 50–53, 2009.
37. Torvinen, S, Kannu, P, Sievänen, H, Järvinen, TA, Pasanen, M, Kontulainen, S, Järvinen, TL, Järvinen, M, Oja, P, and Vuori, I. Effect of a vibration exposure on muscular performance and body balance. Randomized cross-over study. *Clin Physiol Funct Imaging* 22: 145–152, 2002.
38. Torvinen, S, Sievänen, H, Jarvinen, TA, Pasanen, M, Kontulainen, S, and Kannus, P.Effect of 4-min vertical whole body vibration on muscle performance and body balance. A randomized cross-over study. *Int J Sports Med* 23: 374–379, 2002.