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Chronic effects of whole-body vibration on jumping performance and body balance using different frequencies and amplitudes with identical acceleration load

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\textbf{ABSTRACT}

Previous studies on vibration training have all been based on protocols at different combinations of frequencies and amplitudes without controlling the loading intensity.

\textbf{Objectives:} This study investigated the effect of an 8-week vibration training program, under identical acceleration loads with various frequencies and amplitudes, on jumping performance, muscle activation and body balance.

\textbf{Design:} Fifty young adults were randomly assigned to an high-frequency (32 Hz, 1 mm, and 4 g), low-frequency (18 Hz, 3 mm, and 4 g), or a control group. The high-frequency and low-frequency groups underwent 60 s of squats exercise on the specific vibration platform three times a week, whereas the control group was trained without vibration.

\textbf{Methods:} A force platform was used to measure the center of pressure of a static single leg stance, and the heights and impulse of two consecutive countermovement jumps before and after intervention. The activation of the rectus femoris and biceps femoris were also measured synchronously by surface electromyography.

\textbf{Results:} The heights and impulse of both the first and second countermovement jumps were significantly increased and the area of center of pressure was significantly decreased after training in both the high-frequency and low-frequency groups ($P < .05$). Consequently, activation of the rectus femoris during the first countermovement jump was significantly lower than the pre-training value in the HF group but increased in the low-frequency group after training ($P < .05$).

\textbf{Conclusion:} An 8-week identical acceleration vibration training regimen with various frequencies and amplitudes can significantly improve jumping performance and body balance, but the specific neuromuscular adaptation is possibly induced by different training settings.

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1. Introduction

Whole-body vibration (WBV) training has been reported to be an effective approach to relieve muscle tension,\textsuperscript{1} lead to greater strength, and promote higher performance.\textsuperscript{2,3} Hundreds of peer-reviewed papers have recently been published, and the number of ongoing studies on vibration training is still increasing, indicating that the optimal exercise modality remains unclear in the scientific community. Studies in recent years have concluded that vibration training can increase isometric and dynamic strength, as well as improve countermovement jump and bone density.\textsuperscript{4} On the contrary, other studies demonstrated that vibration training could not effectively improve strength, countermovement jumps, or body balance.\textsuperscript{5,6} Contradictory findings are possible because of the dissimilar vibration parameters, which primarily include frequency and amplitude. The interaction of frequency and amplitude determines the acceleration, which is the major loading parameter. Previous studies on vibration training have all been performed by following the protocols at different combinations of frequencies and amplitudes without controlling acceleration, which represents
the loading intensity.\textsuperscript{5} Any change in vibration frequency or amplitude alters the acceleration output from the vibration platform, which generates different training loads.

Incorrect vibration settings may lead to excessive acceleration transmitted to the human body, which can be harmful and increase the risk of injury.\textsuperscript{3,4,6} The minimum acceleration used in previous vibration training studies that generated a positive training effect was 2.28 g, where 1 g is the acceleration of gravity (1 g = 9.81 m/s\(^2\)). Therefore, load intensity for this study was set to 4 g. Moreover, some different mechanisms seem to supportively explain performance enhancement by vibration training. The findings of previous fundamental neuromuscular research indicated that when the muscles performed maximal voluntary contraction, the excitation frequency of the motor unit was nearly 30 Hz.\textsuperscript{8} Consequently, stimulation vibration frequencies at 30–50 Hz could induce significant effects.\textsuperscript{2} Such frequencies are the same as muscle spindle excitation frequencies, as well as the neural input frequencies at the maximal force generation state that can produce synchronized contraction effects.\textsuperscript{9} Furthermore, greater spinal pathway or cortical reflex can be involved in the stretch-shortening cycle.\textsuperscript{10} Thus, the higher-frequency set for this study was based on this premise. Consequently, the natural frequency of muscle tissues, ranging from 10 to 20 Hz, could induce a neural reflex.\textsuperscript{11} We adopted the lower frequency within this range to induce muscle resonance and achieve a training effect.

Optimal vibration frequency for training has been analyzed in previous studies, but instead of controlling the load intensity, a wide variety of vibration accelerations were used in those studies.\textsuperscript{12} To date, no vibration studies clearly indicated different combinations of frequencies and amplitudes with the same accelerations load. Therefore, this study investigated the effect of an 8-week vibration training program, under identical acceleration loads at varying frequencies and amplitudes, on jumping performance, muscle activation and body balance. We hypothesized that 8-week vibration training would result (i) in significant increases of jump height, vertical ground reaction impulse, and SSC ability, and (ii) in reduced area and speed of center of pressure (CoP). We also hypothesized that the HF vibration training would significantly reduce the rectus femoris and biceps femoris muscle activities.

2. Methods

We recruited 50 healthy young adults (age: 20.3 ± 1.1 y; height: 167.9 ± 10.1 cm; weight: 62.2 ± 11.2 kg), who were moderately trained and had neither lower-limb injuries nor bone and neural problems within 6 months prior to participating in the test. This study was approved by the Medical Research Ethics Committee of Taipei Medical University Hospital and all participants completed a statement of informed consent. Two participants could not meet the test requirements of movement; therefore, the total number of participants was 48 after excluding the unqualified two. All eligible participants were randomly divided into 3 groups: a high-frequency group (HF, 32 Hz, 1 mm, male 8, female 8, 20.6 ± 1.2 y, 167.3 ± 9.3 cm, 62.4 ± 8.9 kg), a low-frequency group (LF, 18 Hz, 3 mm, male 8, female 8, 19.3 ± 0.7 y, 168.7 ± 11.1 cm, 60.2 ± 14.1 kg), and a control group (CON, training without vibration, male 8, female 8, 19.7 ± 0.7 y, 166.8 ± 7.7 cm, 60.5 ± 12.9 kg). The loading intensity for both the HF and LF training conditions was set at 4 g.

Both types of vibration were vertical. The HF training used the Magtonic Zen Pro TVR-6900 (frequency: 20–50 Hz, amplitude: 2–4 mm, low: 1–2 mm), and LF training involved using Magtonic Zen Pro TVR-4900 (frequency: 20–50 Hz, amplitude: 1.5 mm). However, to control the vibration accelerations, both machines were adjusted accordingly. The specification of vibration platform was specially tuned by the manufacturer and validated by the researcher. The amplitude and frequency were calibrated to 4 g by using the formula \( a = f(2\pi f)^2 \) [9.81].\textsuperscript{5} Where \( g \) is the acceleration of vibration platform output, \( a \) is the amplitude and \( f \) is the frequency. Frequency and amplitude were adjusted and verified by the number of oscillations per second and peak-to-peak displacement by attaching an accelerometer at the center of the platform.

During the 8-week vibration training program, participants of HF and LF training were asked to perform squats on the vibration platform with vibration stimulation three times a week, whereas the CON group stood on the floor performing the same squats without vibration stimulation. The knee joint angles were confined within 90° and 150° (full knee extension = 180°), which could restrict the transmission of vibrations to the head when knees were semiflexed.\textsuperscript{3} The knee angle during training was constantly monitored by a manual goniometer. A metronome was used to control the speed of squats at 2 s per squat and 60 s for a complete set. The training load was set gradually as follows: four sets in the first and second weeks; 5 sets in the third, fourth, and fifth weeks; and 6 sets in the sixth, seventh, and eighth weeks. There was a 2-min break between each set. This study consisted of a pre-test (conducted within 1 week prior to the 8-week training program) and a post-test (conducted within 1 week after the program).

Both pretest and posttest included the two consecutive countermovement jumps and a 30-s static single leg stance with the eyes closed balance test. Each test session was preceded by a 10-min warm-up that included aerobic exercises and stretching. For the two consecutive countermovement jumps, participants stood upright on the force platform (AMTI BPS00900, Advanced Mechanical Technology Inc., USA) with hands on the waist while squatting rapidly and then jumping upward using their maximal efforts. Participants were asked to perform the second jump immediately which accompanied the feet touchdown of the first jump. The movement of the first jump involved pre-stretch of the first jump, whereas the second jump involved pre-stretch of the second jump. A successful trial was defined that the entire jump process had to be smooth, and landing on the force platform. In addition, the legs had to be fully extended when off the ground.

The vertical ground reaction impulse and jump height were measured using force platform. Jump height was calculated as the flight time (second). Jump height = \( t \times g \times x \) \( g \) is the acceleration of gravity (9.81 m/s\(^2\)), \( t \) is the flight time measured between take-off and landing. The intraclass correlation coefficients of test–retest measures of 1st and 2nd jump height as well as vertical ground reaction impulse were .981, .985, .993 and .983 which provided sufficient evidence of substantial reliability.

The skin where the electrodes were placed was shaved and cleaned with alcohol, and all of the electromyography equipment was connected to the same ground that was attached to the lateral femoral epicondyle. The electrode used in this study had two 1 cm diameter metal plates that were 3 cm apart. Surface electromyography (EMG, TSD150a, Biopac Systems Inc., USA) incorporated a high impedance (100 MΩ) and a differential amplifier (Common Mode Rejection Ratio = 95 dB; gain = 350). The activations of thigh muscle were acquired synchronously with the force platform from the rectus femoris (RF was the midpoint of the muscle belly from the anterior superior iliac spine to patella) and biceps femoris long head (BF was at the midpoint of the muscle belly on the centerline from the ischium to knee joint) on the dominant leg, and with a 1000 Hz sampling frequency. LabVIEW 8.5 (National Instruments, USA) software was applied to analyze the signals of the two consecutive countermovement jumps. A fourth-order Butterworth filter was used to filter and smooth the EMG raw data. Consequently, the EMG signals were first filtered using a band pass filter (10–500 Hz). The signals were then processed using full-wave rectification and were smoothed at a low frequency of 6 Hz to obtain a linear

envelope chart. We concurrently used the movement speed derived from the integral vertical force to distribute the muscle activity into the downward phase (a period starting from the beginning of a downward squating movement until the speed reached zero, and the RF during this period was under eccentric contraction while the BF was under concentric contraction) and upward phase (a period starting from zero speed until the output value of the force platform became zero, and the RF during this period was under concentric contraction while the BF was under eccentric contraction). The EMG data were exhibited as a root mean square (RMS) and were normalized by the maximal voluntary contraction (MVC) before and after training. For the MVC test, participants were positioned on an examination machine (System 3, Biodex Inc., USA) to achieve the maximal force and maintain it for 3 s at least. The intraclass correlation coefficients of test–retest measures of RF during the 1st and 2nd downward phase of muscle activation were .995 and .912, and the intraclass correlation coefficients of RF during the 1st and 2nd upward phase of muscle activation were .921 and .881.

The 30-s balance test was also conducted on the force platform. Each participant placed both hands on the waist and stood on the right leg with the left foot slightly elevated (the left foot was not allowed to make contact with the right leg or the ground), and participants kept their eyes closed with no foot movement for 30 s. To reduce extreme data, 95% of the area within 10 s was defined as the CoP displacement area for this study. The CoP displacement speed was yielded based on the following formula:

\[
\text{CoP displacement speed} = \left( \sum_{n=1}^{1000} \sqrt{\left( X_{n+1} - X_n \right)^2 + \left( Y_{n+1} - Y_n \right)^2} \right) / 10.
\]

The intraclass correlation coefficients of test–retest measures of CoP area and CoP speed were .886 and .731, respectively.

Two-way ANOVAs (3 groups × 2 tests) with repeated measures on "test" variable were chosen to analyze all data. In case of significant main effects, Tukey post hoc tests were used to identify the statistically significant mean differences. The level of significance was set at \( \alpha = .05 \).

3. Results

There were no statistically significant differences in anthropometric characteristics among the 3 groups. After 8 weeks of training, no significant interactions were found for the 1st and the 2nd jump heights and for the vertical ground reaction impulses. The height of the 1st jump significantly increased between pre- and post-training periods in all 3 groups (\( P < .05 \)). The performance of the 2nd jump increased significantly after training in the HF and LF groups (\( P < .05 \)), but had no significant difference after training in the CON group. The vertical ground reaction impulse of the 1st and 2nd jumps in HF and LF groups significantly increased between pre- and post-training (\( P < .05 \)). However, the height and the impulse of the 1st and 2nd jumps showed no significant difference among groups in both pre- and post-training periods (Fig. 1).

ANOVA result showed a significant interaction (3 groups × 2 tests) in muscle activity of RF during the downward phase of the first jump (\( F_{95/2,45} = 8.155, P < .05 \)), the upward phase of the first jump (\( F_{95/2,45} = 4.781, P < .05 \)), and the upward phase of the second jump (\( F_{95/2,45} = 3.474, P < .05 \)). The muscle activity of the RF of HF group was significantly decreased after training in both the downward and upward phases of the first jump (\( P < .05 \)). In contrast, the muscle activity of the RF of LF group was significantly increased after training in both the downward and upward phases of the first jump and the upward phase of the second jump (\( P < .05 \), Fig. 2). The muscle activity of the RF of CON group had no significant difference after training. No significant difference in RF activity was found

Fig. 1. Mean and SD of jump height before (pre-training) and after (post-training) 8 weeks in the HF (high-frequency with low-amplitude), LF (low-frequency with high-amplitude), and CON (control) groups. (a) The height of 1st countermovement jump. (b) The height of 2nd countermovement jump. (c) The vertical ground reaction impulse of 1st countermovement jump; (d) The vertical ground reaction impulse of 2nd countermovement jump. * Indicates that post-test values were significantly higher than pre-training values (\( P < .05 \)).
Fig. 2. Mean and SD of rectus femoris muscle activation before (pre-training) and after 4 (post-training) 8 weeks in the HF (high-frequency with low-amplitude), LF (low-frequency with high-amplitude), and CON (control) groups. (a) Downward phase of the 1st countermovement jump; (b) downward phase of the 2nd countermovement jump; (c) upward phase of the 1st countermovement jump; (d) upward phase of the 2nd countermovement jump. * indicated that post-training values were significantly higher (or lower) than pre-training values (P < .05).

among groups in both pre- and post-training periods. Furthermore, the muscle activity of BF showed no significant difference between pre- and post-tests and among groups.

A significant interaction (3 groups × 2 tests) was found in the CoP area ($F_{0.95(2,45)} = 3.353, P < .05$) and speed ($F_{0.95(2,45)} = 6.298, P < .05$). The CoP area of both the HF and LF groups decreased significantly after training ($P < .05$), but had no significant difference after training in the CON group. The CoP speed of the HF group was significantly increased ($P < .05$), but had no significant difference after training in the LF group. Conversely, the CoP speed of the CON group showed a significant decrease after training ($P < .05$). In addition, the post-training CoP speed of the HF group was significantly greater than that of the LF group ($P < .05$, Fig. 3).

4. Discussion

In accordance with our hypothesis, the findings of this study showed that 8-week vibration training programs with the same acceleration and various frequencies and amplitudes significantly increased jumping performance and body balance, whereas it induced different neuromuscular adaptations. Previous acute and training studies have compared vibration training protocols using various frequencies or amplitudes. However, the acceleration load, which was one of the critical factors to elicit a training effect, was not controlled properly in these studies. To our knowledge, this is the first study to investigate long-term vibration training with varying frequencies and amplitudes under the same acceleration.

The results of our study revealed that jumping height increased by approximately 6.4% and 7.5% for the first jump and by 11.9 and 6.6% for the second jump, in HF and LF protocols, respectively. In the CON group the performance of the first jump improved by 4.8% was most likely due to the execution of squat movements without the vibration during the intervention period. The findings were similar to those of previous acute studies which found that the single vertical jump improved after vibration training with 30 Hz by approximately 5.6%,14 and with 20 Hz by approximately 4%.14 Moreover, the acceleration of vibration training in this study was set to 4 g. The results of previous studies showed that vibration at 4.0–5.7 g increased maximal force by 40%,15 and vibration at 2.28–5.09 g increased the single vertical jump height by 7.6%.16 Specifically, the first jump improved after HF and LF vibration training, in addition to substantial improvements in the second jump.

The two consecutive countermovement jumps were used in this study to determine the effects of vibration training with various frequencies and amplitudes on the stretch-shortening cycle (SSC) of the muscle function. The first jump was a typical countermovement jump, and the second jump was similar to a deep drop jump. The neuromechanical difference was identified between drop jump and counter movement jump in previous study.17 Pre-activity and eccentric action muscle activity of the agonist muscles was significantly higher during the drop jump in comparison with the counter movement jump, and a significant increase in jump performance was associated with increased levels of preactivity and eccentric action muscle activity. In both jumps, the muscle elongates (eccentric action) at the downward phase of the jump, before a concentric (shortening) action that immediately follows.11 Additionally, previous studies pointed out that vibration stimuli could effectively induce the reflex sensitivity of the muscle spindle, resulting in SSC.18 Vibration stimuli could also improve the second jump performance of two consecutive jump more than the first jump by SSC.19 This finding reflected that the contribution of SSC to jumping performance increased after 8 weeks of HF and LF vibration training. It can be concluded that stretch reflex does play an important role in an SSC exercise and contributes to force generation during the downward phase.10 Previous studies found that long-term vibration training induced an increased excitatory state of the neuromuscular system because of an increase in the sensitivity of stretch reflexes.18 Stimulation of the sensory receptors and the afferent pathways with vibration training could lead to a more efficient use of the stretch reflex.
in the countermovement jump. It has been demonstrated that vibration training can activate motoneuron excitability and induce fast-twitch fiber recruitment. Consequently, the performance of continuous jumps, which involves the SSC of muscle function, has substantially increased after vibration training.

These findings suggest that the comparable improvements in jumping performance after HF and LF vibration protocols performed with similar acceleration load are caused by different neuromuscular adaptations. The muscle activation of RF, however, showed no differences during the downward or upward phases in CON. Tonic vibration reflex (TVR) is a commonly postulated response elicited from vibration stimulation. The TVR is characterized by the activation of muscle spindles primarily through la afferents and the activation of efferal muscle fibers through alpha-motor neurons. The TVR is also capable of causing an increasing recruitment of motor units through the activation of muscle spindles and polysynaptic pathways. Muscle spindles are sensory receptors, which primarily detect changes in the length of this muscle. As in this case, we speculated that vibration frequency and amplitude may activate muscle spindles through the speed of change and magnitude of change in muscle length.

Reflex plasticity and neural adaptation are strongly dependent on the vibration parameters (frequency, amplitude, and acceleration). Previous studies have found that excitabilities of the alpha-motoneuron pool and H-reflex do display a significant suppression during the first minute of post-vibration training with 40 Hz and 2–4 mm, as well as no significant changes in average integrated EMG, H_max/M_max ratio, or rate of force development immediately, 8 min, or 16 min post-vibrating exercise with 30 Hz and approximately 3.5 mm. Furthermore, in previous study 8-weeks of vibration training, at frequency of 32 Hz and amplitude of 1 mm, has proved to reduce the excitabilities of the alpha-motoneuron pool and gamma reflex arc. The decrease in excitability of the alpha-motoneuron pool could be related to the change in fiber-type composition, as well as produce greater fiber force, contraction velocity, and power. The vibration training protocol with 30–50 Hz of frequency and less than 4 mm of amplitude has altered muscle activity. WBV with higher-frequency training may induce neural adaptations in the absence of morphological adaptations of the muscle. Therefore, the vibration training protocols with varying frequencies and amplitudes and similar acceleration loads in this study possibly induced different mechanisms of neuromuscular function.

Fig. 3. (a) CoP (center of pressure) area and (b) CoP speed before (pre-training) and after (post-training) 8 weeks are the average data for the entire sample. (c), (e), and (g) the trace of pre-training CoP in the HF (high-frequency with low-amplitude), LF (low-frequency with high-amplitude), and CON (control) groups; (d), (f), and (h) the trace of post-training CoP in the HF, LF, and CON groups are representative data from subject 5. * Indicates significant difference between post-training values of two groups (P < .05).

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The neuromuscular adaptation induced after the vibration intervention is also a reasonable explanation for body balance improvement. This study used the CoP area and speed as a reference index to evaluate the body balance in posture control. The CoP displacement areas were all reduced after 8 weeks of vibration training with varying frequencies and amplitudes at the same acceleration (4 g). HF vibration training particularly reduced the CoP displacement area and increased the CoP displacement speed, so that the CoP could be maintained within a smaller area and be controlled more rapidly. Previous studies might assert that vibration training at 5.8 g (27 Hz, 2 mm) could reduce CoP displacement areas,28 and the human body could produce different strategies to increase body balance.29 These studies have illustrated that vibration training can effectively improve body balance to maintain posture. The improved muscle strength and power and the improved body balance after vibration intervention suggests that neuromuscular adaptation may have occurred in the muscles of the lower extremities in response to single-bout vibration in young participants30 and in response to 8 weeks of vibration training in an older population.29 In addition, vibration training improved in the reflex pathway as their main mechanism,16 increased neural adaptation, proprioception, and body control,29 and enhanced the body balance of healthy young people.30 Our results have confirmed that vibration training can improve body balance in maintaining posture, and that high-frequency vibration training is more effective in increasing the balancing ability while standing on one foot.

Vibration training has been used at various frequencies and amplitudes, causing inconsistencies in training load and resulting in different effects of training protocols.6 These findings could not verify exactly what frequency enhanced performance effectively. However, it should be addressed that a lower vibration training load with limited acceleration might not be able to increase performance. On the contrary, a larger vibration training load with excessive acceleration may result in potential injuries.2 The study has applied the same training load by simultaneously controlling the vibration frequency and amplitude. It is concluded that the same acceleration vibration training with varying frequencies and amplitudes for an 8-week period significantly increased jumping performance, which involved the SSC of muscle function and improved body balance.

5. Practical implications

- Eight weeks of vibration training performed at varying frequencies and amplitudes and with similar acceleration load improves jumping performance and body balance, and induces differing neuromuscular adaptations.
- Vibration training with high-frequency and low-amplitude (32 Hz, 1 mm) improves the performance of the first and second jump, decreases muscle activity during jumping, reduces the CoP displacement area, and increases CoP displacement speed.
- Low-frequency with high-amplitude (18 Hz, 3 mm) vibration training improves the performance of the first and the second jump, increases muscle activity during jumping, and reduces the CoP displacement area.

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