Introduction

Although whole-body vibration (WBV) is receiving much interest as an alternative exercise modality in sport and rehabilitation physiology, its neuromuscular and endocrine system effects have yielded conflicting results [1,2,3,4,5] and are not yet completely understood [6,7]. Additionally, the acute hormonal responses to WBV exercise have not been extensively studied.

In the extensive resistance training literature, a bout of activity (pectoralis major [PM], triceps brachii [TB], anterior deltoid [DE], and flexor carpi radialis [FCR]). LVG, the EMGrms decreased significantly in the DE (P = 0.009) and FCR (P = 0.006) muscles.

Results: The GH increased significantly over time only in the HVG (P = 0.003). Additionally, the testosterone levels changed significantly over time in the LVG (P = 0.011) and the HVG (P = 0.001). MVC during bench press decreased significantly in the LVG (P = 0.001) and the HVG (P = 0.002). In the HVG, the EMGrms decreased significantly in the TB (P = 0.006) muscle. In the LVG, the EMGrms decreased significantly in the DE (P = 0.009) and FCR (P = 0.006) muscles.

Conclusion: Synchronous WBV acutely increased GH and testosterone serum concentrations and decreased the MVC and their respective maximal EMGrms activities, which indicated a possible central fatigue effect. Interestingly, only the GH response was dependent on the acceleration with respect to the subjects’ responsiveness.
muscle fibers that would enable a greater hormone-tissue interaction within a relatively larger total muscle volume [9]. During WBV, as the vibrating platform movement is sinusoidal, the acceleration load is quantified by calculating the acceleration transmitted to the body according to the following equation \( a = A \omega^2 \) [7]. In this equation, \( A \) represents the oscillation amplitude and \( \omega \) represents the frequency. The changes in the amplitude and/or the frequency therefore determine the acceleration and vibrational magnitude changes that are transmitted to the body.

Regarding posture or exercise on the vibrating plate, push-ups (isometric) can provide an adequate stimulus to acutely increase testosterone concentrations [13]. This basic exercise could represent a potent physiological neuroendocrine system stressor because it involves a large muscle volume (trunk + upper arm + lower arm) [14]. Notably, many muscles of this volume require considerable muscle activation relative to their maximal isometric values [15,16]. Additionally, by comparing the standing (half squat) and horizontal positions (similar to a push-up), the trunk muscles are more strongly activated in the horizontal position during WBV [17].

Hypotheses

Based on these previous findings, we hypothesized the following:

Vibration applied to the upper body induces pronounced hormonal and neuromuscular responses, and the magnitudes of the hormonal and neuromuscular responses are dependent on the acceleration load relative to the subjects’ responsiveness.

Aim

The purpose of the present study was to determine the acute residual hormonal (GH and testosterone) and neuromuscular (maximal voluntary contraction, mechanical power, and EMG activity) responses following a single WBV bout superimposed on an isometric push-up using two different acceleration loads. The acceleration loads were individualized relative to the participants’ responsiveness by monitoring the EMG muscle responses (PM, TB, DE, and FCR) of the participants [18,19,20].

Methods

Study design and participants

A randomized double-blind, controlled-parallel trial design was used for this study. The participants were blinded to the study hypotheses, and the assessors were blinded to the group allocation. Among two hundred students within a sport sciences department, 30 male students elected to participate in this experiment after being informed of the procedures and potential risks involved in the study. The exclusion criteria included a history of back pain, acute inflammation in the pelvis and/or lower extremities, acute thrombosis, tumors, recent fractures, recent implants, gallstones, kidney or bladder stones, any disease of the spine, peripheral vascular disease, and severe delayed trunk and arm muscle soreness onset. All participants gave written informed consent. One investigator in the study (author’s last name) enrolled the participants. The sample size for the primary outcomes was computed a priori based on the \( n \) (0.05), power (1-\( \beta \); 0.90) and effect size values of previous studies [1,5,13] by means of a statistical software for power analysis (G*Power 3.1.9, Heinrich Heine-Duesseldorf University). The sample size computation was performed while taking into account the study design and using both parametric and nonparametric procedures. The participants were randomly assigned to a high-vibration group (HVG) (age: 25.0±0.9 years; weight: 73.0±2.9 kg; height: 177±2.1 cm; body mass index: 23.2±0.7 kg m\(^{-2}\); lean body mass: 57.8±1.8 kg), a low-vibration group (LVG) (age: 26.0±1.5 years; weight: 76.0±2.8 kg; height: 178±2.3 cm; body mass index: 23.7±0.6 kg m\(^{-2}\); lean body mass: 59.6±1.8 kg) or a control group (CG) (age: 24.0±0.8 years; weight: 75.7±2.9 kg; height: 178±2.1 cm; body mass index: 23.7±0.6 kg m\(^{-2}\); lean body mass: 59.5±1.82 kg). The lean body mass values were estimated using a semi-mechanistic model [21]. The random allocation sequence was generated using an algorithm with equal allocation ratios, random sorting, and a maximum allowable deviation of 20%. The requirements for this algorithm were that each group exactly 10 subjects and the maximum % deviation was no larger than 20% of the target sample size. The sequences were generated using statistical software (Pass 13-NCSS, LLC Kaysville, Utah 84037, USA). The Ethics Committee of the University of L’Aquila approved the study conducted between May and July 2012. The measurements and interventions were performed at the Laboratory of Biomechanics of the University of L’Aquila. The participants were healthy and recreationally active and all within similar fitness levels to reduce the possible influence on the hormonal serum changes. Similarly, the participants had to eliminate strength and endurance exercises from their training during the period of the experiment. Therefore, the training regimen was composed of only the physical activities (no strenuous exercises) performed in their sport sciences department. No participants reported drug or nutritional supplement ingestion known to interfere with GH and/or testosterone secretion.

Experimental day procedures

For each participant, the measurements were performed over a 2-day period to reduce any potential boredom and fatigue effects. Each test session began with a 15-min warm-up (6 min of treadmill running at a speed of 6 km h\(^{-1}\); 4 min of stretching; conventional trunk, arm, and shoulder joint exercises; and five low-speed push-ups). The participants were introduced to the equipment and procedures during a familiarization period. On the first day, each participant performed maximal voluntary isometric contractions (MVC) during bench press and handgrip tests. The EMG activity, which was synchronized to these strength measurements, was also recorded. Then, the EMG activity was recorded during WBV to estimate the optimal acceleration load in relation to subject responsiveness. All measurements taken on the first day were thus performed to determine the vibrational load, which was normalized to each subject’s MVCs. On the second day (Figure 1), baseline measurements (Pre) were taken, including blood sampling for hormones analyses, MVC synchronized to EMG activities and mechanical variables during the eccentric-concentric bench press test. Next, each subject was provided a treatment (specific to his assigned experimental group, see below), and EMG activities were recorded during the interventions. The measurements were repeated immediately after the treatments ended (Post1) and 1 hour after the treatment ended (Post 2). Blood was sampled also during Post 2 due to hormonal profile changes observed in a previous pilot study. All measurements were performed at consistent times of day (4.00–8.00 PM) to reduce the potential diurnal variation effect on hormone secretion and neuromuscular variables [22].

Blood collection and hormonal analyses. On the second experimental day, the subjects visited the laboratory and rested for 30 min prior to the first blood collection. Blood samples were drawn into vacutainers from the antecubital forearm vein using a 20-gauge needle (without additives) for the total serum testosterone and GH concentration measurements. All samples were obtained with the subjects placed in a seated position in a climate-controlled
The intra-day MVC during bench press and handgrip verbal encouragement was provided during each MVC attempt separated by 1–2 min of rest. The participants were instructed to calculated (Figure S1). Each warm-up and maximal attempt was attempts without a time constraint, and the final average value was min warm-up period, the subjects performed a maximum of three

MVC was also measured on the dominant hand using a custom handgrip attached to a strain gauge (Ergotest-Innovation, Porsgrunn, Norway). The handgrip measurements were performed using acustom exercise rack in which the subjects were positioned in a supine isometric bench press position [23].

Maximal voluntary isometric contraction. MVC was performed using a custom exercise rack in which the subjects were positioned in a supine isometric bench press position [23]. MVC was also measured on the dominant hand using a custom handgrip attached to a strain gauge (Ergotest-Innovation, Porsgrunn, Norway). The handgrip measurements were performed using a standardized method [24]. During MVC, following a 2-min warm-up period, the subjects performed a maximum of three attempts without a time constraint, and the final average value was calculated (Figure S1). Each warm-up and maximal attempt was separated by 1–2 min of rest. The participants were instructed to contract their muscles as hard and fast as possible, and strong verbal encouragement was provided during each MVC attempt [25]. The intra-day MVC during bench press and handgrip

The EMG surface activity was recorded using bipolar disc electrodes (Blue-Sensor Ambu Ag/AgCl, type NF-00-S, dimensions, 44.3×22×22 mm), an amplifier (gain setting, 100 Hz; input impedance, 1000; 2 GΩ common mode rejection rate, 100 dB; input noise level [1 kHz band], 3 μV(c), and a Butterworth band-pass filter (3-dB low cut-off frequency, 8 Hz; 3-dB high cut-off frequency, 1200 Hz) fixed over the muscles. The electrodes were placed according to the surface EMG for non-invasive assessment of muscles (SENIAM) recommendations [27] on the dominant side of the body. To maintain consistent electrode positioning across the inter-day EMG recordings, the subjects’ skin positions were marked with indelible ink.

The EMG recordings. The EMG surface activity was recorded using bipolar disc electrodes (Blue-Sensor Ambu Ag/AgCl, type NF-00-S, dimensions, 44.3×22×22 mm), an amplifier (gain setting, 100 Hz; input impedance, 1000; 2 GΩ common mode rejection rate, 100 dB; input noise level [1 kHz band], 3 μV(c), and a Butterworth band-pass filter (3-dB low cut-off frequency, 8 Hz; 3-dB high cut-off frequency, 1200 Hz) fixed over the muscles. The electrodes were placed according to the surface EMG for non-invasive assessment of muscles (SENIAM) recommendations [27] on the dominant side of the body. To maintain consistent electrode positioning across the inter-day EMG recordings, the subjects’ skin positions were marked with indelible ink.

The EMG activity was recorded with an electronic amplifier (Blue-Sensor Ambu Ag/AgCl, type NF-00-S, dimensions, 44.3×22×22 mm) and a Butterworth band-pass filter (3-dB low cut-off frequency, 8 Hz; 3-dB high cut-off frequency, 1200 Hz) fixed over the muscles. The electrodes were placed according to the Surface EMG for non-invasive assessment of muscles (SENIAM) recommendations [27] on the dominant side of the body. To maintain consistent electrode positioning across the inter-day EMG recordings, the subjects’ skin positions were marked with indelible ink.

Maximal voluntary isometric contraction (Figure S1). The MVC was calculated as the difference between the first and last trials according to the following formula: [(last trial – first trial) / first trial]*100. The intra-day reliabilities were 0.95, 0.92, 0.94, and 0.80 for the PM, DE, TB, and FCR muscles, respectively. The EMG activity was recorded with an electronic amplifier (Blue-Sensor Ambu Ag/AgCl, type NF-00-S, dimensions, 44.3×22×22 mm) and a Butterworth band-pass filter (3-dB low cut-off frequency, 8 Hz; 3-dB high cut-off frequency, 1200 Hz) fixed over the muscles. The electrodes were placed according to the Surface EMG for non-invasive assessment of muscles (SENIAM) recommendations [27] on the dominant side of the body. To maintain consistent electrode positioning across the inter-day EMG recordings, the subjects’ skin positions were marked with indelible ink.
using non-parametric statistical tests. The effect of WBV on the neuromuscular and hormonal variables was assessed over time and in each group using Friedman’s test. The Wilcoxon test was used to detect differences based on within-group comparisons and the Bonferroni correction was used to adjust the P-values according to the number of comparisons that were performed. The between-group comparisons were performed using the Kruskal-Wallis test. Cronbach’s alpha coefficient was used to determine the reliability between the participants. The analyses were performed using XLSTAT 13.02 statistical software (Addinsoft, SARL, NY, USA). Statistical significance was set at P<0.05, and the meaningfulness of the significant outcomes was estimated by using the effect size (ES) of Cohen.

Results

The results of 30 participants were analyzed during the test sessions. The participants did not report side-effects or muscle-tendon injuries, and none of the baseline measurements (descriptive characteristics and experimental data) were significant among the groups (P>0.05).

Hormonal responses

The GH response significantly increased over time in the HVG (P = 0.003) but not in the CG or the LVG. Additionally, comparative analyses revealed significant changes in the HVG at Post1 (P = 0.001, ES = 1.05) and Post2 (P = 0.014, ES = 0.92) (Figure 2). A significant testosterone response over time was also detected in the LVG (P = 0.011) and the HVG (P = 0.001) but not in the CG. The differences were located at Post1 in LVG (P = 0.014, ES = 1.07) and HVG (P = 0.001, ES = 1.53); however, the differences between the two experimental groups were not statistically significant. No significant changes were observed for any group at Post2 (Figure 2).

Maximal voluntary isometric contraction and eccentric-concentric bench press

MVC during bench press decreased significantly in the LVG (P = 0.001, ES = 1.65) and the HVG (P = 0.002, ES = 1.32), whereas there was no significant decrease in the CG; however, no significant differences were detected between the LVG and the HVG. MVC during handgrip did not change significantly in any group (Figure 3). The effects of WBV on the negative and positive power during eccentric-concentric bench press exercise did not significantly change in any group (Figure 4).
The differences were not significant (P>0.05).

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**Figure 4.** The relative changes (mean, SE) in the negative and positive power during eccentric-concentric bench press exercise (pre-post1) are shown for the CG, the LGV, and the HVG.

The differences were not significant (P>0.05).

EMG activity recorded during maximal voluntary isometric contraction

In the PM muscle, the EMG responses did not decrease significantly in any group. The TB muscle EMG decreased significantly in the HVG (P = 0.006, ES = 1.17) but not in the LVG or the CG. Conversely, the DE muscle EMG responses significantly decreased in the LVG (P = 0.009; ES = 0.56); however, no significant changes were detected in the CG or the HVG. Similar to the DE muscle, the FCR EMG responses to WBV were significantly different in the LVG (P = 0.006; ES = 1.41) but not in the CG or the HVG (Figure 5).

EMG activity during interventions

Because the pattern did not change among the muscles during the several repeated trials, the average EMG activity of all muscles within each group was analyzed (Figure 6). The EMG rms increased progressively in all of the groups, and Δ was significantly different in the LVG (P = 0.009, ES = 1.78), the HVG (P = 0.006, ES = 1.88), and the CG (P = 0.014, ES = 0.90). No significant differences between the groups were observed.

**Discussion**

The primary finding of the present study includes a significant increase in GH immediately following the end of exercise (+380-fold) only in the case of the high acceleration load. Additionally, the GH concentration remained elevated until 1 h after the end of WBV exercise (+180-fold). In contrast, the testosterone concentration was elevated for both the 2.88 g (+15%, HVG) and 0.12 g (+21%, LVG) acceleration loads.

It is well known that plasma GH concentrations increase during exercise and that the magnitude of this response appears to be dependent on the exercise selected and the volume of muscle mass recruited, the muscle contraction type, the exercise intensity, the exercise duration, the rest interval between sets, and the total magnitude of work performed [9]. In this study, the GH response magnitude was associated with the peak exercise intensity, as all other variables were equal between the groups. The WBV exercise intensity in the HVG, which was estimated based on the EMGrms activity, produced the greatest muscle activation during the vibrational conditions. Therefore, upon exercise onset (WBV and isometric push-ups), the signals that arose in the central areas of the brain (central command) activated the motor cortex to induce muscle contractions in a potentially parallel manner and activated more endocrine centers to cause increased GH release [28]. Thus, the GH response in our study appears to be proportional to the recruited muscle volume relative to the exercise intensity, similar to resistance exercise [9]. Additionally, the increase in EMG activity recorded toward the end of each repetition (Delta) could cause an increase in reflex activation [29,30], which indicates that the “central command” can be intensified via feed-back signaling from the exercising muscles mediated by the afferent nerves as neural reflex mechanisms [9,28]. Concisely, it may be possible for higher brain centers (i.e., the motor cortex) to play an active role in regulating GH secretion during WBV and this regulatory mechanism may be sensitive to specific peripheral neural mechanisms.

With respect to the testosterone response, it is unclear why this response was not dependent on the WBV intensity. Traditionally, the physiological function of testosterone in skeletal muscle tissue is the maintenance of an increase in skeletal muscle mass (hypertrophy) via genomic (long-term, transcriptional) mechanisms and subsequent indirect increases in muscle strength [8,9]. However, steroid hormones, including testosterone, have been demonstrated to elicit rapid responses (within seconds to minutes) in rat muscle fibers [31] via non-genomic mechanisms (short-term, non-transcriptional). According to this perspective, given that testosterone regulates a wide biological body function spectrum with respect to environmental changes, the acute control of testosterone levels might be more complex (by the system) than the simple and direct regulation of testosterone levels by WBV exercise intensity.

The WBV-induced suppression of MVC and EMG activity could indicate the presence of significant ‘central fatigue’. However, the increase in EMG activity during the treatments (delta) suggests an increase in reflex activation in which the motor units are recruited at the lowest force thresholds (compared with voluntary activation) to compensate for a reduced descending drive in an attempt to maintain the force output during fatigue [29]. Additionally, the selective attenuation of the maximal muscle EMG activity following WBV is dependent on the acceleration load, which suggests that the afferent input could be dependent on the activated muscle fiber types [30,32], the different muscle spindle responses to muscle vibration, and the specific sensory receptor population [33,34]. Neuromuscular propagation failure, muscle-tendon unit compliance, motor cortex excitability, and...
Muscle fatigue status may be related to WBV-induced suppression of the maximal voluntary contraction [32].

Muscle fatigue is characterized by not only a loss of force generation capacity but also a slowing of the muscle contractile speed. Indeed, loss of power is a major consequence of muscle fatigue due to changes in three muscle properties: a decrease in the isometric force, a slowing of the maximal velocity, and an increase in the force–velocity function slope [35]. The metabolic mechanisms underlying these changes have not been identified, but it has been speculated that a decrease in activating calcium might trigger the loss of power during fatigue [55]. In this study, the negative and positive power measured during the eccentric-concentric bench press exercise remained unchanged in all three groups after WBV. Therefore, it appears most likely that WBV-induced suppression of the MVC is not caused by changes in the muscle or tendon mechanical and metabolic properties. Based on the results of prior non-genomic testosterone analyses and the absence of a significant loss of power in our study, we cannot exclude the possibility of protective effects of testosterone against skeletal muscle fatigue as suggested by Bosco et al. [1,36].

Although histological alterations provide a direct evidence for muscle damage, often, this damage is assessed indirectly by increases in muscle proteins in the blood (e.g., creatine kinase: CK), ratings of delayed onset muscle soreness, and decreases in maximal voluntary contraction and range of motion [37]. Therefore, in the present study, the significant MVC decrease could also indicate the presence of muscle damage because MVC peak force measures have been considered to be valid markers of muscle damage [37]. In this connection, a recent study of Hazell et al. [38] has demonstrated that synchronous whole-body vibration superimposed on moderate exercise determines significant increases in interleukins (IL-1β, IL-6, IL-10), indicating the effects on muscle damage and inflammation, even if the reported value in IL-6 (~2–3 pg/ml) is less than that reported after a traditional resistance training session (~5–6 pg/ml) [39].

In our study, the combination of vibration plus posture assumed on the vibrating plate produced an intense exercise during the vibrational interventions, particularly within the high vibration group. In fact, the pectoralis major muscle activation approached the maximal values recorded during the maximal voluntary isometric contraction (bench press). Therefore, during the
vibration training (toward the end of the treatment—the last two repetitions) the participants were not able to sustain the workload and dropped on the plate. As previously described, the fatiguing task is speculated to cause a myofibril disruption that triggers an inflammatory response increasing the circulation of cytokines and hormones that promote muscle tissue remodeling [11,39,40]. However, a conclusive scheme cannot be depicted because pro-inflammatory cytokines (i.e., IL-6) and other systemic muscle proteins (CK) were not measured.

Limitations

GH pulsatile characteristics

The major point of concern in our study is the pulsatile characteristics of the GH response. These pulsatile events in healthy young men are regular and occur during the night [41]. All measurements were performed consistently each day (4.00–8.00 PM). Because two significant peaks relative to the baseline value (Post1 and Post2) were detected in only one experimental group, the possibility of individual diurnal variation effects on the GH concentration in the HVG can be excluded [22].

Plasma volume

Plasma volume changes could influence the hormone concentrations. Furthermore, there are no studies in the literature that have addressed this issue during WBV. However, plasma volume can be influenced by prolonged strenuous endurance exercise (e.g., cycling, ultra-marathon) [42] and/or by prolonged posturing in the horizontal position (for 5 h after intense aerobic exercise performed at 85% of the peak oxygen consumption rate) [43]. Additionally, acute resistance exercise (three sets of 5–7 repetitions of six exercises at an intensity corresponding to 80% of the one-repetition maximum, 1-RM) can decrease the plasma volume by approximately 10% [44]. Therefore, these relative changes cannot explain the large increase in the hormone concentration, particularly GH (+380-fold).

Generalization of the results

Because our study subjects were healthy, male, recreationally active participants, our results cannot be generalized to other populations. A specific type of participants was recruited to reduce the influence of potentially confounding variables (sex, age, and level of training).

Conclusions

EMG activity and acceleration load

The data presented show that EMG monitoring during different acceleration loads can represent an appropriate method of assessing the optimal magnitudes to acutely maximize the GH and testosterone serum concentrations when applying vibration to the upper extremities in a similar manner as resistance exercises [8,9].

Fatigue

Synchronous WBV-induced fatigue decreases the MVC and the related EMG activity, indicating a fatigue effect that appears to be related to “central” [29,45] rather than “peripheral” factors [46].

Supporting Information

Figure S1 Representative MVC and rectified EMG data for the PM, DE, TB, and FCR muscles during the isometric bench press and handgrip tests performed without time constraint by 1 of the subjects. The shaded area represents a 400 ms window around the force peak, which was used to compute the EMGrms values for the selected muscles. (Bench press) The force plate was set to 0 when the bench stood on its own without the subject. BW, body weight. (TIF)

Figure S2 a) Position assumed by the subjects on the vibrating platform (A). b) The peak acceleration and vibrating plate displacement values were measured as the vibration frequency was increased by 5 Hz every 5 s from 20 to 55 Hz. The acceleration load values ranged from 0.1 to 5.7 g (expressed as a multiple of standard gravity, where 1 g is equal to 9.81 m s

Table S1 Characteristics of the vibrational intervention.

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Author Contributions

Conceived and designed the experiments: JT RDG. Performed the experiments: RDG. Analyzed the data: LF. Contributed reagents/materials/analysis tools: GB GC. Wrote the paper: RDG AG.

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