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ORIGINAL ARTICLE

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Effects of vibration and resistance training on neuromuscular and hormonal measures

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Abstract The aim was to study whether whole body vibration (WBV) combined with conventional resistance training (CRT) induces a higher increase in neuromuscular and hormonal measures compared with CRT or WBV, respectively. Twenty-eight young men were randomized in three groups; squat only (S), combination of WBV and squat (S + V) and WBV only (V). S + V performed six sets with eight repetitions with corresponding eight repetition maximum (RM) loads on the vibrating platform, whereas S and V performed the same protocol without WBV and resistance, respectively. Maximal isometric voluntary contraction (MVC) with electromyography (EMG) measurements during leg press, counter movement jump (CMJ) measures (mechanical performance) including jump height, mean power (P_{mean}), peak power (P_{peak}) and velocity at P_{peak} (V_{ppeak}) and acute hormonal responses to training sessions were measured before and after a 9-week training period. ANOVA showed no significant changes between the three groups after training in any neuromuscular variable measured [except $P_{mean,}$ S higher than V ($P < 0.05$)]. However, applying *t* tests within each group revealed that MVC increased in S and S + V after training ($P < 0.05$). Jump height, P_{mean} and P_{peak} increased only in S, concomitantly with increased V_{ppeak} in all groups ($P < 0.05$). Testosterone increased during training sessions in S and S + V ($P < 0.05$). Growth hormone (GH) increased in all groups but S + V showed higher responses than S and V ($P < 0.05$). Cortisol increased only in S + V ($P < 0.05$). We conclude that combined WBV and CRT did not additionally increase MVC and mechanical performance compared with CRT alone. Furthermore, WBV alone did not increase MVC and mechanical performance in spite of increased GH.

Keywords Whole body vibrations · Muscle strength · Muscle power · Jump height · EMG · Anabolic hormones

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Introduction

The effect of whole body vibration (WBV) on neuromuscular measures is an emerging field of research. WBV as a training method is investigated in the fields of sport, space travelling, rehabilitation and in the treatment of osteoporosis (Cardinale and Pope 2003). WBV is often applied through a vibrating platform on which the person stands and with training protocols including 1–10 intervention periods of 1–4 min of vibration (frequency 20–40 Hz and amplitude 2–8 mm) with rest periods in between.

Whole body vibration has been reported to enhance the acute force-generating capacity of the lower limbs because the mechanical vibration induces deformation of the tissues, which was suggested to activate muscle spindles and elicit a reflex contraction to modulate the stiffness of the muscles involved (Bosco et al. 1999; Rittweger et al. 2001; Cardinale and Lim 2003; Cardinale and Pope 2003). This response has been named the tonic vibration reflex (TVR) (Burke et al. 1976). Secondly, Ia afferents driven by tendon vibration were found to have strong effects on motor unit recruitment and generation of force (Romaiguere et al. 1993; Gabriel et al. 2002). Therefore, both a muscle spindle induced and a tendon induced TVR may be involved in acute increases in performance (Mester et al. 2002). In addition, it is believed that WBV inhibits the agonist–antagonist co-activation through Ia-inhibitory neurons thereby decreasing the protective forces around the respective joints (Cardinale and Bosco 2003). Concerning the chronic effects, it is suggested that the mechanism by which WBV could influence the neuromuscular and hormonal system is by increasing the gravitational load on the subject standing on the vibrating platform (Cardinale and Bosco 2003). As the movement of the platform is sinusoidal, the maximal acceleration, a_{max}, is calculated as: $a_{max} = A \times \omega^2 = A \times (2\pi f)^2$. Training at a frequency (f) of 20 Hz and with an amplitude (A) of 4 mm gives a stimulus equal to six times the normal gravitational load (Rittweger et al. 2001).

Studies investigating the acute and chronic effects of WBV show equivocal results. Some studies reports positive results (Bosco et al. 1999, 2000; Issurin and Tenenbaum 1999; Torvinen et al. 2002a, c; Delecluse et al. 2003) and others do not (Torvinen et al. 2002b; De Ruiter et al. 2003a, b) and this may or may not be related to different training protocols.

Delecluse et al. (2003) and Roelants et al. (2004) carried out studies to compare the chronic effect of WBV versus conventional resistance training (CRT) on muscle strength and body composition after training periods of 12 and 24 weeks, respectively. The gain in muscle strength was shown to be comparable between groups doing either WBV or CRT. Ronnestad (2004) compared the combination of squat on a vibrating platform to conventional squat in terms of changes in muscle strength and jump height after a training period of 5 weeks. Both groups increased muscle strength; however, the combination group additionally showed an increase in counter movement jump (CMJ) height, which did not differ from the squat only group.

Several studies dealing with CRT show that the circulating concentrations of testosterone and growth hormone (GH) acutely increase during resistance training (Kraemer et al. 1990; Hakkinen and Pakarinen 1993; Hansen et al. 2001). Furthermore, chronic changes in the resting levels of testosterone have been reported after resistance training periods (Kraemer et al. 1998). A growing body of evidence is linking acute and chronic increases in anabolic hormones to muscle hypertrophy and increased muscle strength (Kraemer and Scott 2002; Ahtiainen et al. 2003). Similar acute responses were observed with WBV as intervention. Hence, Bosco et al. (2000) reported acute increases in plasma concentrations of testosterone and GH, whereas cortisol concentrations decreased.

The inconsistency of the results reported above legitimates the investigation of neuromuscular and hormonal responses to CRT alone, WBV alone and to the combination of the two. In addition, no study has investigated the acute hormonal responses during a short-term training period of WBV. Therefore, the aim of the present short-term study was to test the hypothesis that WBV combined with CRT induces a more pronounced neuromuscular and hormonal response compared with CRT and WBV, respectively. It was speculated that this would occur due to two mechanisms: (1) increase in training intensity during WBV due the greater gravitational load (i.e. chronic effect), (2) according to the acute effect of WBV (i.e. enhancement of force-generating capacity), the subjects performing CRT on the vibrating platform may be able to lift heavier loads compared with the group performing CRT.

Methods

Subjects

Twenty-eight moderately trained (participating in leisure sport once or twice a week) young men participated in the study (Table 1, Tanita Body Composition Analyzer TBF-300, Japan). The subjects had no or only minor previous experience with resistance training (1 h/week) and no one was participating in resistance training activities on a regular basis. Health examination of the subjects was performed before the actual experiment and no subjects got disqualified due to exclusion criteria (angina pectoris, low back disorders, prescribed heart or lung medicine, trauma to any part of the body). The subjects were familiarized with the experimental procedures 1 week prior to the testing session. The study was approved by the local Ethics Committee (VF 20020193) and the subjects were informed of the risks and purposes of the study before their written consent was obtained.

Study design

To test the effect of three different training regimens on relevant dependent variables, a typical research design including testing before and after an intervention period was used. Subjects were randomized in three groups and were assigned to three training regimens; (1) a squat group (S group) which performed squat with a weight loaded bar, (2) a squat and vibration group (S + V group) which performed squat with a weight loaded bar on a vibrating platform and (3) a vibration group (V group) which performed squat without a weight loaded bar and only with a broomstick on the vibrating platform. The three groups were carefully matched due to the principle of block randomization according to Maximal isometric voluntary contractions (MVC) (Fig. 1).

Training protocol

S group: Six sets of eight repetitions of weight loaded squat performed on the floor with 2 min rest between sets. S + V group: Six sets of eight repetitions of weight

Table 1 Anthropometrics of the subjects before the 9-week period of training (mean ± SE)

Group	Age (years)	Height (cm)	Body mass (kg)	Fat (%)
S (n=9)	24 (±1.7)	181.0 (±2.4)	81.2 (±3.4)	17.1 (±1.9)
S+V (n=10)	23 (±0.6)	179.5 (±2.1)	75.7 (±3.3)	13.9 (±1.2)
V (n=9)	23 (±0.7)	181.9 (±2.9)	73.6 (±3.0)	12.8 (±0.8)

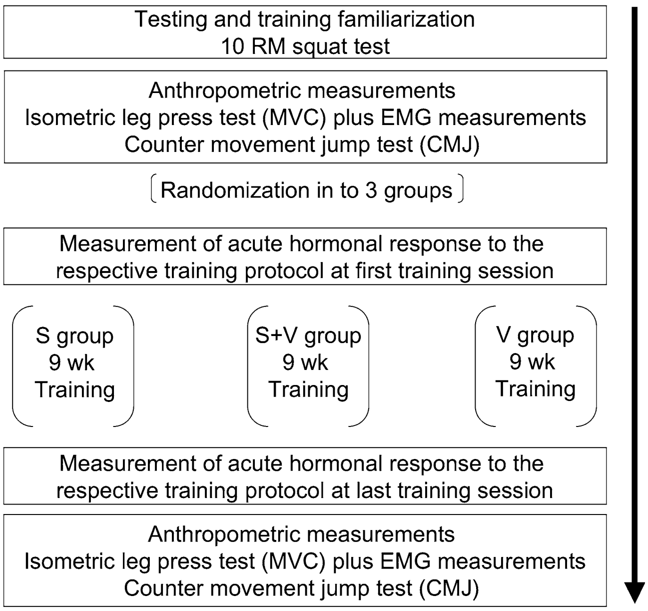

Fig. 1 Overview of the study design. *Each box* represents a session completed on a separate day

loaded squat performed on the vibrating platform with 2 min rest between sets. V group: Six sets of eight repetitions of squat without weight load performed on the vibrating platform with 2 min rest between sets (i.e. six sets of vibration with 2 min of rest between the 30 s vibration sets). The frequency of vibration for S + V group and V group was 20 Hz during the first 5 weeks and 25 Hz during the last 4 weeks with an amplitude of 4 mm during the entire training period. Before each training session all subjects performed a standardized warming up consisting of 3 sets of 20 repetitions of squat without load with 1 min rest between sets.

To ensure a reasonable progression during the training period all groups performed a half training session (only three sets) during the first week, a complete training session during the following week, two training sessions a week for 2 weeks and then three training sessions a week for the last 5 weeks of the training period. Furthermore, the groups training with loads (S group and S + V group) performed eight repetitions per set with a load corresponding to 10 Repetition Maximum (RM) during the first five training sessions. Subsequently, an 8 RM test was performed and the load was increased corresponding to 8 RM and thereafter the training loads were adjusted every fifth training session by an 8 RM test (see Table 2 for training loads). The first 10 RM test was performed on the floor before the subjects were randomized into their respective groups. The following 8 RM tests were performed on the vibrating platform for the S + V group. This was implemented because the acute effect of WBV previously reported (i.e. enhancement of force-generating capacity), likely enabled the subjects in the S + V group to lift heavier loads during 8 RM testing and thereby increasing the training intensity. We used the table "Estimating 1 RM and training loads" for RM testing: if a subject performed six repetitions to muscular failure, the subject was asked to stop and the 8 RM or 10 RM load was estimated according to the table "Estimating 1 RM and training loads" from Baechle et al. (2000). The study consisted of 9 weeks of a total of 20½ training sessions. All training sessions were individually supervised in order to control training techniques, training loads and training logbooks. Two subjects from the S group missed one and three training sessions, respectively. Three subjects from each of the S + V and V groups missed one training session.

Training techniques

Whole body vibration was performed on a commercially available vibration platform (Galileo 2000, Novotec Maschinen GmbH, Germany). Vibration to the entire body is applied by alternating rotation around the central axis of the platform on which the subject is standing. The amplitude increases with distance from the rotational centre, and the frequency can be freely chosen between 1 and 30 Hz.

During familiarization subjects were introduced to the squat exercise and the technique was carefully corrected until proper squatting technique was achieved. All subjects were instructed to perform the squat exercise at the same pace, by squatting down and up in cycles of 3–4 s independently of the load. For that reason one set took about 30 s for each group. All subjects trained barefooted and the foot position and squatting technique was identical between groups. To ensure the squatting technique was identical between groups, all subjects trained with constant attention from the instructors. Thus, each subject was individually and visually inspected to ensure that the squat exercise was performed to a knee angle of 90°. The respective frequencies (20 and 25 Hz) were chosen after preliminary pilot studies. Frequencies higher than 25 Hz resulted in difficulties in performing the training protocol with a weight-loaded bar.

Table 2 Training loads for the S and S ± V group (mean ± SE)

Group	First 10 RM test in the training period (kg)	First 8 RM test in the training period (kg)	Last 8 RM test in the training period (kg)
S	84.4 ± 4.8	105.3 ± 4.5	132.8 ± 6.1
S + V	83.3 ± 3.5	102.5 ± 4.6	130.5 ± 5.8

There was no significant difference between any RM test in the S and S + V group

Testing

During the first week anthropometrics, MVC and mechanical performance assessed as CMJ were measured. Subjects had 5 min rest between the MVC and the CMJ tests. During the second week the acute hormonal responses to one training session were measured. In the ninth and tenth weeks the procedures from the first and second weeks were repeated, respectively (Fig. 1). The standardized warming up was performed before testing. Prior to the testing days, the subjects were told to refrain from ingestion of alcohol and caffeine for 24 h and strenuous physical activity for 48 h. In addition, prior to the blood sampling days, the subjects consumed a standard breakfast (oatmeal with milk and sugar) 3 h in advance.

Maximal isometric voluntary contractions

A one leg press test was performed in an isometric custom built leg press device (Kistler 9367/8 B, sampling frequency 1 KHz, Switzerland). The leg tested was randomly chosen independently of the dominant leg. Subjects were tested with a knee angle of 110° and were instructed to hold their arms crossed on the chest. Visual online feedback was given, with the highest value reported on the computer monitor. Three maximal voluntary contractions with 1 min of recovery between trials were performed and the highest absolute value was used for further analysis.

EMG measurements

During the MVC test EMG signals were measured. After careful preparation of the skin (shaving and cleaning with alcohol), pairs of surface electrodes (Blue Sensor, Ambu, Denmark) were positioned (inter-electrodes distance, 5 mm) at the *vastus lateralis* and the *biceps femoris (caput longus)* representing leg extensor and flexor muscles. Electrodes' positioning was carefully measured individually according to the European Recommendations (Hermens et al. 1999), in order to ensure the same placements before and after the training period. This was further controlled by measuring distance to the floor from the electrodes while standing and circumference of the leg at electrodes' positioning. The signals were conducted directly to small amplifiers taped to the skin (Muscle Tester ME 3000, Mega Electronics LtD, Finland) and sent to a computer for sampling in LabView 7 (National Instruments, USA).

Signal processing

Synchronous sampling of the force and the EMG signals was performed at 1,000 Hz, analogue-to-digital conversion rate using an external A/D converter (DAQ6023E, National Instruments, Austin, TX, USA). The EMG amplifier (Muscle Tester ME 3000, Mega Electronics Ltd, Finland) had a built-in band pass filter with high cut-off frequency of 8 Hz and low pass cut-off frequency of 500 Hz and a common mode rejection ratio (CMRR) of 110 dB, signal-to-noise ratio of 61 dB. During the later process of analysis, the EMG signal was digitally filtered using a symmetric moving RMS averaging routine (50 ms window length) followed by detection of the peak EMG value (EMG_{peak}) (μV). Furthermore, a time interval of 200 ms prior to the instant of peak force was used to calculate the average integrated EMG of the RMS filtered EMG at peak force (EMG_{200}) (μVs).

Counter movement jump/mechanical performance

All subjects performed three maximal CMJs on a force platform (Kistler 9281 B, Switzerland). The vertical signal from the force platform was sampled at 1 KHz using an external A/D converter (dt28ez Data Translation, USA) and later analysed using customized analysis software according to the method of Davis and Rennie (1968) and Caserotti et al. (2001). Maximal performance was identified as maximal jump height. Furthermore, in order to estimate training-related changes of the behaviour of the body centre of mass which could influence maximal jump height, several kinetic and temporal variables were selected. Such changes included, for example, a greater concentric displacement of the body centre of mass (i.e. due to a deeper countermovement) which would allow the centre of mass to travel along a longer distance potentially increasing the work performed and hence the kinetic take-off impulse and finally jump height. Thus, mechanical power was continuously calculated throughout the movement as the instantaneous product of force (Fz) and vertical velocity. Kinetic variables included peak power (P_{peak}) which was subdivided into force and velocity at P_{peak} (Fz_{ppeak} and V_{ppeak}, respectively), mean power (P_{mean}) and mean force (Fz_{mean}) calculated as the average mechanical power and force, respectively, produced during the concentric phase, starting from the lowest position of the body centre of mass to the instant of take-off. In addition, mechanical work (work) was calculated as the work performed by the body centre of mass during the concentric phase of the CMJ. The duration of the concentric phase (T_{con}) starting from the lowest position of the body centre of mass to the instant of take-off was included as a temporal variable.

Acute hormonal response to training

Blood samples were drawn from an anti-cubital vein during the first and last complete training sessions. Blood samples were taken at the same time of the day from each subject (between 8:15 a.m. and 14:00 p.m.) to minimize diurnal hormonal variations. Blood samples were taken before the training session (after resting in supine position for 15 min) (pre), immediately after the training session (post) and subsequently after 15 min of rest following the training session (+15 post). For the analysis of testosterone, GH and cortisol, 10 ml of blood was collected in pre-cooled tubes containing ethylendiaminetetraacetic acid (EDTA). The samples were immediately chilled on ice, centrifuged at 3,000 rpm for 10 min and plasma stored at −80°C until assayed. Commercially available ELISA kits were used for the measurements of the plasma concentrations of testosterone (total testosterone), GH and cortisol (DRG instruments GmbH, Marburg, Germany). Results were analysed (EL800, bio-Tek Instruments Inc, Winooski, VT, USA) and expressed as mean of duplicates. The intra- and inter-assay variances for testosterone were 4 and 3%, respectively; for cortisol 4 and 10% and for GH 4 and 7%.

Statistics

Body mass, hormonal pre-values, MVC-, CMJ- and EMG measurements were analysed using a closed test procedure. To analyse whether the three training groups responded differently to the training period, we used an ANOVA analysis with an interaction test. If this was significant we proceeded with Fisher's PLSD test as a post hoc analysis.

The hormone data measured during the training sessions on a given day in the three groups were compared using a two-way ANOVA analysis of variance for repeated measures for comparisons between groups and within a group. In addition, the repeated measure design was also applied to compare the hormonal response pattern in the first and last training sessions.

As a secondary analysis, we investigated whether the subjects responded to the training protocol, applying a paired *t* test within each group. All data are presented as means ± SE and the level of statistical significance was set at $P<0.05$ (Stat View, SAS institute 1998, USA).

Results

Body mass

No significant changes were seen in body mass between groups or within group following the training period.

MVC

The changes in MVC following the 9-week training period were not significantly different between the three groups, but there was a tendency towards a higher increases in the S group compared to the V group ($P=0.057$). Applying *t* tests within each group, the S and S+V groups responded to the training by a significant increase, from 2,146±101 N to 2,405±118 N, and 2,130±126 N to 2,329±175 N, respectively (Fig. 2).

EMG

No significant changes between the three groups were observed in EMG_{200} and EMG_{peak} after 9 weeks of training (Fig. 3).

CMJ/mechanical performance

The 9-week training period revealed no significant changes in jump height, P_{peak}, Fz_{ppeak}, V_{ppeak}, work, T_{con}, F_{zmean} between the three groups except from P_{mean} with the S group increasing significantly more than the *V* group.

Applying *t* tests within each group showed that the S group responded to the training by a significant increase in jump height from 29.5±0.9 to 31.8±0.5 cm, whereas the S+V group exhibited a tendency towards an increase ($P=0.052$) from 32.5±2.9 to 33.9±3.6 cm. The S group showed a significant increase in P_{peak} from 45.1±1.5 W kg^{-1} to 47.3±1.7 W kg^{-1} after training, whereas all three groups displayed a significant increase in V_{ppeak} from 2.26±0.03 m s^{-1} to 2.34±0.02 m s^{-1}in the S group, from 2.40±0.03 m s^{-1} to 2.45±0.04 m s^{-1} in the S+V group and from 2.35±0.07 m s^{-1} to 2.41±0.07 m s^{-1} in the V group. Finally, the S group responded to the training by a significant increase in P_{mean} from 25.9±1.0 W kg^{-1} to 27.4±0.9 W kg^{-1}, in work from 6.7±0.2 J kg^{-1} to 7.0±0.2 J kg^{-1} and in Fz_{mean} from 19.19±0.60 to 19.65±0.59 N kg^{-1} (Table 3).

Acute hormonal response to training

Testosterone

A significant acute increase of testosterone from rest was observed in the S and S+V groups both at the first and last training sessions. The V group showed no acute response of testosterone (Fig. 4). There were no signifi-

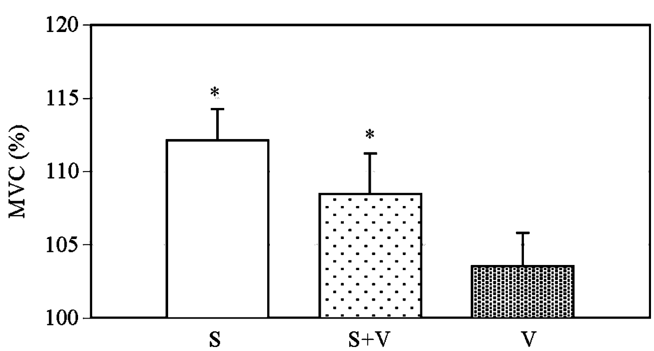

Fig. 2 Changes in MVC after the 9-week period of training. Data are presented as mean ± SE from a baseline with before training representing 100%. S group: ($n=9$), S+V group: ($n=10$), V group: ($n=9$). *Significant increase following training ($P<0.05$)

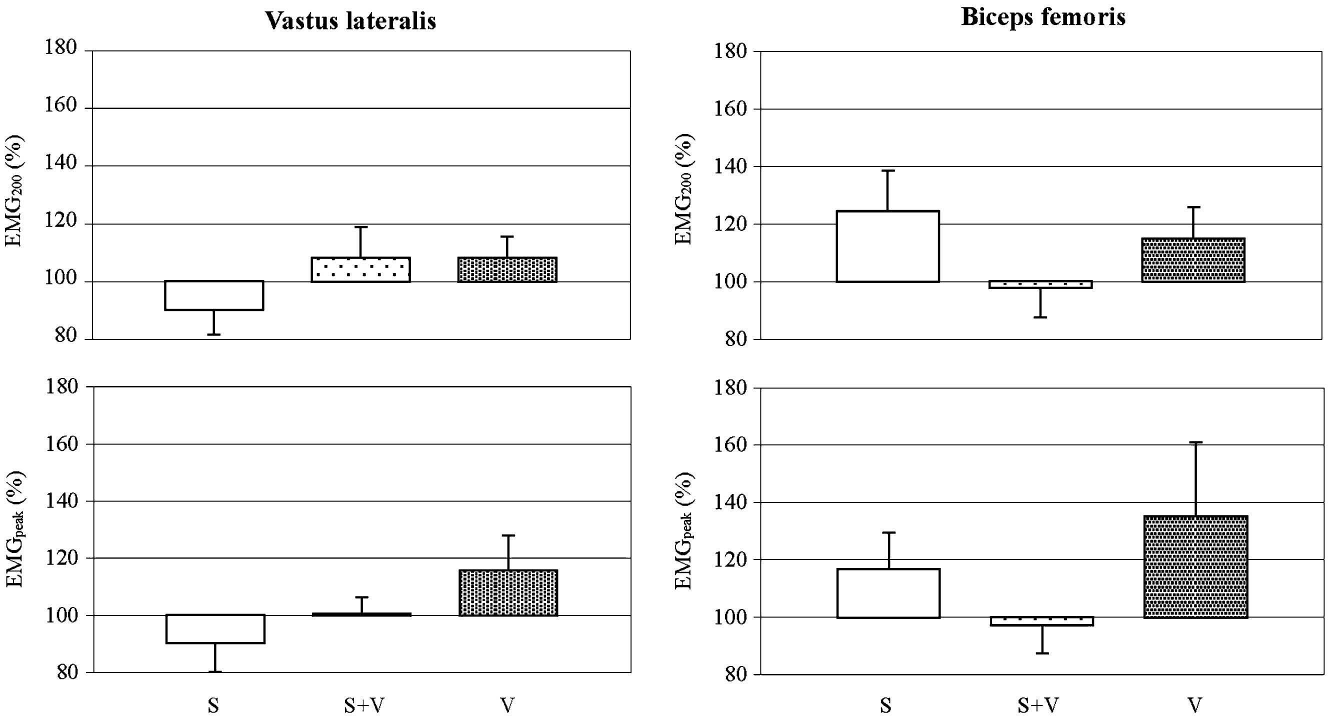

Fig. 3 Changes in EMG measurements after the 9-week period of training. Data are presented as mean ± SE from a baseline with before training representing 100%. S group: ($n = 9$), S + V group: ($n = 10$), V group: ($n = 9$). *Significant increase following training ($P < 0.05$)

cant changes in pre-values for testosterone for any group after 9 weeks of training (Table 4).

Growth hormone

A significant acute response of GH was observed in all groups at the first training session and also for the S + V group in the last training session. In addition, there was a significant time effect between groups with the S + V group showing higher concentrations compared to S and V groups during the first training session (Fig. 4). There were no significant changes in pre-values for GH for any group after 9 weeks of training (Table 4).

Cortisol

A significant acute response of cortisol was seen in the S + V group in the first and last training sessions. In addition, there was a significant time effect between groups with the S + V group showing higher concentrations compared to S and V groups. The V group showed an acute significant decline during the first training session. The S group demonstrated no acute cortisol response to the training session (Fig. 4). There were no significant changes in pre-values for cortisol for any group after 9 weeks of training (Table 4).

There were no within-group differences between hormonal response patterns measured during the first and last training sessions, for testosterone, GH and cortisol (Fig. 4).

Discussion

The main finding in the present study was that the combination of WBV and CRT (S + V group) did not increase MVC and mechanical performance assessed as CMJ to a larger extent than CRT (S group). The acute effect of the training session on testosterone and GH levels was similar in the S and S + V group, but cortisol showed a significant increase in the S + V group. Furthermore, WBV alone (V group) did not increase MVC and mechanical performance, although a significant increase in GH and decrease in cortisol was observed during the training session.

Contrary to our findings, Mester et al. (2005) found further increase in muscle strength and drop jump when performing the squat exercise with 50% of 1 RM combined with WBV compared to the same training protocol without WBV. These observations are supported by Ronnestad (2004). However, it could be argued that performing CRT with a load of 50% of 1 RM may be insufficient to induce adaptation, therefore, adding WBV to the training protocol may induce further increase in muscle strength and drop jump. Concerning WBV alone, the V group did not increase MVC and jump height significantly which is in agreement with the studies by De Ruiter et al. (2003b) and Cochrane et al. (2004), but different from Torvinen et al. (2002a) and Delecluse et al. (2003) who observed significant increased muscle strength and jump height after a training period of WBV.

Table 3 Mechanical performance measured before and after the 9-week period of training (mean ± SE)

Group	Jump height (cm)		P_{peak} (W kg^{-1})		Fz_{ppeak} (N kg^{-1})		V_{ppeak} (m s^{-1})		P_{mean} (W kg^{-1})		Work (J kg^{-1})		T_{con} (ms)		Fz_{mean} (N kg^{-1})	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
S	29.5 ± 0.9	31.8 ± 0.5[a]	45.1 ± 1.5	47.3 ± 1.7[a]	20.0 ± 0.6	20.2 ± 0.8	2.26 ± 0.03	2.34 ± 0.03[a]	25.9 ± 1.0	27.4 ± 0.9[a,b]	6.7 ± 0.2	7.0 ± 0.2[a]	261.0 ± 15.3	258.2 ± 14.2	19.19 ± 0.60	19.65 ± 0.59[a]
S + V	32.5 ± 0.9	33.9 ± 1.1	46.9 ± 1.4	48.0 ± 1.3	19.5 ± 0.4	19.5 ± 03	2.40 ± 0.03	2.45 ± 0.03[a]	26.3 ± 0.9	26.6 ± 0.8	7.5 ± 0.2	7.8 ± 0.2	286.0 ± 12.6	292.2 ± 9.2	18.73 ± 0.47	18.65 ± 0.35
V	31.3 ± 2.1	32.4 ± 1.9	45.8 ± 2.2	47.0 ± 1.9	19.4 ± 0.4	19.1 ± 0.3	2.35 ± 0.07	2.41 ± 0.07[a]	25.3 ± 1.0	24.7 ± 0.8	7.4 ± 0.4	7.8 ± 0.4	291.3 ± 12.5	314.2 ± 11.4	18.25 ± 0.36	17.78 ± 0.23

S group: ($n = 9$), S + V group: ($n = 10$), V group: ($n = 9$)
[a]Significant increase following training
[b]S group increases more than the V group ($P < 0.05$)

It is important to emphasize the fact that there are no significant differences between the S, S + V and V groups in any variable measured (except for P_{mean}, S higher than V). However, when taking into consideration how each group responded individually to the training period, the S group responded to a greater extent compared to S + V and V groups. In addition, it is important to call attention to the fact that the training load in the present study was measured on the floor and on the vibrating platform for the S and S + V groups, respectively. However, the training loads in the S and S + V groups did not differ significantly at any RM test through out the training period (Table 2). This is against our hypothesis because we expected that the acute effect of WBV (i.e. enhancement of force-generating capacity) enabled the subjects in the S + V group to lift heavier loads during 8 RM testing and as a result increasing the training intensity. Furthermore, assuming that WBV has no effect on mechanical performance, how do we explain the fact that the S + V group responds less pronounced compared to the S group in almost all mechanical performance parameters measured? To the author's best knowledge, no previous studies dealing with WBV as training intervention have evaluated mechanical performance (CMJ test) using force plate analyses, but rather have used contact mat analyses (i.e. flight time analyses) (Bosco et al. 1998, 2000, Torvinen et al. 2002a, b, c; De Ruiter et al. 2003b; Delecluse et al. 2003; Cochrane et al. 2004; Ronnestad 2004). However, the contact mat does not allow to identify changes in mechanical muscle output (i.e. P_{mean} P_{peak}, work) or whether changes in jump height after WBV exposure occurs as modified motor strategy (e.g. deeper countermovement, more efficient torque transfer from joint to joint) or as a combination of the two above-mentioned changes. The mechanical and temporal variables obtained from the force plate in the present study highlighted that the increase in jump height in the S group did not occur as a consequence of modified behaviour of the body centre of mass but rather as increased capacity of the muscle–tendon complex to develop greater mean mechanical muscle power (P_{mean}) which was translated into a greater take-off kinetic impulse and hence a higher jump height (Table 3). This was further supported by the increase in the concentric work for the S group, which occurred for a greater mean force (Fz_{mean}), while the duration of concentric phase (T_{con}) and the concentric displacement of the body centre of mass (data not shown) remained unchanged. These findings may have occurred because concentric work is a combined variable which results from the interaction between displacements of the body centre of mass, T_{con} and mean concentric force (Fz_{mean}). Similarly, the increase for the S group in P_{peak}, the product of velocity and force at peak power (V_{ppeak} and Fz_{ppeak}, respectively) was determined by a significant greater V_{ppeak} while Fz_{ppeak} remained unchanged. The increase in jump height after CRT (S group) is in agreement with previous reports (Baker et al. 1994; Glowacki et al. 2004; McCurdy et al.

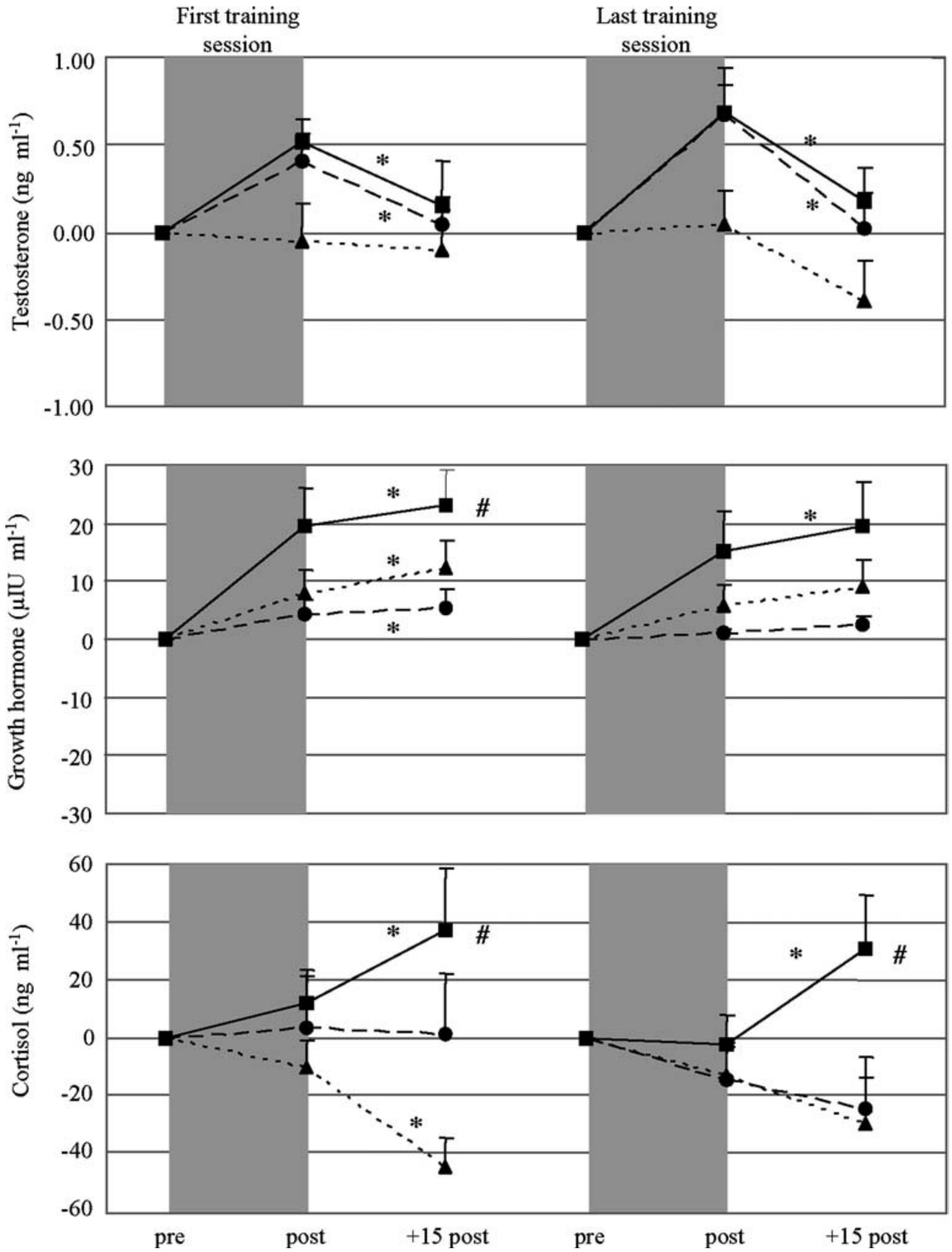

Fig. 4 Absolute changes in hormone concentrations shown as delta values relative to the respective resting values (mean ± SE) measured before (pre), after (post) and 15 min after (+15 post) the first and the last training sessions of the 9-week period of training. *Filled circle* S group ($n=8$), *filled square* S+V group ($n=10$), *filled triangle* V group ($n=7$). *Significant time effect within a group ($P<0.05$). # Significant time effect between groups; S+V higher than S and V ($P<0.05$)

2005). However, the S+V group showed only a trend for increase ($P=0.05$), whereas the V group did not change after training. Earlier studies investigating the effect of the combination of WBV and resistance training reports increases in jump height (Ronnestad 2004; Mester et al. 2005). Concerning the V group where no changes in jump height were seen after a training period of WBV agrees with De Ruiter et al. (2003b) and Cochrane et al. (2004) but disagrees with the findings from Torvinen et al. (2002a, 2003) and Delecluse et al. (2003).

In the present study despite increases in P_{peak} occurred only in the S group, mediated exclusively by greater V_{ppeak}, also S+V and V groups exhibited a significant higher V_{ppeak} without a concurrent increase in P_{peak} (Table 3). P_{peak} roughly occurs in the semi-extended position of the lower limb (Caserotti et al. 2001) prior to the ankle push-off phase. Hence, despite the difference in training volume and intensity for each group, the increase in V_{ppeak} in S+V and V likely indicates a learning transfer due to the similar knee-hip flexion-extension motor pattern employed during training (squat exercise) and during testing (ballistic squat, CMJ). The non-significant response to training in the CMJ test for the S+V group likely occurred for two possible reasons: (1) despite the training intensity was superior compared with the S group due to the acceleration of the load (i.e. chronic effect), this may have

Table 4 Pre-training values for hormones measured before the first and the last training sessions of the 9-week period of training (mean ± SE)

Group	Testosterone (ng ml^{-1})		Growth hormone (μIU ml^{-1})		Cortisol (ng ml^{-1})	
	First	Last	First	Last	First	Last
S	5.32 ± 0.50	4.69 ± 0.28	0.50 ± 0.48[b]	0 ± 0[b]	175.3 ± 20.8	215.7 ± 23.3
S + V	5.28 ± 0.56	5.12 ± 0.53	1.17 ± 0.81	0.30 ± 0.19	227.4 ± 32.2	244.0 ± 36.4
V	6.45 ± 0.41	5.68 ± 0.34	0.24 ± 0.19[a]	0.20 ± 0.15[a]	199.7 ± 15.3	200.2 ± 26.5

S group: (n = 9), S + V group: (n = 10), V group: (n = 9)
[a] n = 7; [b] n = 8

elicited a compromised training response in S + V, (2) the extra training stimuli induced by WBV coupled to the CRT affected negatively the motor control strategy during the CMJ. The lack of performance enhancement in the S + V group may have occurred due to overreaching symptoms and/or negatively affected jump motor programmes (e.g. altered Ia and Ib afferent CNS inputs from muscle spindles and golgi organs, respectively) with the use of WBV during training. The effect of long-term exposure to WBV has been studied extensively in occupational medicine and has been shown to determine dangerous side effects (e.g. low back pain) (Fishbein and Salter 1984). Thirty minutes of continuous vibration (30 Hz) of the *rectus femoris* was previously reported to significantly attenuated muscle strength and EMG (Jackson and Turner 2003). The authors concluded that prolonged vibration may lead to an acute attenuation of the Ia afferent function which again could attenuate α-motoneuron activity which could explain the reduced performance following vibration. Although the acute effect of WBV was not measured in the present study, it seems reasonable in the light of our results to speculate that the combination may have produced an excessive training load during each training session which finally may have coursed overreaching symptoms.

Bosco et al. (1999) performed strength and power testing with EMG measurements, measured before and after an acute vibration training protocol and reported increase in acute performance without simultaneous increases in EMG measurements. However, no previous studies have performed muscle strength testing with concurrent EMG measurements measured before and after a training period including WBV. We expected that EMG measurements would reveal increased neural activation, at least in the S group, as previously reported after a resistance training period by Moritani and de Vries (1979). Minor details make the testing situation different from the training situation. Despite that *vastus lateralis* and *biceps femoris* are extending and flexing the knee, respectively, EMG signals measured from only these two muscles may underestimate the EMG signal of the muscle groups involved in training and testing.

The acute hormonal response to CRT has already been studied for many years, and a growing body of evidence deals with the fact that anabolic hormones mediate an anabolic phase after each resistance training session. It seems plausible that anabolic hormones induce synthesis of contractile proteins in the subsequent recovery phase (Kadi 2000; Ahtiainen et al. 2003).

The acute hormonal responses in the present study reveal that heavy loads need to be present to stimulate release of testosterone, as confirmed by the S and S + V groups. This is in agreement with earlier studies, which report that hormonal responses to CRT appeared to be related to heavy loads, short rest periods and large volumes of training (Kraemer et al. 1990; Hakkinen and Pakarinen 1993; Hansen et al. 2001). However, as displayed by the similar response for testosterone in the S and S + V groups, combining CRT and WBV did not increase the hormonal response. Nevertheless, the combination seems to stimulate larger increases in GH compared to resistance training alone, during the first training session, yet this larger increase in GH does not affect MVC and mechanical performance measures in the S + V group. The increase in cortisol in the S + V group may indicate that a larger training stimulus was present and that a certain amount of physical stress is needed to trigger a cortisol response (Häkkinen and Pakarinen 1993). As already discussed, it seems that the S group adapts more positively to the training period compared to the S + V group in terms of mechanical performance. Likewise, the S + V group was exposed to an excessively high training stimulus which may have caused overreaching. In support of this, the S + V group reacts to the training by increases in cortisol, which could dampen or reduce the muscles' ability to hypertrophy because of the catabolic effects of cortisol. However, the pre-values for cortisol do not increase after the training period. Therefore, the acute increase in cortisol may instead reflect the metabolic demands of the training session rather than a catabolic phase.

In the present study the exposure to WBV alone (V group) decreased cortisol and increase GH, similar to the previous study by Bosco et al. (2000). However, they reported increases in testosterone, whereas the V group in the present study shows no increases in testosterone. Cardinale and Bosco (2003) argue that the mechanical characteristics of WBV (increase in gravitational load) seem to provide an adequate stimulus for the secretion of testosterone and GH concomitantly to a decrease in cortisol secretion. Bosco et al. (2000) discuss the hormonal response after WBV, as mediating factors for improved performance. The difference in training protocols must be taken into consideration when comparing our study with Bosco et al. (2000). The volume of one training session in our study might not be sufficient to stimulate increases in testosterone, similar to low intensity resistance training (Kraemer and Ratamess 2005). In the study by Bosco et al. (2000), the subjects performed 10×1 min with 1 min rest between sets (frequency 26 Hz and amplitude of 4 mm). In comparison, the subjects in our study did 6×30 s with 2 min rest between sets (frequency 20–25 Hz and amplitude 4 mm).

Comparing the hormonal response pattern for testosterone, GH and cortisol in the first and last training sessions, no differences were seen. Therefore, the training performed in the S, S+V and V groups does not induce changes in the acute hormonal response to a training session after a training period. An earlier study with CRT has shown a decreased acute response of GH and a tendency to a decreased acute response of testosterone after a training period (Ahtiainen et al. 2003), whereas Kraemer et al. (1998) reported a significantly higher acute hormonal response to the training session after a training period.

In a study with many outcome variables, it is appropriate to discuss family-wise type I error inflation. When we use the Bonferroni method to correct the few significant *P* values obtained from the ANOVA analysis, they all turned out as non-significant. Likewise, when correcting the significant *P* values obtained from the *t* test for within-group differences, no significant changes were seen. On the other hand, since all our outcome measures are conceptually correlated, we know that the Bonferroni method will be quite conservative. When we consider the overall picture which we obtain from all these variables, we observe almost the same pattern in all of them, with the S group showing a more pronounced response to the training intervention. Thus, despite the Bonferroni correction, we still find some evidence to support our discussion and conclusion.

Conclusions

Combined WBV and CRT did not additionally increase MVC and mechanical performance compared with resistance training alone after a short-term training period. Rather, the combination seemed to partly inhibit the adaptation to the training stimulus. In addition, WBV alone showed no increases in MVC and mechanical performance after the same short-term training period. It is reasonable therefore, to reject the hypothesis that WBV could optimize resistance training by further increasing neuromuscular and anabolic hormonal responses.

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