Effects of 6 Weeks of Periodized Squat Training With Or Without Whole-Body Vibration on Short-Term Adaptations in Jump Performance Within Recreationally Resistance Trained Men

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Abstract

Lamont, HS, Cramer, JT, Bemben, DA, Shehab, RL, Anderson, MA, Bemben, MG. Effects of 6 weeks of periodized squat training with or without whole-body vibration on short-term adaptations in jump performance within recreationally resistance trained men. *J Strength Cond Res* 22(6): 1882–1893, 2008—The purpose of this study was to examine the effects of a 6-week, periodized squat training program, with or without whole-body low-frequency vibration (WBLFV), on jump performance. Males ranged in age from 20 to 30 years and were randomized into groups that did squat training with (SQTV, $n = 13$) or without (SQT, $n = 11$) vibration, or a control group (CG, $n = 6$). Measures of jump height (cm), peak power (Pmax), Pmax per kilogram of body mass (Pmax/kg), and mean power were recorded during 30-cm depth jumps and 20-kg squat jumps at weeks 1 (pretraining), 3 (midtraining), and 7 (posttraining). No significant group differences were seen for 30-cm depth jump height between weeks 1 and 7 ($p > 0.05$). Trial three (W7) measures were greater than those for trial two (W3) and trial one (W1) ($p < 0.05$). Significant group differences were seen for 20-kg squat jump height, with SQTV > SQT between weeks 1 and 7 ($p < 0.05$). Significant trial differences were seen, with W7 > W3 > W1 ($p < 0.05$) as well as for 30-cm depth jump Pmax percent change (W7 > W3 and W1 $p < 0.05$)). A significant trial effect was seen for 20-kg squat jump Pmax (W7 > W1, $p < 0.05$) and 20-kg squat jump Pmax/kg percent change (W7 > W3 > W1, $p < 0.05$). The addition of vibration to SQTV seemed to facilitate Pmax and mean power adaptation for depth jumps and Pmax for squat jumps, although not significantly ($p > 0.05$). Stretch reflex potentiation and increased motor unit synchronization and firing rates may account for the trends seen. Baseline squat strength, resistance training experience, and amplitude, frequency, and duration of application of WBLFV seem to be important factors that need to be controlled for.

Key Words periodized resistance training, jump performance, post activation depression

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Introduction

Resistance training interventions have increased measures of lower-body power through central and peripheral adaptations such as increased descending cortical drive, increased alpha motor neuron input, increased motor unit firing rates, preferential motor unit synchronization, and decreased activation threshold for type II motor units (2,10,12,15,24,25,33,36). Resistance training has also been shown to increase the probability and frequency of short interspike doublets before initiation of ballistic actions leading to enhanced power production (2,15,37,39,40).

Because power is the product of force and velocity, resistance training methods aimed at increasing muscle power development have focused on improving both factors (19,20,27,34). Improvements in lower-body power transferable to ballistic tasks, such as vertical jumps, seem to be dependent on a number of factors including loading parameters, volume of exercise, velocity of exercise, movement intent of the exercise, and the specificity of the exercise to the jumping task (19,20,25,33,40).

Periodized resistance programs using "mixed method" regimens such as heavy-load (greater than 80% of one-repetition maximum [1RM]) resistance training using maximal movement intent combined with moderate to lighter-load (15–70% of 1RM) resistance exercises performed in a ballistic manner seem to be the most effective at increasing jump power (19,27). Harris et al. (19) evaluated a mixed-methods training regimen vs. heavy-load and lighter-load regimens during a 9-week training period and report that the mixed-method design resulted in significantly greater scores on a wider range of power tests when compared with more conventional power training methods ($p < 0.05$).

Other modalities have recently been employed in an attempt to enhance power output for the short term (11,16–18). Of these interventions, the use of maximal voluntary contractions (MVCs) has produced the most significant acute potentiation of jump performance (16–18); however, a number of recent studies have also reported increased jump height and power output after whole-body low-frequency vibration (WBLFV) exposure (4,5,7,13,29). Whole-body vibration has been shown to stimulate both mono- and polysynaptic reflex pathways leading to acute and chronic adaptations similar to those attributed to moderate-load resistance training (4,5,9,13,25,29). Two previous studies have looked at a combination of resistance training and whole-body vibration applied during the resistance exercise, producing contrasting results (23,29).

Rønnestad (29) compared Smith machine squatting on a vibration platform at a vibration frequency of 40 Hz (no amplitude reported) vs. conventional Smith machine squatting. After 5 weeks of periodized training (6- to 10-repetition maximum, two to three workouts per week), similar significant increases in Smith machine 1RM were seen for both groups, but only the group receiving vibration saw an improvement in countermovement vertical jump (CMVJ) height, although this was not found to be significantly different from that produced by the squat group not receiving vibration. This would suggest that a positive enhancement in power generation was afforded by the addition of vibration to the resistance training protocol but no additional enhancement in peak dynamic force.

Kvorning et al. (23) compared squatting on a vibration platform (S+V) with squatting alone (S) and vibration alone (V) during a 9-week training period (six sets at 8- to 10-repetition maximum, one to three workouts per week). Measures recorded included isometric MVCs performed during a unilateral leg press (knee angle 110°) with concurrent electromyographic recordings from the vastus lateralis and biceps femoris as well as CMVJ height (cm), peak power (Pmax; W), force at Pmax (N), and velocity at Pmax ($m \cdot s^{-1}$). The results indicate that MVC increased similarly for S and S+V, but only S saw significant improvements in jump height and Pmax. Analysis of EMG data revealed a significant increase in the MVC/EMG ratio in the squat group but no other significant effects. Hormonal analysis revealed similar significant increases in testosterone (T) for S and S+V and significantly larger increases in human growth hormone (HGH) for S+V. Cortisol was found to be significantly elevated only in the S+V group. The addition of vibration to resistance training did not seem to afford any additional advantage over resistance training alone. It is possible that the addition of vibration to the resistance training (20–25 Hz, 4-mm amplitude) initially improved average force/power output during the first two sets but then led to fatigue during successive sets, ultimately reducing the total work performed throughout the six sets. Also, the increased cortisol response for S+V may have led to a less favorable anabolic environment post training compared with squat training or vibration exposure alone.

The use of whole-body vibration between sets of resistance training may be a more viable alternative to vibration applied during resistance training in an attempt to synchronize and, possibly, preferentially recruit (via a reduction in activation threshold) higher-threshold motor units before heavy-load resistance exercise. Applying vibration between sets rather than concurrently during resistance exercise may reduce the fatigue potential and, possibly, further facilitate neuromuscular adaptations to the primary resistance training stimulus.

Therefore, the purpose of this study was to examine the effects of a 6-week, periodized squat training program, with or without concurrent low-frequency vibration applied between sets of Smith machine squats on power/velocity characteristics during two different jump tasks.

Methods

Experimental Approach to the Problem

After an orientation period, subjects trained for 6 weeks (with the exception of the control group) with a periodized squat training program, with or without whole-body vibration, applied before and between sets. Measures of jump performance for both the 30-cm depth jump and the 20-kg squat jump were evaluated before training (week 1), midtraining (week 3), and posttraining (week 7).

Subjects

Thirty-six men ($n = 36$) between the ages of 20 and 30 years of age gave written informed consent, which had been approved by a university institutional review board (Table 1). Subjects were then randomly assigned to either of two training groups or to a nontraining control group. There were no statistically significant differences between the three groups at baseline for age, height, weight, and percent body fat. Sample sizes were adequate to attain a statistical power of at least 0.80 based on the effect size (ES = postmeasurement mean − premeasurement mean/pooled standard deviation) calculated from a similar study (35). Group one (CG, $n = 8$) acted as an active control group that did not participate in the 6-week Smith machine squat protocol and only participated in testing sessions. Group two (SQTV, $n = 14$) performed Smith machine back squat training but also received WBLFV (50 Hz) before and between sets of Smith machine squats.

TABLE 1. Physical characteristics of subjects at baseline.

	Group 1 ($n = 6$): control	Group 2 ($n = 13$): resistance + vibration	Group 3 ($n = 11$): resistance only
Age (y)	22.8 ± 0.9	24.1 ± 0.9	23.2 ± 0.9
Height (cm)	177.7 ± 3.5	182.0 ± 1.9	179.3 ± 2.0
Weight (kg)*	87.2 ± 5.8	83.8 ± 3.4	73.9 ± 2.3
% Fat	15.2 ± 3.5	15.1 ± 1.4	15.7 ± 1.6

All values are expressed as means ± *SE*.
*Significant group difference $p < 0.05$ (but not detected with post hoc analysis).

The third group (SQT, $n = 14$) performed 6 weeks of Smith machine squats without vibration application.

A total of six control subjects completed the study (CG), with two subjects dropping out because of conflicting time commitments. One subject failed to complete the training protocol with vibration (SQTV), and three subjects failed to complete the full 6-week intervention with squat training alone (SQT). Thirty subjects completed all components of the study. Each subject's prior training status was assessed by way of a combination of questionnaire, self-reported training experiences, and Smith machine 1RM ability.

Procedures

Subjects were required to attend two familiarization sessions (at least 48 hours apart) during which Smith machine back squats, 30-cm depth jumps, 20-kg squat jumps, and whole-body vibration exercises were performed. During the 6-week training period, subjects were required to complete 12 Smith machine squat workouts with variable loads (55–90% 1RM) and sets (three to five). Testing sessions were carried out during weeks 1 (pretraining), 3 (midtraining), and 7 (posttraining) and consisted of standing height (cm), weight (kg), 1RM Smith machine squat, 30-cm depth jump performance, and 20-kg squat jump performance. The Sayers mathematical Pmax nomogram (38) was used to estimate depth jump and 20-kg squat jump Pmax using the subject's body mass and the height measure attained while jumping off a switch mat.

Jump Procedures

Thirty-Centimeter Depth Jump. Subjects were instructed to drop onto a contact mat (Just Jump) with a two-footed landing and to then rebound as quickly and as forcefully as possible so as to minimize ground-contact time. Additionally, subjects rested a broom handle across their upper trapezius and shoulders as if performing a barbell back squat so that a Fitrodyne (FitroDyne; Fitronic, Bratislava, Slovakia) linear line accelerometer chord could be attached to one end. The Fitrodyne provided data concerning mean power (W) and velocity ($m{\cdot}s^{-1}$) during the upward, concentric phase of the jumps. Height jumped was estimated from flight time (milliseconds), and measures of Pmax were calculated using the Sayers Pmax nomogram (31). A total of two trials were performed, with 45 seconds of rest between trials, and the average of the two trials was used for data analyses. Such a jump test was performed because it requires the performance of a moderate-load stretch shortening cycle (SSC). Such an SSC uses both stored elastic potential energy within the series elastic component of the targeted musculature and reflex activation of the targeted musculature via the medium-latency stretch reflex loop (3,17,28,38). Because whole-body vibration has previously been suggested to affect reflex activation of musculature via type Ia afferent feedback in the short term (4–7,13,29), it was expected by this author that using such a jump could help track training-associated plasticity within the medium-latency stretch reflex. Measures of reliability (single-measure intraclass correlation coefficients) for height (cm), Pmax (W), mean power (W), and Pmax/kg ranged from $r = 0.937$ to 0.972.

Twenty-Kilogram Squat Jump

The squat jump was also performed using both the Just Jump mat and the Fitrodyne apparatus. Subjects used the same broom-placement position that was used for the 30-cm depth jumps but instead used a 20-kg barbell. Foot position during the squat jump was standardized to that used during the speed squat. Subjects were prompted to step on the mat, descend to a position where their knees were bent at a 90° angle, and hold that position for a count of three; they were then prompted to jump as high as possible. The 3-second hold was implemented in an attempt to minimize the contribution of potential energy stored within the series elastic component of the lower extremities. Also, holding the static posture for the 3-second period would greatly reduce the contribution of type Ia afferent feedback to reflex contraction of the lower extremities and the resultant concentric impulse generation (20,25,26,33,34). Data recorded included mean power (W) and mean velocity ($m{\cdot}s^{-1}$) from the Fitrodyne (Fitronic, Bratislava, Slovakia) and maximal height (in), flight time (milliseconds), and Pmax estimation from the switch mat (31). A total of two jumps were performed with 45 seconds of rest between trials, and the average of the two trials was used for data analyses. Measures of reliability (single-measure intraclass correlation coefficients) for height (cm), Pmax (W), mean power (W), and Pmax/kg mass ranged from $r = 0.850$ to 0.977.

Training Procedures

Subjects were required to perform the Smith machine back squat exercise with or without low-frequency vibration applied before and between sets. The program followed a periodized design focusing on maximal force generation during the first 3 weeks, then maximal power and rate of force generation during the final 3 weeks (Table 2). A mixed design was used because previous work has supported the efficacy of such an extended microcycle (19,27,33). Training adaptations in force and power production were expected to be primarily neural in origin (increases in motor unit recruitment and firing frequency, increased doublet discharge, increased synchronization of motor units) with a secondary, smaller, concurrent increase expected because of muscular hypertrophy (increase in physiological cross-sectional muscle area [PCSA] with a concurrent increase in muscle angle of pennation). Such a pattern of adaptation has previously been reported after 5 weeks of maximal coupled concentric/eccentric training of the quadriceps (32).

Subjects performed the Smith machine back squat twice per week with sessions 72 hours apart. This recovery period was used to minimize potential residual fatigue from the previous workout session. Loading ranged from 55 to 90% of the subjects' predetermined 1RM at weeks 1 and 3. Loads used during the final 3 weeks of the protocol ranged from 55 to 85% of Smith machine back squat 1RM. During the second workout of a week, the load was reduced by 10–15% to allow recuperation from the previous "heavy session" as well as to improve the potential for increased bar velocity and dynamic rates of force development. Additionally, during the second session of the week, from week 4 onwards, subjects were instructed to perform "speed squats" by continuing the squat movement upward, raising onto their toes by way of a strong contraction of the gastrocnemius muscles of the lower leg.

Table 2. Loading progression throughout the 6-week, periodized Smith Machine training program.

Week	Sets	Repetitions	% 1RM (W1) (W2)
1	4†	5	(85%) (70%)
2	3	4	(88%) (75%)
3	3†	3	(90%) (80%)
4	3	5	(85%) (70%)
5	4	5	(75%) (60%*)
6	4	6	(65%*) (55%*)

1RM = one-repetition maximum; W1 = first workout of the week; W2 = second workout of the week.
*Denotes squats performed as speed squats.
†Denotes reduced volume of sets performed during W1 on weeks 1 and 3 because of 1RM assessment.

Subjects were verbally encouraged to push as forcefully as possible throughout the full range of motion of the Smith machine squat exercise. Rest periods between sets were set at 4 minutes to allow for recovery of force-generating capabilities in readiness for the next set.

Vibration Protocol

Whole-body vibration was applied by way of a power plate (Next Generation vibrating platform). Subjects stood on the platform holding an isometric quarter squat position. Foot position was the same as that used during both the Smith machine back squat and squat jumps. Subjects reached out and held the handles in front and slightly to the sides of their body.

Subjects were initially exposed to low-frequency vibration (50 Hz) for 30 seconds at a low amplitude (2–4 mm). A rest period of 180 seconds (3 minutes) after vibration exposure was used in an attempt to allow for possible stretch reflex potentiation before the first set of Smith machine squats (4–7). Vibration was then applied intermittently using three exposures of 10 seconds, in an attempt to reduce the potential for inducing postactivation depression, at the same frequency but at a high amplitude setting (4–6 mm) at time points corresponding to 60, 120, and 180 seconds into the 240-second rest period (Table 3). This procedure was followed between all subsequent Smith machine squat sets with the intent to compensate for possible reductions in alpha motor excitability by initiating type Ia afferent reflex volleys in response to vibration stimulation. When subjects were not receiving vibration, they were instructed to sit in a chair with their legs elevated on a wooden box. Such an instruction was given so as to reduce the mechanical loading of the lower extremities during this time period. The group not receiving whole-body vibration sat down for the full 240-second rest period between sets of squats.

Statistical Analyses

Statistical analyses were performed using SPSS for Windows (version 12.0). Descriptive statistics were used to describe the physical attributes and each parameter of interest, expressed as means ± standard errors. Each parameter that had multiple trials was subject to one-way repeated-measures analysis of variance (ANOVA) to produce the most stable representation for that parameter. Bonferroni pairwise comparisons were used as a post hoc analysis if significant differences were found ($p \leq 0.05$). The initial analysis included a one-way ANOVA to explore baseline (pretest) values for each parameter of interest. If there was a significant group effect then a Bonferroni pairwise comparison was used as a post hoc analysis. If significant baseline differences were determined, then analysis of covariance (ANCOVA) was used to control for the initial differences based on 1RM Smith machine squat values from week 1. For jump test variables recorded during weeks 1, 3, and 7, two-way repeated-measures ANOVA (group [3] × trial [3]) was used with Bonferroni post hoc comparisons to assess potential between-group differences.

Table 3. Vibration treatment time line.

Squat + Vibration Group (SQTV)
−210 s /(sit) /Squat/ 0…(sit)…60…(sit)…120…(sit)…180…(sit)…240s/squat
↑ (V1*) ↑ (180s) ↑ (V2†) ↑ (V3†) ↑ (V4†)
Squat Only Group (SQT)
−210 s /(sit) /Squat/ 0…(sit)…60…(sit)…120…(sit)…180…(sit)…240s/squat
↑ (V1‡) ↑ (180s) ↑ (V2‡) ↑ (V3‡) ↑ (V4‡)

*Denotes vibration applied at frequency of 50Hz and low amplitude (2–4mm) for 30 seconds.
†Denotes vibration applied at frequency of 50Hz and high amplitude (4–6mm) for 10 seconds.
‡Denotes no vibration applied.

A similar analysis was then performed with the data set sorted by group to assess potential within-group trial differences. One-way ANOVAs were used to compare groups' percent changes in variables between weeks 1 and 3, weeks 3 and 7, and weeks 1 and 7. A Bonferroni correction was used when multiple comparisons were calculated to account for inflation of alpha associated with multiple comparisons.

Results

Analysis of Variance and Analysis of Covariance for 30-cm Depth Jump Measures

This study was conducted to investigate the effects of a 6-week, periodized Smith machine squat training regimen, with or without WBLFV on select force/velocity characteristics during two different jump tasks.

At baseline (pretraining), there were significant differences between the three groups for jump Pmax (W) and jump mean power (W) for the 30-cm depth jumps and the 20-kg squat jumps.

Jump height for the 30-cm depth jump condition was found to be significantly greater than height achieved during the 20-kg squat jump condition ($p < 0.05$). After the intervention, there was a significant group by trial interaction ($p = 0.040$) as well as a significant main effect for trial ($p = 0.00$) for 30-cm depth jump height (Figure 1A). Depth jump height was statistically similar between the three groups at weeks 1, 3, and 7 ($p > 0.05$) (Figure 1B).

A two-way ANOVA with repeated measures (sorted by group) revealed no significant differences between trials for CG. A significant main effect for trial was found for SQTV ($p = 0.00$), with week 7 significantly greater than week 1 ($p = 0.007$) and week 3 ($p = 0.030$). The SQT group also had a significant improvement in jump height for the 30-cm depth jump ($p = 0.00$), with week 7 significantly greater than week 1 and week 3.

A two-way group (3) by trial (3) ANCOVA performed on depth jump Pmax (W) (analysis covaried by week 1 squat 1RM) revealed a significant group by trial interaction ($p = 0.033$) but no significant main effect for group ($p = 0.218$). A significant main effect was seen for trial ($p = 0.034$). Post hoc analysis revealed that Trial 3 (Tr3) was significantly greater than both Trial 2 (Tr2) and Trial 1 (Tr1), and Tr2 was greater than Tr1 ($p < 0.05$). A significant main effect was also seen for the covariate of week 1 squat 1RM ($p = 0.002$). (Figure 2A).

A two-way ANCOVA with repeated measures (sorted by group) revealed no significant differences between trials for CG, SQTV, or SQT ($p > 0.05$) (Figure 2A). The SQTV group saw a main effect for week 1 squat 1RM ($p = 0.020$).

Percent change in 30-cm depth jump Pmax (covaried by week 1 squat 1RM) revealed significant trial ($p = 0.043$) effects, with trial three (weeks 1–7) significantly greater than Tr1 (weeks 1–3), with trial one and two the same (Figure 2b). No significant differences were seen for group*trial ($p = 0.673$) or group ($p = 0.080$). A significant main effect was seen for trial ($p = 0.043$), with Tr3 > Tr1. Although no significant group differences were seen, there was a trend favouring SQVT percent change (7.28%) over SQT percent change (5.51%) and CG percent change (1.51%) ($p = 0.080$).

Analysis of depth jump mean power (W) by way of a two-way group (3) by trial (3) ANCOVA revealed no significant group by trial interaction ($p = 0.108$) or significant main effects for trial ($p = 0.220$). The covariate of week 1 squat 1RM was found to have a significant impact on between-subject effects ($p = 0.001$) (Figure 3A).

A two-way group (3) by trial (3) ANCOVA (sorted by group) revealed no significant within-subjects effects for CG ($p > 0.05$). For SQTV, no significant within-group effects were seen for trial ($p > 0.05$); a significant main effect was seen for the covariate of week 1 squat 1RM ($p = 0.020$). No significant within-group differences were seen for SQT ($p > 0.05$) (Figure 3A).

The percent change data for mean power (W) when covaried by week 1 squat 1RM revealed no significant interaction between group and trial, covariate and trial, or main effects for group or trial ($p > 0.05$) (Figure 3B).

Analysis of Variance and Analysis of Covariance for 20-kg Squat Jump Measures

A two-way group (3) by trial (3) ANOVA performed on squat jump height revealed no significant group by trial interaction

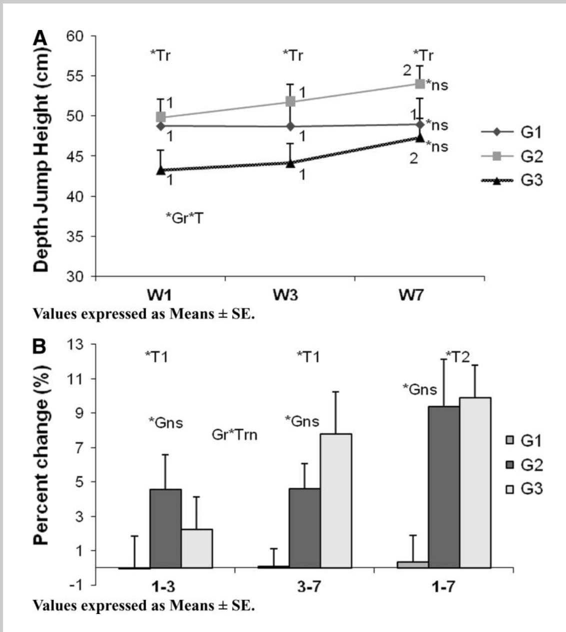

Figure 1. (A) Group by trial interaction for 30-cm depth jump height (cm). G1 = control group (CG); G2 = back squat trained plus vibration (SQTV); G3 = back squat (SQT) trained only; W1 = pretraining (week 1); W2 = midtraining (week 3); W3 = posttraining (week 7). *Tr1 and *Tr2 denote significant trial differences ($p < 0.05$). *ns denotes no significant group differences ($p > 0.05$). 1 and 2 denote significant within-group differences for trial ($p < 0.05$). (B) Percent changes in 30-cm depth jump height. G1 = control group (CG); G2 = back squat trained plus vibration (SQTV); G3 = back squat trained only (SQT); 1–3 = change between pretraining (week 1) and midtraining (week 3); 3–7 = change between midtraining (week 3) and posttraining (week 7); 1–7 = change between pretraining (week 1) and posttraining (week 7). *T1 and *T2 denote significant trial differences ($p < 0.05$). *Gns denotes no significant group differences ($p > 0.05$).

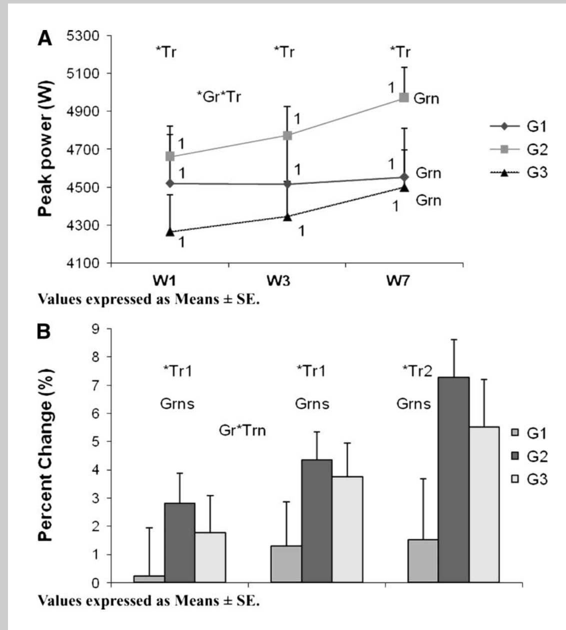

Figure 2. (A) Group by trial interaction for 30-cm depth jump peak power (W). G1 = control group (CG); G2 = back squat trained plus vibration (SQTV); G3 = back squat trained only (SQT); W1 = pretraining (week 1); W2 = midtraining (week 3); W3 = posttraining (week 7). *Tr1 and *Tr2 denote significant trial differences ($p < 0.05$). Grns denotes no significant group differences ($p > 0.05$). 1 denotes no significant within-group differences for trial ($p > 0.05$). (B) Percent change in 30-cm depth jump peak power. G1 = control group (CG); G2 = back squat trained plus vibration (SQTV); G3 = back squat trained only (SQT); 1–3 = change between pretraining (week 1) and midtraining (week 3); 3–7 = change between midtraining (week 3) and posttraining (week 7); 1–7 = change between pretraining (week 1) and posttraining (week 7). *Tr1 and *Tr2 denote significant trial differences ($p < 0.05$). Grns denotes no significant group differences ($p > 0.05$).

($p > 0.05$). A trend toward significance was seen ($p = 0.056$), with both SQTV and SQT improving by a similar amount between weeks 1 and 7. There were significant main effects for trial ($p = 0.00$) and group ($p = 0.042$). Trial three was greater than Tr2, which was greater than Tr1. Post hoc analysis performed on group revealed that SQTV was significantly greater than SQT ($p = 0.042$) (Figure 4A).

A two-way group (3) by trial (3) ANOVA (sorted by group) performed on squat jump height revealed no significant effects for trial for G1 ($p > 0.05$). For SQTV, a significant effect for trial was seen ($p = 0.00$), with Tr3 greater than Tr2, which was greater than Tr1. A similar, significant trial effect was seen for SQT ($p = 0.00$) (Figure 4A).

A two-way group (3) by trial (3) ANOVA performed on squat jump height percent change revealed a significant group by trial interaction ($p = 0.027$) as well as main effects for trial ($p = 0.00$). No significant main effects for group were seen ($p > 0.05$). Trial three percent change was greater than Tr2 and Tr1 percent change. Trial two and Tr1 percent change were statistically similar (Figure 4B).

A two-way group (3) by trial (3) ANCOVA performed on squat jump Pmax revealed no significant group by trial interaction ($p > 0.05$). Significant main effects were seen for trial ($p = 0.00$) and for week 1 squat 1RM ($p = 0.010$). Trial three was significantly greater than Tr2, which was significantly greater than Tr1 ($p = 0.00$) (Figure 5A).

A two-way group (3) by trial (3) ANCOVA (sorted by group) performed on squat jump power for CG revealed significant trial by week 1 squat 1RM interaction ($p = 0.049$) as well as a significant main effect for week 1 squat 1RM ($p = 0.028$). For SQTV, no significant interaction was seen between trial and week 1 squat 1RM ($p > 0.05$). Significant main effects were seen for trial ($p = 0.005$) and for week 1 squat 1RM ($p = 0.022$). Post hoc analysis revealed that Tr3 was significantly greater than Tr2, which was greater than Tr1 ($p < 0.05$). No significant effects were seen for SQT ($p > 0.05$) (Figure 5A).

Analysis of percent change data between weeks 1–3, 3–7, and 1–7 revealed no significant group by trial interaction or main effects for group ($p > 0.05$). Significant main effects were seen for trial ($p = 0.002$) and week 1 squat 1RM ($p =$

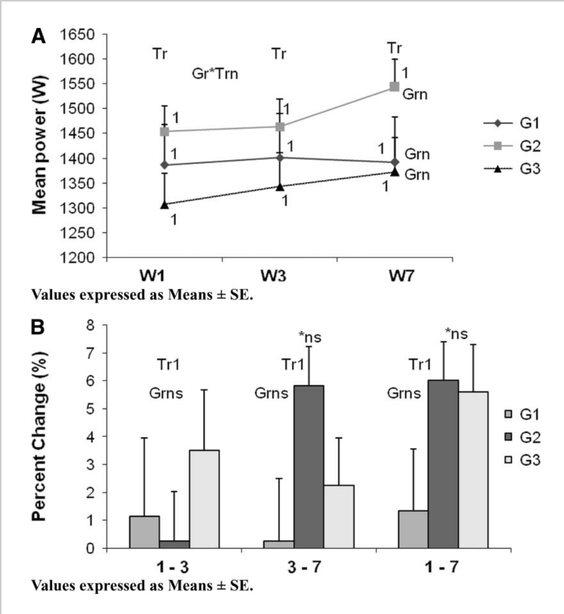

Figure 3. (A) Group by trial interaction for 30-cm depth jump mean power (W). G1 = control group (CG); G2 = back squat trained plus vibration (SQTV); G3 = back squat trained only (SQT); W1 = pretraining (week 1); W2 = midtraining (week 3); W3 = posttraining (week 7). Tr 1 denotes no significant trial differences ($p > 0.05$). Grns denotes no significant group differences ($p > 0.05$). 1 denotes no significant within-group differences for trial ($p > 0.05$). (B) Percent change in 30-cm depth jump mean power. G1 = control group (CG); G2 = back squat trained plus vibration (SQTV); G3 = back squat trained only (SQT); 1–3 = change between pretraining (week 1) and midtraining (week 3); 3–7 = change between midtraining (week 3) and posttraining (week 7); 1–7 = change between pretraining (week 1) and posttraining (week 7). Tr1 denotes no significant trial differences ($p > 0.05$). Grns denotes no significant group differences ($p > 0.05$).

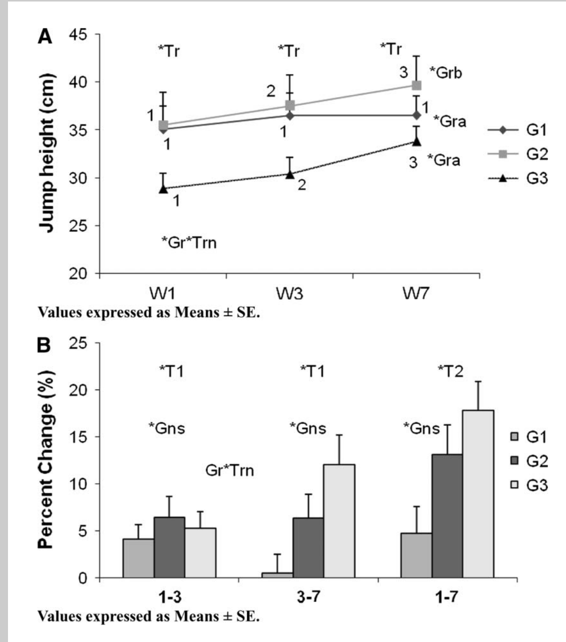

Figure 4. (A) Group by trial interaction for squat jump height (cm). G1 = control group (CG); G2 = back squat trained plus vibration (SQTV); G3 = back squat trained only (SQT); W1 = pretraining (week 1); W2 = midtraining (week 3); W3 = posttraining (week 7). *Tr1, *Tr2, and *Tr3 denote significant trial differences ($p < 0.05$). *Gra, *Grab, and *Grb denote significant group differences ($p < 0.05$). 1, 2, and 3 denote significant within-group differences for trial ($p < 0.05$). (B) Percent change in squat jump height. G1 = control group (CG); G2 = back squat trained plus vibration (SQTV); G3 = back squat trained only (SQT); 1–3 = change between pretraining (week 1) and midtraining (week 3); 3–7 = change between midtraining (week 3) and posttraining (week 7); 1–7 = change between pretraining (week 1) and posttraining (week 7). *T1 and *T2 denote significant trial differences ($p < 0.05$). *Gns denotes no significant group differences ($p > 0.05$).

0.007). Post hoc analysis revealed that Tr3 was greater than both Tr2 and Tr1 ($p < 0.05$), and T2 was similar to Tr1 ($p > 0.05$). A significant interaction was seen between week 1 squat 1RM and trial ($p = 0.013$) (Figure 5B).

A two-way group (3) by trial (3) ANCOVA performed on squat jump mean power revealed no significant group by trial interaction ($p < 0.05$). A significant main effect was seen for week 1 squat 1RM ($p = 0.00$) A two-way group (3) by trial (3) ANCOVA (sorted by group) performed on squat jump mean power revealed no significant within-group differences for CG ($p > 0.05$). A significant trial by week 1 squat 1RM interaction was seen ($p = 0.050$), as were significant main effects for trial ($p = 0.035$) and week 1 squat 1RM ($p = 0.001$) for SQTV. Post hoc analysis revealed that Tr3 was significantly greater than Tr1 ($p = 0.001$). No significant effects were seen for CG or SQT ($p > 0.05$).

Finally, there was a significant group by trial interaction ($p = 0.040$) and a significant trial effect ($p = 0.00$) for squat jump Pmax/kg (Figure 6A). Trial three was greater than Tr2, which was greater than Tr1 ($p < 0.001$). No significant main effects for group were seen ($p > 0.05$). The CG and SQTV groups were generally higher than SQT at each time period, except week 7 (Figure 6A).

A two-way group (3) by trial (3) ANOVA (sorted by group) performed on squat jump Pmax/kg revealed no significant changes for CG ($p > 0.05$). A significant main effect for trial was seen for SQTV, with Tr3 significantly greater than Tr1 ($p = 0.006$). Trial two and Tr1 were statistically similar ($p > 0.05$). A significant trial effect was seen for SQT, with Tr3 greater than Tr2, which was greater than Tr1 ($p < 0.05$) (Figure 6A).

The analysis of percent change revealed a significant group by trial interaction ($p = 0.030$) and a significant main effect for trial ($p = 0.001$). No significant main effects for group were seen ($p > 0.050$) (Figure 6B).

Discussion

Two jump tests were used to assess differing aspects of explosive power generation. The 30-cm depth jump was used because its performance requires subjects to place the lower extremities under an eccentric loaded prestretch before

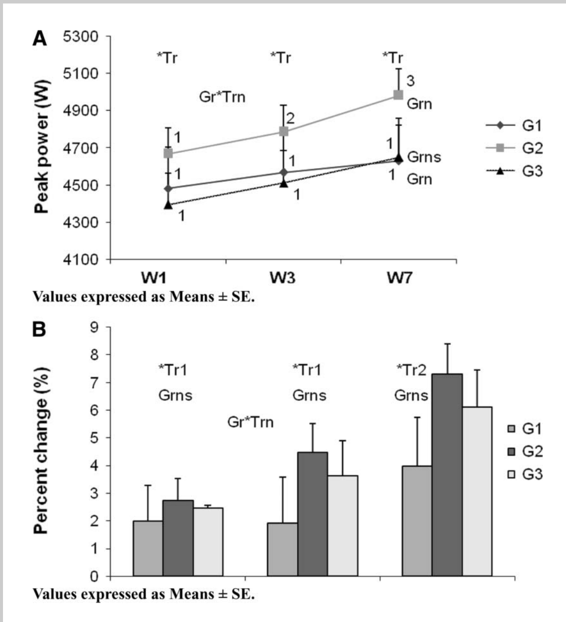

Figure 5. (A) Group by trial interaction for squat jump peak power (W). G1 = control group (CG); G2 = back squat trained plus vibration (SQTV); G3 = back squat trained only (SQT); W1 = pretraining (week 1); W2 = midtraining (week 3); W3 = posttraining (week 7). *Tr1 and *Tr2 denote significant trial differences ($p < 0.05$). Grns denotes no significant group differences ($p > 0.05$). 1, 2, and 3 denote significant within-group differences for trial ($p < 0.05$). (B) Percent change in squat jump peak power. G1 = control group (CG); G2 = back squat trained plus vibration (SQTV); G3 = back squat trained only (SQT); 1–3 = change between pretraining (week 1) and midtraining (week 3); 3–7 = change between midtraining (week 3) and posttraining (week 7); 1–7 = change between pretraining (week 1) and posttraining (week 7). *Tr1 and *Tr2 denote significant trial differences ($p < 0.05$). Grns denotes no significant group differences ($p > 0.05$).

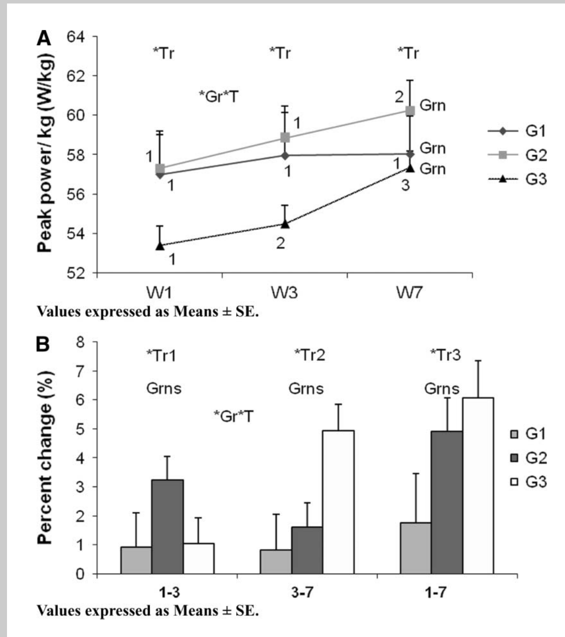

Figure 6. (A) Group by trial interaction for squat jump peak power per kilogram ($W \cdot kg^{-1}$). G1 = control group (CG); G2 = back squat trained plus vibration (SQTV); G3 = back squat trained only (SQT); W1 = pretraining (week 1); W2 = midtraining (week 3); W3 = posttraining (week 7). *Tr1, *Tr2, and *Tr3 denote significant trial differences ($p < 0.05$). Grns denotes no significant group differences ($p > 0.05$). 1, 2, and 3 denote significant within-group differences for trial ($p < 0.05$). (B) Percent change in squat jump peak power per kilogram. G1 = control group (CG); G2 = back squat trained plus vibration (SQTV); G3 = back squat trained only (SQT); 1–3 = change between pretraining (week 1) and midtraining (week 3); 3–7 = change between midtraining (week 3) and posttraining (week 7); 1–7 = change between pretraining (week 1) and posttraining (week 7). *Tr1, *Tr2, and *Tr3 denote significant trial differences ($p < 0.05$). Grns denotes no significant group differences ($p > 0.05$).

entering the concentric propulsive phase of the jump (20,38). The second jump condition was a squat jump performed with a 20-kg Olympic sized barbell, which required subjects to hold a fixed position for 3 seconds before moving explosively through a concentric propulsion phase without a prior eccentric preload phase.

The vibration protocol selected was based on acute post-activation potentiation data collected within our laboratory (Lamont et al., 2006 unpublished pilot data) that suggested that using a higher frequency (50 Hz) and amplitude (4–6 mm) for three bouts of 10 seconds was superior (acutely elevated CMVJ jump height and Pmax/kg) to using a lower frequency (30 Hz) or using 30 continuous seconds of vibration. However, results from the jump analyses suggest that no significant benefit was afforded by the addition of vibration to the resistance training protocol, although trends were observed that may hold "practical significance" for the strength and conditioning practitioner.

Initial analysis of depth jump height data revealed that SQTV and SQT improved (week 1 to week 7) by 8.49 and 9.45%, respectively, which is in line with data reported by Rønnestad (29) after a somewhat similar 5-week training intervention. The Rønnestad study differed from the current study in that it required subjects to perform Smith machine squats on a vibrating platform at a frequency of 40 Hz (amplitude not specified).

Increased descending cortical drive, alpha motor input, increased motor unit recruitment and firing rates, preferential motor unit synchronization, and decreased activation threshold for type II motor units have all been cited as key central and peripheral adaptations to resistance training (1,2,10,15,21,33). With this in mind, the periodized plan of the workout, which first emphasized maximal force development and then focused on power development, seemed to have facilitated explosive power adaptation. The background training status of the subjects was classified as "recreational trained," with all subjects having at least 6 months of resistance training of the lower extremities but working out no more than three times per week before the study. On the basis of such selection criteria, it was expected that the training program would facilitate primarily neural adaptations such as those motioned elsewhere and also produce a small amount of muscular hypertrophy.

The 6-week training time period seems to have been of sufficient length to have produced significant improvements in power measures for both experimental groups when compared with the control condition. No significant difference was seen in depth jump height between weeks 1 and weeks 3, but significant improvements were seen between weeks 3 and 7 for the depth jump condition. The lack of significant adaptation during the first 3 weeks may have been attributable to the heavy loads used. An increase in strength alone within the targeted musculature of the lower extremities does not necessarily transfer to increased jump performance. Bobbert et al. (3) carried out a CMVJ simulation study where a 20% increase in maximal strength in the lower extremity actually led to a reduction in jump height if concurrent increases in power and motor coordination specific to optimizing jump height were not seen. Although there were no significant differences seen between groups between weeks 1 and 3, the greatest actual improvement in depth jump height was seen by SQTV (4.54%).

Whole-body vibration has been shown to stimulate both mono- and polysynaptic reflex pathways leading to acute and chronic adaptations similar to resistance training (4,5,7,8,13,14,25,29). The addition of vibration to SQTV may have led to increased reflex excitation of alpha motor neurons within the targeted musculature as well as increased synchronization of certain populations of motor units before the back squat exercise. McBride et al. (25) have suggested that vibration may lead to increased synchronization of motor units allowing for enhanced performance during ballistic movements as well as movements performed with maximal movement. Sale (30) has suggested that movement intent is as important as actual movement velocity if dynamic rates of force development and velocity are the primary outcome goals of resistance training.

Resistance training has also been shown to increase the probability and frequency of short interspike doublets (<10 milliseconds) before initiation of ballistic actions (1,2,37,40). The application of vibration before and between sets of resistance training may have enhanced doublet discharge probability and frequency, leading to greater average rates of force development and power outputs during multiple sets of squats. A combination of the aforementioned factors coupled with possible stretch reflex potentiation after withdrawal of the vibration stimulus may help explain the nonsignificant increases in depth jump performance for SQTV after only 3 weeks of training.

The significant increases in both jump performances observed between weeks 3 and 7 may in part be attributable to the shift from heavy-load resistance training to lighter-load resistance training (loads reduced as low as 55% of 1RM) coupled with the performance of speed squats. The speed squat required subjects to squat upward, continuing up onto their toes while at the same time minimizing the time between repetitions. Such a motion shares some biomechanical similarity to the depth jump. Percent change data revealed that there were no significant differences between experimental groups (SQTV and SQT) at weeks 1, 3, and 7.

The only parameters that differed between groups at baseline were depth jump peak and mean power. Analysis of covariance was used to apply a correction to group analysis based upon week 1 squat 1RM. Such a covariate was chosen to account for the potential effects of differing strength levels at baseline between subjects. Both SQTV and SQT increased depth jump power by nearly 7% during the 7-week period (SQTV = 6.94% increase, SQT = 6.62% increase). This near 7% increase is in line with other studies looking at changes in jump power using a countermovement during a similar time period (30).

Analysis of changes in depth jump mean power revealed significant interactions between groups and trials as well as main effects for trial and the covariate of week 1 squat 1RM. Again, an ANCOVA was used in an attempt to normalize the data with respect to baseline strength level. Although no significant differences were seen between groups, the CG produced the lowest actual increase in mean power during the 7-week period (CG percent change 1–7, 1.35%; SQTV percent change 1–7, 6.02%; SQT percent change 1–7, 5.62%) This result is not unexpected because this group did not complete the 6-week specialized strength/power mesocycle. Both experimental groups saw a significant increase in depth jump mean power between weeks 1 and 7 ($p < 0.05$). For SQTV, the majority of improvement came between weeks 3 and 7 (5.83%). Interestingly, SQTV depth jump mean power only increased by 0.28% from week 1 to week 3. A Pmax measure recorded over the same time period for SQTV showed a 2.8% increase that was accompanied by a 4.54% increase in height. Peak and mean power are two distinct measures, Pmax being a representation of the greatest power output during the concentric phase of the jump, and mean power being the average power generated during the concentric phase of the jump. Peak power (especially when expressed relative to kilograms of body mass) has a greater impact on take of velocity and, subsequently, maximal height jumped, because mean power has a greater impact on total work and concentric impulse.

The significantly higher 1RM squat measures at baseline for SQTV and CG may be indicative of a slightly greater training status than the subjects within SQT. As mentioned elsewhere, simply increasing the strength of the lower extremities does not always transfer to concurrent improvements in jump performance (3). This lack of transfer becomes increasingly apparent if the subjects already have a moderate level of training experience. The transition to more power-specific loading, coupled with the use of speed squats, would seem to have been more appropriate for the subjects within SQTV because most of the improvement seen between weeks 1 and 7 (about 97% of the total change) occurred during the final 4 weeks. It is also possible that the addition of the vibration stimulus during the final 3 weeks of the training protocol potentiated mean power for the short term during the semiballistic speed squats, resulting in the 6.02% increase seen in depth jump mean power.

Measures of squat jump height revealed significant differences between groups and trials ($p < 0.05$). Jump height collapsed over trials at weeks 1, 3, and 7 revealed that SQTV and CG were similar, with SQTV significantly greater than SQT ($p < 0.05$). Measures recorded for the control group did not increase during the 7-week period ($p > 0.05$). For SQTV and SQT, squat jump height was 11.75 and 14.74% greater, respectively, at week 7 compared with week 1 group values ($p < 0.05$), but these values were not found to be significantly different from one another. The lack of significance between groups could also be a statistical power issue in that uneven numbers of subjects were used for the final data analysis because of subject drop-out.

The greatest improvement in squat jump height for SQTV occurred between weeks 1 and 3 (6.49% increase); for SQT, the greatest improvements came between weeks 3 and 7 (12.05% increase). The different responses between SQTV and SQT may be attributable to the addition of the vibration to SQTV as well as the different 1RM squat values measured at baseline. The addition of vibration during the first 3 weeks of the training study to SQTV may have facilitated improvements in dynamic rates of force production, which transferred to improved squat jump performance. A similar level of improvement was seen for SQTV from weeks 3 to 7. During the same period from week 3 to week 7, SQT saw a 12.05% improvement in squat jump height. Previous research has suggested that there may be a certain lag period associated with power improvement, which would seem to be the case with SQT (2,19–21,27,33,34). The addition of vibration may have reduced this lag period somewhat from weeks 1 to 3 for SQTV but then afforded no additional benefit.

Squat jump power assessed at weeks 1, 3 and 7 revealed no significant interaction for group by trial, but it did see an interaction between week 1 squat 1RM and trial. This suggests that baseline squat strength significantly impacted subjects' responsiveness to the 6-week training intervention. Further group analyses revealed no significant differences for CG on any testing occasions, which suggests that there was no significant improvement in squat jump Pmax for the control group during this period. However, baseline squat 1RM measures had a significant impact on squat jump power development through the three testing occasions. This interaction was not seen for SQTV or SQT over the testing time points, although a significant main effect for week 1 squat 1RM was seen for SQTV. This main effect suggests that there were significant differences between subjects within the squat + vibration group but that it did not significantly impact on Pmax development during the 7-week period.

Peak power measures recorded at weeks 3 and 7 were found to be significantly greater than week 1 measures for SQTV only, suggesting that although there were no between-group differences, the addition of vibration would seem to have had a performance-enhancing effect.

Analysis of squat jump power percent change data revealed similar improvements for SQTV (7.29%) and SQT (6.11%) between weeks 1 and 7. The slightly greater nonsignificant improvement in Pmax seen for SQTV at week 7 may be directly related to the greater proportional increase in lean tissue within the lower extremities seen (data not shown) for that group. The SQTV group had a 2.10% increase in lean tissue within the legs, which equated to a 0.464-kg increase. The combination of increased mass coupled with an increase in force-generating cross bridges within the lower extremities targeted during the jump tasks could explain some of the variance between groups. The SQT group also recorded increases in lean tissue within the legs (1.44% increase, 0.256 kg) but saw the greatest relative increase in lean tissue within the trunk (1.72% increase, 0.500 kg). Such changes in body composition were deduced from body composition measures taken by way of dual-energy X-ray absorptiometry in weeks 1 and 7.

The application of the vibration stimulus to SQTV could have had a positive impact on both systemic and localized anabolic hormone release above that afforded by resistance training alone. Previous research has shown large, short-term elevation in HGH coupled with small elevations in testosterone and decreased cortisol responses after whole-body vibration exposure (4,5,8,23). However, because no serum hormonal analysis was performed during the current study, such claims remain speculative at best. It is possible that the addition of vibration to some of the subjects acted to prefatigue rather than prime subsequent squat performance, forcing the musculature of the lower body to work even harder, thus triggering a greater hypertrophic response. Such a prefatiguing response may have forced a greater total motor unit recruitment and fatigue within the target musculature, thus stimulating a greater muscle tissue accretion (5,21–23).

The SQT group produced its greatest gains in jump squat height, Pmax, and Pmax/kg mass between weeks 3 and 7, most likely because of the shift from heavy loads to more moderate loads emphasizing power generation.

A similar pattern of increase was seen for Pmax/kg for SQTV between weeks 1 and 3, although differences were also seen between weeks 3 and 7 ($p < 0.05$). Vibration seemed to help accelerate initial improvements in squat jump height and Pmax generation expressed relative to body mass during the heavy resistance training phase. The aforementioned increase in leg lean tissue coupled with increased motor unit synchronization beyond that produced by heavy resistance training alone could have resulted in preferential training adaptations in explosive power during this phase.

Some of the key limitations of the study include uneven group sizes as well as significant differences between groups for select power measures at baseline. Also, because no ground-reaction force and EMG data were collected, direct measures of force-velocity characteristics during the two jump types, as well as measures of muscle activation in response to WBLFV, could not be presented.

The majority of subjects did not respond favorably to the vibration frequency, amplitude, and time course of exposure used. The vibration frequency and amplitude used seemed to have been too strong a stimulus for resistance trained individuals deemed to be at the lower limit of the inclusion criterion for the study. The application of vibration before the first "work set" would seem to have fatigued rather than potentiated subsequent sets of Smith machine squats within the majority of the subjects. The application of WBLFV before and then during interset rest periods did not seem to significantly improve jump performance above that afforded by squat training alone. Trends were seen favoring the addition of vibration between sets of resistance training with regard to squat jump and depth jump Pmax, although these were not found to be statistically significant. Baseline Smith machine squat ability seemed to have a significant impact on individual subjects' responsiveness to both the resistance training and the vibration stimulus applied. This factor, along with the potential differing fiber type composition of the subjects, the amplitude and the frequency of vibration used, and the method of application, seems to have elicited highly variable responses within the three subject groups. Finally, the length of the current study may have impacted the results, with studies using similar methods but for shorter or longer training periods potentially producing different outcomes.

Practical Applications

The addition of WBLFV before, and then in between, sets of resistance exercise does seem to have practical merit, although significant group differences were not seen during the current study. Prior resistance training experience seems to play a strong role regarding individual subject responsiveness to vibration at higher amplitudes and frequencies. Background training status, as well as fatigue state, should be taken into consideration before applying whole-body vibration before, and then between, sets of resistance exercise. Less heavily resistance trained individuals may benefit from vibration applied at a lower frequency and lower amplitude compared with more heavily resistance trained individuals.

It may prove more practical to "periodize" the vibration exposure starting at lower frequencies and amplitudes for longer durations before progressing on to higher frequencies and amplitudes for shorter exposure times. Such a gradual increase in the intensity of the vibration exposure may lead to greater adaptation, allowing for acute modification of the spinal stretch reflex response while, at the same time, reducing the potential for presynaptic inhibition at type Ia and type II afferents. Such adaptations could be very helpful to strength/power athletes who want to maximize their dynamic rates of force development and power generation during both heavy-load and lighter-load ballistic resistance training exercises.

Vibration platforms positioned strategically throughout a training facility would allow athletes and their strength and conditioning coaches convenient access to a potentially helpful training aid.

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