EFFECTS OF ADDING WHOLE BODY VIBRATION TO SQUAT TRAINING ON ISOMETRIC FORCE/TIME CHARACTERISTICS

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ABSTRACT

Lamont, HS, Cramer, JT, Bemben, DA, Shehab, RL, Anderson, MA, and Bemben, MG. Effects of adding whole body vibration to squat training on isometric force/time characteristics. *J Strength Cond Res* 24(x): 000–000, 2009—Resistance training interventions aimed at increasing lower-body power and rates of force development have produced varying results. Recent studies have suggested that whole-body low-frequency vibration (WBLFV) may elicit an acute postactivation potentiation response, leading to acute improvements in power and force development. Potentially, the use of WBLFV between sets of resistance training rather than during training itself may lead to increased recruitment and synchronization of high-threshold motor units, minimize fatigue potential, and facilitate the chronic adaptation to resistance exercise. The purpose of this study was to determine the effects of applying TriPlaner, WBLFV, prior to and then intermittently between sets of Smith machine squats on short-term adaptations in explosive isometric force expression. Thirty recreationally resistance trained men aged 18–30 were randomly assigned to 1 of 3 groups: resistance training only (SQT, $n = 11$), resistance plus whole-body vibration (SQTV, $n = 13$), or active control (CON, $n = 6$). An isometric squat test was performed prior to and following a 6-week periodized Smith machine squat program. Whole-body low-frequency vibration was applied 180 seconds prior to the first work set (50 Hz, 2–4 mm, 30 seconds) and intermittently (50 Hz, 4–6 mm, 3 × 10 seconds, 60 seconds between exposures) within a 240-second interset rest period. Subjects were instructed to assume a quarter squat posture while positioning their feet directly under their center of mass, which was modified using a handheld goniometer to a knee angle of 135 ± 5°. Instructions were given to subjects to apply force as fast and as hard as possible for 3.5 seconds. Isometric force (N) and rates of force development ($N \cdot s^{-1}$) were recorded from the onset of contraction (F_0) to time points corresponding to 30, 50, 80, 100, 150, and 250 milliseconds, as well as the peak isometric rate of force development (PISORFD), and rate of force development to initial peak in force (RFDinitial). Repeated measures analysis of variance and analysis of covariance revealed no significant group by trial interactions for isometric rate of force development (ISORFD) between 0–30, 0–50, 0–80, 0–100, 0–150, and 0–250 milliseconds and PISORFD ($p > 0.05$). A significant group × trial interaction was seen for RFDinitial with SQTV >CG ($p = 0.04$, mean difference 997.2 $N \cdot s^{-1}$) and SQTV >SQT ($p = 0.04$, mean difference 1,994.22 $N \cdot s^{-1}$). Significant trial by covariate interactions (week one measures for ISORFD) and main effects for trial were observed for ISORFD between 0–80, 0–100, 0–and 150 milliseconds; PISORFD; and RFDinitial ($p < 0.01$). A significant trial effect was seen for Finitial (%) when expressed as a relative percentage of maximal voluntary contraction (MVC) (MVC = 100%) ($p = 0.015$; week 1 > week 7, mean difference, 5.82%). No significant differences were seen for any other force variables from the onset of contraction to MVC between weeks 1 and 7 ($p > 0.05$). The data suggest that there was a significant benefit afforded by adding WBLFV to a short-term resistance training protocol with regard to "explosive" strength expression. The addition of vibration prior to and between sets of resistance exercise may be a viable alternative to vibration applied during resistance exercise when trying to improve "explosive" isometric strength.

KEY WORDS explosive strength, low-frequency vibration, potentiation, rate of force development, resistance training

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0(0)/1–13

Journal of Strength and Conditioning Research
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INTRODUCTION

Resistance training interventions aimed at increasing lower-body power and rates of force development (RFDs) have produced varying results. Increased cortical drive, alpha motor neuron input, and motor unit firing rates, coupled with preferential motor unit synchronization and decreased activation threshold for type II motor units, have been cited as central and peripheral adaptations to resistance training (1–3,9,10,15,20,21,25,28,30,41). Resistance training has also been shown to increase the probability and frequency of short interspike doublets prior to the initiation of ballistic actions leading to enhanced power production (1–3,9,18,23,41). Previous research has reported training-induced improvements in both dynamic and isometric rates of force development (ISORFD) following heavy load and lighter load ballistic resistance training (1,2,10,11,22,23,37,38,42). Therefore, the ability to generate force rapidly has major implications for both high performance and reflexive postural correction in response to unexpected perturbations (slips and falls).

Specific force/time integrals derived from an isometric force/time curve have been shown to correlate with dynamic athletic endeavors with varying movement latencies (1–3,9,18,21,28,29,34,37,38,42,44). Combat sports, which involve punching and kicking, produce movement latencies ranging from 40 to 150 milliseconds depending on the complexity of the movement. In these instances, the ability to rapidly accelerate an unweighted limb is vital to success (1–3,24,36–38,42). Force developed in the earliest time (first 30–40 milliseconds) frame following the onset of contraction is commonly referred to as "starting strength" and correlates strongly with the increased incidence of doublet discharges, leading to high initial motor unit discharge rates (1–3,36–38). Sprinting involves foot contact time between 85 and 100 milliseconds when looking at subelite to elite athletes (36–38, 42) with body mass acting as the primary resistance. Other ballistic tasks such as throwing a shot typically have greater movement times between 150 and 180 milliseconds depending on the skill and the technique used by the athlete (36,38). Such tasks with movement latencies between 85 and 180 milliseconds have been suggested to be more dependent on "explosive strength" or the ability to rapidly accelerate a limb against an external load (11,12,24,26,29,36–38,42,44). Explosive strength has been correlated with the ability to rapidly recruit higher threshold motor units while maximizing their discharge frequencies (1–3,18,19,24,29,36–39,42,44).

Pervious training studies have varied from 4 to 24 weeks in length using a progressive overload or a periodized plan (2,10,18,21–23,28,30). Aagaard (3) carried out a 14-week resistance training study using heavy load resistance for a total of 38 workouts. Significant increases in force integrals from the onset of contraction to a time point of 200 milliseconds, as well as increased contractile impulse (time-integrated force), electromyography (EMG) signal amplitude, and rate of EMG rise, were observed. Harris et al. (21) reported that a "mixed methods" approach using heavier and lighter load resistance exercises produced the greatest improvements in strength, power, and rates RFDs over the widest range of the loading spectrum. Cormie et al. (10,11) also found that a mixed methods approach leads to the greatest improvements in power and RFD over a wide load spectrum of jump squats compared with loading, which maximized peak power output (body mass). Newton et al. (30) reported similar improvements for measures of both strength and power in younger and older men.

In addition to traditional resistance training, other techniques have been employed to elicit acute increases in power output and improved RFDs (5,8,12–14,16–18,20,32,36,37,39). For example, maximal voluntary contractions (MVCs) prior to jumping tasks have resulted in potentiation of jump height and power output (16–18,20). Postactivation potentiation (PAP) may be induced following whole-body low-frequency vibration (WBLFV) albeit via slightly different proposed mechanisms (5–8,12–14,26,32,37). Whole-body low-frequency vibration has been shown to stimulate both mono- and polysynaptic reflex pathways, leading to acute and chronic adaptations, which have been compared with moderate-load resistance training (5–8,14,26,32,39). If these findings can be validated, WBLFV may be an attractive modality by which to improve performance and may offer an alternative to the use of MVCs.

The mode of WBLFV application also appears to be of importance with different manufactures using vertical, horizontal, or pivot/wobble-based vibration platforms with variable results. Recent work has also used multiplaner randomized WBLFV in Parkinson's patients with some success (40) The present study used the Power Plate Next Generation (Power Plate USA, Northbrook, IL, USA), which is described as a TriPlaner with the majority of the vibration within the Z-plane (43).

The combining of resistance training and WBLFV methods in an attempt to improve both acute and chronic adaptations to resistance training is a growing research area. Ronnestad (32) examined the effects of a 5-week, periodized, Smith machine back squat training regimen, with or without WBLFV, on 1-repetition maximum (1RM) back squat and countermovement vertical jump (CMVJ) performance. Both groups significantly ($p < 0.05$) increased 1RM Smith machine back squat strength; however, only the WBLFV group improved vertical jump performance. Contrasting results were reported by Kvorning et al. (26), comparing squatting on a vibration platform with squatting alone or vibration alone over a 9-week training period (6 sets at 8–10 RM, 1–3 workouts per week). Isometric strength increased similarly for both squat trained groups, but the squat training–only group also had a significant improvement in jump height and peak power.

Potentially, the use of WBLFV in between sets of resistance training rather than during resistance training itself may be

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useful for facilitating high-threshold motor unit recruitment (5–8,12–14,26,32,37). Also, there may be a preferential synchronization of these high-threshold motor units coupled with a maintenance of or possible facilitation of Type 1a afferent feedback from muscle spindles housed within the targeted musculature (5–8,32). Practically, this may result in greater adaptations in ISORFD and may be reflected in improved dynamic performance. Such an application of WBLFV between sets of resistance exercise is a novel concept and has not been extensively studied. Therefore, the purpose of this study was to test the efficacy of using WBLFV prior to and between sets, rather than during sets of Smith machine squats, on isometric force/time characteristics obtained during an isometric quarter squat.

METHODS

Experimental Approach to the Problem

This study used a longitudinal design where subjects were randomly assigned to either of 2 training groups: resistance training only (SQT, $n = 14$) or resistance training plus vibration (SQTV, $n = 14$) or a non-training control group (CG, $n = 8$). (Figures 1 and 2) Subjects were required to attend 2 familiarization sessions during which Smith machine back squats, MVC quarter squats, and whole body vibration exercises were performed. Over the 6-week training period, subjects were required to complete 12 Smith machine squat workouts with variable loads (55–90% 1RM) and sets (3–5). Testing sessions were carried out during weeks 1, 3, and 7 and consisted of MVC quarter squat and 1RM Smith machine squat measures. Subjects performed isometric quarter squats (knee joint angle 135 ± 5°) within a modified Smith machine and 2 Omega LCM101 K S Bean Loads Cells (Omega Engineering, INC, Stamford, CT, USA). Force was summed and averaged while being sampled at a 500 Hz analog to digital conversion rate. A total of 4 maximal trials were recorded following a standardized submaximal warm-up. Measures of isometric force and RFDs were recorded from the onset of contraction in select integrals up to 250 milliseconds using LabView software (LabView v 7.1; National Instruments, Austin, TX, USA).

Subjects

Thirty-six men between the ages of 18 and 30 years were informed of the experimental risks before completing a written informed consent form, which had been approved by the University of Oklahoma's Institutional Review Board concerning experimentation with human subjects. However, only 30 participants completed the entire protocol (SQT = 11, SQTV = 13, and CG = 6). The physical characteristics of the

Squat + Vibration Group (SQTV)

-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 – 4 mm) for 30 seconds.**
† Denotes vibration applied at frequency of 50Hz and high amplitude (4 – 6 mm) for 10 seconds.

Figure 1. Time line depicting WBLFV applied prior to and in between sets of Smith Machine Squats for the SQTV group.

Squat Only Group (SQT)

-210 s / (sit) /Squat/ 0….(sit)….60….(sit)....120….(sit)….180….(sit)….240s/Squat
↑ ↑ ↑ ↑ ↑
(V1‡) (180s) (V2‡) (V3‡) (V4‡)

‡Denotes no vibration applied

Figure 2. Time line depicting no WBLFV applied prior to and in between sets of Smith Machine Squats for the SQT group.

TABLE 1. Anthropometric data for all subjects ($n = 30$) by group.*

Group	CON ($n = 6$)	SQTV ($n = 13$)	SQT ($n = 11$)
Age (y)	22.8 ± 0.90	24.1 ± 0.87	23.2 ± 0.86
Height (cm)	177.67 ± 3.53	181.98 ± 1.89	179.27 ± 2.02
Weight (kg)	87.15 ± 5.81	83.83 ± 3.44	73.86 ± 2.27
BF (%)	15.15 ± 3.53	15.10 ± 1.41	15.65 ± 1.58

*Data expressed as mean ± *SD*. No significant group differences at week baseline (week 1). BF% = Body Fat percentage

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Table 2. Six-week periodized squat training protocol.*†

Week	Sets	Reps	%1RM load (W1–W2)	Adjusted volume
1	4	5	85–70	2 × 5 (W1)
2	3	4	88–75	
3	3	3	90–80	1 × 3 (W3)
4	3	5	85–70	
5	4	5	75–60‡	
6	4	6	65‡–55‡	

*W1 denotes adjusted volume due to 1RM assessment at beginning of week 1 during workout 1. W2 denotes adjusted volume due to 1RM assessment at beginning of week 3 during workout 1.

†Reps = repetitions.

‡Performed as speed squats.

subjects are presented in Table 1. The subjects' prior training status was assessed using a questionnaire, self-reported training experiences, and the Smith machine 1RM squat ability. The subjects were deemed to be recreationally resistance trained with at least 6 months of resistance training experience while not performing more than 3 workouts per week. Self-reported training histories as well as pre participation health screening and physical activity questionnaires were used to establish resistance training status. Sample sizes were adequate to attain a statistical power of at least 0.80 based on effect size (ES) (ES = postmeasurement mean − premeasurement mean/pooled standard deviation) calculated from a similar study (32).

Procedures

Six-Week Resistance Training Protocol. The periodized 6-week training program focused on strength development during the first 3 weeks and power development over the final 3 weeks (Table 2) based on previous studies (21,28,30,35). Smith machine back squat exercises were performed twice per week, each separated by 72 hours. Loading ranged from 55 to 90% of the subjects' predetermined 1RM between weeks 1 and 3 and from 55 to 85% 1RM during weeks 4–6. During weeks 4–6, the load was reduced to improve the potential for increased bar velocity and dynamic RFDs. Also, during the second sessions of weeks 4–6, subjects were instructed to perform "speed squats" by continuing the squat movement upward, rising up onto their toes using a strong contraction of the plantar flexor muscles. Subjects were verbally encouraged to push as forcefully as possible throughout the full range of motion of the Smith machine squat exercise. Four minutes of rest was allowed between sets.


[redacted]

Figure 3. Front view of Isometric squat test set up with heels positioned over marker 1, feet shoulder width apart and Knee joint angle standardized to 135° ± 5°.

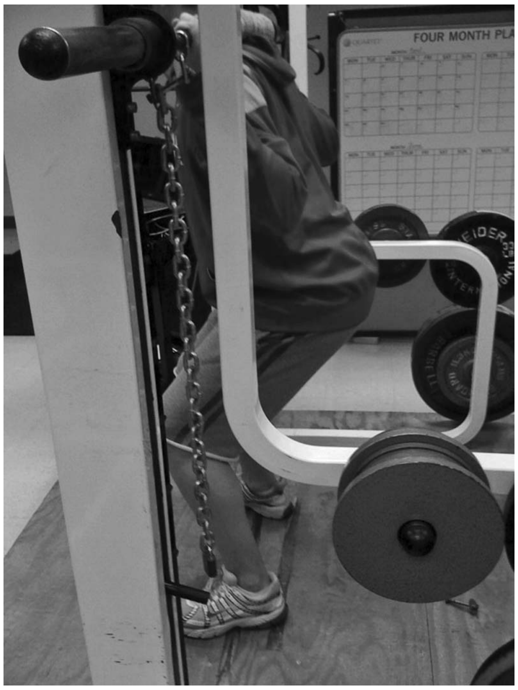

Figure 4. Side view of isometric squat test set up with heels positioned over marker 1, feet shoulder width apart and Knee joint angle standardized to 135° ± 5°.

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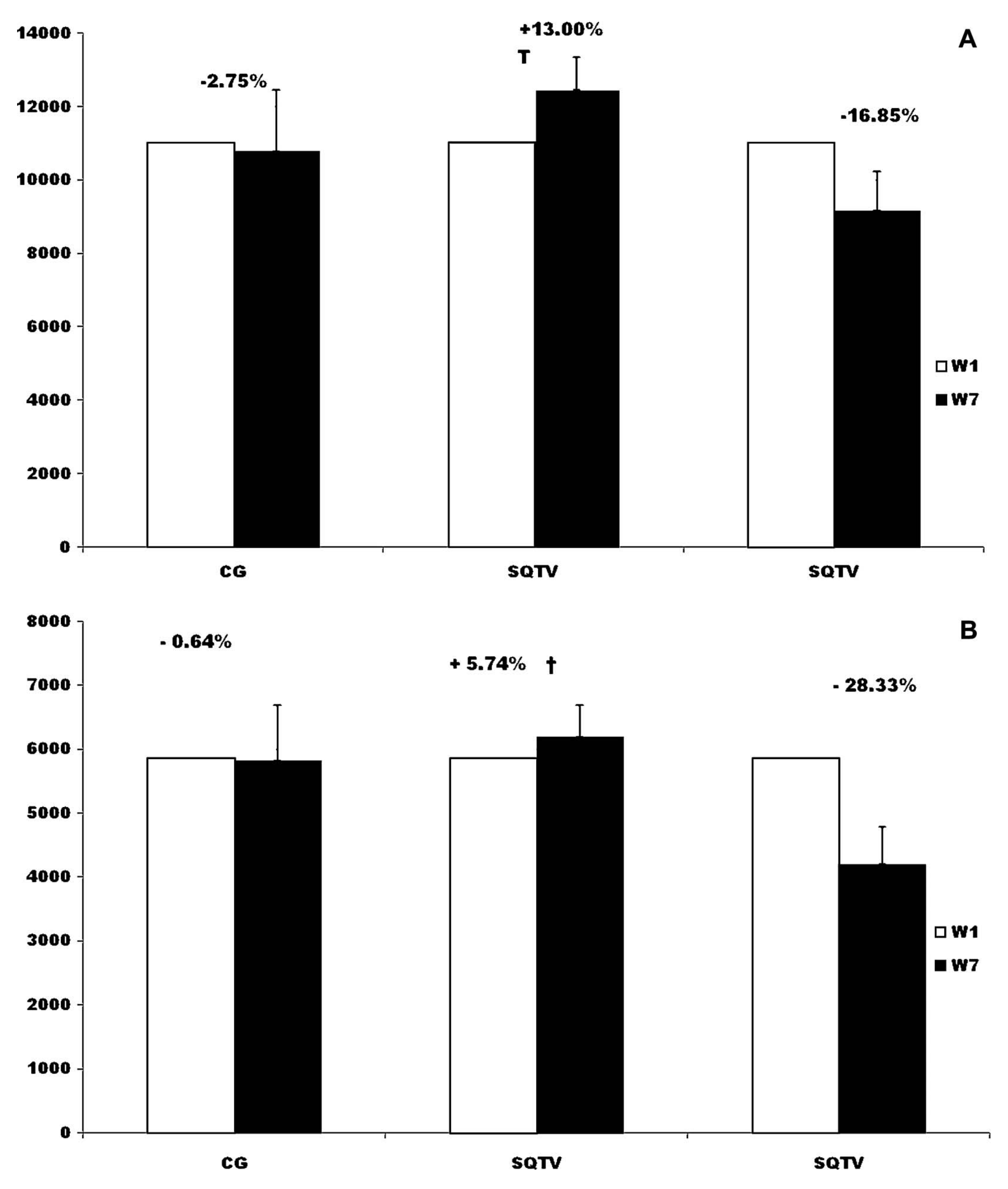

Figure 5. A) Within- and between-group measures recorded at week 1 (baseline) and week 7 (post training) for ISOPRFD ($N\cdot s^{-1}$) for CG, SQTV, and SQT. Covariate (week 1 ISOPRFD values) appearing in ANCOVA model at baseline as 11,004.52 $N\cdot s^{-1}$ ($p = 0.00$). T denotes trend toward significance ($p = 0.067$), SQTV > SQT (mean difference week 7, 3,284.80 $N\cdot s^{-1}$). B) Within- and between-group measures recorded at week 1 (baseline) and week 7 (post training) for isometric rate of force development at initial peak in force (ISORFDinitial, $N\cdot s^{-1}$) for CG, SQTV, and SQT. †Significant between-group difference ($p = 0.041$), SQTV > SQT (mean difference week 7, 1,994.22 $N\cdot s^{-1}$). Figures expressed as mean ± *SE*. ANCOVA = analysis of covariance; ISOPRFD = isometric peak rate of force development.

Isometric Quarter Squat Maximal Voluntary Contraction Test. The MVC quarter squat was performed on the first day of the week, 10 minutes prior to the start of the 1RM assessment. The MVC quarter squat was performed within a freestanding scaffold, which allowed for a bar to be moved to accommodate specific knee joint angles for each subject. The angle used for each subject was 135 ± 5° as peak force has previously been shown to be maximized during an isometric quarter squat at this angle (11,34,41). Subjects positioned themselves underneath the bar as if to perform a Smith

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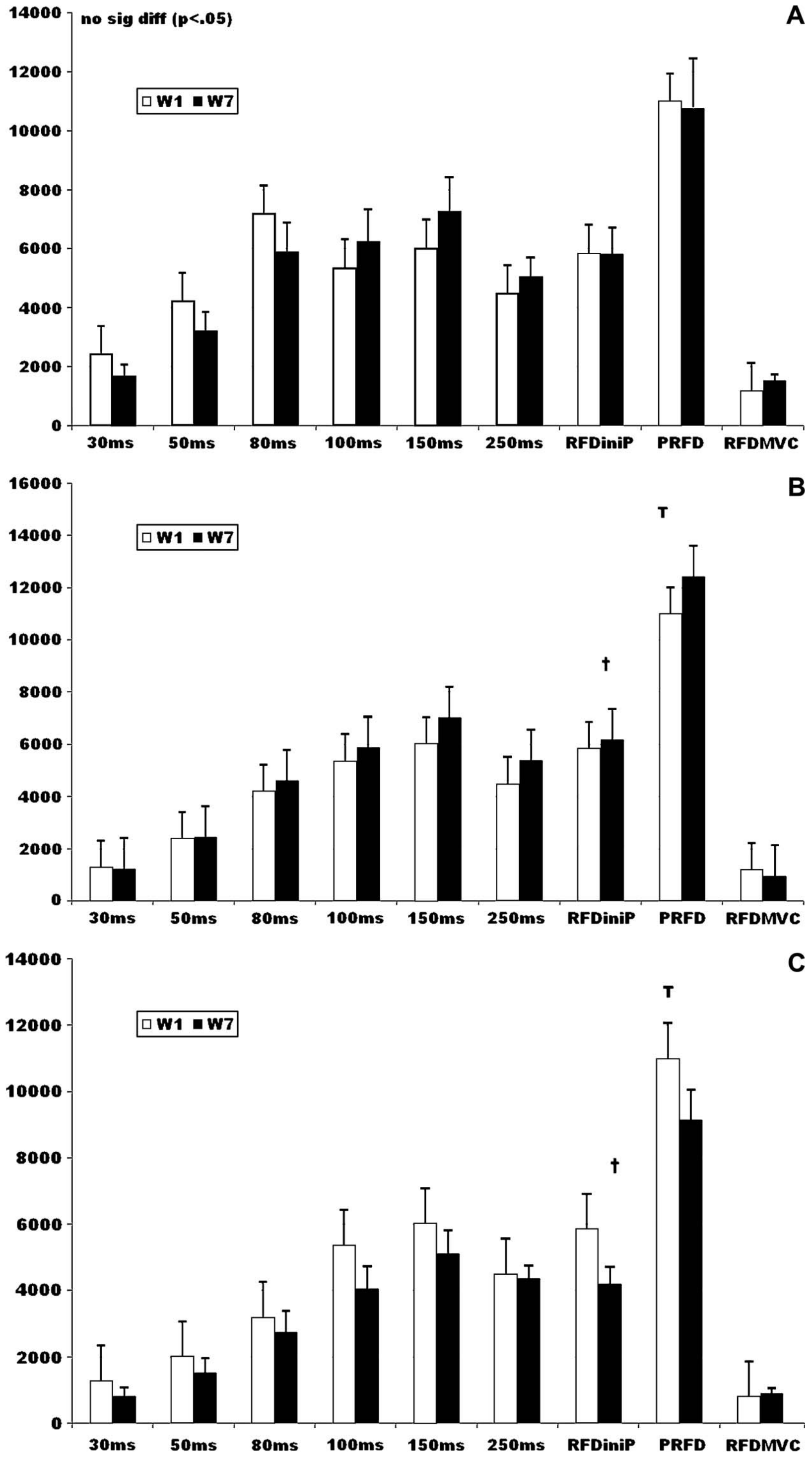

Figure 6. A) Control group (CG) isometric rates of force development (ISORFD, $N \cdot s^{-1}$) from the onset of contraction to MVC (MVC, N). No significant within-group differences ($p > 0.05$). B) Squat + vibration group (SQTV) isometric rates of force development (ISORFD, $N \cdot s^{-1}$) from the onset of contraction to MVC (N). †Significant between-group difference ($p = 0.041$), SQTV > SQT (mean difference week 7: 1,994.22 $N \cdot s^{-1}$). T denotes trend toward significance ($p = 0.067$) SQTV > SQT (mean difference week 7: 3,284.80 $N \cdot s^{-1}$). C) Squat-only group (SQT) isometric rates of force development (ISORFD, $N \cdot s^{-1}$) from the onset of contraction to MVC (N). †Significant between-group difference ($p = 0.041$), SQT ↓ SQTV (mean difference week 7: 1,994.22 $N \cdot s^{-1}$). T denotes trend toward significance ($p = 0.067$) SQT ↓ SQTV (mean difference week 7: 3,284.80 $N \cdot s^{-1}$). Figures expressed as mean ± *SE*. MVC = maximal voluntary contraction.

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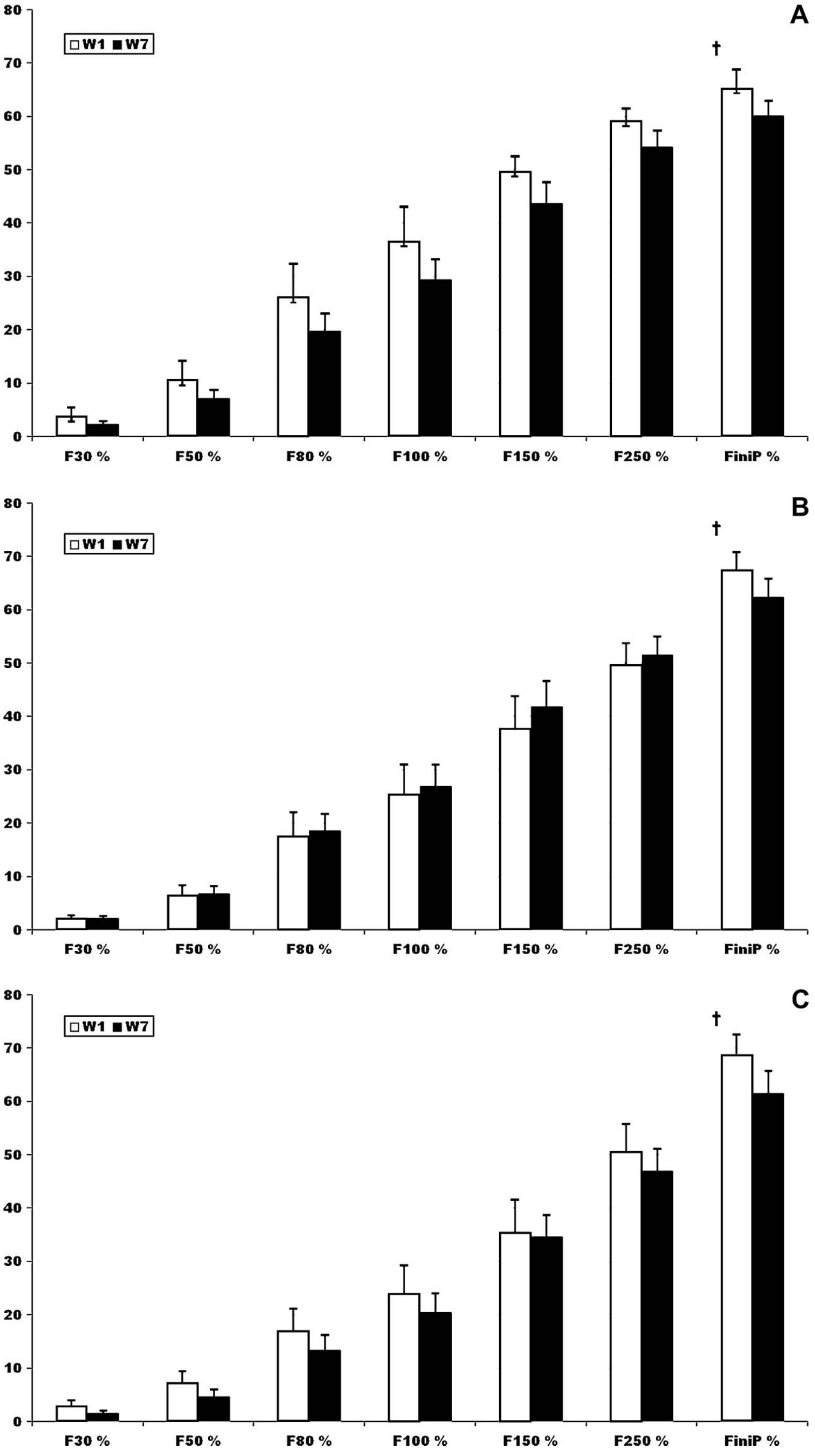

Figure 7. A) Force/time integrals expressed as a percentage of MVC (%) for the CG group. †Significant between-group difference at week 7. A significant main effect was seen for Finitial expressed as a percentage of MVC ($p = 0.015$, week 1 > week 7, mean difference 5.82%). B) Force/time integrals expressed as a percentage of MVC for the SQTV group. †Significant between-group difference at week 7. A significant main effect was seen for Finitial expressed as a percentage of MVC ($p = 0.015$, week 1 > week 7, mean difference 5.82%). C) Force/time integrals expressed as a percentage of MVC for the SQT group. †Significant between-group difference at week 7. A significant main effect was seen for Finitial expressed as a percentage of MVC ($p = 0.015$, week 1 > week 7, mean difference 5.82%). Figures expressed as mean ± *SE*. MVC = maximal voluntary contraction.

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machine back squat. The bar height was then adjusted so that knee angle could be set to 135° by way of handheld goniometer. Foot spacing was the same as that used during the Smith machine back squat so as to assess force/time characteristics, but the heels were positioned directly underneath the bar to allow for maximal force transmission upward against the bar. Once situated under the bar, subjects were given verbal instructions to "push as hard and as fast as possible" against the fixed bar for a duration of 3.5 seconds. A total of 4 trials were (Figures 3 and 4) performed with 90-second rest in-between attempts. The force signal (N) was low-pass filtered with a 10 Hz cutoff, zero-phase, fourth--order Butterworth filter. Measures of isometric force and isometric rate of force development (ISORFD) recorded from the onset of contraction to time integrals up to MVC were later analyzed using LabView software.

Force (N) and RFDs (N/s) were assessed from force/time curves produced within the LabView program. Time integrals taken from force/time curve included the peak isometric rate of force development (PISORFD), rate of force development at the initial peak in force (ISORFDinitial), and ISORFD between integrals: 0–30, 0–50, 0–80, 0–100, 0–150, and 0–250 milliseconds. Peak isometric rate of force development was derived from the force/time curve as a 50 data point sample taken from the steepest section of the curve (1). Rate of force development at the initial peak in force development (ISORFDinitial) was calculated from the onset of contraction up to the first apparent peak in force. The peak was determined to be the greatest force level achieved prior to a 10 N or more drop in force production. For all other time integrals, the average ISORFD was calculated between the onset of contraction and the respective time integral. Such time integrals were selected as they have been found to correlate with differing aspects of neuromuscular activation and athletic performance (1–3,18–20,29,31,36,38,41,44).

Table 3. Measurements of isometric force (N) and percent change (%Δ) between weeks 1 and 7.*†

Variable	Week 1	Week 7	% Δ
F30 (N)			
CG	76.48 ± 19.65	53.94 ± 13.08	−29.47
SQTV	41.39 ± 12.08	39.83 ± 7.07	−3.77
SQT	37.02 ± 11.86	24.73 ± 9.39	−33.20
F50 (N)			
CG	222.25 ± 41.69	170.76 ± 33.05	−23.17
SQTV	126.06 ± 34.69	131.41 ± 21.65	+4.24
SQT	99.64 ± 28.45	79.57 ± 26.32	−20.14
F80 (N)			
CG	580.62 ± 65.79‡	483.67 ± 60.39	−16.70
SQTV	339.02 ± 81.14‡	376.78 ± 55.29	+11.14
SQT	245.91 ± 62.52‡	224.56 ± 55.82	−8.70
F100 (N)			
CG	842.79 ± 67.96‡	726.78 ± 75.72	−13.76
SQTV	493.78 ± 105.94‡	562.14 ± 77.67	+13.84
SQT	352.56 ± 83.48‡	339.69 ± 66.95	−3.65
F150 (N)			
CG	1,224.64 ± 144.27‡	1,116.28 ± 149.98	−8.85
SQTV	749.90 ± 114.70‡	901.88 ± 109.44	+20.27
SQT	520.12 ± 102.77‡	565.58 ± 74.77	+8.74
F250 (N)			
CG	1,484.69 ± 198.84‡	1,401.13 ± 176.42	−5.63
SQTV	1,008.78 ± 71.46‡	1,131.28 ± 79.55	+12.14
SQT	714.97 ± 85.50‡	771.17 ± 85.14	+7.86
FINIP (N)			
CG	1,623.56 ± 217.12‡	1,561.28 ± 211.71	−3.84
SQTV	1,386.43 ± 86.10‡	1,380.06 ± 91.68	−0.5
SQT	976.94 ± 69.08‡	1,001.15 ± 61.93	+2.49
MVC (N)			
CG	2,533.52 ± 290.52‡	2,503.74 ± 268.37	−1.95
SQTV	2,103.77 ± 184.90‡	2,259.69 ± 215.86	+7.41
SQT	1,418.87 ± 74.34‡	1,611.98 ± 94.28	+13.61

*No significant within- or between-group differences found from weeks 1 to 7 ($p > 0.05$).
†MVC = maximal voluntary contraction.
‡Significant between-group differences at week 1.

Whole-Body Low-Frequency Vibration Application. Whole-body low-frequency vibration was applied using a Power Plate Next Generation vibrating platform (Power Plate USA). Its action is TriPlaner, but the majority of the vibration is vertical (Z-plane), making it quite distinct from the Galileo (Galileo Fitness, Stuttgart, Germany) and Nemes Bosco (Elite Sport Sciences, Athens, Greece) vibration platforms (43). Such a plate produces a sinusoidal waveform at a fixed frequency and amplitude dependent on settings selected. Other plates use pivot/wobble mechanisms using lower frequencies, but greater peak-peak amplitudes (43). The acceleration imparted upon the body is a result of the combination of the frequency (30, 35, 40, and 50 Hz) and amplitude ("low" 2–4 mm, "high" 4.1–6 mm, and peak-peak amplitude) used (43). While holding onto the handles, subjects stood on the platform in a quarter squat position

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with the feet shoulder width apart (similar to the Smith machine back squat position). A 50 Hz low-frequency vibration was applied for 30 seconds at an amplitude of 2–4 mm prior to the first set of the squat exercise. Three minutes of rest was allowed after the vibration, prior to the first set. The same frequency but a higher amplitude setting (4–6 mm, 5.83 G) was then applied intermittently for 10-second bouts at 60, 120, and 180 seconds into the rest periods between squat sets. When subjects were not receiving WBLFV, they were instructed to sit in a chair with their legs elevated upon a wooden box. The group not receiving vibration (SQT) sat down for the entire 4-minute rest period between squat sets.

Statistical Analyses

Statistical analyses were performed using SPSS for Windows (V.15.0, Chicago, IL, USA). Descriptive statistics were used to describe the physical attributes, and each parameter of interest is expressed as mean ± *SE*s. Each parameter that had multiple trials was subject to 1-way repeated measures analysis of variance (ANOVA) to produce the most stable representation for that parameter. No significant differences were seen between the 4 trials for any of the outcome measures, suggesting a high reproducibility between trials; therefore, the data were averaged. One-way ANOVAs assessed group differences at week 1 (baseline). If significant differences were found, analyses of covariance (ANCOVAs) were used, using the respective week 1 (baseline) measures as the covariate. Bonferroni pairwise comparisons were used as a post hoc analysis if significant differences over time were found ($p \leq 0.05$). A 2-way repeated measures ANOVA (group [3] × trial [2]) was then used with Bonferroni post hoc and correction factors. If significant interactions were found, the data would then be reanalyzed by group to highlight the nature of any group differences.

RESULTS

Tables 3 and 4 show measures of isometric force (Table 3) and isometric rates of force development (Table 4) percentage change (%Δ) between weeks 1 and 7 for the CG, SQTV, and SQT groups. A significant group {[3 (CG, SQTV, SQT)] × trial [2 (W1, W7)]} interaction was seen for ISORFD at initial peak in force (ISORFDinitial) with SQTV >CG ($p = 0.041$, mean difference 997.2 N·s^{-1}) and SQTV >SQT ($p = 0.041$, mean difference 1,994.22.11 N·s^{-1}) (Figure 6B). Significant trial × covariate interactions were seen for ISORFD from 0–100, 0–150, and 0–250 milliseconds; PISORFD; and ISORFDinitial ($p < 0.001$) (Figure 5A–C). A trend was seen

TABLE 4. Measures of ISORFD and percent change (% Δ) between weeks 1 and 7.*

Variable (N·s^{-1})	Week 1 ± *SE*	Week 7 ± *SE*	% Δ
RFD (0–30 ms)			
CG	2,410.59 ± 642.87	1,677.47 ± 419.68	−30.41
SQTV	1,292.40 ± 380.30	1,230.82 ± 221.36	−4.76
SQT	1,270.82 ± 421.99	806.09 ± 292.49	−36.57
RFD (0–50 ms)			
CG	4,227.45 ± 845.48	3,197.00 ± 664.68	−24.38
SQTV	2,386.58 ± 664.84	2,443.46 ± 411.47	+2.38
SQT	2,015.43 ± 592.19	1,512.69 ± 509.18	−24.95
RFD (0–80 ms)			
CG	7,191.85 ± 940.36	5,894.85 ± 843.55	−18.03
SQTV	4,200.23 ± 1,053.82†	4,606.78 ± 700.28	+9.68
SQT	3,183.31 ± 842.86†	2,755.27 ± 752.28	−13.45
RFD (0–100 ms)			
CG	8,765.64 ± 836.50†	7,448.87 ± 840.52	−15.03
SQTV	5,144.35 ± 1,178.07†	5,801.17 ± 829.30	+12.77
SQT	3,768.44 ± 943.88†	3,476.05 ± 783.91	−7.76
RFD (0–150 ms)			
CG	9,788.57 ± 899.80†	8,845.67 ± 1,085.39	−9.63
SQTV	5,889.45 ± 1,031.09†	6,976.96 ± 897.69	+18.47
SQT	4,136.04 ± 909.58†	4,321.46 ± 627.02	+4.48
RFD (0–250 ms)			
CG	6,821.43 ± 1,206.44†	6,424.52 ± 956.86	−5.82
SQTV	4,525.87 ± 310.65†	5,399.10 ± 475.41	+19.29
SQT	3,186.21 ± 467.44†	3,592.15 ± 366.34	+12.74
RFDINIP			
CG	9,253.70 ± 660.75†	7,111.21 ± 1,071.14	−23.15
SQTV	5,635.85 ± 693.60†	6,106.26 ± 533.51‡	+8.35
SQT	4,254.48 ± 744.38†	3,585.64 ± 475.77	−15.72
PRFD			
CG	17,373.43 ± 1,835.57†	13,952.37 ± 2,137.33	−19.69
SQTV	10,461.4 ± 1,008.79†	12,164.89 ± 979.93T	+16.28
SQT	8,172.45 ± 1,080.64†	7,739.53 ± 843.87T	−5.30
RFDMVC			
CG	1,178.50 ± 195.07	1,531.07 ± 361.14	+29.92
SQTV	1,197.70 ± 252.49	948.37 ± 65.10	−20.82
SQT	807.98 ± 122.58	899.71 ± 128.74	+11.35

*ISORFD = isometric rates of force development; RFD = rate of force development; PRFD = peak rate of force development.

†Significant between-group differences at week 1.

‡Significant group × time point interaction (SQTV > SQT: $p = 0.041$, mean difference 1,944.22 N·s^{-1}).

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favoring the addition of vibration for increased PISORFD for SQTV when compared with SQT ($p = 0.067$) (Figure 6A). No significant group × trial interaction or main effects for group or trial were seen for any of the force values from the onset of contraction up to MVC ($p \geq 0.05$). Significant differences were seen between groups at baseline for all force measures except between the onset of contraction to 50 milliseconds ($p < 0.05$). A significant main effect was seen for Finitial expressed as a percentage of MVC ($p = 0.015$, week 1 > week 7, mean difference 5.82%) (Figure 7A–C). No significant differences were seen for any other measures of force within or between groups between weeks 1 and 7 ($p > 0.05$).

Discussion

Pervious training studies varied from 4 to 24 weeks in length using a progressive overload or a periodized plan with varying loadings (2,10,21–23,26,28,30,32,35). Aagaard (1) reported significant increases in force/time integrals from the onset of contraction to 200 milliseconds following 14 weeks of variable load resistance exercise. The greatest percent increase was seen in the early (0–80 milliseconds) time phase. Significant increases were also reported in contractile impulse and signal amplitude and rate of EMG rise. The present study was of a shorter duration (6 weeks in length with 12 total workouts) and was periodized to emphasize maximal strength development (force production) during the first 3 weeks and then maximal power during the final 3 weeks. During the first 3 weeks, when heavier loads were used relative to 1RM measures (70–88% of 1RM), subjects were instructed to push as forcefully as possible against the bar in an attempt to maximize acceleration and dynamic RFDs against the heavy load (19,24,36–38,42).

Ronnestad (32) used a 5-week periodized Smith machine training protocol with and without WBLFV applied during squat exercise. The periodized program used was similar in length (5 vs. 6 weeks of training) as well as the total number of workouts performed per week (13 vs. 12 workouts). The present study differed primarily in the nature of vibration application (applied prior to and then in-between sets compared with vibration applied during the performance of the back squat exercise) using a higher frequency (50 vs. 40 Hz) and a different time course of application (three 10-second bouts during interset rest periods vs. continuous vibration exposure throughout the duration of each set of squat exercise). Although Ronnestad's (32) study did not measure RFDs during an isometric or dynamic task, the authors did see large nonsignificant increases in Smith machine back squat 1RM (32.4%) and CMVJ height (9.1%). Only the CMVJ percent increase was found to be significantly greater for the group receiving vibration. This suggests that the addition of vibration to the resistance training protocol afforded an additional neuromuscular training adaptation, which manifests as an added improvement in CMVJ height.

During the present study, measures of RFD taken during the early stages following the onset of contraction revealed interesting between-group differences. When performing the statistical analyses on measures of ISORFD 0–30 and 0–50 milliseconds, repeated measures ANOVAs were used as no significant group differences were found at baseline ($p > 0.05$). The remaining analysis performed on ISORFD 0–80, 0–100, 0–150, and 0–250 milliseconds; PISORFD; TPISORFD; and RFDinitial required repeated measures ANCOVA as significant differences were seen between groups at week 1 ($p < 0.05$). With this in mind, data for ISORFD from 50 milliseconds and upward were covariate weighted by the respective week 1 ISORFD values in an attempt to "normalize" baseline values between groups. Such normalization shifted the magnitude of the changes from week 1 to week 7 favoring the control group (going from reductions to improvements), while attenuating changes for the SQT group (further reducing changes).

Rate of force development between 0 and 30 milliseconds was found to be significantly reduced (−30.4%) at week 7 compared with week 1 for the control group ($p = 0.035$). No such differences were seen for the SQTV or SQT groups ($p > 0.050$). The SQTV group showed a nonsignificant ($p > 0.050$) 4.8% reduction in ISORFD at 30 milliseconds post contraction onset. This value was considerably less than the 36.6% reduction seen for the SQT group. Van Cutsem et al. (41) suggested that if the beginning tension is greater than 10% of the resultant MVC, then the RFD during the early time integrals is attenuated. Resting tension did not reach higher than 5.2% of the respective MVC value achieved for any of the groups for both of the testing time points, suggesting that this was not a factor. The small nonsignificant reduction in ISORFD 0–30 milliseconds for SQTV suggests that the addition of vibration helped maintain initial "starting strength" capability. Such a time integral holds practical significance as force produced, and the rate of force developed during the first 30 milliseconds following the onset of contraction correlates strongly to unweighted limb ballistic movements such as punching and kicking. The term "starting strength" has been coined to explain high initial motor unit firing rates at the onset of contraction that are facilitated by an increase in doublet discharge (1–3,12,16–19,21,24,29,36,38).

When comparing between-group measures for ISORFD 0–50 milliseconds, no significant differences were seen; however, a strong trend was seen favoring the SQTV group, which produced a small 2.4% improvement ($p = 0.070$). Both the CG and SQT groups exhibit similar percent decrements (−24.4 and −24.9%, respectively). The trend suggests that WBLFV facilitated early phase force/time characteristics, which could be viewed as an increase in starting strength. The trend continued between 0 and 80 milliseconds favoring the SQTV group, which was the only group that saw an actual improvement at week 7. Such a result would seem to favor the addition of WBLFV to the resistance training if a further preferential neuromuscular adaptation regarding

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early-phase RFD was desired. Looking at ISORFD 0–100 milliseconds, both the CG and SQTV groups saw improvement (+16.2 and +9.6%, respectively), whereas the SQT group saw a decrement between weeks 1 and 7 (−24.6%); however, there were no significant differences between groups, suggesting that there was a high degree of inter- and intrasubject variability. The use of ANCOVA instead of ANOVA due to week 1 differences in ISORFD 0–100 milliseconds favored the CG. Measures of ISORFD 0–150 milliseconds revealed improvements of 20.6 and 16.7%, respectively, for the CG and SQTV groups and a 15.1% reduction for the SQT condition.

Anderson and Aagaard (3) suggest that the ability to generate maximal isometric force correlates with forces generated at 90 milliseconds and later. Contractile properties such as the total amount of sarcomere's parallel to one another available to provide cross bridges, as well as optimal muscle length, may start to contribute increasingly more to force production following 90–100 milliseconds. Force development during the first 90 milliseconds of contraction may be more dependent on high initial motor unit firing rates, increased doublet discharge, and motor unit synchronization, as well as upregulated myosin light chain phosphorylation rates (1–3,16,20,27,29,36,38,41). The moderate nonsignificant increases seen for CG and SQTV groups compared to the moderate nonsignificant reduction in ISORFD 0-150 milliseconds for SQT suggests similar training back grounds for the former. The greater relative percent increases seen for the CG group appear to be in part a result of the covariate analysis correcting for between-group differences at week 1. The difference between the 3 groups changes somewhat when looking at ISORFD 0–250 milliseconds with a nominal change (−2.8%) seen for the SQT group and a moderate increase (+19.7%) for the SQTV group and 12.2% for the CG group. The overall trends seen favoring the addition of WBLFV during the first 250 milliseconds from the onset of contraction would suggest that such an application is more effective than resistance training alone in this particular population.

Aagaard et al. (2) reported that the greatest increases in ISORFD were seen between 0 and 50 milliseconds (23–26%) with a slightly smaller increase after 14 weeks of training between 100 and 200 milliseconds (17–20%). The nonsignificant reduction in the disparity from weeks 1 to 7 between SQTV and SQT groups for measures of ISORFD from 100 milliseconds onward suggests that resistance training alone produced its greatest adaptations between 100 and 250 milliseconds, which would be in agreement with Aagaard et al. (2).

Practically, if maximal strength is the main desired outcome, asynchronous firing of motor units appears to be more economical than stimulus-driven motor unit synchronization. The opposite would appear to be true if high RFDs over short time periods are required such as during punching or sprinting (1,2,9,15,18,20–24,28–30,33,36,38,44).

Measures of RFD from the onset of contraction to initial peak in force (ISORFDinitial) revealed significant between-group differences favoring the addition of WBLFV. Following ANCOVA adjustment (covariate week 1 RFD at initial peak values), SQTV values were significantly greater than SQT at week 7 ($p = 0.041$, mean difference 1,994.2 $\text{N}\cdot\text{s}^{-1}$). The time at which initial peak was achieved varied nonsignificantly at week 1 from 204.7 ± 61.6 milliseconds to 352.4 ± 41.8 milliseconds, which equated to an average value of 299.8 milliseconds across groups. This force/time variable was recorded and analyzed because it may represent an isometric measure of "explosive strength," that is, the ability to recruit and then maximize firing frequency of high-threshold motor units during the first initial explosive drive.

Analysis of PISORFD measures between groups produced no significant differences, although a strong trend was seen in favor of adding WBLFV ($p = 0.067$), with the SQTV group being the only condition to see a practical improvement (+13.0%) at week 7. The mean difference at week 7 between SQTV and SQT ($p = 0.072$) was 1,642.4 $\text{N}\cdot\text{s}^{-1}$, which equated to a 29.9% total difference (SQTV 13% increase and SQT 16.9% reduction). Also, of interest was the −10.5% reduction in the time of onset of PISORFD for the SQTV group, suggesting a trend favoring WBLFV application. A practical increase in the PISORFD coupled with an earlier onset of such a contractile phenomena would appear to be a preferential adaptation in "explosive strength" expression. At week 1, the time of onset of PISORFD for the SQTV group started at 144.8 milliseconds while at week 7 was 128.4 milliseconds, which equated to a 16.5-millisecond (−11.4%) reduction. It is possible that adding WBLFV to SQTV increased alpha motor neuron excitability and synchronization of high-threshold motor units prior to and then in-between sets of resistance exercise, leading to an increased neuromuscular training stimulus above resistance training alone. Practically, the ability to produce a combination of increased PISORFD at an earlier onset would allow an athlete to produce a similar impulse but at an earlier time point and over a shorter duration.

The analysis of force measures from weeks 1 to 7 expressed as a relative percentage of MVC (MVC = 100%) revealed a significant trial effect for Finitial (%), with week 1 measures greater than week 7 measures. Practical trends were seen for the SQT condition with regard to increased capacity to express force at integrals from the onset of contraction up to 250 milliseconds. The practical trend to "shift" the training-induced adaptation to earlier time integrals may be a result of the vibration stimulus facilitating reflex-induced motor unit discharge characteristics such as increased synchronization and doublet discharge prior to the resistance exercise (1,2,13,26).

In conclusion, it appears that the training adaptations seen for both experimental groups were of a similar magnitude when all components of force up to MVC were considered. The difference appears to be in how the neuromuscular adaptation was distributed with the addition of WBLFV

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seeming to favor the early force/time components over peak force expression (MVC). This would be a case of the macrostate (bigger picture, overall training adaptation) being directly related to the micromanipulation (addition of WBLFV with the intent to elicit an acute PAP state). Sale (33) suggested that a PAP stimulus can slightly reduce the resultant MVC (high frequency force expression) while preferentially improving the RFD and force generated at lower activation frequencies, resulting in a leftward shift in the force/time curve (7,15–20,23,24,29,30,33,36,38,41,44). High inter- and intrasubject variability may account in part for the moderate nonsignificant group differences for measures of PISORFD; however, significant improvements were seen in ISORFDinitial, indicating a preferential adaptation in "explosive strength" expression. Practical trends also favored the addition of WBLFV with regard to improved PISORFD and other earlier force/time characteristics.

Baseline ISORFD ability appeared to significantly affect the resultant training adaptation. Potentially, varying the vibration frequency, amplitude, exposure time, and time points of application prior to and then in-between sets of resistance exercise could lead to greater group delineation resulting in preferential adaptations. Also, different results may be seen between groups with longer (>8 weeks) training periods as well as greater subject numbers (>15) and equality of numbers between groups. The appropriate selection of amplitude, frequency, and duration, coupled with the athlete's background resistance training status and fatigue state, would all appear to be important factors to consider when designing a combined resistance and WBLFV protocol. More chronic combined resistance and WBLFV training studies are needed using male and female subjects of varying resistance training backgrounds in order to work out the appropriate "dose response" for such a combined training approach.

The type of WBLFV plate used would also appear to have an impact on its relative effectiveness as an ancillary aid to resistance exercise. Plates using pivot/wobble mechanisms or variable stochastic resonance could provide a different stimulus, so further studies are warranted comparing WBLFV mode of application (40,44).

PRACTICAL APPLICATIONS

Applying WBLFV between sets of exercise rather than during resistance exercise is a novel concept that can readily be used by strength and conditioning practitioners who have access to WBLFV platforms. The results from the present study suggest that there is some practical merit to applying WBLFV prior to and between sets of resistance exercise. The application of WBLFV between sets, rather than during sets of resistance exercise, may be more appropriate, potentially leading to a greater resultant acute neuromuscular stimulus and subsequent chronic adaptation at similar volume loads. For coaches wanting to use such a method with highly trained athletes, potentially using a variable "dose" with adjustments in frequency, amplitude, and period of application throughout a periodized resistance model may be based on knowledge of the athlete's background and training status. Also, holding off on vibration application between sets until force or power output drops below a predetermined level may be a practical approach to help preserve dynamic RFD while allowing for PAP typically seen between the first and second sets of resistance exercise. The use of a linear position transducer or modified accelerometer attached to a barbell may be a practical way of assessing fluctuations in force, power, and velocity to give the coach or researcher an objective means of monitoring PAP and fatigue during successive repetitions and sets of exercise.

The use of Olympic lifts (Snatch, Clean, and Jerk) and their derivatives (full snatch and clean pulls, as well as pulls from the low waist and mid thigh positions, respectively) in conjunction with WBLFV would appear to be the next logical area to study because such semiballistic lifts produce some of the highest dynamic RFDs and peak and mean power outputs of any total body movements.

ACKNOWLEDGMENTS

This project was funded by internal funds allocated by the College of Arts and Sciences at the University of Oklahoma. The results of the present study do not constitute endorsement of the Power Plate Next Generation whole body vibration platform by the authors or the National Strength and Condition Association.

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