HYPERTROPHY AND EXPLOSIVE-REACTIVE FUNCTIONING IN SEDENTARY MEN AFTER 10 WEEKS OF WHOLE-BODY VIBRATION

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ABSTRACT

Ebing, J, Gast, U, Hauptmann, C, Felsenberg, D, and Belavý, DL. Hypertrophy and explosive-reactive functioning in sedentary men after 10 weeks of whole-body vibration. *J Strength Cond Res* 32(1): 27–36, 2018—The objective of this study was to determine the impact of vertical (Power-plate; POW) and side-alternating (Galileo; GAL) whole-body vibration exercise on muscle mass and lower-limb neuromuscular function. Forty-three sedentary male subjects (18–30 year) randomized into 3 groups underwent 2 upper-body exercise sessions per week for 10 weeks. Two groups of subjects underwent additional squat exercises on the GAL ($N = 15$) or POW ($N = 14$) devices. The third group was control. On magnetic resonance imaging, volume of the thigh muscles was measured. Countermovement jump, multiple one-leg hopping, drop jump, landing test, 15-m sprint, and grip strength were performed. Measurements were performed at baseline, and at 5 and 10 weeks. Significantly greater increases in vasti volume were seen in the GAL (+4.15%; $p = 0.00076$ vs. control) and POW (+4.81%; $p = 0.0074$ vs. control) groups than in the control group (−1.22%) at 10 weeks. The adductor magnus volume increased in the GAL (+2.24%; $p = 0.00038$ vs. baseline) and POW (+2.33%; $p = 0.00038$ vs. baseline) groups at 10 weeks, but this was not significantly different from the control (−0.67%; $p = 0.54$ vs. baseline). Hamstring volume decreased in GAL (−1.85%; $p = 0.00038$ vs. baseline) at 5 weeks with the reduction in the POW group at 5 weeks (−1.73%; $p = 0.17$ vs. baseline) not reaching significance. There were no significant differences between the POW and GAL groups ($p \geq 0.084$) and no significant changes in neuromuscular performance. Twice weekly squat exercises with whole-body vibration, progressing from 3- to 5-minute time under tension, lead to thigh muscle hypertrophy but no improvements in explosive-reactive function.

KEY WORDS powerplate, Galileo, intervention, exercise

INTRODUCTION

Whole-body vibration (WBV) exercise is an exercise form where an individual receives a vibratory stimulus with the aim of increasing muscle contraction. It is thought to act via stretch reflexes (33). Prior interventional studies with WBV have shown improvements in muscle power (5,7,20,35), muscle force production (5,9,26,40,42), and jump performance (9,21,26,28,37,40). Beyond functional performance, WBV has also been shown to impact hormonal status (10), skin perfusion (32), patellar tendon size (31), flexibility (27), and bone mineral density (24). The most common implementation of WBV is performing exercises in the upright posture with the superimposed vibratory stimulus (20). Two different types of WBV currently exist for training in the upright posture: some devices apply vibration in a vertical direction (e.g., Power-plate; POW) and others in a left-right side-alternating manner (Galileo; GAL). There is some evidence that the 2 vibration forms might have differential effects on improving neuromuscular performance (20). Specifically, in collating data from 17 WBV studies with intervention periods ranging from 2 to 48 weeks, a recent meta-analysis (20) found vertical vibration (POW-type) to have a greater impact on muscle power than side-alternating (GAL-type) vibration. Another meta-analysis from the same researchers (19) found a greater effect of vertical vibration on muscular strength than side-alternating vibration. One aim of the current work was to perform a comparison between the POW and GAL forms of WBV on neuromuscular function.

Beyond improving function, muscle hypertrophy is a common goal for people engaging in fitness programs. There are 2 main mechanisms by which exercise is, in general, known

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Table 1. Training protocol.

	Training maneuvers			Group		
Exercises	Study weeks	Sets × duration per set	Rest period (s)	CON	POW*	GAL*
Vibration Exercise						
Dynamic squat†	1–4	3 × 60 s	60	–	✓	✓
	5–8	3 × 70 s	60	–	✓	✓
	9–12	3 × 80 s	60	–	✓	✓
	13–16	3 × 90 s	60	–	✓	✓
	17–20	3 × 100 s	60	–	✓	✓
Static squat‡	1–4	–	–	–	–	–
	5–8	–	–	–	–	–
	9–12	1 × 80 s	60	–	✓	✓
	13–16	1 × 90 s	60	–	✓	✓
	17–20	1 × 100 s	60	–	✓	✓
Upper-Body Circuit Training§						
Seated Bench Press	1–4	2 × 60 s (2 × 6 rep)	60	✓	✓	✓
Vertical Butterfly	5–8	2 × 70 s (2 × 7 rep)	60	✓	✓	✓
Lat Pull Down	9–12	2 × 80 s (2 × 8 rep)	60	✓	✓	✓
Military Press	13–16	2 × 90 s (2 × 9 rep)	60	✓	✓	✓
Bicep Curl	17–20	2 × 100 s (2 × 10 rep)	60	✓	✓	✓
Tricep Extension						

*Vibration frequency was set at 30 Hz with amplitude 4 mm in the Power-plate (POW) group and 24 Hz and 5 mm in the Galileo (GAL) group.

†Dynamic squat: dynamic squatting between 0° and 90° knee flexion. Four-second eccentric phase, 2-second isometric hold, 4-second concentric phase.

‡Static squat: isometric squat position in 90° knee flexion.

§Dynamic upper body circuit training: all exercises were performed in every treatment session. Four-second eccentric phase, 2-second isometric hold, 4-second concentric phase. Load was set at 70% of the 1 repetition maximum which was determined in the first training session and then maintained at this loading level for the remainder of the study. The number of repetitions was progressed.

to induce hypertrophy. One mechanism is mechanical, with microtrauma and subsequent healing to the individual muscle fibers (6). A second mechanism is via metabolic effects, with hypoxia of muscle tissue during exercise inducing muscle hypertrophy (12). Whole-body vibration could potentially influence both pathways, in part with additional force of contraction in the musculature during exercise and also greater energy consumption by the musculature (43). Two studies (5,36) have investigated the impact of WBV in combination with other exercises in comparison to a no-intervention control group on thigh muscle volume (5) and quadriceps muscle area (36), with both studies finding evidence of muscle hypertrophy. A third study (26) examined lumbar spine muscle size in comparing the additional effect of WBV in trunk muscle exercises. The authors of the third work (26) found a significant impact of adding WBV on psoas and erector spinae muscle size. In addition to investigating the impact of POW and GAL on measures of neuromuscular performance, we also aimed to investigate their impact on muscle hypertrophy.

A third issue is that manufacturers, such as those of the POW device (29) and GAL device (4), provide guidelines for how often people should train on the exercise to attain improvements. These guidelines suggest 2 exercise sessions per week of 10- to 20-minute WBV for a whole-body program. Most of the exercise protocols in prior WBV studies published in the literature had a higher training volume. It is important for strength and conditioning coaches, personal trainers, and people who aim to improve their physical performance to understand whether the implementation of exercise protocols suggested by WBV manufacturers indeed provides the promised benefit. Therefore, an additional aim of the current study was to implement the WBV manufacturer-recommended training guidelines. We implemented this in a 10-week intervention study and examined its impact on muscle size and neuromuscular function. Specifically, we focused intervention and measurement on the lower limbs.

We hypothesized that both WBV protocols would lead to hypertrophy in the thigh musculature and improvements in jump power and height. Untrained individuals have a relatively greater capacity for adaptation than trained individuals (1). This implies that a ceiling effect might exist for the response of already trained individuals to exercise. Therefore, we evaluated an untrained sedentary, but otherwise healthy, young male population. To improve compliance, reduce dropouts, and reduce the likelihood that people randomized to the control group would start exercise independent of the study, we implemented upper-body training in all subjects, including in the non-vibration control (CON) group.

Methods

Experimental Approach to the Problem

All subjects underwent an upper-body exercise program twice a week for 10 weeks. Subjects were randomized to a Galileo vibration exercise group (Mean +/− SD GAL; $n = 15$, age: 25.7 [3.0] years, height: 182.9 [5.2] cm, and weight: 81.5 [13.3] kg), a Power-plate vibration exercise group (POW; $n = 14$, age: 24.3 [4.0] years, height: 182.2 [7.7] cm, and weight: 85.7 [13.0] kg), or an upper-body-exercise-only control group (CON; $n = 14$, age: 24.9 [2.6] years, height: 182.1 [7.0] cm, and weight: 88.8 [18.8] kg). All outcome measures, with the exception of the 15-m sprint, were performed 3 times: (a) at baseline within a week of the first training session, (b) between 2 and 4 days after the 10th training session in week 5, and (c) within 3–7 days after the completion of the 10-week intervention period. The 15-m sprint was performed at baseline and at the end of the intervention period.

Subjects

Forty-three sedentary untrained male subjects aged between 18 and 30 years with no history of participation in any sport in the past year participated in the study. Exclusion criteria included any current bone, joint, tendon, or muscular disease; any balance impairments; any prior participation in competitive sport; performance of resistive exercise in the past 5 years; prior or current cardiac disease; acute venous thrombosis; and any of the following additional exclusion criteria for vibration exercise: history of gallstones or thrombosis, epilepsy, acute migraine episodes, or fresh or healing wounds in the lower limbs. The study was approved by the ethics committee of the Charité University Medical School Berlin. All subjects gave their informed written consent before participation in the study.

Procedures

Interventions. Two training sessions were performed per week. To improve subject compliance, all groups performed the same upper-body training program. Only the GAL and POW groups performed additional lower-body vibration exercise. All exercises were supervised by 1 of the 3 sport scientists involved in the study, and at least 2 of the 3 trainers were present during each training session.

The training protocol is presented in Table 1. All subjects performed the following upper-body exercises using gym equipment (Paramount Fitness, San Deigo, CA, USA): seated bench-press, vertical butterfly, pectoral curls, lat pull downs, military press, biceps curls, and triceps extensions. Attention was paid to ensure that the subjects did not fixate their legs in the machine and, in so doing, use any leg muscles to aid the maneuvers. At the first training session, a 6 repetition maximum (6RM) was performed and then the 1RM was estimated based on this (11). The load was then set at 70% of the 1RM, and the number of repetitions was progressed during the course of the study.

The GAL and POW groups performed additional lower body squat exercises on a WBV device (Table 1). Before the beginning of the study, approval of the training plan was obtained from the manufacturer Novotec Medical (Dr. Rawer, Novotec Medical, Pforzheim, Germany, personal communication) and the German advisor of Power Plate (Dr.Kleinöder, German Sports Unviersity Cologne, personal communication).

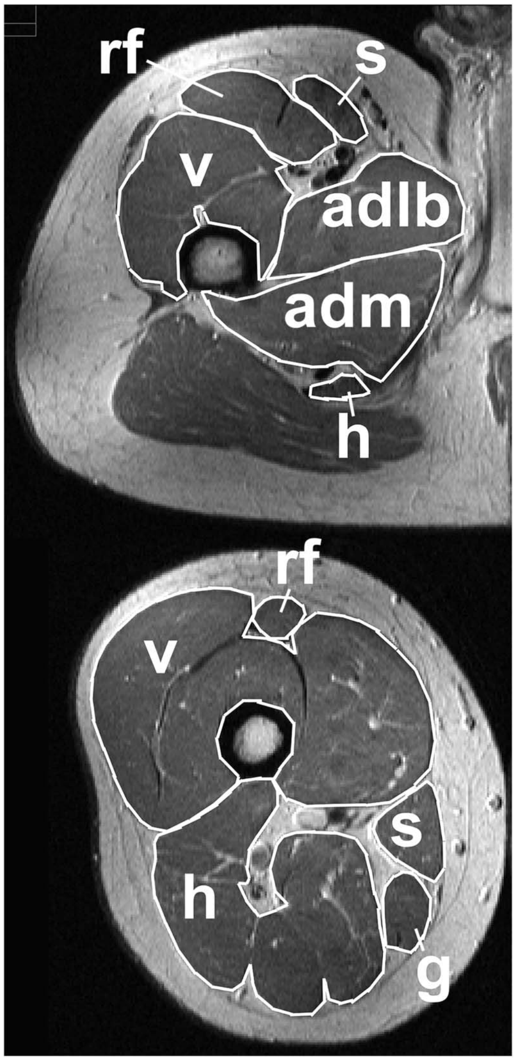

Figure 1. Muscle measurements on magnetic resonance images. Top: proximal thigh and bottom: distal thigh. v = vasti; rf = rectus femoris; s = sartiorius; g = gracilis; h = Hamstrings; adlb = adductor longus and brevis with pectineus; adm = adductor magnus with obturator externus and quadratus femoris.

Subjects performed squat exercises on the vibration platform; starting from full-knee extension, subjects squatted down to 90° knee flexion whilst maintaining their lower legs as vertically as possible (Table 1). Three sets of dynamic squats were performed. In trained athletes, performing 1 or 2 sets can be sufficient as such individuals are familiar with achieving full muscle exhaustion with exercise. However, in sedentary individuals, it is recommended (2) to implement additional sets to ensure that

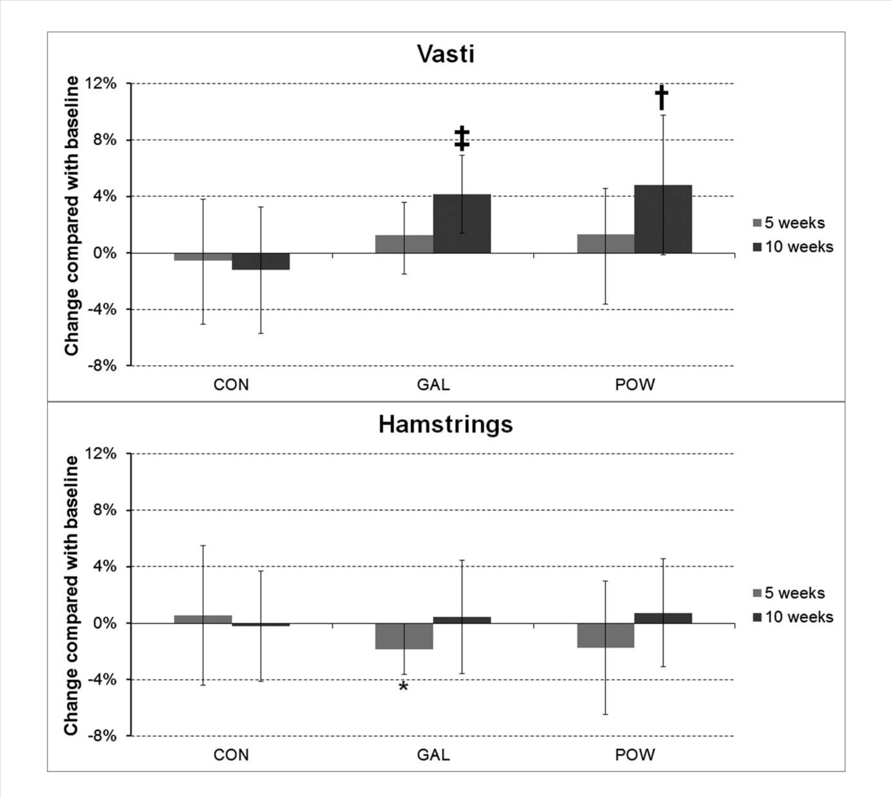

Figure 2. Change in vasti and hamstring volume. Values are mean (*SD*) percentage change compared with baseline. *$p \le 0.05$; †$p < 0.01$; ‡$p < 0.001$; they indicate significance of within-group difference compared with baseline. CON = control group; GAL = Galileo (side-alternating) vibration exercise group; POW = Power-plate (vertical) vibration exercise group. POW and GAL differed significantly to CON for the vasti only.

muscular exhaustion is achieved. Sixty seconds of exercise duration for dynamic squats was chosen to achieve exhaustion in these sedentary individuals and was progressed to 100 seconds per set in later weeks of the study. From week 9, static squats were added to ensure that the exercise protocol continued to achieve muscular exhaustion.

In the GAL group, a Galileo 2000 (Novotec Medical, Pforzheim, Germany) was used and set to a side-alternating vibration frequency of 24 Hz and peak-to-peak amplitude of 8 mm (acceleration of the vibrating plate $\approx 9.3g$; $g = 9.81$ m·s^{-2}). In the POW group, a Power Plate professional (Next Generation; Power Plate GmbH, Frankfurt am Main, Germany) was used and set to a vertical vibration frequency of 30 Hz, peak-to-peak amplitude of 4 mm ($7.2g$). On both devices, the feet were positioned 49 cm apart. Vibration settings remained the same during the 10-week intervention period. The vibration settings for the POW (30 Hz, 4 mm) and GAL (24 Hz, 5 mm) groups were chosen as these were, given the parameters suggested by the manufacturer, those that lay the closest.

Magnetic Resonance Imaging. Transverse magnetic resonance (MR) images were acquired from the thigh using a 1.5-Tesla Magnetom Vision system (Siemens, Erlangen, Germany). Fifty images of the thigh from the greater trochanter to the proximal tibial plateau (slice thickness: 5 mm, interslice distance: 5 mm, repetition time: 6,000 millisecond, echo time: 15 millisecond, field of view 450 × 450 mm interpolated to 512 × 512 pixels) were acquired. Images were then stored for offline analysis. To blind the operator to group and study date, each data set was coded using a random number (obtained from www.random.org). The operator used ImageJ (version 1.49n, http://rsb.info.nih.gov/ij/) to measure the area of the muscles of the lower limb in every image on the right side of the body (Figure 1). The following muscles were measured: vasti, rectus femoris, sartorius, gracilis, hamstrings, adductor longus and brevis with pectineus, and adductor magnus with obturator externus and quadratus femoris. The volume of each muscle was then calculated via linear interpolation, given the slice thickness of 5 mm and interslice gap of 5 mm, from the individual area measurements. Using data from our previous work (23), we calculated that the reproducibility of the vasti muscle volume measurements was very good showing a between-day correlation of 0.950.

Lower-Limb Neuromuscular Tests on a Ground Reaction Force Platform. A series of neuromuscular tests were performed on a 60 × 60-cm ground reaction force platform (Leonardo Mechanograph GRFP; Novotec GmbH, Pforzheim, Germany). The software provided by the manufacturer (Leonardo Mechanography v4.2) was used for recording and storage of data and for subsequent calculation of the variables of interest. All neuromuscular tests occurred on the same day along with the grip-force measurements and were performed by the same operator.

Countermovement Jump Testing. Subjects were instructed to perform a countermovement (i.e., a brief squat beforehand) jump as high as possible. Subjects first stood on the testing platform with their arms resting at their sides. Three jumps were performed during each testing session with a break of 1 minute between each jump. The same verbal

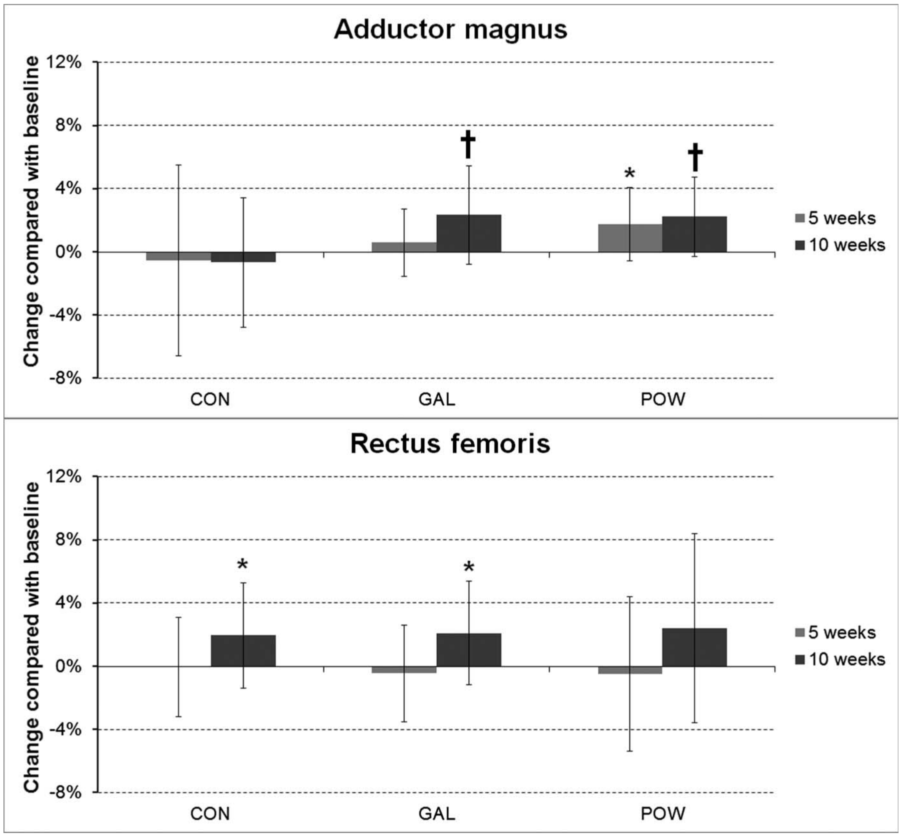

Figure 3. Adductor magnus (with obturator externus and quadratus femoris) and rectus femoris volume changes. Values are mean (*SD*) percentage change compared with baseline. *$p \leq 0.05$; †$p < 0.01$; ‡$p < 0.001$; they indicate significance of within-group difference compared with baseline. CON = control group; GAL = Galileo (side-alternating) vibration exercise group; POW = Power-plate (vertical) vibration exercise group. No significant between group differences.

encouragement was given for every jump by the same operator. Before the first jump, the subject's body mass was measured for use in subsequent calculations. The data from the jump of maximal jump height from all 3 trials were used in further analysis. Countermovement jump height and peak power per unit body weight were used in further analysis. The reproducibility of countermovement jump power in adult and elderly subjects is excellent (22), with data from our own laboratory showing that 24 sedentary men tested 4 days apart as part of an earlier work (15) showed a between-day correlation of 0.943 for countermovement jump power.

Multiple One-Leg Hopping. The subject was required to perform 10 continuous single leg hops whilst maintaining their knee close to full extension, and no arm swing was permitted. The aim of this test is to examine storage of elastic energy in the musculotendinous system and peak force development at the ankle joint. Subjects were instructed to keep their heel off the ground for all hops. Verbal encouragement was given for every test. Each leg was tested twice with a break of 1 minute between test runs. Using the same software as per the countermovement jump test, peak hop force was calculated and expressed relative to the body mass. The single hop of the greatest force from the 2 sets of 10 consecutive hops on each leg was chosen for further analysis. The peak force per unit body mass was used in further analysis. The reproducibility of multiple one-legged hopping parameters has been shown to be excellent with a between-day coefficient of variation of <3% (22).

Drop Jump. The subject was instructed to let themselves drop down from a 45-cm high platform onto the ground reaction force platform and then jump up as quickly as possible. The subject landed on the force platform. Three drop jumps were performed with a break of 1 minute between repetitions. As the focus of this test was for the subject to jump back off the force plate as quickly as possible, the drop jump with the shortest contact time (41) was chosen for further analysis. Contact time on the force plate was used in further analysis.

Landing Test. The subject was instructed to jump from a platform at a height of 45 cm and land as quietly and

TABLE 2. Change in medial thigh adductor and iliopsoas volume.*†

	Study-day		
Group	Baseline	5 wk (%)	10 wk (%)
Iiopsoas (cm^3)			
CON	76.0 (10.6)	0.3 (12.8)	−2.7 (6.7)
GAL	69.3 (14.9)	−3.2 (9.4)	3.2 (9.7)
POW	79.0 (16.8)	0.3 (12.0)	1.4 (12.5)
Adductor longus and brevis with pectineus (cm^3)			
CON	263.6 (50.9)	−0.3 (4.7)	−1.4 (4.9)
GAL	247.4 (45.6)	−1.3 (2.9)	0.1 (3.9)
POW	263.7 (41.6)	−0.5 (3.3)	1.6 (5.5)
Sartorius (cm^3)			
CON	123.8 (30.2)	0.9 (4.8)	−0.5 (4.6)
GAL	119.2 (28.4)	−1.2 (2.8)	0.2 (2.9)
POW	135.6 (35.1)	−0.7 (6.4)	0.7 (4.1)
Gracilis (cm^3)			
CON	76.1 (14.7)	−0.2 (5.5)	−1.0 (3.5)
GAL	73.6 (17.7)	−0.6 (2.3)	0.3 (3.5)
POW	83.3 (22.4)	−0.4 (6.3)	0.6 (5.2)

*Values are mean (*SD*). Values at baseline are in the units given next to each parameter name. No significant differences between or within groups.

†CON = control group; GAL = Galileo (side-alternating) vibration exercise group; POW = Power-plate (vertical) vibration exercise group.

softly as possible on the ground reaction force platform. This test aimed to assess the coordination and ability to absorb energy within the neuromuscular system with minimal peak ground reaction forces. The test was performed twice. As the focus of this test was for the subject to absorb and minimize the landing forces, the landing of the lowest peak force per unit body weight was used in further analysis.

Sprints and Grip Force

Fifteen-Meter Sprint. Sprint tests were performed indoors in a multifunction sports hall. The subject started from a marked position 2 m ahead of the first infrared detector (TC Timing System; Brower Timing Systems, Salt Lake City, UT, USA) and then passed through a second intrared detector 15 m further ahead. The subject performed 3 sprints at each testing session with 2-minute breaks in-between sprints. The quickest sprint was used in further analysis. The same operator conducted all sprint tests.

Maximal Grip Force Testing. Maximal grip force testing was examined as a within-subject control, as no change was expected in this parameter. The test was conducted in standing using a digital hand dynamometer (Takei Scientific Instruments Co. Ltd., Tokyo, Japan) and the same operator supervised the conduct of this test. The shoulder was placed in an adducted and neutrally rotated position with the elbow at 90° flexion, the forearm in neutral supination-pronation position, and the wrist to 20° of extension. Three repetitions were performed on the subject's dominant and nondominant hands with a 30-second break between tests. The peak grip strength value from both hands was used in further analysis.

Statistical Analyses

Linear mixed-effects models, with subsequent analysis of variance (ANOVA), were used to examine whether the groups differed in their response during the course of the study. The main effects of "group" ("GAL," "POW," and "CON") and "study-date" ("Baseline," "5 weeks," and "10 weeks") were examined as well as their interaction. Allowances for heterogeneity of variance (e.g., due to "group" and/or study-date") were made when necessary. Where the group × date interaction was significant, subsequent secondary 2-group (i.e., GAL vs. CON, POW vs. CON, and GAL vs. POW) linear mixed-effects models were built using the same approach to examine which group differed. Analysis was performed on an intent-to-treat (ITT) approach. An ITT analysis approach, with the reporting of differences in findings on "per protocol" analysis, is appropriate in interventional studies to ensure that treatment effects are not unjustly overestimated (38). A priori t-tests within each group compared with baseline were also performed. An alpha-level of 0.05 was taken for statistical significance. The normality of distribution of the residuals was confirmed by the Kolmogorov-Smirnov test. The "nlme" package was used for linear mixed-effects modeling in the "R" statistical environment (version 3.0.2; www.r-project.org). Unless otherwise specified, results are presented as mean (*SD*).

RESULTS

There were no significant baseline differences between the groups. All subjects completed all training sessions as planned. Two subjects (1 each in the GAL and POW groups) did not complete the multiple one-leg hop test on their left (non-dominant) leg at baseline and one subject (GAL group) could not complete the landing test at week 5.

Muscle Volume

The volume of the vasti muscles was increased at 10 weeks in both training groups (GAL: $p = 0.00001$, +4.15%; POW: $p = 0.0018$, +4.81%) with no change in the control (Figure 2). The differences between the groups on 3-group ANOVA were significant ($p = 0.0044$), with both GAL ($p = 0.00077$) and POW ($p = 0.0074$) differing from CON on subsequent 2-group ANOVA. The adductor magnus with quadratus femoris and obturator externus (Figure 3) increased in volume in the POW group at 5 weeks ($p = 0.010$, +1.76%) and 10 weeks

TABLE 3. No impact of vibration exercise on neuromuscular performance.*

	Study-day		
Group	Baseline	5 wk (%)	10 wk (%)
Countermovement jump height (m)			
CON	0.54 (0.10)	10.5 (41.5)	0.6 (29.1)
GAL	0.47 (0.06)	6.7 (15.4)	3.3 (18.0)
POW	0.51 (0.07)	8.4 (14.5)	−2.1 (9.4)
Countermovement jump power ($W \cdot kg^{-1}$)			
CON	49.4 (5.5)	1.2 (8.7)	2.1 (7.0)
GAL	47.0 (6.8)	0.4 (9.9)	3.1 (7.1)
POW	50.3 (6.4)	0.2 (4.0)	2.5 (5.0)
Multiple one-leg hop force ($N \cdot kg^{-1}$)			
CON	36.2 (6.3)	−0.3 (7.3)	−3.8 (9.5)
GAL	35.7 (6.4)	−3.7 (15.2)	−1.1 (11.3)
POW	34.1 (4.2)	−1.9 (10.9)	−3.8 (10.4)
Drop jump contact time (s)			
CON	3.7 (0.3)	−3.8 (5.7)†	0.2 (6.0)
GAL	3.6 (0.3)	−2.4 (8.4)	−0.7 (8.8)
POW	3.5 (0.3)	0.7 (6.6)	3.5 (6.6)
Landing test force ($N \cdot kg^{-1}$)			
CON	28.5 (3.4)	−4.9 (14.2)	−2.0 (14.3)
GAL	27.3 (3.8)	−0.8 (11.9)	−3.2 (13.4)
POW	29.7 (5.2)	−5.6 (12.8)	−9.8 (21.6)
Fastest 15-m sprint (s)			
CON	2.56 (0.16)		−0.7 (2.9)
GAL	2.55 (0.17)		0.2 (2.1)
POW	2.46 (0.13)		0.5 (2.1)
Grip strength (kg)			
CON	51.1 (7.4)	0.8 (8.9)	0.8 (9.0)
GAL	52.6 (9.9)	−1.0 (8.4)	0.6 (9.1)
POW	50.9 (5.6)	0.5 (7.2)	0.9 (7.3)

*Values are mean (*SD*). Values at baseline are in the units given next to each parameter name. No significant differences were seen between groups on analysis of variance.

†$p \leq 0.05$.

($p = 0.003$, +2.24%) and was also hypertrophied in the GAL group at 10 weeks ($p = 0.0083$, +2.33%), but there was no significant difference to CON with ANOVA ($p \geq 0.099$). Rectus femoris (Figure 3) volume increased in the GAL group at 10 weeks ($p = 0.023$, +2.09%) and in the CON group at 10 weeks ($p = 0.043$, 1.96%), with the change in the POW group not being significant ($p = 0.15$, +2.41%), and there was no significant difference between groups with ANOVA. Hamstring (Figure 2) volume was decreased at 5 weeks in the GAL group ($p = 0.00038$, −1.85%), with the change in the POW group being nonsignificant (−1.73%, $p = 0.18$), and the reduction was no longer apparent at 10 weeks. Changes in hamstring muscle volume did not differ significantly between groups on ANOVA ($p = 0.35$). In the remaining muscles (gracilis, sartious, adductor longus and brevis with pectineus, iliopsoas; Table 2), no significant changes in volume were seen during the course of the study.

Neuromuscular Performance

No significant change in the neuromuscular performance tests (countermovement jump height and power per unit body mass, multiple one-leg hopping force per unit body mass, drop jump contact time, landing test peak force per unit body weight, sprint time, grip force; Table 3) was seen in the training groups during the course of the study. In the control group, there was a reduction in contact time during the drop jump test at 5 weeks ($p = 0.014$, −3.85%), but there was no significant difference between groups.

DISCUSSION

The current study implemented WBV device manufacturer guidelines for WBV exercise and investigated its impact on thigh muscle mass and neuromuscular function. The 2 vibration exercise groups achieved hypertrophy of the vasti muscles, and this was significantly different from the control. Hypertrophy of the adductor magnus muscle group was seen in both side-alternating (GAL) and vertical vibration (POW) exercise groups, but this was not significantly different from the control. The hamstring muscle volume was reduced in the GAL group at 5 weeks. No significant improvements in neuromuscular function parameters were seen.

A number of prior studies have provided evidence for how WBV might impact neuromuscular performance and coordination. Whole-body vibration may impact local muscle fatigue and increase force of muscle contraction during exercise and hence present a greater hypertrophic stimulus. For example, increased perfusion (18) is thought to occur due to WBV. Increased activity of muscle spindles (34) occurs during vibratory stimuli applied directly to the musculature, which is considered to stimulate greater muscle activity via enhanced stretch reflexes (33). Coordination may also be improved due to WBV by improved proprioception (14).

Despite this, we observed no impact of the WBV protocols on the explosive-reactive functional and coordination measures. This was despite having 3 dedicated sport scientists conducting each training session to ensure a high level of compliance and correct technique. The finding contrasts with a number of prior studies which did see improvements in neuromuscular performance, with improvements in countermovement jump (9,21,26,28,37,40) and peak muscle power (5,7,20,35). Whole-body vibration squat exercises in the current study were progressed from 3-minute time under tension at the start of the 10-week intervention twice a week to 4-minute 40-second time under tension by the end of the study. This training volume is, although in line with the recommendations made by manufacturers, at the lower end of training volumes seen in previous studies. Hence, we believe that no impact of either WBV protocol on peak neuromuscular performance (countermovement jump, multiple one-leg hop, drop jumps, and 15-m sprints) or coordination (landing-test) was observed because of insufficient exercise time. Thus, the findings from the current study help to define the lower limits for WBV exercise intervention time in ambulatory studies and design exercise protocols for sedentary people.

We did, however, see evidence of muscle hypertrophy. Specifically, increases in the volume of the vasti and adductor magnus were seen in both WBV groups, although only the increases in vasti volume were significantly different from the control group. Squat and leg-press (i.e., combined hip and knee concentric extension/eccentric flexion) type of exercises strongly recruit the vasti muscles, whereas the biarticular rectus femoris is less strongly recruited (13,30,39). The adductor magnus is nominally grouped with other adductor muscles but has an "extensor portion" originating at the ischial tuberosity which is innervated by the sciatic nerve and an "adductor portion" innervated by the obturator nerve (3). In lower vertebrates, this "extensor portion" is actually a separate "presemimembranosus" muscle grouped with the hamstring muscles (16), whereas in human embryos, these 2 sections of the adductor magnus muscle develop separately and later fuse (3). Accordingly, in combined hip and knee extension tasks, the adductor magnus shows stronger recruitment than, for example, the adductor longus (13,30,39). This helps to explain our findings of hypertrophy in the adductor magnus muscle.

There is some evidence from an ambulant study that WBV can have an additive effect, on top of other exercises, on trunk muscle size changes (26). However, 2 other studies in spaceflight simulation (strict bed rest) (23,43) did not find an additive effect of WBV in preventing muscle atrophy during prolonged bed rest. High load resistive exercises are recommended (2) for achieving muscle hypertrophy. Nonetheless, it is interesting that the current exercise protocol, involving such low volume and relatively low load exercise, led to muscle hypertrophy in the thigh. Performing squat exercises with WBV until exhaustion will result in hypoxia of muscle tissue and hence as a stimulus (12) for hypertrophy. Anecdotally, our previously sedentary subjects did report delayed onset of muscle soreness in the earlier weeks of the study. Damage to muscle fibers due to mechanical overload will have also provided a stimulus (6) for muscle hypertrophy.

In the current study, we saw reductions in the volume of the hamstring muscles at 5 weeks in the WBV groups, and this was significant in the GAL group only. A reduction was seen in the POW group, but this did not reach significance. This effect was no longer apparent at 10 weeks. We consider this effect unlikely to be due to the squat exercise maneuver per se, as the hamstrings, in particular semimembranosus and biceps femoris long head, are still activated in squat and leg-press type of exercises as hip extensors (25); rather, we consider the effect more likely to be a consequence of neuronal reciprocal inhibition. In a study of WBV in prolonged bed rest, other groups (43) have noticed some evidence that antagonist muscle groups showed greater atrophy when WBV was applied. Specifically, Zange et al. (43) performed a static squat exercise with and without WBV and found significantly greater atrophy of the hamstring muscles during bed rest when WBV was added. One mechanism by which WBV is thought to work is via stretch reflexes (33). In a squat exercise, any facilitation of muscle contraction should in particular affect the agonists (i.e., knee and hip extensors). As part of the stretch reflex, reciprocal inhibition of antagonist muscles occurs (8). Thus, it is quite possible that the WBV stimulus during squat exercise led to the reduction of activation of the hamstrings muscles and hence to an initial atrophic response.

Increase in the volume of the rectus femoris muscle was seen in all groups (Figure 3). This suggests systemic effect of study participation rather than an impact of WBV per se on this muscle. This may have been a result of the neuromuscular testing protocol which involved explosive and ballistic exercise. Ballistic exercise is thought (17) to in particular require activity in multijoint muscles, such as the rectus femoris.

It is appropriate to consider some of the limitations of the current study. We examined sedentary but otherwise healthy young men, as we reasoned (1) that this population would be more likely to show an adaptive response than, for example, already trained individuals. The results of the study cannot, however, be generalized to other age groups or to women. We did not examine isometric muscle force, and this may have provided additional information on the impact of vibration. The acceleration loads in the POW ($9.2g$) and GAL ($7.2g$) groups differed. The vibration settings for the POW (30 Hz, 4 mm) and GAL (24 Hz, 5 mm) groups were chosen as these were, given the parameters suggested by the manufacturers, those that lay the closest. Since we did not, for logistical and financial reasons, have a fourth group performing squat exercises only without vibration, we cannot definitively say for the muscle hypertrophy observed, what contribution was due to WBV versus the squat exercises alone. The calf muscles were not imaged since these are not prime movers in squat exercises and also for scanning cost limitations. Also, the number of subjects enrolled in the current project was approximately in the middle range in comparison with other WBV studies published to date. Having more subjects enrolled may have improved chances of detecting statistically significant changes. However, we argue that if an effect is not detectable with otherwise reliable measures in a relatively small subject pool, then the clinical significance of any such effect size would need to be considered critically depending on the needs and goals of the individual being trained.

In conclusion, we observed hypertrophy of the knee (vasti) and hip (adductor magnus) extensor muscles due to the side-alternating (Galileo device) and vertical (Powerplate device) WBV exercise protocols. However, no improvements in peak neuromuscular performance (countermovement jump, multiple one-leg hop, drop jumps, and 15-m sprints) and coordination (landing test) were seen due to the WBV exercise protocols. These findings suggest that WBV exercise protocols as suggested by the device manufacturers were insufficient to attain improvements in neuromuscular performance in otherwise healthy sedentary men. These findings help to define lower limits for WBV exercise for attaining improvements in explosive-reactive neuromuscular performance. Finally, we did not find evidence for differences between WBV type (vertical versus side-alternating) on muscle hypertrophy.

Practical Applications

In sedentary but otherwise healthy men, WBV squat exercises performed twice a week with a training volume progressing from 3- to 5-minute time under tension per exercise session led to hypertrophy of the knee extensors after 10 weeks and hip extensors after 5 weeks. The WBV protocol, however, did not lead to improvements in explosive-reactive neuromuscular function and coordination. Given prior studies showing improvements in explosive power and strength due to WBV, greater WBV training volume is necessary to improve functional outcomes.

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