Strength Increase after Whole-Body Vibration Compared with Resistance Training

CHRISTOPHE DELECLUSE[1], MACHTELD ROELANTS[1], and SABINE VERSCHUEREN[2]

[1]Exercise Physiology and Biomechanics Laboratory, and [2]Laboratory of Motor Control, Faculty of Physical Education and Physiotherapy, Department of Kinesiology, Katholieke Universiteit Leuven, Leuven, BELGIUM

ABSTRACT

DELECLUSE, C., M. ROELANTS, and S. VERSCHUEREN. Strength Increase after Whole-Body Vibration Compared with Resistance Training. *Med. Sci. Sports Exerc.*, Vol. 35, No. 6, pp. 1033–1041, 2003. **Purpose:** The aim of this study was to investigate and to compare the effect of a 12-wk period of whole-body vibration training and resistance training on human knee-extensor strength. **Methods:** Sixty-seven untrained females (21.4 ± 1.8 yr) participated in the study. The whole-body vibration group (WBV, $N = 18$) and the placebo group (PL, $N = 19$) performed static and dynamic knee-extensor exercises on a vibration platform. The acceleration of the vibration platform was between 2.28 g and 5.09 g, whereas only 0.4 g for the PL condition. Vibration (35–40 Hz) resulted in increased EMG activity, but the EMG signal remained unchanged in the PL condition. The resistance-training group (RES, $N = 18$) trained knee extensors by dynamic leg-press and leg-extension exercises (10–20 RM). All training groups exercised 3× wk^{-1}. The control group (CO, $N = 12$) did not participate in any training. Pre- and postisometric, dynamic, and ballistic knee-extensor strength were measured by means of a motor-driven dynamometer. Explosive strength was determined by means of a counter-movement jump. **Results:** Isometric and dynamic knee-extensor strength increased significantly ($P < 0.001$) in both the WBV group (16.6 ± 10.8%; 9.0 ± 3.2%) and the RES group (14.4 ± 5.3%; 7.0 ± 6.2%), respectively, whereas the PL and CO group showed no significant ($P > 0.05$) increase. Counter-movement jump height enhanced significantly ($P < 0.001$) in the WBV group (7.6 ± 4.3%) only. There was no effect of any of the interventions on maximal speed of movement, as measured by means of ballistic tests. **Conclusions:** WBV, and the reflexive muscle contraction it provokes, has the potential to induce strength gain in knee extensors of previously untrained females to the same extent as resistance training at moderate intensity. It was clearly shown that strength increases after WBV training are not attributable to a placebo effect. **Key Words:** MUSCLE STRENGTH, TONIC VIBRATION REFLEX, COUNTER-MOVEMENT JUMP, STRENGTH TRAINING

Whole-body vibration (WBV) is a neuromuscular training method that has recently been developed. In WBV training, the subject stands on a platform that generates vertical sinusoidal vibration at a frequency between 35 and 40 Hz. These mechanical stimuli are transmitted to the body where they stimulate in turn sensory receptors, most likely muscle spindles. This leads to the activation of the alpha-motoneurons and initiates muscle contractions comparable to the earlier described "tonic vibration reflex" (6,11,15). Initially, WBV training was used in elite athletes to improve speed-strength performance. More recently, it is becoming tremendously popular in European health and fitness clubs as an alternative training method.

However, there is still a lack of scientific support about the benefits of WBV on fitness and health. Bosco et al. (3,5) found an increase in force-velocity, force-power and vertical-jump performance immediately after one WBV session. A placebo controlled study showed that a single bout of WBV transiently improves isometric strength of the knee extensors and vertical-jump performance by 3.2% and 2.5%, respectively (22). These effects were recorded 2 min after the intervention but disappeared in the next 60 min.

Some studies analyzed the effect of WBV training on muscle performance over a longer period. Bosco et al. (2) reported the effect of a 10-d training program of a daily series (5 × 90 s) of vertical sinusoidal vibrations at a frequency of 26 Hz. They found a significant improvement of the height and mechanical power during the 5-s continuous-jumping test. It was suggested that WBV training finally might result in neuromuscular adaptations similar to the effect produced by explosive strength training. However, 10 d of training is too short to determine the long-term effects of WBV. Runge et al. (20) showed gains of 18% in chair-rising time in elderly persons after 12 wk WBV training (27 Hz). Recently, Torvinen et al. (23) reported a significant increase in jump performance (8.5%) and a nonsignificant increase in isometric limb extension strength (2.5%) after a 4-month WBV intervention (25–30 Hz) in young nonathletic adults. As none of these long-term studies were placebo controlled, it is impossible to determine whether the training effect on strength and jump performance resulted from the exercises that were performed on the platform or

---

Address for correspondence: Christophe Delecluse, Ph.D., Faculty of Physical Education and Physiotherapy, Tervuursevest 101, 3001 Leuven, Belgium; E-mail: christophe.delecluse@flok.kuleuven.ac.be.
Submitted for publication October 2002.
Accepted for publication January 2003.

0195-9131/03/3506-1033
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/01.MSS.0000069752.96438.B0

from the vibration induced muscle activation. Additionally, there are no studies available to compare the effect of WBV and resistance training on muscle strength.

This is the first long-term study to differentiate between the effects resulting from the exercises performed on the platform with vibration and without vibration (placebo) and to compare the effects of WBV training and resistance training by means of weight machines at moderate intensity. Therefore, the changes in isometric, dynamic, ballistic knee-extensor strength, and counter-movement jump (CMJ) height were analyzed in young female adults after a 12-wk training period.

As WBV elicits a high degree of muscle activation, it was hypothesized that WBV would result in strength increase in previously untrained persons. These strength increases should be significantly larger than the training effects resulting from an identical exercise program performed in absence of vibration (placebo condition). As the tonic vibration reflex facilitates the activation of high-threshold motor units and the reflex sensitivity (1,18), WBV training may be more efficient to improve ballistic strength and jump performance compared with resistance training at moderate intensity.

METHODS

Experimental Approach to the Problem

A four group prepost design was used in this study to determine whether a 12-wk period of WBV-training (3 times/wk) would result in a considerable increase in knee-extensor strength, and whether WBV training, compared with moderate resistance training, would be more efficient to improve ballistic and explosive strength in previously untrained subjects. The four groups included a WBV group, a resistance-training group, a control group, and a placebo group. This latter group was added to determine whether the expected training effect in the WBV group resulted from the exercises that are performed on the platform or from the vibration induced muscle activity. Isometric strength, dynamic strength, and ballistic strength of the knee extensors were measured in pre- and post-test conditions. Explosive strength was measured by means of a CMJ.

Subjects and Study Design

A group of 74 young female adults (age 21.5 ± 1.9 yr; body mass 61.6 ± 9.1 kg; height 165.3 ± 10.3 cm) volunteered to participate in the study. None of them were engaged in regular organized physical activities nor in sports or strength training. Reasons for exclusion were pregnancy, acute hernia, and any history of severe musculoskeletal problems. Subjects with a history of diabetes or epilepsy were also excluded from the study. All subjects were informed about the training and test protocol and about the possible risks and benefits of the study. They all gave written informed consent to participate. This study was approved by the University's Human Ethics Committee according to the declaration of Helsinki.

TABLE 1. Training volume and training intensity of the WBV program.

	Start	End
Volume		
Total duration of vibration in one session (min)	3	20
Series of one exercise (*N*)	1	3
Different knee-extensor exercises (*N*)	2	6
Longest duration of vibration loading without rest (s)	30	60
Intensity		
Rest period between exercises (s)	60	5
Vibration amplitude (mm)	2.5	5
Vibration frequency (Hz)	35	40

The status of each variable is described at the start and at the end of the 12-wk training period.

Power analysis revealed that a sample size of 17 subjects in the experimental groups was necessary to achieve a power of 0.80 with $\alpha = 0.05$. In anticipation of inevitable dropout, it was decided to select a minimum of 20 subjects in the experimental groups.

All subjects were randomly assigned to one of three interventions: the whole-body vibration (WBV, $N = 20$), the placebo vibration (PL, $N = 21$), the resistance training (RES, $N = 20$), or a control group (CO, $N = 13$). All intervention programs consisted of 36 training sessions within a 12-wk period. Training frequency was three times a week with at least 1 d of rest between two sessions. The control group did not participate in any training program.

WBV and PL Conditions

The subjects of the WBV group and the PL group performed static and dynamic knee-extensor exercises on the vibration platform: squat, deep squat, wide-stance squat, one-legged squat, and lunge. At the moment, there are no scientific-based, long-term WBV-training programs available. Therefore, we developed a 12-wk WBV program with a low training load at the beginning but slowly progressive according to the overload principle. The training volume increased systematically over the 12-wk training period by increasing the duration of one vibration session, the number of series of one exercise, or the number of different exercises. The training intensity was increased by: shortening the rest periods or by increasing the amplitude (2.5–5 mm) and/or the frequency (35–40 Hz) of the vibration (Table 1).

The vibration platform (Power Plate®) produced vertical sinusoidal vibrations at a frequency between 35 and 40 Hz. The peak-to-peak amplitude of the vibration was 2.5 mm at low amplitude and 5 mm at high amplitude. The acceleration of the platform as recorded by means of an accelerometer (Monitran, MTN 1800) varied between 2.28 *g* and 5.09 *g* (Table 2). In the PL condition, the subjects, standing on the platform, could hear the motor and experienced tingles on their foot soles, but the acceleration of the platform was only 0.4 *g* (Table 2) with a negligible amplitude. Bipolar surface EMG (Noraxon Myosystem 2000), recorded from m. rectus femoris and from m. gastrocnemius, illustrates the difference between the impact of the WBV condition and the PL condition on muscle activity. Standing in the squat posture on the platform during WBV leads to an

TABLE 2. Maximal acceleration (g) on the WBV platform at low (2.5 mm) and high (5 mm) peak to peak amplitude and on the PL platform (amplitude negligible).

AMP	FREQ	WBV Platform	PL Platform
Low	35 Hz	2.28	0.38
	40 Hz	2.71	0.37
High	35 Hz	3.91	0.41
	40 Hz	5.09	0.40

g is the Earth's gravitational field or 9.81 $m\cdot s^{-2}$.
AMP is the vibration amplitude.
FREQ is the vibration frequency.

increase in muscle activity for the m. rectus femoris and the m. gastrocnemius, whereas the PL condition did not (Fig. 1).

During all of the vibration-training sessions, the subjects wore the same gymnastic shoes to standardize the damping of the vibration due to the footwear. The subjects were asked to report possible side effects or adverse reactions in their training diary. Every 3 wk, exercise supervisors performed an inquiry into the attitude and the satisfaction of the subjects in both groups. As the WBV group and the PL group exercised in different rooms and at different moments, they could not compare both conditions, and they could not share their training experiences. Exercise specialists closely supervised all training sessions of all intervention groups.

Resistance Training

The RES group trained in the university fitness center. After a standardized warming-up consisting of 20-min stepping, running, or cycling, they performed a moderate resistance-training program for knee extensors on a leg-press and a leg-extension apparatus (Technogym®). The resistance-training program was slowly progressive, similar to the WBV program, starting at a low threshold of 20 RM in the first 2 wk. The training load was first increased to 15 RM in the next 3 wk, followed by another 3-wk period at 12 RM. Subjects trained at 10 RM during the last 4 wk. Leg press and leg extension exercises were executed systematically to fatigue failure with the objective to perform the prescribed number of repetitions. The starting load was determined by an exercise specialist at the first training session. During the whole training period, subjects were observed, and they were instructed to increase the resistance systematically in the after set or in the following session if they were able to perform the current workload for two or more repetitions over the prescribed number (14). The subjects performed two sets of repetitions on each apparatus with at least 1 min of rest in between.

Tests

The contractile properties of the knee extensors were evaluated at the start (pretest) of the study and after 12 wk of training (posttest). All subjects participated in a standardized warm-up and test protocol on a motor-driven dynamometer (REV9000, Technogym®), consisting of isometric tests, dynamic tests, and ballistic tests for the knee extensors. In addition, all subjects performed a vertical CMJ. The subjects were asked to perform all these tests at maximal intensity. During a standardized warm-up, the subjects exercised the different types of contractions to experience all test conditions before testing. Posttests were performed at least 72 h after the last training session to avoid any acute effect of training sessions on test results.

Dynamometry. The isometric, dynamic, and ballistic tests were performed unilateral on the right side, in a seated position on a backward inclined (15°) chair. The upper leg, the hips, and the shoulders were stabilized with safety belts. The rotational axis of the dynamometer was aligned with the transverse knee-joint axis and connected to the distal end of the tibia by means of a length-adjustable rigid lever arm. The alignment of the dynamometer was systematically controlled by inspecting the position of the lever arm with respect to anatomical reference points during passive movements. The three-dimensional positions of the rotational axis, the position of the chair, and the length of the lever arm were identical in pre- and post-test condition.

Isometric strength (ISO). The subjects performed twice a maximal voluntary isometric contraction of the knee extensors. The knee joint angle was 130°. The isometric contractions lasted 3 s each and were separated by a 2-min rest interval. The highest torque (N·m) was recorded as isometric strength performance. The intraclass correlation coefficient (ICC) for test-retest reliability of isometric strength, recorded in a comparable group of untrained females, was 0.93.

Dynamic strength (DYN). The subjects performed a series of four consecutive isokinetic flexion-extension movements against the lever arm of the dynamometer that moved at a velocity of $100°\cdot s^{-1}$. The knee extension was initiated at a joint angle of 90° and ended at 160°. After each extension, the leg was returned passively to the starting position from which the next contraction was immediately initiated. Maximal dynamic strength was determined as the peak torque (N·m) recorded during these series of knee extensions. The ICC for test-retest reliability of dynamic strength, recorded in a comparable group of untrained females, was 0.98.

Ballistic strength (BAL). The subjects performed four ballistic tests for the knee extensors. They were asked to extend the lower leg at the highest possible speed from a knee-joint angle of 90° to an angle of 160°. This exercise was performed once without external resistance on the lever arm (0%), followed by three identical tests with a controlled resistance on the lever arm. Hereby the degree of resistance was individually determined at a percentage of the isometric maximum in the knee angle from where the movement was initiated (90°). The ballistic tests were performed with a resistance of 20%, 40%, and 60% of this isometric maximum. At each test, the maximal velocity of the lever arm ($°\cdot s^{-1}$) was recorded to determine ballistic strength. The ICC for test-retest reliability of the maximal velocity during ballistic tests, recorded in a comparable group of untrained females, varied between 0.87 and 0.96, dependent on the resistance.

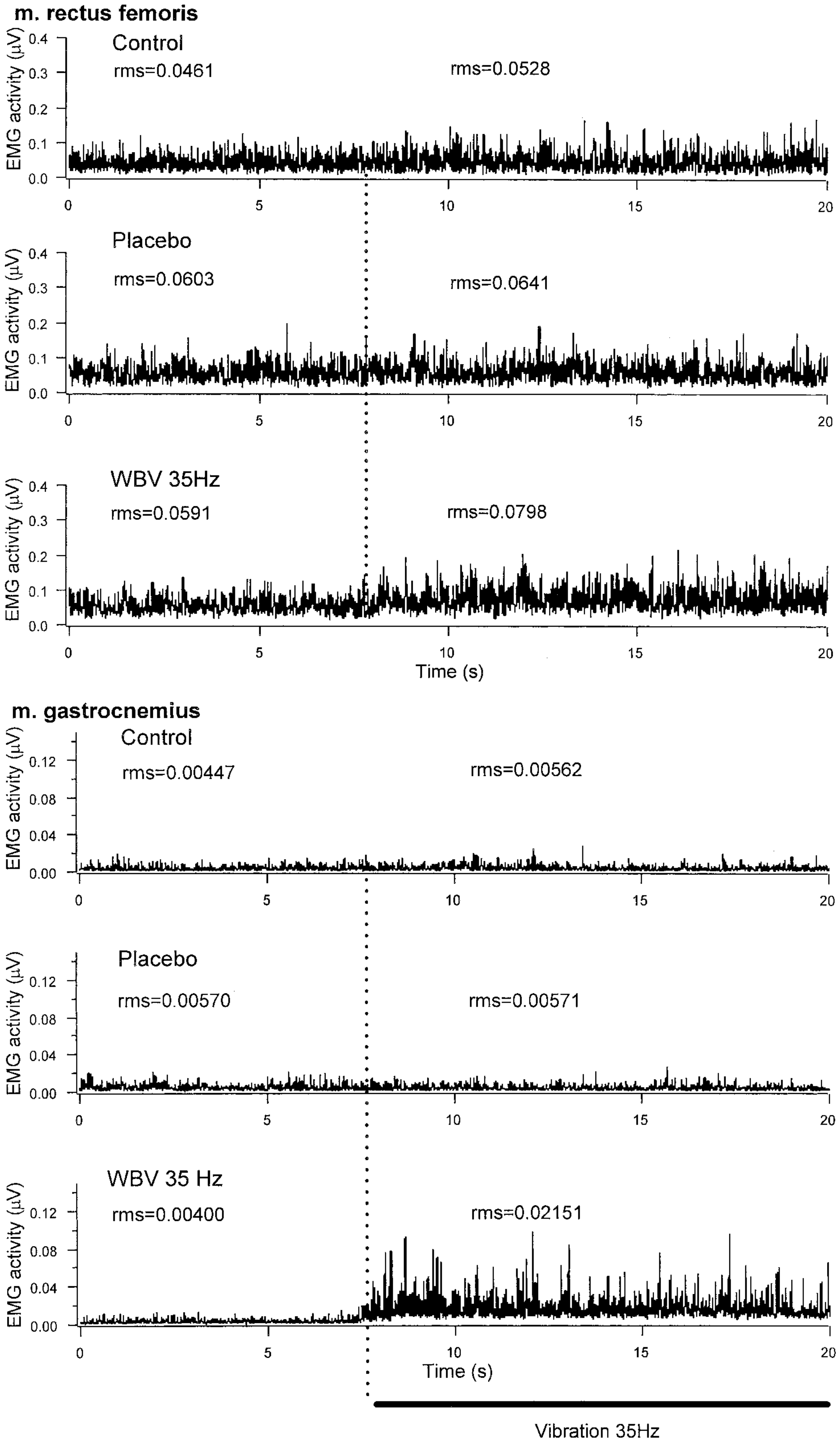


FIGURE 1—Root means square (RMS) EMG activity (mV) in the m. rectus femoris (top) and in the m. gastrocnemius (bottom) recorded in static half squat position. The preamplified signal (gain 80 dB) was bandpass filtered (15–10,000 Hz) before sampling at 2000 Hz. RMS-EMG activity was calculated of the rectified EMG signal for a period of 10 s prior vibration, during vibration, and after vibration at 35 Hz with a vertical peak to peak amplitude of 5 mm.

Explosive strength. A vertical CMJ with hands positioned in the waist was used to assess the lower-limb explosive performance capacity (4) after stretch shortening of the muscles. This test was performed on a contact mat, recording the flight time in milliseconds. The obtained flight time (t) is further used to determine the increase in the center of gravity (h), i.e., $h = gt^2/8$, where $g = 9.81\ m \cdot s^{-2}$. The best of three trials was recorded to determine the test score. The ICC for test-retest reliability of CMJ performance, recorded in a comparable group of untrained females, was 0.99.

TABLE 3. Physical characteristics of the subjects in the different groups.

	RES (N = 18) Mean ± SD	WBV (N = 18) Mean ± SD	PL (N = 19) Mean ± SD	CO (N = 12) Mean ± SD	P Value
Age (yr)	21.4 ± 2.1	21.5 ± 2.1	22.2 ± 1.4	20.6 ± 1.7	0.106
Body mass (kg)	58.1 ± 6.9	63.5 ± 8.4	62.1 ± 9.5	63.3 ± 11.8	0.380
Height (cm)	165.2 ± 6.3	167.5 ± 4.8	165.3 ± 7.2	162.1 ± 20.8	0.443

Values are mean ± SD.
P value: results of one-way ANOVA between group means.

Statistical Analysis

The effect of the different interventions on strength parameters was analyzed by means of ANOVA for repeated measures [4 (group) × 2 (time)] (GLM) using the least square method (LS means). After an overall F-value was found to be significant, preplanned contrast analyses were performed to evaluate the significance of effects (prepost, between groups). A Bonferroni correction was used to adjust the P-value in relation to the number of contrasts that were performed. All analyses were executed using the statistical package Statistica, version 6 (Statsoft, Inc.). Significance level was set on $P < 0.05$.

RESULTS

Training experiences, compliance, and drop-out. In the WBV and PL groups, subjects acquainted very rapidly the exercise protocol. There were no reports of adverse side effects. Most subjects experienced the vibration loading (WBV group) as enjoyable and fatiguing, but they did not consider it as a hard workout. The supervising staff reported no doubts, concerning the training modalities, in the PL group. All of these subjects (PL) felt confident that they were participating in a real WBV program. During the first weeks of the study, seven subjects dropped out: two subjects of each training group (RES, WBV, and PL), respectively, and one subject of the CO group. All of these drop-outs were related to an incompatibility of the test/training program and other commitments (e.g. work, studies, etc.) of the subjects. All remaining subjects of the training groups (WBV, PL, and RES) performed 36 training sessions. Some subjects needed one extra week to complete all sessions, as they missed up to three sessions during the 12-wk period. The characteristics of the 67 subjects that completed all pre and post tests are given in Table 3. No significant differences in age, body mass, and height among all groups were detected at the start of the study (Table 3).

Muscle performance. For isometric strength a significant interaction effect (group × time) was found [$F(3)=15.94$, $P < 0.001$]. Contrast analysis clarified that isometric knee-extensor torque (Fig. 2) increased significantly ($P < 0.001$) over 12 wk in the RES group (14.4 ± 5.3%) and in the WBV group (16. 6 ± 10.8%) whereas no significant increase was found in the PL- or the CO group. Regarding dynamic strength a significant interaction effect [$F(3)=7.81$, $P < 0.001$] was found. Contrast analysis showed a significant increase ($P < 0.001$) in dynamic strength (Fig. 2) for the RES group (7.0 ± 6.2%) and the WBV group (9.0 ± 3.2%). The PL group and the CO group did not improve in dynamic strength.

The ballistic test results (Fig. 3) revealed no significant effect ($P > 0.05$) in unloaded speed of movement (0%) or in speed of movement with standardized resistance (20%, 40%, or 60% of maximal isometric strength).

CMJ height showed a significant interaction effect (group × time) [$F(3)= 5.88, P < 0.001$]. Contrast analysis clarified that jumping height increased significantly ($P < 0.001$) over 12 wk in the WBV group (7.6 ± 4.3%), but remained unchanged in all other groups (Fig. 4).

DISCUSSION

This is the first placebo-controlled study that compares the effects of 12 wk of WBV training and resistance training on knee-extensor strength and CMJ performance in previously untrained subjects. The results of this study clearly

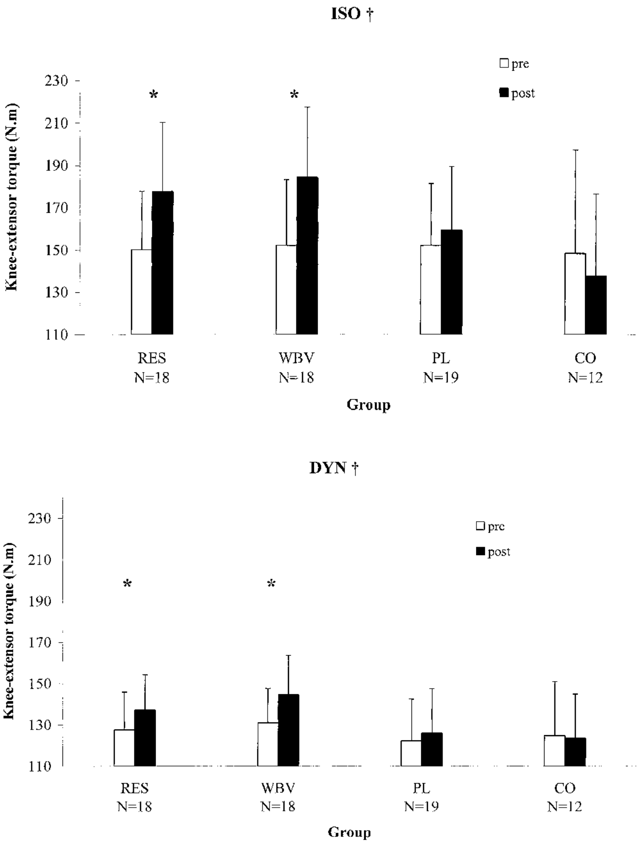
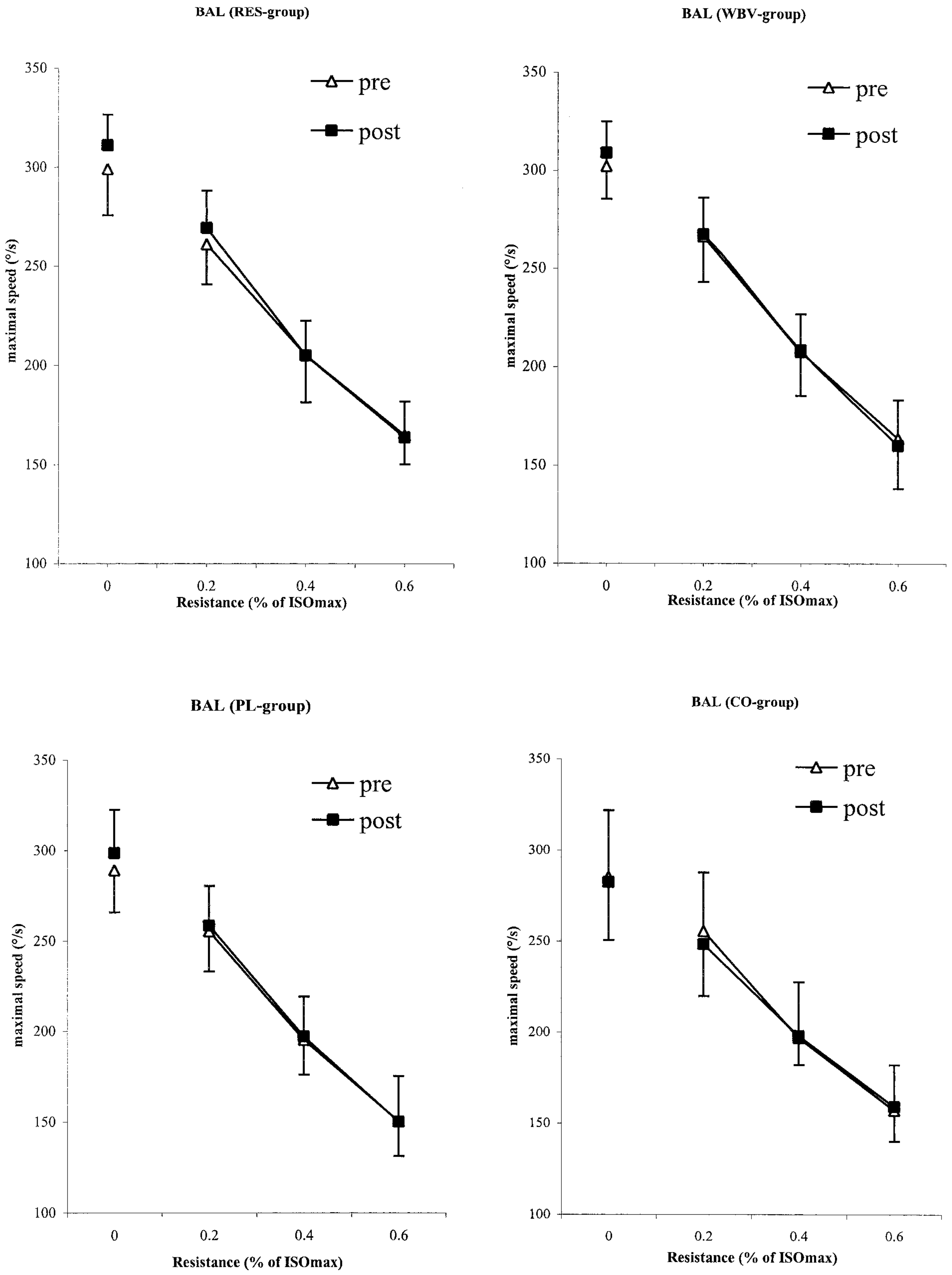


FIGURE 2—Mean and SD before (pre) and after (post) 12 wk in the RES, WBV, PL, and CO groups. Top: maximal isometric knee-extensor torque (ISO). Bottom: maximal dynamic knee-extensor torque (DYN). † refers to a significant interaction (group × time) effect at $P < 0.05$. * indicates that posttraining values are significantly higher than pretraining values at $P < 0.05$ (contrast analysis).


BAL (RES-group)

BAL (WBV-group)

BAL (PL-group)

BAL (CO-group)

FIGURE 3—Maximal speed of movement during ballistic tests (BAL) without resistance (0%) or with resistances of 20%, 40%, and 60% of the isometric maximum (ISO_{max}). Mean and SD before (pre) and after (post) 12 wk in the RES, WBV, PL, and CO groups.

indicate that strength, and more specifically isometric and isokinetic strength, significantly improved after WBV training. The magnitude of the strength increase in isometric and dynamic strength of the quadriceps, 16.6% and 9.0%, respectively, is comparable to the increase that was realized by an equal number of resistance training sessions, 14.4%

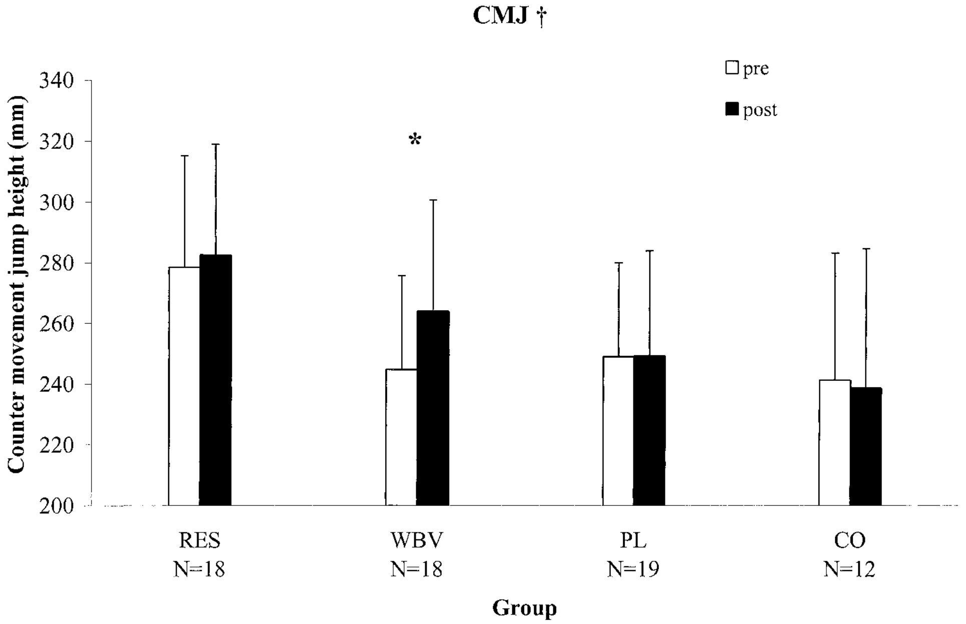


FIGURE 4—Counter movement jump height (CMJ). Mean and SD before (pre) and after (post) 12 wk in the RES, WBV, PL, and CO groups. † refers to a significant interaction (group × time) effect at $P < 0.05$. * indicates that posttraining values are significantly higher than pretraining values at $P < 0.05$ (contrast analysis).

and 7.0%, respectively. Additionally, CMJ height, a measure of explosive strength after stretch shortening of the muscles, increased by 7.6% in the WBV group but did not change in any of the other groups. The data of this study clearly indicate that strength increases in the WBV group are not related to a placebo effect. Besides, these training effects may not be considered as acute effects as the posttest measurements were performed at least 72 h after the last training session. WBV training, and the muscle contractions it provokes, appears to be an efficient training stimulus to increase muscle strength.

The induced improvement in CMJ (7.6%) found in the present study is comparable to the 8.5% increase in jump height in the study of Torvinen et al. (23). In addition, Torvinen et al. (23) recorded an increase of 3.7% in isometric knee-extensor strength after 2 months of WBV training; this effect disappeared partly in the next 2 months of WBV training. In this study, a 16.6% increase in isometric knee-extensor strength was found. This difference in isometric strength gain could be partially explained by the use of other WBV-training programs. In the study of Torvinen et al. (23), subjects stood only 4 min per session on the WBV platform compared with a systematic increase of the training volume from 3 to 20 min per session in this study (Table 1). Sale (21) suggested that full activation of the muscle may lead to motor unit fatigue and consequently to strength gain. EMG recordings (Fig. 1) show the impact of WBV on muscle activity. It is likely that a prolonged period of standing on the WBV platform results in full motor unit activation. However, a 4-min WBV session could be too short to induce motor unit fatigue. The 3.7% increase in isometric strength in the study of Torvinen et al. (23) is comparable to the nonsignificant increase in isometric strength in the PL group of this study (4.7%) and may result from the static and dynamic exercises on the platform.

Generally, the adaptations that occur in the neuromuscular system with chronic levels of physical activity can be assessed in a variety of ways. The most common approach is to distinguish between the neural and intramuscular mechanisms that influence muscle power and strength (9). It has been observed that in resistance training the first phase of adaptation may be attributed to an improvement in neural factors, the intramuscular factors become more important as training continues over several months. Although not measured in this study, a certain degree of hypertrophy may be expected after 12 wk of resistance training, and it cannot be excluded that it occurred as well in the WBV group. In rats, a vibration-induced enlargement of slow- and fast-twitch fibers has been demonstrated (16). However, it is well known that the cross-sectional area of muscle does not increase to the same extent as maximal strength does. Therefore, intramuscular adaptations are not expected to be the most important mechanism responsible for strength increase after 12 wk of training (12,19). Evidence also indicates that voluntary activation is a limiting factor in force production and that improvements in force generated per unit cross-sectional area are responsible for the initial gain in strength (10).

It is likely that WBV elicits a biological adaptation that is connected to the neural potentiation effect, similar to that produced by resistance and explosive strength training. Recently, it was suggested that resistance training might alter the connectivity between corticospinal cells and spinal motoneurons (7,8). Interneurons in the spinal cord receive input from afferent fibers, descending fibers, and the fibers of other interneurons and ultimately influence the activity of motoneurons. The interaction of these various inputs onto interneuronal circuitry determines which motor units are recruited during movement. The activation of motoneurons via both corticospinal cells and spinal reflex pathways is partly determined by the manner in which supraspinal and segmental elements interact to set the excitability states of interneuronal circuits. An important consequence of this arrangement is that the same corticospinal output can activate different populations of motoneurons dependent of the state of circuitry within the spinal cord (7).

It is well known that the input of proprioceptive pathways (Ia, IIa, and probably Ib afferents) is used in the production of force during isometric contractions (10). During WBV, these proprioceptive pathways are strongly stimulated. The vibratory stimulus is activating the sensory receptors that results in reflexive muscle contractions. The increase in isometric strength after 12 wk of training, and thus after extensive sensory stimulation, might thus be the result of a more efficient use of the positive proprioceptive feedback loop in the generation of isometric force.

Additionally, the results show also an increase in CMJ due to WBV training that was not found in the RES, PL, or in the CO group. Komi (13) showed the involvement of the stretch reflex and thus Ia afferent input in the force potentiation during a stretch-shortening contraction (SSC) in the CMJ. The stimulation of the sensory receptors and the afferent pathways with WBV might thus lead to a more efficient use of the stretch reflex. It is suggested that the tonic vibration reflex induced a reflex sensitization of the muscle spindles and increased a facilitation of the reflex action on the motoneuron pool (18). The sensory stimulation that is the basis of muscle activity in WBV training seems hereby crucial in the facilitation of the SSC as resistance training with little sensory stimulation did not improve the CMJ. However, one should take care when comparing the CMJ data of the RES group to other groups in this study. In the pretest condition (Fig. 4), a significantly higher (± 35 mm) [$F(3)=3.99$, $P = 0.012$] CMJ performance was recorded in the RES group compared with all other groups. Considering that pretest isometric and dynamic strength was identical in all groups ($P > 0.05$), this difference in CMJ performance is most probably related to a lower (± 4–5 kg), nonsignificant, body weight in the RES group (Table 3). This includes that the potential for progression in CMJ was smaller in the RES group compared with all other groups. Though the WBV group did make significant gain in CMJ performance and the RES group did not improve, it is quite obvious that there was no difference in the posttest CMJ performance between the RES and the WBV group (Fig. 4). So the results of this study clearly show a significant increase in jump performance when WBV is compared with PL and CO, but differences in pretest condition may have interacted when the effect on CMJ is compared with RES. Further research is needed to analyze the impact of resistance training and WBV on CMJ performance. It should also be emphasized that the resistance training program in this study was not specifically designed to improve CMJ performance.

At motor unit level, it was suggested that the tonic vibration reflex affects primarily the subjects ability to generate high firing rates in high-threshold motor units (1). The recruitment thresholds of the motor units during WBV are expected to be lower compared with voluntary contractions (18), probably resulting in a more rapid activation and training of high-threshold motor units. Therefore, it has been suggested that WBV training renders specific training of fast-twitch fibers (17), which have an important contribution in ballistic strength. However, the results of this study cannot support these suggestions. No effect of any of the interventions on the speed of movement, as measured by means of ballistic tests with a resistance of 20, 40, or 60%, relative to the isometric strength of the subject was found. This latter finding indicates that there was no significant chronic effect of WBV or resistance training on the relative force-velocity curve of the knee extensors. The maximal speed of movement recorded in unloaded ballistic conditions remained also unchanged after any of the interventions.

Whatever may be the mechanisms behind it, it is clear that WBV elicits muscle contraction involuntary and it induces strength gain in previously untrained subjects within a short period of time and without much effort. The subjects did not experience the WBV training as exhausting training sessions. This suggests that WBV has a great potential in a therapeutic context where it may enhance muscular performance in patients and elderly, who are not attracted to or who are not able to perform standard exercise programs. It may also enhance performance of athletes in a stretch-shortening cycle, as suggested by the results on the CMJ.

In conclusion, this is the first study that demonstrates that the stimulation of propriospinal pathways provoked by WBV and the resulting increase in muscle activity have the potential to induce strength gain in the knee extensors of previously untrained subjects to the same extent as resistance training at moderate intensity. The findings of this study clearly indicate that strength increases after 12 wk of WBV training are not attributable to a placebo effect. The CMJ height increased significantly in the WBV group only. The results of this study suggest that strength increases recorded in the WBV group are mainly resulting from neural adaptations and can be ascribed to a more efficient use of sensory information in the production of force. It is clear that more research on WBV is needed to clarify the mechanisms of muscle contractions and strength gain.

This research was technically supported by Power Plate®.

The authors thank Guus van der Meer, Jelte Tempelaars, and Nick De Poot for designing the WBV training program. The authors also thank Els Van den Eede and Karel Pardaens for the medical screening of the subjects. The cooperation of the subjects is greatly appreciated.

REFERENCES

1. Bongiovanni, L. G., K. E. Hagbarth, and L. Stjernberg. Prolonged muscle vibration reducing motor output in maximal voluntary contractions in man. *J. Physiol.* 423:15–26, 1990.
2. Bosco, C., M. Cardinale, O. Tsarpela, et al. The influence on whole body vibration on jumping performance. *Biol. Sport* 15: 157–164, 1998.

3. Bosco, C., M. Iacovelli, O. Tsarpela, et al. Hormonal responses to whole-body vibration in men. *Eur. J. Appl. Physiol.* 81:449–454, 2000.
4. Bosco, C., P. Luhtanen, and P. V. Komi. A simple method for measurement of mechanical power in jumping. *Eur. J. Appl. Physiol. Occup. Physiol.* 50:273–282, 1983.
5. Bosco, C., R. Colli, E. Introini, et al. Adaptive responses of human skeletal muscle to vibration exposure. *Clin. Physiol.* 19: 183–187, 1999.
6. Burke, D., and H. H. Schiller. Discharge pattern of single motor units in the tonic vibration reflex of human triceps surae. *J. Neurol. Neurosurg. Psychiatry* 39:729–741, 1976.
7. Carroll, T. J., S. Riek, and R. G. Carson. Neural adaptations to resistance training: implications for movement control. *Sports Med.* 31:829–840, 2001.
8. Carroll, T. J., S. Riek, and R. G. Carson. The sites of neural adaptation induced by resistance training in humans. *J. Physiol.* 544:641–652, 2002.
9. Enoka, R. M. Neural adaptations with chronic physical activity. *J. Biomech.* 30:447–455, 1997.
10. Gandevia, S. C. Spinal and supraspinal factors in human muscle fatigue. *Physiol. Rev.* 81:1725–1789, 2001.
11. Hagbarth, K. E., and G. Eklund. Tonic vibration reflexes (TVR) in spasticity. *Brain Res.* 2:201–203, 1966.
12. Jones, D. A., and O. M. Rutherford. Human muscle strength training: the effects of three different regimens and the nature of the resultant changes. *J. Physiol.* 391:1–11, 1987.
13. Komi, P. V. Stretch-shortening cycle: a powerful model to study normal and fatigued muscle. *J. Biomech.* 33:1197–1206, 2000.
14. Kraemer, W. J., K. Adams, E. Cafarelli, et al. American College of Sports Medicine position stand: progression models in resistance training for healthy adults. *Med. Sci. Sports Exerc.* 34:364–380, 2002.
15. Lance, J. W., D. Burke, and C. J. Andrews. The reflex effects of muscle vibration. In: *New Developments in Electromyography and Clinical Neurophysiology*, J. E. Desmedt (Ed.). Basel: Karger, 1973, pp. 444–462.
16. Necking, L. E., R. Lundstrom, G. Lundborg, L. E. Thornell, and J. Friden. Skeletal muscle changes after short term vibration. *Scand. J. Plast. Reconstr. Surg. Hand Surg.* 30:99–103, 1996.
17. Rittweger, J., G. Beller, and D. Felsenberg. Acute physiological effects of exhaustive whole-body vibration exercise in man. *Clin. Physiol.* 20:134–142, 2000.
18. Romaiguere, P., J. P. Vedel, and S. Pagni. Effects of tonic vibration reflex on motor unit recruitment in human wrist extensor muscles. *Brain Res.* 602:32–40, 1993.
19. Roth, S. M., F. M. Evey, G. F. Martel, et al. Muscle size responses to strength training in young and older men and women. *J. Am. Geriatr Soc.* 49:1428–1433, 2001.
20. Runge, M., G. Rehfeld, and E. Resnicek. Balance training and exercise in geriatric patients. *J. Musculoskelet. Neuron Interact.* 1:61–65, 2000.
21. Sale, D. G. Influence of exercise and training on motor unit activation. *Exerc. Sport Sci. Rev.* 15:95–151, 1987.
22. Torvinen, S., P. Kannu, H. Sievanen, et al. Effect of a vibration exposure on muscular performance and body balance. Randomized cross-over study. *Clin. Physiol. Funct. Imaging* 22:145–152, 2002.
23. Torvinen, S., P. Kannu, H. Sievanen, et al. Effect of four-month vertical whole body vibration on performance and balance. *Med. Sci. Sports Exerc.* 34:1523–1528, 2002.