Physiological Response to Whole-Body Vibration in Athletes and Sedentary Subjects

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Summary

Whole-body vibration (WBV) is a new exercise method, with good acceptance among sedentary subjects. The metabolic response to WBV has not been well documented. Three groups of male subjects, inactive (SED), endurance (END) and strength trained (SPRINT) underwent a session of side-alternating WBV composed of three 3-min exercises (isometric half-squat, dynamic squat, dynamic squat with added load), and repeated at three frequencies (20, 26 and 32 Hz). VO_2, heart rate and Borg scale were monitored. Twenty-seven healthy young subjects (10 SED, 8 SPRINT and 9 END) were included. When expressed in % of their maximal value recorded in a treadmill test, both the peak oxygen consumption (VO_2) and heart rate (HR) attained during WBV were greatest in the SED, compared to the other two groups (VO_2: 59.3 % in SED vs 50.8 % in SPRINT and 48.0 % in END, $p<0.01$; HR 82.7 % in SED vs 80.4 % in SPRINT and 72.4 % in END, $p<0.05$). In conclusions, the heart rate and metabolic response to WBV differs according to fitness level and type, exercise type and vibration frequency. In SED, WBV can elicit sufficient cardiovascular response to benefit overall fitness and thus be a potentially useful modality for the reduction of cardiovascular risk.

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Introduction

Whole-body vibration (WBV) is a fairly recent training modality, commercially available since the start of the millennium. It has been developed in the 1970s in the former Soviet Union, with the purpose of training cosmonauts in order to prevent loss of bone mineral and muscle mass during space flights, and the first reports on athletic training came after 1985 (Nazarov and Spivak 1985). It is nowadays widely used for personal training purposes, with numerous claims from manufacturers, encompassing enhanced muscular strength, bone mass, proprioception, balance, flexibility, along with beneficial metabolic effects, such as augmentation in lipolysis, glucose tolerance, growth hormone and testosterone secretion. Some but not all of these claims are supported by data (Verschueren *et al.* 2004, Bautmans *et al.* 2005, Bruyere *et al.* 2005, Gusi *et al.* 2006, Rehn *et al.* 2007, Cardinale *et al.* 2010, Slatkovska *et al.* 2010). The subjects in the various trials vary greatly in age, metabolic profile, physical activity levels or types of sports they are actively involved in, and these issues have been recently addressed elsewhere (Cochrane 2011). The review papers trying to sort out the effects observed with this training method all single out the need for standardization of the exercise protocols, especially regarding the type of vibratory stimulus used (vertical and/or lateral plate displacement, or side-alternating oscillation around a fixed center axis), duration of exercise bouts, number of repetitions, frequency and amplitude of platform movement (Lorenzen *et al.* 2009). All of these parameters vary considerably between the

different trials, resulting in manufacturers claiming effects observed in trials conducted with different machines and specifications of platform movement. Nevertheless, since the vibration platforms are widely available for athletes and non-athletic subjects looking for ways to improve their general health, it seems useful to have comparative data for the same exercises in differently trained subjects.

The importance of physical activity in maintenance or improvement of general health is widely accepted, and is based on the observation that the higher the fitness level, the better the outcome with regards to health (Sesso *et al.* 2000, Myers *et al.* 2002, Warburton *et al.* 2006). The potential benefit of WBV towards promotion of overall fitness has not been ascertained, and findings regarding the impact on aerobic fitness are equivocal. Bogaerts *et al.* (2009) have observed an 18.6 % improvement in VO$_2$max in elderly inactive women, after 12 months of WBV training, while Vissers *et al.* (2010) have found no such improvement after 6 months of WBV in overweight and obese middle-aged subjects. During acute WBV exposure, a few studies have observed no or little effect on heart rate or oxygen uptake during WBV exercices (Rittweger *et al.* 2001, Hazell *et al.* 2008). There definitely is a lack of understanding and agreement regarding the cardiovascular response elicited by WBV training in general.

In the present study, we aimed to investigate the physiology of vibration training, particularly the cardiac and metabolic response to various exercises at various frequencies. We hypothesized that baseline fitness levels will influence the response to the vibratory stimulus, which is why we chose sedentary subjects and two athletic populations. We aimed at identifying the maximal metabolic and heart rate load attainable with the most commonly investigated vibration exercises.

Materials and Methods

This study was approved by the Institutional Review Board of the University of Lausanne and carried out in accordance with the Declaration of Helsinki. Written informed consent was obtained from each participant.

Subjects

Twenty-seven male volunteers aged 20 to 40 years old were recruited in local sports organizations and within the Lausanne University community. We used a convenience sample of 10 inactive subjects (SED), 8 strength-velocity trained athletes (SPRINT) and 9 endurance trained athletes (END). The SED group comprised subjects categorized as inactive according to the IPAQ short form questionnaire (Gauthier *et al.* 2009) minimal physical activity requirements (less than 20 to 60 min of vigorous physical activity three times a week, or less than 30 min of moderate physical activity five times a week). Some of them had been active in sports in the past, but not in the last 12 months. The SPRINT group comprised athletes currently active in competitive sports, mostly short distance track sprinters, American football receivers and one decathlete. The END group comprised triathletes and one long-distance runner. All subjects were naïve to vibration training and had been training in their sport for the last two years, a minimum of 5 h per week, and without a break lasting more than one week in the past three months. Exclusion criteria included smoking, epilepsy, any fracture in the preceding 6 months, any implanted prosthetics, thrombosis in the preceding 3 months, history of diabetes, cardiovascular disease, or lipid disorders. Subjects' characteristics are listed in Table 1.

Data collection

After a detailed medical history and physical examination, subjects weight, height, blood pressure and body composition parameters were determined by electrical bioimpedance (Body Impedance Analyzer, Nutrigard-M, Frankfurt, Germany). All tests were conducted in a climate controlled (temperature and relative humidity) laboratory.

VO$_2$max recordings

Subjects' VO$_2$max was directly assessed with the CPX/MAX cardiopulmonary diagnostic system (MedGraphics®, St Paul, Minnesota) during a graded exercise treadmill test (initial speed 7 km·h^{-1} in SED, 8 km·h^{-1} in SPRINT and 10 km·h^{-1} in END, 0.5 km/h increments per minute). The exercise test was considered maximal when any of the following was fulfilled: plateau in oxygen uptake with increasing work rate, respiratory exchange ratio greater than 1.10, attainment of expected maximal heart rate ≤5 bpm, or appearance of symptoms (exhaustion, severe shortness of breath, abnormal stride pattern). The values reported are time-averaged over the last 30 s of each exercise. Maximal heart rate was recorded and used for further calculations of percentage of maximum (%HRmax).

Isokinetic strength testing

Maximal strength evaluation was carried out on an isokinetic knee extension/flexion machine (Biodex Medical Systems®, Shirley, New York). The testing protocol is standardized according to the Swiss Olympic guidelines for athletic evaluation (Tschopp 2003), and consists of 5 repetitions of flexion/extension sequences at an angular velocity of 60 and 180 degrees/s, and 30 repetitions at 300 degrees/s.

Table 1. General characteristics of the three study groups.

	SED	SPRINT	END	*p values*		
				SPRINT vs SED	*END vs SED*	*END vs SPRINT*
Number of subjects	10	8	9			
Age (years)	24.5±3.3	25±2.5	29.8±7.4	*ns*	*ns*	*ns*
Weight (kg)	73.9±7.5	77.4±12.9	71.9±4.9	*ns*	*ns*	*ns*
Height (m)	1.8±0.08	1.78±0.04	1.81±0.05	*ns*	*ns*	*ns*
BMI (kg·m^{-2})	22.8±2.1	24.3±3.4	21.9±1.2	*ns*	*ns*	*ns*
% body fat	20.3 ±4.3	17.0±4.8	15.0 ±2.2	*ns*	*0.007*	*ns*
% fat-free mass	46.2±5.6	56.7±9.3	52.1±6.6	*0.007*	*ns*	*0.007*
Resting heart rate (bpm)	67.8±10.6	71.9±12.8	60.2±7.9	*ns*	*ns*	*ns*
Blood pressure (mm Hg)						
Systolic	122.7±8.2	127±7.6	126±7	*ns*	*ns*	*ns*
Diastolic	67.6±5.3	67.8±6.1	68±6.9	*ns*	*ns*	*ns*
VO$_2$max (ml·kg^{-1}·min^{-1})	47.9±4	52.9±6	63.9±6.5	*ns*	*<0.001*	*<0.001*
Peak leg extensor torque (Nm·kg^{-1})						
Right	191.2±44	252±41.3	198±39.4	*0.005*	*ns*	*0.014*
Left	190.8±39.4	223±36.9	191±35.6	*ns*	*ns*	*ns*

SED, sedentary; SPRINT, strength-velocity trained; END, endurance-trained; BMI, body mass index; VO$_2$max, maximal oxygen uptake. Peak leg extensor torque reported at an angular velocity of 60° per second. Difference between right and left leg peak extensor torque non significant in all three groups. Data are mean and ± SD.

Vibration exercise

Our oscillatory vibration platform consists of a plate oscillating around a middle axis, with feet placed on either side, resulting in alternating up and down movements (Sismo Fitness Elite®, Sismo Fitness International, 94230 Cachan, France). Vibration frequency range is from 1 to 32 Hz, with peak-to-peak amplitude of 10.4 mm (middle toe of each foot placed at 22.5 cm from the center of the platform). Our subjects underwent a short eleven-minute familiarization session on the platform on a separate day, in which they executed three-minute isometric and dynamic squatting without and with added load, with 1 min rest in between. After a five-minute light warm-up on a stationary bicycle (50 Watts), subjects were equipped with gas analyzer and the protocol exercise was started at a frequency of 20 Hz (peak acceleration = 8.37 g), because lower frequencies may be uncomfortable and deleterious due to tissue resonance (Rittweger 2009). Participants were standing on the platform in unpadded socks, with feet placed at a fixed distance of the middle axis to assure constant amplitude. They did three different exercises lasting three minutes each, with one minute rest in between. The first exercise was a semi-squat isometric stance (60 degrees of knee flexion). The second exercise consisted of slow dynamic (3 s down, 3 s up, to the beat of a 1 Hz metronome) squats to 90 degrees of knee flexion, i.e. thirty repetitions overall. The third exercise was the same with added load equal to 30 % of body weight in a tightly fitting backpack. After ten minutes of rest,

this eleven-minute sequence was repeated at 26 Hz (peak acceleration = 14.15 g) and then again at 32 Hz (peak acceleration = 21.43 g). Subjects repeated the same sequence a week apart (hereafter named V1 and V2), to help account for any habituation effect. The exercises and the frequencies have not been randomized, but rather we chose to start with the presumed easier exercises and frequencies to minimize any carry-over fatigue in subsequent exercises.

Heart rate (Polar Electro®, Finland) and gas exchange were continuously monitored throughout the experiment, except during the 10-min resting periods. The VO_2 values reported are averaged over the last 30 s of each exercise, in order to average out breath-to-breath variation and capture the end of the third minute of exercise, where steady-state is habitually attained (Roberts *et al.* 2010). Subjects could hold the handles in front of them, but only to balance themselves.

Statistical analysis

Regarding demographic and baseline characteristics, statistical differences between the three groups were evaluated with one-way analysis of variance. The impact of experimental conditions on oxygen uptake (expressed as % of VO_2max), heart rate (expressed as % of maximal heart rate), and Borg dyspnea score were assessed with analysis of variance for repeated measures. Before analysis, oxygen uptake and heart rate were log transformed because of heteroscedascity. Fixed nominal factors in the model were group membership (3 levels), exercise type (3 levels), and session (2 levels). Vibration frequency was included as a continuous covariate. Subjects nested within group were considered as random effects. Models containing either all 2- and 3-way interactions between the fixed nominal factors or only simple effects were first compared, in terms of goodness of fit. On this basis, and for all three variables, it was decided that the simpler model without interactions was appropriate. The normality asumption was checked from the linear shape of normal quantile plots of residuals. When the omnibus F test for a particular effect was significant, Fisher's least significant differences were used to carry out pairwise comparisons in the case of effects with 3 levels. The alpha level of all tests was set at 0.05. Data are summarized as the mean and SD.

Results

The subjects' baseline characteristics differed as expected per protocol, reflecting the level of activity of each group. In particular, END had the highest, SPRINT the intermediate and SED the lowest VO_2max (p<0.001 between groups). BMI, total fat mass, and resting heart rate were also lower in END, although only percent body fat was significantly lower (p<0.01). Percentage of fat-free mass was the highest in SPRINT, intermediate in END and lowest in SED (56.7 %±9.3 vs. 52.1±6.6 vs. 46.2±5.6, p<0.001 between groups), and peak leg extensors torque was similarly distributed (Table 1).

Heart rate response

In all participants, the maximal measured heart rate response was elicited by the loaded squats at 32 Hz vibration frequency. In SED, it amounted to 82.7 %±8.1 (% of HRmax) at V1, and 81.7 %±10.5 at V2. SPRINT showed a slightly lower response, 80.4 %±8.5 and 77.3 %±10.5, and END an even lower one, 72.4 %±7.3 and 71.6 %±6.5. See Figure 1 for all heart rate responses.

Effect of exercise type and vibration frequency

Heart rate response increased with vibration frequency (p<0.01) and was different between exercise types (highest for loaded squats and lowest for isometric squats, p<0.001).

Effect of familiarization

All subjects were able to manage V2 better, with a lower HR for each exercise (p<0.01). Some subjects were unable to finish the last loaded exercise due to exhaustion in V1, mostly in SED (5 SED, 1 SPRINT, 1 END), while only 3 SED could not finish the last stage in V2.

Effect of athletic background

The heart rate response was lower in END than in either SED (p<0.001) or SPRINT (p<0.05), and did not differ between the latter two groups. The addition of age, weight, and BMI as covariates in the repeated measures ANOVA had no impact on the results of statistical analysis.

Oxygen consumption

Regarding the peak VO_2, the effects of the various investigated factors was the same as for HR, reaching 58.8 %±10.3 of VO_2max (V1) and 59.3 %±11.8 (V2) in SED, 50.8 %±9.2 and 46.8 %±6.9 in SPRINT, and 48.0 %±11.3 and 43.8 %±11.4 in END. See Figure 2 for all oxygen uptake responses.
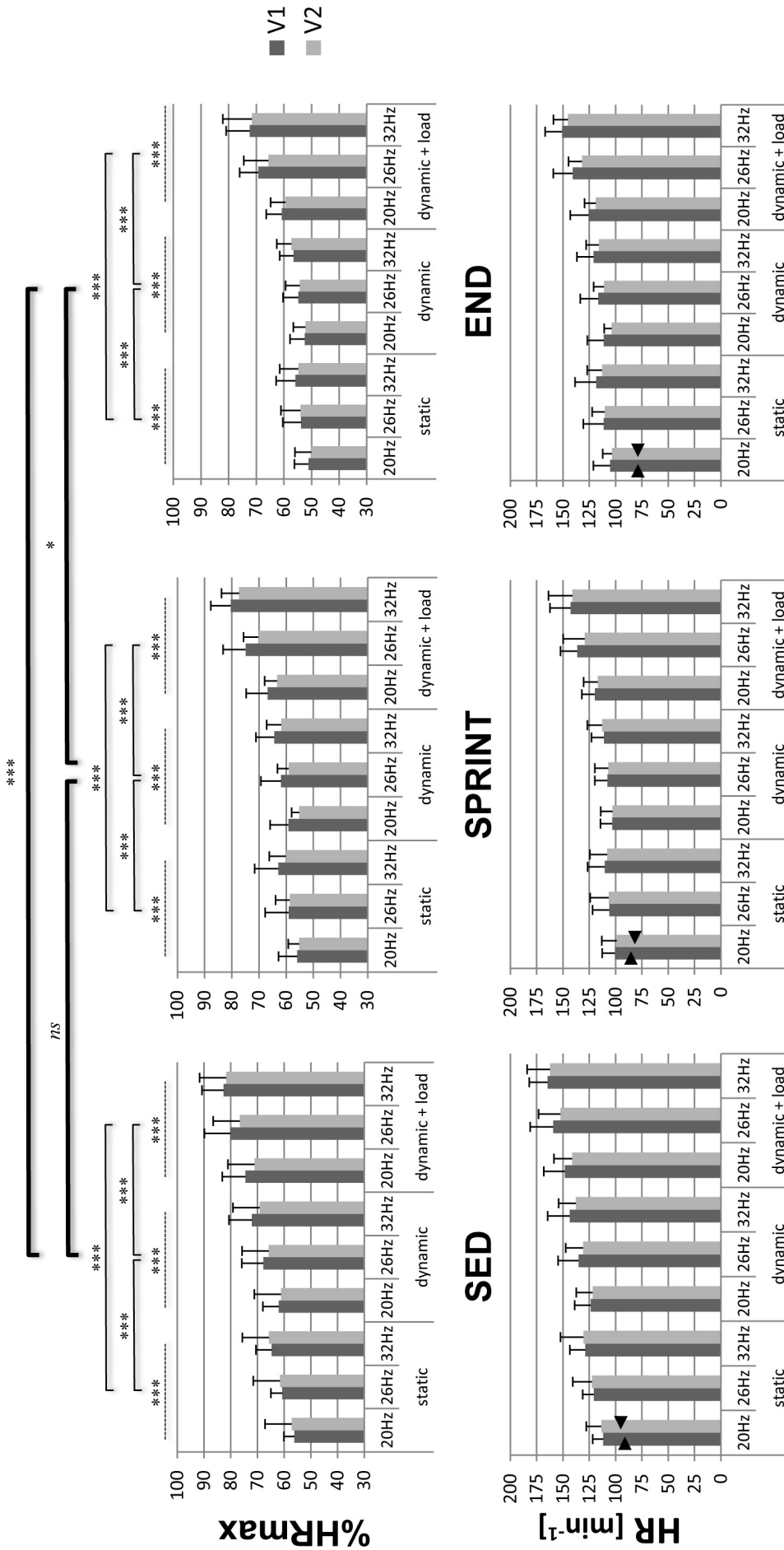
Fig. 1. Heart rate response for the various exercise position and frequencies (percentage of individual maximum heart rate). Black arrows indicate values before start of first vibration exercise (▲ before V1, ▼ before V2). Results of statistical analysis indicated by horizontal bars with superimposed p values. Thin dashed bars: effects of vibration frequency (treated as a continous variable). Thin continuous bars: effects of type of effort. Thick continuous bars: effects of training background. *** p<0.001. ** p<0.01. * p<0.05. *ns* not significant. P values are those associated with the main effects in repeated measures ANOVA. All two and three-way interactions were not significant.
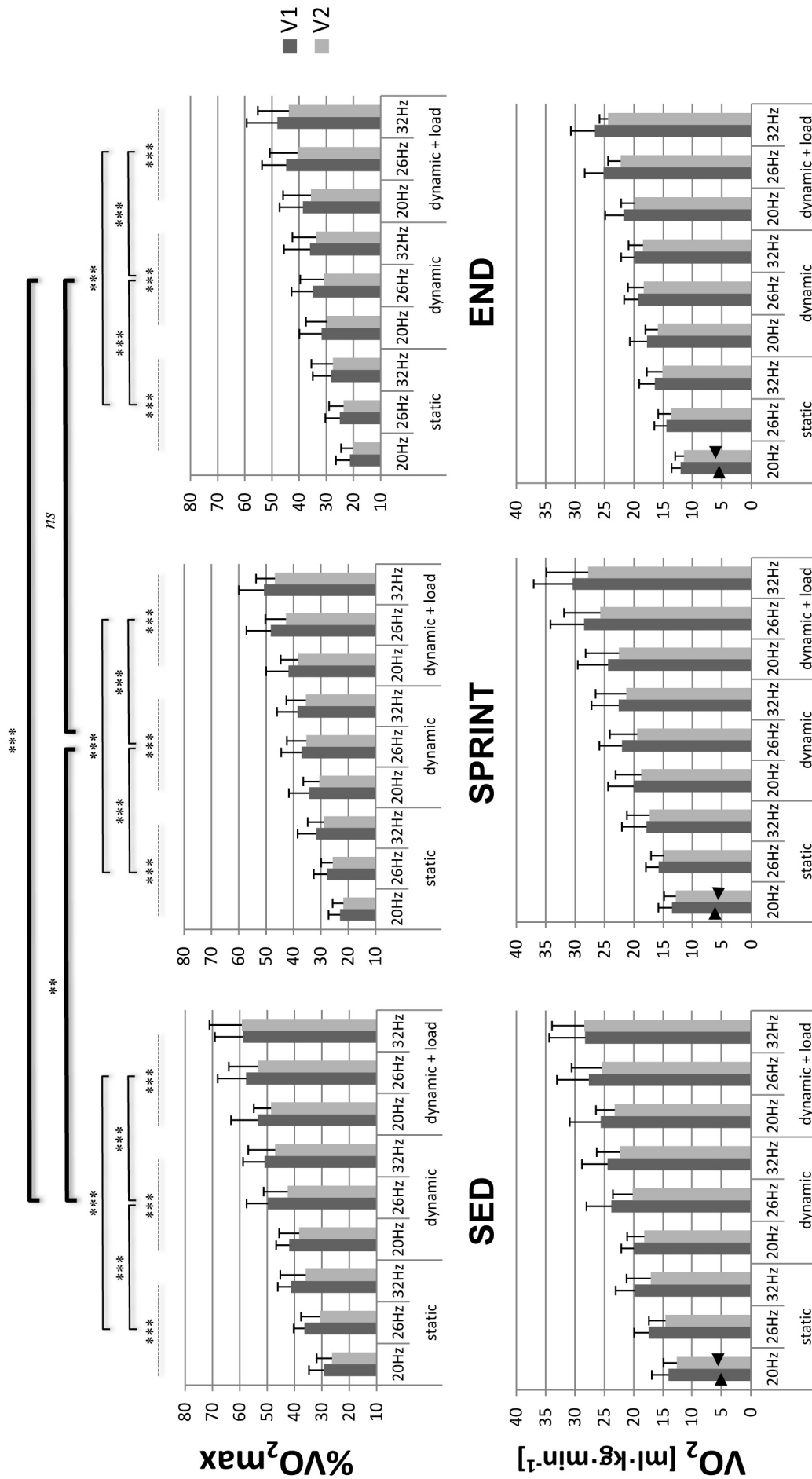
Fig. 2. Oxygen consumption for the various exercise position and frequencies (percentage of individual VO_2max). Black arrows indicate values before start of first vibration exercise (▲before V_1, ▼before V_2). Results of statistical analysis indicated by horizontal bars with superimposed p values. Thin dashed bars: effects of vibration frequency (treated as a continous variable). Thin continuous bars: effects of type of effort. Thick continuous bars: effects of training background. *** p<0.001. **p< 0.01. * p<0.05. *ns* not significant. P values are those associated with the main effects in repeated measures ANOVA. All two and three-way interactions were not significant.

Effect of exercise type and vibration frequency

Oxygen uptake increased with vibration frequency ($p<0.01$), and also from isometric to dynamic to dynamic loaded squats ($p<0.001$).

Effect of familiarization

All subjects presented lower O_2 uptake values in the second session (V2), and showed an ability to carry out the drills more efficiently ($p<0.001$).

Effect of athletic background

SED had the highest relative VO_2 response ($p<0.01$ compared to SPRINT, $p<0.001$ compared to END). END and SPRINT had a similar response. The addition of age, weight, and BMI as covariates in the repeated measures ANOVA had negligible impact on the results of statistical analysis.

Perceived effort
Effect of exercise type and vibration frequency

In all three groups Borg score increased with vibration frequency ($p<0.001$), but no differences were present between isometric and dynamic squats, while loaded squats elicited higher scores than the other two exercises ($p<0.001$).

Effect of familiarization

There was a significant difference between both vibration sessions in all subjects, with an average decrease in Borg value of 0.7 (SED), 1.5 (SPRINT) and 1.0 (END) ($p<0.001$) from V1 to V2.

Effect of athletic background

No differences were present between groups. The addition of age, weight, and BMI as covariates in the repeated measures ANOVA had negligible impact on the results of statistical analysis.

Discussion

We have investigated the impact on heart rate and oxygen uptake of three different side-alternating vibration training exercises in sedentary or trained subjects, at three different vibration frequencies. The main new result is that the elicited exercise intensity depends on all of these variables. Namely, exercise intensity, measured as percentage of maximal heart rate (HRmax) or of maximal oxygen uptake (VO$_2$max), increases with frequency, and as subjects progress from static squats, to dynamic squats and finally to loaded dynamic squats. These facts should be taken into consideration when the effect of WBV exercises on health and fitness is discussed.

We observed that typical squatting exercises for three continuous minutes can elicit sufficient heart rate and oxygen uptake responses in order to have a potential health and fitness enhancing effect in sedentary subjects, more so than in trained athletes. This is to our knowledge the first time a comparison of the metabolic response in differently trained subjects is reported for WBV exercises.

Athletes

In athletes, it is obviously not the goal to use WBV for any cardiovascular training purposes, and benefits for improvements in strength and power have been reported (Ronnestad 2004, Fagnani *et al.* 2006, Mahieu *et al.* 2006), but in general the WBV program is not more effective than a regular resistance training program in order to improve muscle strength or power. One study measured energy expenditure in recreationally resistance trained subjects with or without vibration during a training session involving 5 sets of 10RM half-squats (to 90 degrees knee flexion), and reported an 18 % higher energy expenditure with vibration, although heart rate was not significantly higher (Da Silva *et al.* 2007). Our athletes were either strength trained (mostly sprinters – SPRINT) or endurance trained (runners and triathletes – END). All relative VO_2 responses (%VO$_2$max) were lower in athletes when compared to sedentary subjects, which is expected, since the athletes have by definition a higher baseline aerobic fitness level and each exercise should require a similar amount of energy to be produced by all subjects. But we also observed a 10-15 % lower absolute O_2 uptake for each exercise type and frequency in SPRINT compared to SED and END (data not shown). This means that the task efficiency or economy of exercise is better in SPRINT, potentially because of better neuro-muscular ability to generate muscle contractions directed at accomplishing the task at hand (squatting). This type of exercise is one that is as a general rule part of their usual training, and therefore more specific to their abilities. On the other hand END showed no differences compared to SED in absolute VO_2 for each task, reflecting their similar task efficiency and lack of specific training for squatting. When relative heart rate is considered, we observed that the END athletes had lower percentages of HRmax compared to SED and SPRINT.

Table 2. Studies investigating the metabolic (oxygen uptake or heart rate) response to vibration exercises.

Authors	Participants		Platform type	Exercise type	Vibration parameters				Metabolic response			Heart rate		Comparisons
	Age	Activity level			Frequency (Hz)	Amplitude (mm)	Reported A_{peak} (g)	Calculated A_{peak} (g)	VO$_2$					
Avelar et al. (2011)	18 15♀ 3♂	72 inactive, overweight (BMI 29.6)	Fitvibe™ oscillation	Squats to 60 degrees, 8 sets of 5 reps (40 s on), 40 s recovery	40	4	2 to 5 g (verified by accelerometer)	25.8 g (12.9 g)	↑	VO$_2$ reaches 5.69 (no WBV) and 6.81 ml/kg·min (WBV), 20 % higher elevation in VIB, equals 32.4 % of theoretical VO$_2$max		↑	WBV elevates HR compared to no WBV (84 bpm vs. 78 bpm), reaching 56 % HRmax (220-age)	WBV vs. No vibration
Bogaerts et al. (2009)	94 ♀&♂	67 not reported, overweight	Powerplate™ synchronous vibration	8 different static and dynamic exercises	35-40	2.5-5	none	12.3 g (6.2 g) to 32.2 g (16.1 g)	↑	VO$_2$max improves by 18 % after 1 year (21 % for fitness program), no acute response reported		↑	avg. 41 % of HR reserve (max 62 %)	WBV vs. Regular fitness training program
Cochrane et al. (2008)	8 ♀&♂	28 moderately active	Galileo® oscillation	Squats to 90 degrees for 10 min (3 s down/3 s up)	26	6 (p-p)	none	8.2 g	↑	VO$_2$ reaches 19 ml/kg·min (5.4 METs), equivalent to cycling at 70W		↑	WBV elevates HR to 105 bpm	comparison with Bicycle ergometer at 70 Watts, no difference
Da Silva et al. (2007)	17 ♂	18 highly active, resistance trained	Nemes™ synchronous vibration	Halfsquats 5 sets of 10 reps (2 s down/2 s up), 2 min recovery	30	4	none	14.5 g (7.2 g)	↑	Energy expenditure 18 % higher in WBV (52 vs. 44 kcal), corresponds to walking at 4 km/h. Also 22 % higher during recovery period		ns↑	HR higher during wach set in WBV, absolute values reach 150 bpm in sets 4 and 5 of WBV	WBV squats vs. Regular no vibration squats
Garatachea et al. (2007)	9 ♂	24 recreationally active and sports participation	Nemes™ synchronous vibration	Squats to 90 degrees, 3 min cycles at various speeds (6,4,2 s), 30 % BW added load	30	4	14 g	14.5 g	↑	VO$_2$ increase by 2 to 12 % (up to 6.5 ml/kg·min) compared to no WBV, higher values for faster cycles.		↔	no difference	WBV squats vs. Regular no vibration squats
Hazell et al. (2008)	8 ♂	25 recreationally active, BMI 27	Wave™, synchronous vibration	Squats to 120 degrees, 15 reps of 1 min, 1 min recovery	45	4 (p-p)	none	16.3 g	?	not reported		↔	no difference	WBV vs. No vibration
Rittweger et al. (2000)	37 ♀&♂	24 not reported, healthy	Galileo™ oscillation	Squats to exhaustion (6 s cycles), with 35-40 % BW added load, duration 5-6 min - 2 sessions on different days	26	10.5 (p-p)	15 g	14.3 g	↑	VO$_2$ reaches 21.3 and 22.1 ml/kg·min at exhaustion, i.e. 48.8 and 49.3 % VO$_2$max		↑	HR reaches 128 and 129 bpm (75 % HRmax)	compared to Bicycle ergometry graded test to exhaustion

Study	n (sex)		Subjects / Training	Device	Exercise	Frequency (Hz)	Amplitude (mm)	Reported A$_{peak}$	Calculated A$_{peak}$	VO$_2$	VO$_2$ effect	HR	HR effect	Comparison
Rittweger et al. (2001)	12 ♀&♂	25	not reported	Galileo™ oscillation	Standing, Squats, Squats with load, for 3 min	26	12 (p-p)	18 g (for 30 Hz and 5 mm)	16.3 g	↑	VO$_2$ increases to 10.2, 14.0 and 17.1 ml/kg·min respectively, with average effect of WBV of +4.5 ml/kg·min compared to no WBV	?	not reported	WBV vs. No vibration
Rittweger et al. (2002)	10 ♂	28	regularly trained	Galileo™ oscillation	Standing for 3 min	18,26,34	5	none	6.5 g, 13.6 g, 23.3 g	↑	VO$_2$ increases to 5.7, 6.4 and 7.8 ml/kg·min respectively, compared to no WBV	?	not reported	Various WBV frequencies vs. Rest values
Rittweger et al. (2002)	8 ♂	28	regularly trained	Galileo™ oscillation	Standing for 3 min	26	2.5,5,7.5	none	6.8 g, 13.6 g, 20.4 g	↑	VO$_2$ increases to 4.2, 5.0 and 7.3 ml/kg·min respectively, compared to no resting WBV	?	not reported	Various WBV amplitudes vs. Rest values
Rittweger et al. (2002)	8 ♂	28	regularly trained	Galileo™ oscillation	Standing for 3 min, with added load (40 % FFM on shoulders or waist)	18,34	5	none	6.5 g, 23.3 g	↑	VO$_2$ increases with frequency and with distance from center of gravity, reaches 10.2 ml/kg·min.	?	not reported	WBV with load on waist or shoulders
Vissers et al. (2009)	20 ♀	38	not reported, obese and overweight	Powerplate® synchronous vibration	Standing, dynamic squats, dynamic calf exercises, each for 3 min	35	4	none	19.7 g (9.9 g)	↑	VO$_2$ reaches 0.60, 0.71 and 0.93 l/min respectively, higher in all WBV conditions by 50, 22 and 21 %	↑	HR reaches 95, 103 and 111 bpm respectively, higher in all WBV conditions by 6, 7 and 8 %	WBV vs. No vibration

Arrows in the columns for VO$_2$ and HR indicate direction of effect compared to no vibration. Some studies reported acceleration measurements or calculations (reported A$_{peak}$), in the next column are our calculation (calculated Apeak) based on vibration settings (frequency and amplitude) mentioned by the authors. Two values are presented when the amplitude has not been specified as peak-to-peak. HR, heart rate; BW, body weight; WBV, whole-body vibration; BMI, body mass index; A$_{peak}$, peak platform acceleration; p-p, peak-to-peak.

The increased metabolic demand of the exercises elicited different chronotropic adaptations in END, with a lower heart rate response, although the absolute VO_2 was similar to SED, which could be explained by their probable increased heart compliance and contractility, resulting in a more pronounced increase in stroke volume, although this was not measured in our protocol.

Sedentary subjects

As the untrained subjects have a lower VO_2max, a higher percentage of VO_2max is necessary for the completion of the exercises, but we also observed that the energetic cost (when looking at absolute oxygen uptake) was higher in SED overall. As discussed above, one explanation lies in the fact that SED are unaccustomed to these various types of muscle contractions, do not have as good a balance as athletes, and are thus more prone to accessory muscle use and compensations which raise the metabolic demand. In a similar exercise protocol, Rittweger *et al.* (2000) have observed a lower VO_2 and heart rate response compared to our results, in young healthy male and female subjects: during continuous dynamic squatting to exhaustion with additional load (40 % of body weight for males and 35 % for females), they were only able to elevate oxygen uptake to 49 % of VO_2max, while their peak heart rate was 128 bpm or 75 % of HRmax determined in a maximal bicycle ergometer test. Their protocol differed from ours in that it was an exercise to exhaustion that lasted 5 to 6 min, while our subjects did the exercise for three times three minutes with one minute recovery between bouts. If we look at the oxygen uptake at the end of the second bout, i.e. six minutes of exercise, our sedentary subjects who were doing dynamic squatting with additional load at 26 Hz (with a similar peak-to-peak displacement as the subjects in Rittweger's study) reached 57.7 % of VO_2max, which is higher than the 49 % they observed. Our last three minute bout elevated oxygen uptake to 58.8 %. As for heart rate, our subjects reached 80.1 % of HRmax after six minutes and 82.7 % after nine minutes. Recently Avelar *et al.* (2011) showed in elderly inactive subjects that squatting with vibration increased O_2 uptake by 20 % compared to normal squatting, although the absolute values reached only 6.8 ml·kg⁻¹·min⁻¹ (2 METs). Their vibration settings generated accelerometer measurements of 2 to 5 g. These low acceleration values could explain the smaller metabolic effect seen in their subjects compared to our sedentary subjects. In further experiments, Rittweger's group confirmed an elevated oxygen uptake with added vibrations (Rittweger *et al.*

2001, 2002), albeit the peak VO_2 attained with vibrations in their study was lower than in ours. Squatting for 3 min with vibration elevated O_2 uptake to 14.0 ml·kg⁻¹·min⁻¹, while our subjects doing the same vibration exercise reached 22.8 ml·kg⁻¹·min⁻¹ (V1), and 20.1 ml·kg⁻¹·min⁻¹ (V2). We believe that our protocol with intermittent short recovery allowed our subjects to go to higher intensities of exercise, which is typical of interval training techniques, but these differences are important and still difficult to explain. Rittweger *et al.* (2002) conclude that the amount of O_2 uptake they observed elicits an energy expenditure comparable to moderate walking. Others have also observed elevated O_2 uptake with various WBV exercises and settings (Da Silva *et al.* 2007, Garatachea *et al.* 2007, Cochrane *et al.* 2008, Vissers *et al.* 2009). Table 2 summarizes the studies that have measured oxygen uptake or heart rate response to vibration exercise.

From these various studies, it appears that there is an important variability in the amount of oxygen uptake elicited by various vibration exercises, and especially by different vibration platforms and settings (frequency and amplitude). Although some of the studies use similar technology with almost equivalent peak accelerations, the VO_2 response varies. To address this discrepancy, a few possible explanations can be offered. First, the vibration settings reported in the various studies lack standardization, most notably for amplitude, which needs to be reported as peak-to-peak displacement to avoid any confusion. Second, the numbers reported for frequency and amplitude are the ones given by the platform manufacturers, and only very few of the studies discussed previously have reported actual parameters, with measurements done by accelerometers. The accuracy of the data from manufacturers would need to be experimentally challenged, as it seems that certain devices are more reliable and accurate than others. One study looked at actual measurements of mechanical properties of different platforms, finding that those ones most commonly used in research (Galileo 2000® and Powerplate®) were more reliable than others (Pel *et al.* 2009), which is also confirmed by the accelerometer measurements done by Avelar *et al.* (2011) on their platform. Admittedly, our device was not tested for accuracy and this may play a role in our observations. Third, the studies generally do not report the type of shoes worn by the subjects and their potential damping effect. Our subjects wore only regular unpadded socks, which could have minimized vibration damping and therefore elicited more muscle response compared to subjects who

would be wearing athletic shoes. This has not been measured or compared, though, and could be addressed in the future, as it is accepted that the transmission of vibration diminishes importantly as it travels its way up the musculoskeletal chain from the foot up (Pel *et al.* 2009).

Physical fitness and health have been extensively studied in the last few decades, and most of the studies put emphasis on cardiovascular fitness, i.e. aerobic fitness, by measurement or estimation of VO_2max. Lately however, muscular strength has been shown to help reduce overall and cancer mortality, independently of aerobic fitness (Ruiz *et al.* 2008), and the accumulated evidence has led to the latest exercise and physical activity guidelines from the American College of Sports Medicine (ACSM), which insist on the benefits of an endurance-type and resistance-type activity (Haskell *et al.* 2007). WBV exercises have already shown benefits for strength, especially in population subgroups

that have a lower starting strength (elderly, middle-aged and inactive women). A couple of studies have shown positive effects on VO_2max through a WBV training program of 2 months (Behboudi *et al.* 2011) and 12 months (Bogaerts *et al.* 2009), while others claim that the increased metabolic stimulation by added vibration cannot be sufficient to that effect (Rittweger 2009, Cochrane 2011). In our trial, typical exercises such as the dynamic squat raised oxygen uptake close to 50 % of VO_2max, which corresponded to 65-70 % of HRmax, and also fits the definition of vigorous physical activity (>6 METs). These exercises can meet the ACSM guidelines on exercise training for health (Haskell *et al.* 2007) and dynamic WBV exercise at ≥26 Hz or isometric squats at 32 Hz, carried out three times per week for at least 20 min, could fulfill the requirements for physical activity for health (450-750 MET·min·wk^{-1}) (Fig. 3).

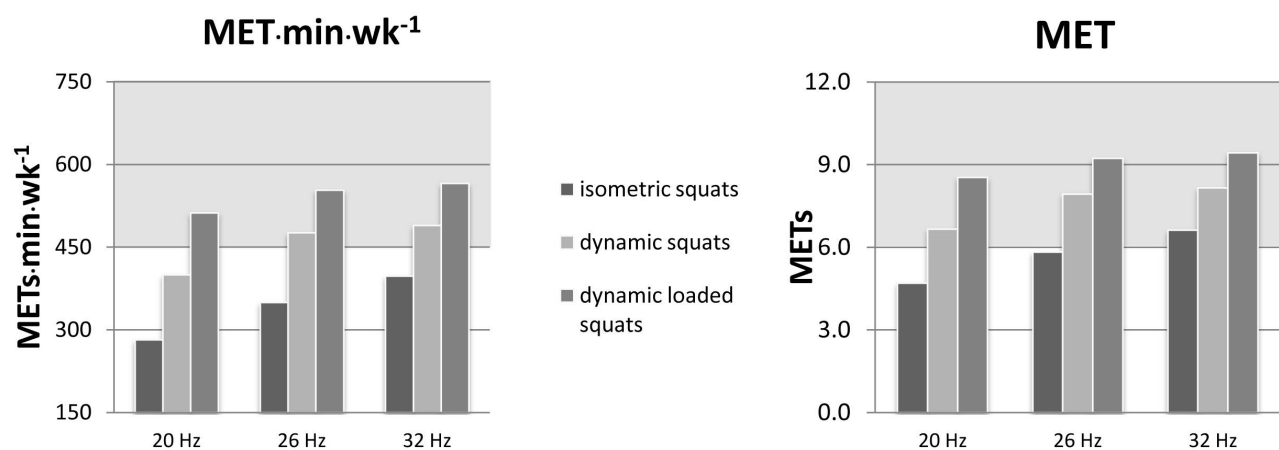**Fig. 3**. Exercise intensities in METs (right) and corresponding total weekly energy expenditure in MET·min·wk^{-1} (left), if three weekly WBV sessions of at least twenty minutes were carried out, in sedentary subjects (SED). The shaded upper zone corresponds to exercise intensities (right) above the definition of vigorous physical activity (>6 METs), and weekly totals (left) sufficient to meet physical activity guidelines (450-750 MET·min·wk^{-1}).

Limitations

The main limitation in our design is the lack of comparison with the absence of vibration. However our main purpose was to investigate the impact of exercise type and the dose-responses relationships with vibration frequency. The very existence of the latter, clearly shown by our results, implies that vibrations *per se* had an effect, as reported by other studies. In addition, the different exercise conditions were not randomized, but carried out one after the other in a sequence that aimed to increase the intensity with time. This was confirmed by the data, but a fatiguing effect of previous exercise might have modified the response to the subsequent one. Another

issue that can raise a few questions is the familiarization with the exercise. We saw that the second session (V2) elicited lower responses in all measurements, and it is not known what the response would be after a longer time of adaptation to this type of training. We think a habituation effect will certainly be present to some extent. We also acknowledge the facts that our sample size was small and that the vibration platform settings (frequency and amplitude) have not been measured objectively in our protocol, as we relied on the parameters given by the manufacturer, which should not be the case if possible in future research.

Conclusion

Our study shows that the metabolic and heart rate response to WBV depend on fitness level and type, and especially that young sedentary or untrained individuals could potentially benefit from WBV training for overall fitness, alongside gains in strength already shown in other studies (Rehn *et al.* 2007, Marin and Rhea 2010). With the growing interest in WBV, we believe our observations bring an addition to the potential benefits for health of this new training modality.

Conflict of Interest

There is no conflict of interest.

References

AVELAR NC, SIMAO AP, TOSSIGE-GOMES R, NEVES CD, MEZENCIO B, SZMUCHROWSKI L, COIMBRA CC, LACERDA AC: Oxygen consumption and heart rate during repeated squatting exercises with or without whole-body vibration in the elderly. *J Strength Cond Res* **25**: 3495-3500, 2011.

BAUTMANS I, VAN HEES E, LEMPER JC, METS T: The feasibility of Whole Body Vibration in institutionalised elderly persons and its influence on muscle performance, balance and mobility: a randomised controlled trial [ISRCTN62535013]. *BMC Geriatr* **5**: 17, 2005.

BEHBOUDI L, AZARBAYJANI MA, AZARBAYJANI H, SALAVATI M: Effects of aerobic exercise and whole body vibration on glycaemia control in type 2 diabetic males. *Asian J Sports Med* **2**: 83-90, 2011.

BOGAERTS AC, DELECLUSE C, CLAESSENS AL, TROOSTERS T, BOONEN S, VERSCHUEREN SM: Effects of whole body vibration training on cardiorespiratory fitness and muscle strength in older individuals (a 1-year randomised controlled trial). *Age Ageing* **38**: 448-454, 2009.

BRUYERE O, WUIDART MA, DI PALMA E, GOURLAY M, ETHGEN O, RICHY F, REGINSTER JY: Controlled whole body vibration to decrease fall risk and improve health-related quality of life of nursing home residents. *Arch Phys Med Rehabil* **86**: 303-307, 2005.

CARDINALE M, SOIZA RL, LEIPER JB, GIBSON A, PRIMROSE WR: Hormonal responses to a single session of wholebody vibration exercise in older individuals. *Br J Sports Med* **44**: 284-288, 2010.

COCHRANE DJ: Vibration exercise: the potential benefits. *Int J Sports Med* **32**: 75-99, 2011.

COCHRANE DJ, STANNARD SR, SARGEANT AJ, RITTWEGER J: The rate of muscle temperature increase during acute whole-body vibration exercise. *Eur J Appl Physiol* **103**: 441-448, 2008.

DA SILVA ME, FERNANDEZ JM, CASTILLO E, NUNEZ VM, VAAMONDE DM, POBLADOR MS, LANCHO JL: Influence of vibration training on energy expenditure in active men. *J Strength Cond Res* **21**: 470-475, 2007.

FAGNANI F, GIOMBINI A, DI CESARE A, PIGOZZI F, DI SALVO V: The effects of a whole-body vibration program on muscle performance and flexibility in female athletes. *Am J Phys Med Rehabil* **85**: 956-962, 2006.

GARATACHEA N, JIMENEZ A, BRESCIANI G, MARINO NA, GONZALEZ-GALLEGO J, DE PAZ JA: The effects of movement velocity during squatting on energy expenditure and substrate utilization in whole-body vibration. *J Strength Cond Res* **21**: 594-598, 2007.

GAUTHIER AP, LARIVIERE M, YOUNG N: Psychometric properties of the IPAQ: a validation study in a sample of northern Franco-Ontarians. *J Phys Act Health* **6** (Suppl 1): S54-S60, 2009.

GUSI N, RAIMUNDO A, LEAL A: Low-frequency vibratory exercise reduces the risk of bone fracture more than walking: a randomized controlled trial. *BMC Musculoskelet Disord* **7**: 92, 2006.

HASKELL WL, LEE IM, PATE RR, POWELL KE, BLAIR SN, FRANKLIN BA, MACERA CA, HEATH GW, THOMPSON PD, BAUMAN A: Physical activity and public health: updated recommendation for adults from the American College of Sports Medicine and the American Heart Association. *Med Sci Sports Exerc* **39**: 1423-1434, 2007.

HAZELL TJ, THOMAS GW, DEGUIRE JR, LEMON PW: Vertical whole-body vibration does not increase cardiovascular stress to static semi-squat exercise. *Eur J Appl Physiol* **104**: 903-908, 2008.

LORENZEN C, MASCHETTE W, KOH M, WILSON C: Inconsistent use of terminology in whole body vibration exercise research. *J Sci Med Sport* **12**: 676-678, 2009.

MAHIEU NN, WITVROUW E, Van DE VOORDE D, MICHILSENS D, ARBYN V, Van DEN BROECKE W: Improving strength and postural control in young skiers: whole-body vibration versus equivalent resistance training. *J Athl Train* **41**: 286-293, 2006.

MARIN PJ, RHEA MR: Effects of vibration training on muscle strength: a meta-analysis. *J Strength Cond Res* **24**: 548-556, 2010.

MYERS J, PRAKASH M, FROELICHER V, DO D, PARTINGTON S, ATWOOD JE: Exercise capacity and mortality among men referred for exercise testing. *N Engl J Med* **346**: 793-801, 2002.

NAZAROV V, SPIVAK G: Development of athlete's strength abilities by means of biomechanical stimulation method (in Russian). *Theory and Practice of Physical Culture* **12**: 445-450, 1985.

PEL JJ, BAGHERI J, Van DAM LM, Van DEN BERG-EMONS HJ, HOREMANS HL, STAM HJ, Van DER STEEN J: Platform accelerations of three different whole-body vibration devices and the transmission of vertical vibrations to the lower limbs. *Med Eng Phys* **31**: 937-944, 2009.

REHN B, LIDSTROM J, SKOGLUND J, LINDSTROM B: Effects on leg muscular performance from whole-body vibration exercise: a systematic review. *Scand J Med Sci Sports* **17**: 2-11, 2007.

RITTWEGER J: Vibration as an exercise modality: how it may work, and what its potential might be. *Eur J Appl Physiol* **108**: 877-904, 2009.

RITTWEGER J, BELLER G, FELSENBERG D: Acute physiological effects of exhaustive whole-body vibration exercise in man. *Clin Physiol* **20**: 134-142, 2000.

RITTWEGER J, SCHIESSL H, FELSENBERG D: Oxygen uptake during whole-body vibration exercise: comparison with squatting as a slow voluntary movement. *Eur J Appl Physiol* **86**: 169-173, 2001.

RITTWEGER J, EHRIG J, JUST K, MUTSCHELKNAUSS M, KIRSCH KA, FELSENBERG D: Oxygen uptake in whole-body vibration exercise: influence of vibration frequency, amplitude, and external load. *Int J Sports Med* **23**: 428-432, 2002.

ROBERGS RA, DWYER D, ASTORINO T: Recommendations for improved data processing from expired gas analysis indirect calorimetry. *Sports Med* **40**: 95-111, 2010.

RONNESTAD BR: Comparing the performance-enhancing effects of squats on a vibration platform with conventional squats in recreationally resistance-trained men. *J Strength Cond Res* **18**: 839-845, 2004.

RUIZ JR, SUI X, LOBELO F, MORROW JR JR, JACKSON AW, SJOSTROM M, BLAIR SN: Association between muscular strength and mortality in men: prospective cohort study. *BMJ* **337**: a439, 2008.

SESSO HD, PAFFENBARGER RS JR, LEE IM: Physical activity and coronary heart disease in men: The Harvard Alumni Health Study. *Circulation* **102**: 975-980, 2000.

SLATKOVSKA L, ALIBHAI SM, BEYENE J, CHEUNG AM: Effect of whole-body vibration on BMD: a systematic review and meta-analysis. *Osteoporos Int* **21**: 1969-1980, 2010.

TSCHOPP M: Performance Diagnostics. In: *Book Performance Diagnostics.* Swiss Olympic Medical Centers (ed.) Davos, Loèche-les-Bains, Macolin, Muttenz, Zurich, 2003, p. 63.

VERSCHUEREN SM, ROELANTS M, DELECLUSE C, SWINNEN S, VANDERSCHUEREN D, BOONEN S: Effect of 6-month whole body vibration training on hip density, muscle strength, and postural control in postmenopausal women: a randomized controlled pilot study. *J Bone Miner Res* **19**: 352-359, 2004.

VISSERS D, BAEYENS JP, TRUIJEN S, IDES K, VERCRUYSSE CC, Van GAAL L: The effect of whole body vibration short-term exercises on respiratory gas exchange in overweight and obese women. *Phys Sportsmed* **37**: 88-94, 2009.

VISSERS D, VERRIJKEN A, MERTENS I, Van GILS C, Van de SOMPEL A, TRUIJEN S, Van GAAL L: Effect of long-term whole body vibration training on visceral adipose tissue: a preliminary report. *Obes Facts* **3**: 93-100, 2010.

WARBURTON DE, NICOL CW, BREDIN SS: Health benefits of physical activity: the evidence. *CMAJ* **174**: 801-809, 2006.