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Whole-body vibration dosage alters leg blood flow

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Summary

The effect of whole-body vibration dosage on leg blood flow was investigated. Nine healthy young adult males completed a set of 14 random vibration and non-vibration exercise bouts whilst squatting on a Galileo 900 plate. Six vibration frequencies ranging from 5 to 30 Hz (5 Hz increments) were used in combination with a 2·5 mm and 4·5 mm amplitude to produce twelve 1-min vibration bouts. Subjects also completed two 1-min bouts where no vibration was applied. Systolic and diastolic diameters of the common femoral artery and blood cell velocity were measured by an echo Doppler ultrasound in a standing or rest condition prior to the bouts and during and after each bout. Repeated measures MANOVAs were used in the statistical analysis. Compared with the standing condition, the exercise bouts produced a four-fold increase in mean blood cell velocity ($P<0{\cdot}001$) and a two-fold increase in peak blood cell velocity ($P<0{\cdot}001$). Compared to the non-vibration bouts, frequencies of 10–30 Hz increased mean blood cell velocity by approximately 33% ($P<0{\cdot}01$) whereas 20–30 Hz increased peak blood cell velocity by approximately 27% ($P<0{\cdot}01$). Amplitude was additive to frequency but only achieved significance at 30 Hz ($P<0{\cdot}05$). Compared with the standing condition, squatting alone produced significant increases in mean and peak blood cell velocity ($P<0{\cdot}001$). The results show leg blood flow increased during the squat or non-vibration bouts and systematically increased with frequency in the vibration bouts.

Introduction

Indirect vibration of the body, commonly referred to as whole-body vibration, has become a popular exercise method in recent years. It can be delivered to the body through a hand-held vibrating bar (Issurin & Tenenbaum, 1999) or through the feet by an oscillating platform (Rittweger *et al.*, 2001). Currently, there are two types of vibration platforms available on the market. A platform that moves or oscillates in a vertical direction (fixed frequency and amplitude) and a platform that rotates about a fixed horizontal axis (variable frequency and amplitude). This investigation utilized the latter type of platform as frequency and amplitude (peak-to-base displacement) can be changed. Additionally, this system does not directly accelerate the body's centre of mass and therefore larger peak accelerations are tolerated than with linear acceleration. The aim of this study was to investigate the effect of whole-body vibration on leg blood flow velocity when delivered at different dosage levels (frequency and amplitude) by a rotary style plate. This information is important in order to ascertain whether whole-body vibration delivered by these systems might provide therapeutic benefit to people with reduced or impeded leg blood flow such as the elderly or those with diabetes mellitus.

Many effects of low-frequency (50 Hz or less) whole-body vibration have been reported in the literature. These include increased leg power, strength and flexibility in athletes (Bosco *et al.*, 1999; Mester *et al.*, 2006; Rees *et al.*, 2008), increased bone formation in post-menopausal women (Russo *et al.*, 2003; Verschueren *et al.*, 2004), improved postural control and mobility in adults with multiple sclerosis (Schuhfried *et al.*, 2005) and reduced arterial atrophy in people undergoing bed rest (Bleeker *et al.*, 2005). Immediate effects include increased oxygen consumption, heightened muscle activity and leg blood flow velocity in healthy adults and increased knee extension strength in recovering stroke patients (Rittweger *et al.*, 2000; Kerschan-Schindl *et al.*, 2001; Cardinale & Bosco, 2003; Tihanyi *et al.*, 2007a). On the other hand, there is evidence to show that high-frequency vibration (above 80 Hz) can restrict blood flow (Greenstein & Kester, 1992; Bovenzi *et al.*, 1999) and even cause hypertrophy of the smooth vascular muscle cells (Takeuchi *et al.*, 1986). These problems are often encountered by operators of power tools.

Only a few studies involving healthy young adults have investigated the effect of whole-body vibration on leg blood flow. Kerschan-Schindl *et al.* (2001) found vibrations delivered by a rotary type platform with a frequency of 26 Hz and amplitude of 3 mm (Galileo 2000, Novotec, Pforzheim, Germany) doubled leg blood flow (measured with a Doppler ultrasound system) after 9 min of vibration. Zhang *et al.* (2003) similarly found increased leg blood flow, measured by photoplethysmography, after direct transmission of vibration to the foot of subjects (Zhang *et al.*, 2003).

Our hypothesis was that leg blood flow systematically increases with vibration frequency (up to 30 Hz) and amplitude (up to 4·5 mm). Blood flow velocity, measured by a Doppler ultrasound system, in the common femoral artery of a group of healthy young adults was recorded before, during and after 1-min bouts of whole-body vibration (Radegran, 1997; Radegran & Saltin, 1998).

Methods

Subjects

Nine healthy, community-dwelling male adults participated in this study (age = 21·8 years, SD = 4·4 years; stature = 175·6 cm, SD = 6·3 cm; mass = 75·0 kg, SD = 9·1 kg). Subjects were recruited from staff and students of the University of Melbourne. Exclusion criteria were smoking, known vascular disease and diabetes. Subjects were not allowed to consume caffeine 12 h before testing or food 3 h before testing. Additionally, no strenuous exercise was permitted 48 h before testing. Written informed consent was obtained from each subject. The study was approved by the Human Research Ethics Committee of the University of Melbourne and performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

Study protocol

Each subject's stature, mass and age were recorded. Subjects wore a pair of loose-fitting shorts, a T-shirt and were barefooted. Prior to the session, subjects lay in a supine position on a plinth for a period of 5 min. Following this period, the diameters (systolic and diastolic) and red blood cell velocity (BCV) of the common femoral artery of each subjects' right leg were recorded by a pulsed colour-coded Doppler ultrasound device with a 5–10 MHz broadband linear array transducer (LOGIQ™ Book, GE Medical, Milwaukee, WI, USA). The transducer was placed in the centre of the common femoral artery about 2 cm above the bifurcation into the superficial and deep femoral arteries. Two images of the common femoral artery diameters were recorded during the peak systolic and end-diastolic phases (as determined from flow profile). For the blood cell velocity measurements, the transducer was positioned parallel to the vessel with the inclination angle held below 60°. This protocol was used by the same investigator throughout the study.

The ultrasound probe was held in the same position throughout the test session. This was possible as only the legs were accelerated by the vibration plate whereas the body from the hips upwards remained relatively still due to the dampening of the vibration by the ankles, knees and hips. This was investigated at the beginning of the study with a 3D accelerometer (HOBOware; Onset Computer Corp., Bourne, MA, USA) placed on the site of the ultrasound probe. A subject stood in the squat position on the vibration plate for five 1-min bouts of vibration with 1-min rest between each bout. Amplitude and frequency were set at 4·5 mm and 30 Hz respectively so as to produce the highest acceleration. The accelerometer was set at 100 Hz and recorded the resultant acceleration for each 1-min bout. On a second occasion, the accelerometer was gripped between the teeth in order to measure the acceleration experienced at the head. The resultant acceleration, including gravity, experienced at the ultrasound probe site and head (gripped between teeth) were 1·07 g (SD = 0·06 g) and 1·01 g (SD = 0·03 g) respectively. These values fall well below the ISO2631 zone where health risks are likely (Mansfield, 2005).

The placement site for the probe was easily identified by anatomical landmarks. Once identified it was marked with a crayon. In order to establish the reliability of the measurement protocol, intraclass correlation coefficients (ICCs) (Portney & Watkins, 2000) were calculated for the common femoral artery, mean BCV and peak BCV data recorded during the standing position before each exercise bout. In total, 14 measures of these data were recorded for each subject. These values were found to demonstrate good reliability. The ICCs for the common femoral artery, mean BCV and peak BCV data recorded prior to the vibration bouts were 0·997, 0·868 and 0·935 respectively ($P<0·001$).

The vibration frequency of the plate was set by an operator, whereas amplitude was set by the position of the feet on the plate. Feet were placed parallel to each other at 28 or 50 cm apart (measured from the midlines of the feet). The smaller distance corresponded to a 2·5 mm amplitude (peak-to-base displacement), whereas the larger distance corresponded to a 4·5 mm amplitude. Six vibration frequencies ranging from 5 to 30 Hz (full range of system) at 5 Hz increments were used in combination with the two amplitudes to produce 12 exercise bouts of vibration. Subjects also completed another two exercise bouts where no vibration was applied (a bout for each foot placement or amplitude condition). In total 14 exercise bouts were completed: 12 vibration bouts and two non-vibration bouts. The 14 exercise bouts were randomized for each subject. During each bout a squat posture was adopted with 50° of knee flexion (as measured by a goniometer) with weight supported on the forefeet. This posture was adopted in order to minimize transmissibility of the ground-based vibrations to the pelvis and upper body. Previous work has shown a bent knee posture greatly attenuates the mechanical signals generated by vibration (Rubin *et al.*, 2003). A straight leg posture was not used as unacceptably high accelerations can be transmitted to the upper body (Griffin, 1998). All subjects were encouraged to report any unusual symptoms (e.g. discomfort, queasiness) and were allowed to stop the vibration at any time.

Prior to each exercise bout, subjects sat on a chair and rested for 3 min before standing on the vibration plate (Novotec). Subjects stood on the plate (not activated) for a period of 1 min whilst common femoral artery diameters (systolic and diastolic) and BCVs were recorded. Following this period, the subjects flexed the knees and hips to achieve 50 degrees of flexion and lightly grasped a handrail. The plate was then activated for a period of 1 min. One minute exercise bouts were used as it is difficult for people to hold a squat position, especially at high vibration frequencies, for periods greater than 1 min (Mester *et al.*, 2006). Upon completion of a bout, each subject slowly returned to a standing position (within 5 s) and then remained on the plate for a period of 2 min. Continuous recordings of BCV were made during the exercise bouts and for 2 min after each bout. Common femoral artery (CFA) diameters were captured 2 min after each bout. These recording processes were repeated for each bout and took about 7 min. Overall, the test session for each subject lasted about 1 h and 45 min.

Heart rate and blood pressure were recorded by a UA-767 Plus blood pressure monitor (A & D Medical, Milpitas, CA, USA) in the supine and the standing positions before each bout, during each bout (45 s into exercise bout), and at 1- and 2-min after each bout.

Data analysis

Common femoral artery diameter measures were taken in the standing period before each bout and 2-min after each bout. Three diameter readings were extracted from two images. An average diameter was calculated from these readings.

On average, five blood cell velocity profiles were captured at the following time points: (i) 30 s before each exercise bout during which the subjects were standing; (ii) at 15, 30 and 45 s during each exercise bout: and, (iii) at 5, 10, 15, 30, 45, 75 and 105 s of quiet standing after each exercise bout. These were automatically recorded by software that drew an envelope around the root mean square signal. This information was used to extract mean and peak BCV data.

Statistical analysis

SPSS (version 12.0.1) was used for all statistical analyses. A two-way repeated measures MANOVA was used to examine the effects of amplitude and frequency. In order to further examine the effect of frequency, the BCV measures recorded at 15, 30 and 45 s into the vibration bouts of 5–30 Hz were compared with the same measures recorded during the non-vibration bouts (standing in squat position). Heart rate and blood pressure measures recorded at 45 s into the vibration bouts of 5–30 Hz were also compared with the equivalent measures recorded during the non-vibration bouts. Common femoral artery diameters recorded 1-min before an exercise bout (standing position) were compared with common femoral artery diameters recorded 2-min after the bout (standing position).

One-way repeated measures MANOVAs were used to determine when BCV, heart rate and blood pressure measures had returned to resting levels (recorded during the standing position before the exercise bouts). Specifically, BCV measures recorded at 5, 10, 15, 30, 45, 75 and 105 s after the bouts (subjects had returned to a standing position) were compared with resting levels recorded in the standing position before the exercise bouts. The alpha level was set to 0·01 for this part of the analysis due to the high number of comparisons. The supine measurements were not used in the MANOVA analyses and were only used for reference.

Results

A typical plot of a BCV signal recorded during and after a vibration exercise bout (30 Hz and 2·5 mm) is shown in Fig. 1. This plot shows two signals during the period of vibration (left panel) and one signal after vibration (right panel). Importantly, the pattern and magnitude of the BCV signal recorded during and after vibration are similar; that is, the signal was unaffected by vibration. For comparison purposes, the heart rate, blood pressure, CFA diameter and BCV data recorded during the supine and standing positions before the exercise bouts are listed in Table 1.

Statistical analysis revealed the CFA diameter measures were not affected by vibration amplitude and frequency. For this reason, these data are not presented in this paper. In contrast, mean blood cell velocity (refer to Table 2) increased over three-fold (*c.* 46 cm s^{-1}) during the non-vibration exercise bouts (squat only) and over four-fold (*c.* 59 cm s^{-1}) during the vibration exercise bouts (squat with vibration) when compared to the mean blood cell velocity (*c.* 14 cm s^{-1}) recorded during the standing position immediately before the exercise bouts (Table 1).

Vibration amplitude had a significant affect upon blood cell velocity (refer to Fig. 2). Mean BCV measures recorded 45 s into the exercise bouts were significantly increased by the 4·5 mm amplitude condition ($P = 0{\cdot}018$). This condition resulted in a 27% higher mean BCV value ($P = 0{\cdot}013$) than

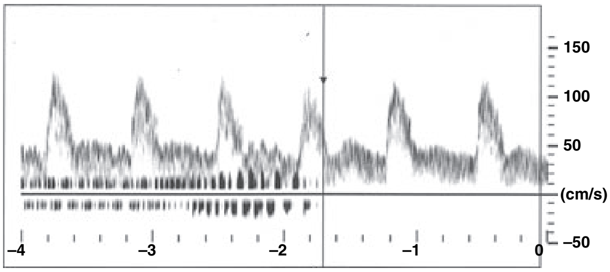

Figure 1 Ultra-sound blood cell flow velocity signal over a 4 s time period during and at the end of a vibration bout of 30 Hz frequency and 2·5 mm amplitude. The horizontal axis indicates time in seconds and the *y*-axis indicates blood cell velocity in cm s^{-1}. The arrow identifies the termination of the vibration. Squatting position was unchanged during the shown sequence.

Table 1 Descriptive statistics for heart rate, blood pressure, CFA diameter and blood cell velocity recorded in the supine and standing positions before the exercise bouts.

	Supine							Standing						
Subject	**HR bpm**	**BP_{sys} [mmHg]**	**BP_{dia} [mmHg]**	**CFA $diameter_{sys}$ [mm]**	**CFA $diameter_{dia}$ [mm]**	**Mean velocity [cm s^{-1}]**	**Peak velocity [cm s^{-1}]**	**HR bpm**	**BP_{sys} [mmHg]**	**BP_{dia} [mmHg]**	**CFA $dia\text{-}meter_{sys}$ [mm]**	**CFA $dia\text{-}meter_{dia}$ [mm]**	**Mean velocity [cm s^{-1}]**	**Peak velocity [cm s^{-1}]**
1	45	110	68	1·16	1·15	15·5	106·2	53	124	84	1·18	1·17	8·9	52·4
2	60	107	63	0·92	0·91	13·2	119·4	72	110	77	0·95	0·95	17·0	64·7
3	61	107	55	0·91	0·88	10·7	93·4	78	117	74	0·94	0·92	15·8	71·7
4	67	114	71	0·9	0·90	18·1	112·2	75	112	85	0·94	0·93	28·8	71·3
5	51	110	64	0·97	0·96	18·1	111·0	54	124	76	1·01	1·00	6·7	49·5
6	67	112	69	0·87	0·87	14·4	155·3	83	115	85	0·94	0·93	12·1	68·2
7	65	112	95	0·80	0·80	8·0	121·5	75	116	95	0·89	0·90	15·6	77·5
8	66	128	78	0·96	0·96	33·9	125·4	75	129	94	1·02	1·02	8·3	37·5
9	66	157	98	1·01	1·01	9·5	86·8	65	158	110	1·05	1·04	11·6	56·9
Mean	61	117	73	0·94	0·94	15·7	114·6	70	123	87	0·99	0·98	13·9	61·1
SD	8	16	15	0·10	0·10	7·7	19·9	10·5	15	11	0·09	0·08	6·7	12·9

Table 2 Descriptive statistics for heart rate, blood pressure and blood cell velocities at 45 s into the 60 s of the exercise bouts.

Frequency [Hz]	**HR [bpm]**		**BP_{sys} [mmHg]**		**BP_{dia} [mmHg]**		**BCV_{mean} [cm s^{-1}]**		**BCVpeak [cm s^{-1}]**	
Amplitude [mm]	2·5	4·5[a]	2·5	4·5[a]	2·5	4·5	2·5	4·5[a]	2·5	4·5
Non-vibration	79·6 (10·4)	80·2 (9·2)	121·4 (10·8)	118·7 (15·9)	86·7 (11·9)	84·8 (13·4)	45·4 (12·8)	46·6 (10·5)	99·1 (18·7)	105·5 (20·3)
5	84·9* (7·7)	95* (3·8)	120·4 (13·0)	132·2 (12·3)	83 (14·3)	87·2 (10·5)	47·7 (12·2)	48·5 (11·7)	122·8* (23·5)	118·2* (28·0)
10	92·8* (4·0)	96·8* (8·6)	114 (9·7)	120·3 (17·9)	82·3 (4·6)	83·5 (8·2)	52·1** (14·6)	56·2** (8·2)	110·7** (25·3)	119·3** (21·0)
15	82·8* (10·0)	92* (6·3)	123·1 (12·3)	119·1 (12·1)	81·7 (9·3)	80·3 (12·7)	53·3* (10·9)	58·8* (15·1)	118** (27·4)	122·8** (27·1)
20	80·6 (10·8)	85·6 (10·9)	121·2 (16·5)	128·4 (16·3)	80·8 (12·8)	88·4 (10·4)	58·9* (11·1)	64·1* (19·5)	121·4* (18·9)	121·8* (31·0)
25	84·3 (8·6)	83·6 (11·4)	123 (8·6)	121 (6·8)	88·8 (15·6)	85·8 (12·9)	57·7* (14·1)	70·4* (21·3)	119·2* (23·0)	132·9* (35·4)
30	81·3 (10·6)	85·1 (11·8)	115·8 (11·4)	132·7 (20·4)	82·1 (6·4)	88·9 (13·7)	61·5* (15·5)	78·4* (21·8)	129·8* (29·2)	151·8* (41·4)

[a] P<0·01 for main effect of amplitude.
*P<0·01 for main effect of frequency (compared to non-vibration bout).
**P<0·05 for main effect of frequency (compared to non-vibration bout).

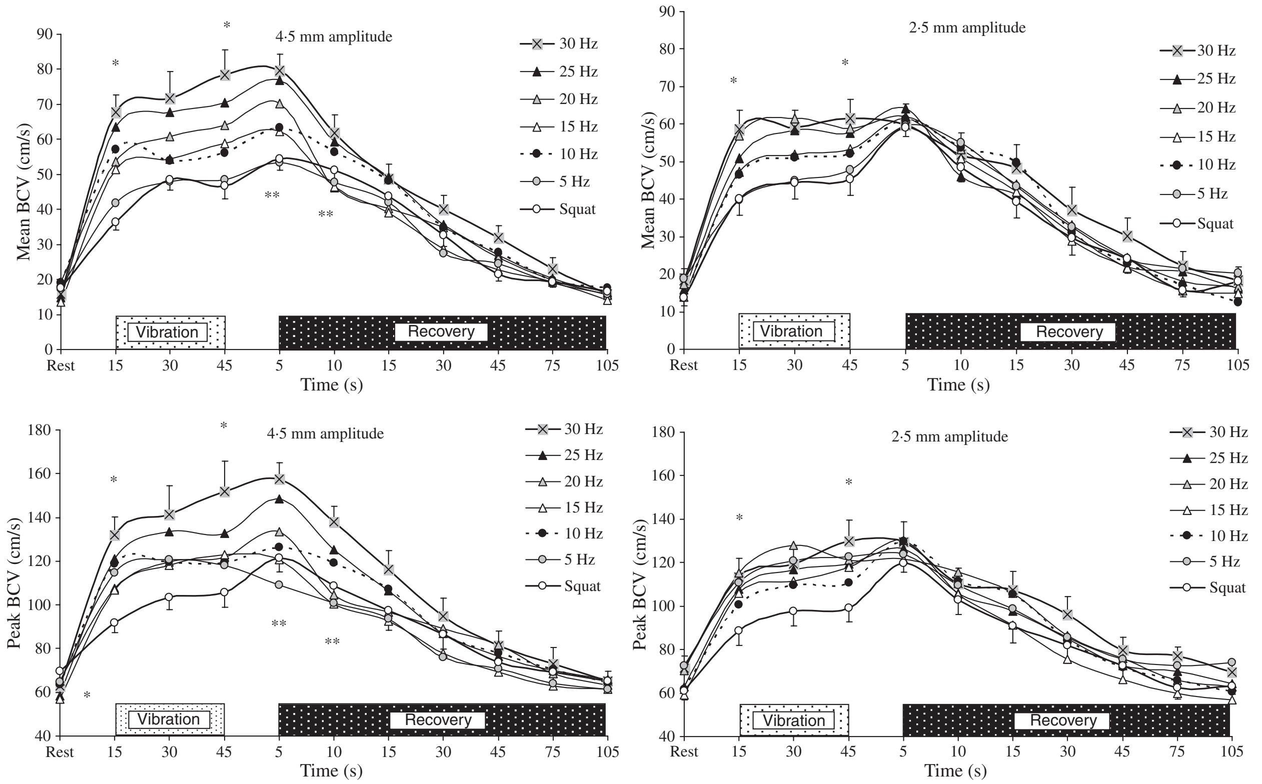

Figure 2 Plots of mean (top panels) and peak (bottom panels) blood cell velocity at different frequencies and amplitude. The large amplitude plots (4·5 mm) are shown in the left panels, whereas the small amplitude plots (2·5 mm) are shown in the right panels. Error bars depict standard errors and are only shown for the non-vibration bouts and the 30 Hz vibration frequency bouts. **P<0·05 for MANOVA interactive effect of frequency and amplitude, *P<0·01 for MANOVA main effect of frequency.

the 2·5 mm amplitude condition (refer to Table 2). The larger amplitude was also associated with (P = 0·004) higher heart rate and systolic blood pressure measures (Table 2). On average, heart rates during the 4·5 mm bouts were approximately 5% higher than the 2·5 mm bouts.

Vibration frequency was found to have a significant effect upon the measures of blood cell velocity (P<0·001). During vibration bouts of 10 Hz and above (i.e. squat with vibration), mean BCVs measured at the 15 and 45 s marks were significantly higher (P<0·05) than velocities recorded at the equivalent time points during the non-vibration bouts where subjects only stood in the squat position on the vibration plate (refer to Table 2 and Fig. 2). On average, the 30 Hz vibration bouts resulted in mean BCV values of about 70 cm s^{-1} that were approximately 50% higher than the non-vibration bouts (*c.* 46 cm s^{-1}). Similarly, vibration frequencies of 5 Hz and above resulted in significantly higher peak BCV values than the non-vibration bouts (P<0·05). On average, the vibration bouts resulted in peak BCV values (*c.* 127 cm s^{-1}) that were about 25% higher than the non-vibration bouts (*c.* 102 cm s^{-1}).

Blood cell velocity (mean and peak values) rose sharply in the initial 15 s (refer to Fig. 2) and increased at a lesser rate until the end of the exercise bouts. Compared with the rest condition (standing with straight legs before a bout), these measures remained elevated for 30 s after each bout (P<0·01) but decreased rapidly thereafter. Seventy-five seconds after the bouts, these measures had returned to resting levels.

Discussion

Compared with the mean blood cell velocity recorded in the standing position immediately prior to the exercise bouts (13·9 cm s^{-1}), whole-body vibration of 4·5 mm amplitude at frequencies of 20–30 Hz produced a five-fold increase in mean BCV (*c.* 71 cm s^{-1}) whereas vibration of 2·5 mm amplitude at frequencies of 20–30 Hz produced a four-fold increase in mean BCV (*c.* 60 cm s^{-1}). Interestingly, the non-vibration condition, where subjects stood in the squat posture with no vibration produced a three-fold increase (*c.* 46 cm s^{-1}) in mean BCV. Hence, squatting alone produces significant increases in mean blood cell velocity.

In a previous study that used the same vibration device, Kerschan-Schindl *et al.* (2001) found a two-fold increase in mean blood flow velocity in the popliteal artery after a 9 min vibration bout at 26 Hz and 3 mm amplitude. The difference in blood flow response is most likely due to differing methodologies as this study used the common femoral artery whereas Kerschan-Schindl used the popliteal artery. The common femoral artery supplies the whole leg whereas the popliteal artery only supplies the ankle extensors.

The concomitant increase of blood flow velocity and heart rate suggests that muscle metabolic demand drove the increased blood flow. This is supported by Rittweger and colleagues (Rittweger *et al.*, 2002) who investigated oxygen uptake during whole-body vibration delivered by a Galileo plate with three frequencies of 18, 26 and 34 Hz and three amplitudes of 2·5, 5 and 7·5 mm. They found a proportional increase in oxygen uptake with increasing vibration frequency and a small increase from 2·5 to 5 mm amplitude and a larger increase from 5 to 7·5 mm. In another study, squatting on a rotary vibration plate at a frequency of 26 Hz and amplitude of 6 mm was found to increase oxygen uptake by 4·5 ml min^{-1} kg^{-1} (Rittweger *et al.*, 2001). This study, however, did not compare oxygen demand during vibration to oxygen demand during isometric squatting. Our study found that 1-min of isometric squatting increases blood flow to the legs two-threefold compared to quiet standing. A rise in mean and peak BCV (significant at $P<0{\cdot}001$ for both amplitudes) was found 5 s after the bouts, which was when subjects started to slowly return to a standing position. This implies the presence of ischemia in the knee and ankle extensors with 1-min of isometric squatting causing the compensatory increase in blood flow after relaxation of the isometrically contracting muscles. A rise in BCV was also found after some of the whole-body vibration bouts, however, this rise tended to be smaller than after isometric squatting and at some frequencies it was even absent (Fig. 2). This indicates that whole-body vibration may prevent at least some of the ischemia that develops during isometric contraction in a static squatting position.

A study by Rittweger and colleagues (Rittweger *et al.*, 2000) compared responses in heart rate and blood pressure immediately after slow squatting on a vibration plate to exhaustion and cycle ergometry to exhaustion. A Galileo vibration device was used with a frequency of 26 Hz and amplitude of 5·3 mm. Squatting (at 3 s down and 3 s up) was performed with an additional load fixed around the waist of 40% body mass for males and 35% body mass for females. Heart rate and systolic blood pressure increased after whole-body vibration squatting to exhaustion, but these increases were significantly less than after cycling to exhaustion. Diastolic blood pressure decreased significantly more after whole-body vibration squatting compared to cycling. They suggested that arterial vasodilation may have caused the drop in diastolic blood pressure at concomitant increases of systolic blood pressure and heart rate, but could not specify whether the dilation occurred during or only after cessation of whole-body vibration. The present study found no effect of vibration on diastolic blood pressure. The different findings between our study and that of Rittweger and colleagues is most likely due to the active exercise employed, whereas our study employed quasi-isometric muscle contractions; the small vibration amplitude causes small changes in hip, knee and ankle angles, however these changes may be compensated for by passive rather than active structures of the muscle-tendon apparatus.

Vibration may lead to an increase in shear forces at the vascular endothelium due to the inertia of the blood. Endothelial-derived vasodilators such as nitric oxide and prostaglandins are thought to be released as a response to increased shear forces at the vascular endothelium. Shear stress at the endothelium represents the frictional force of the blood on the endothelial layer and is dependent on blood flow velocity, vessel diameter and blood viscosity. As common femoral artery diameter remained unchanged 2 min after vibration, there is no indication that endothelial dependent vasodilation in conduit arteries was a contributing factor in the present study. As with this study, Kerschan-Schindl and colleagues also found no change in systolic arterial diameter before and after vibration (Kerschan-Schindl *et al.*, 2001; Tihanyi *et al.*, 2007b). It is proposed, therefore, that the increase in blood flow with whole-body vibration is most likely due to heightened muscle activity and muscle metabolic demand resulting from the activation of muscle spindle reflexes (Cardinale & Wakeling, 2005).

Kerschan-Schindl and colleagues have proposed that a reduction in blood viscosity may be another possible mechanism for increased blood flow after whole-body vibration (Kerschan-Schindl *et al.*, 2001). While this seems plausible, it is unclear as to why blood viscosity would remain affected after a bout of whole-body vibration.

A limitation of this study was that the squat posture could not be maintained throughout the 2 min follow-up period after the vibration bout, instead, subjects returned to a standing position within 5 s of the bout. This meant that the follow-up period was performed in a different position. However, even if subjects could have managed to squat longer, muscle fatigue would have started to affect the measurements. Fatigue cannot be excluded in the present study, however, fatigue would have affected all trials at different frequencies (including the non-vibration bout) similarly, hence the comparison of 5–30 Hz to the non-vibration condition is still valid.

The results of this investigation show that isometric squatting alone can significantly increase leg blood flow. Significant increases in leg blood flow were also found with whole-body vibration. Increasing frequency produced systematic increases in leg blood flow whereas the increase in amplitude was found to be additive to frequency. The 4·5 mm amplitude, for example, only produced a significant increase in leg blood flow when combined with a 30 Hz frequency. Essentially, isometric squatting during short 1-min bouts of whole-body vibration is an exercise modality that increases leg blood flow and muscle activity above that achieved by isometric squats alone. However, squatting alone produces significant increases in leg blood flow. All considered, whole-body vibration may be a safe and effective exercise modality to increase leg blood flow providing a person can dampen the vibration experienced at the pelvis, upper body and head. Based on the findings of this study, it is reasonable to conclude that a vibration amplitude of 2·5 mm coupled with vibration frequencies in the order 5–20 Hz produce significant increases in leg blood flow that are higher than that achieved by isometric squatting alone.

Higher amplitudes and frequencies are not warranted due to the fact that high accelerations may be transmitted to the upper body.

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