Whole-body vibration exercise leads to alterations in muscle blood volume

K. Kerschan-Schindl[1], S. Grampp[2], C. Henk[2], H. Resch[3,4], E. Preisinger[1], V. Fialka-Moser[1] and H. Imhof[2]

[1]Department of Physical Medicine and Rehabilitation, University of Vienna, [2]Department of Radiology, Osteology, University of Vienna, [3]Department of Internal Medicine, KH der Barmherzigen Schwestern, and [4]Ludwig Bolzmann Institution of Ageing Research, 1220 Vienna

Received 16 October 2000; accepted 5 February 2001

Correspondence: Katharina Kerschan-Schindl MD, Department of Physical Medicine and Rehabilitation, Waehringer Guertel 18-20, A-1090 Vienna, Austria

Summary

Occupationally used high-frequency vibration is supposed to have negative effects on blood flow and muscle strength. Conversely, low-frequency vibration used as a training tool appears to increase muscle strength, but nothing is known about its effects on peripheral circulation. The aim of this investigation was to quantify alterations in muscle blood volume after whole muscle vibration – after exercising on the training device Galileo 2000 (Novotec GmbH, Pforzheim, Germany). Twenty healthy adults performed a 9-min standing test. They stood with both feet on a platform, producing oscillating mechanical vibrations of 26 Hz. Alterations in muscle blood volume of the quadriceps and gastrocnemius muscles were assessed with power Doppler sonography and arterial blood flow of the popliteal artery with a Doppler ultrasound machine. Measurements were performed before and immediately after exercising. Power Doppler indices indicative of muscular blood circulation in the calf and thigh significantly increased after exercise. The mean blood flow velocity in the popliteal artery increased from 6·5 to 13·0 cm s^{-1} and its resistive index was significantly reduced. The results indicate that low-frequency vibration does not have the negative effects on peripheral circulation known from occupational high-frequency vibration.

Keywords: arterial blood flow, muscle contraction, tissue blood flow, vibration.

Introduction

As early as in 1949, Whedon *et al.* (1949) reported the positive effect of passive exercise, by means of an oscillating bed, on metabolic abnormalities in plaster-immobilized patients. In an experimental study it has been shown that the application of 50 Hz, 10 ***g*** vibration for 2–5 h daily increased the cross-section of muscle fibres and reduced the fat content of muscle tissue (Hettinger, 1956). A randomized study showed that, in athletes, 3 weeks of strength training (sitting bench-press) with superimposed vibratory stimulation led to an almost 50% increase in the one-repetition-maximum compared with an average gain of 16% with conventional training and no gain for the control group (Issurin *et al.*, 1994). On the other hand, investigating forestry operators, Bovenzi *et al.* (1991) showed that a loss in grip strength may occur after prolonged occupational vibration exposure. Workers who use hand-held vibrating tools may also experience finger blanching attacks as a result of episodic vasospasm in the digital vessels (Bovenzi & Griffin, 1997). An experimental study with rats attached to a vibrating table (80 Hz, 32 m s^2) 5 h daily for 2 days indicated that vibration may lead to muscle injury (Necking *et al.*, 1996).

The power Doppler sonography technique allows quantification of relative moving blood volume (Rubin *et al.*, 1995). MR imaging and conventional colour Doppler imaging correlate well with other physiological measures of exercise-induced changes in blood flow (Hirsch *et al.*, 1995; Pena *et al.*, 1996). Fleckenstein *et al.* (1988) showed that a few minutes of muscle activity led to signal intensity changes on MR images, which correlated moderately with the level of exertion.

When standing on a vibrating platform, one tends to attenuate the imposed vibration and misalignment of stance by physical activity. The rhythmic muscle contractions evoked by standing on a vibrating platform may be beneficial in counteracting the lack of other physical exercise, but its effects on peripheral circulation are not thoroughly examined yet.

So far, most studies investigating the effect of vibration on blood flow have used frequencies common among tools used in industry which generally means 80–100 Hz (Lundström & Burstöm, 1984). In this study this range of frequency is summarized as 'high frequency' and frequencies below that are called 'low frequency'. A comparison of different magnitudes (22 and 87 m s^{-2}) and frequencies (31·5 and 125 Hz) revealed that the high-frequency vibration stimulus produced a greater reduction in finger blood flow (Bovenzi & Griffin, 1997). The authors conclude that the digital circulatory response to acute vibration depends upon the magnitude and frequency of vibration.

The aim of this study was to determine whether standing on a vibrating platform that moves up and down at a frequency of 26 Hz and with an amplitude of 3 mm has negative effects on blood flow, as is known from occupational studies investigating high-frequency vibration.

Methods

Subjects

Healthy volunteers between 25 and 35 years of age were allowed to participate in the study. With respect to regular physical activity they were required not to have a sedentary lifestyle but also not to engage in regular strenuous physical activity, especially weight-lifting exercises. Informed consent was given by all participants and the protocol conformed to the Declaration of Helsinki.

Training

Prior to the experiment, the subjects' age, height and weight were recorded. The level of regular occupational and recreational physical activities were assessed according to the American Heart Association (1975).

The subjects were exposed to whole-body vibration using the Galileo 2000 device (Novotec GmbH, Pforzheim, Germany). They stood on a platform fixed on a sagittal axle which alternately pushes the right and left leg upwards and downwards at a frequency of 26 Hz (amplitude = 3 mm, peak acceleration = 78 m s^{-2}). Three sets of different positions were used.

During the first set, the subjects stood with their legs straight and their forefeet parallel to each other on the platform. The second bout was performed with the entire feet standing on the platform and moderately (60–70°) bent knees. Position 3 was the same as position 2 but the legs were rotated externally by about 30° and the knees were bent by about 60–70°.

Each of the three positions was held for 3 min and the exercise was continued without break between the positions. Thus, the total work out was 9 min. The subjects stood barefoot in order to avoid footware-dependent attenuation of the vibrations. To avoid biorhythmic changes, all subjects performed the experiment at the same time of the day between 10 a.m. and 12 p.m.

Outcome measurements

Heart rate was monitored with suitable devices (Polar beat, Polar Electro Oy, Kempele, Finland) and blood pressure was measured using conventional manometer technique (Heintel Rudolf, GesmbH, Vienna, Austria). Using a diagnostic ultrasound machine (Ultramark 9, ATL Advanced Technology Laboratories, Inc., Bothell, WA, USA) with colour Doppler and power Doppler, relative moving blood volume was quantified according to Newman's method (Newman *et al.*, 1997). During the measuring procedure the subjects were standing. First, measuring points were marked on the skin. For evaluating the gastrocnemius muscle, the point of axial measurement was marked on the dorsal aspect of the calf 15 cm distal to the right knee. For evaluating the quadriceps muscle, a point on the ventral aspect of the thigh 20 cm proximal to the right knee was marked. The relative moving blood volume of these two muscles was quantified with a power Doppler method. The number of distinctly visualized vessels in the colour box with a diameter of 2 mm or more were assigned a point value: 1 (five of fewer vessels), 2 (6–10 vessels), 3 (11–15 vessels), 4 (16–20 vessels) or 5 (>20 vessels) (Newman *et al.*, 1997). The blush score, defined by three or more vessels with contiguous margins at some point, was assigned a value 0 (no contact), 1 (three or more vessels in contact but <50% of the vessels within the portion of the colour box overlapping the gastrocnemius or quadriceps muscles, respectively) or 2 (>50% vessel contiguity in visualized gastrocnemius or quadriceps muscles for the portions of the gastrocnemius or quadriceps muscles, respectively, in the colour box) (Newman *et al.*, 1997). Blood flow in the popliteal artery was measured along the axis of the vessel by means of Doppler sonography, the speed of flow was registered and the resistive index (Pourcelot, 1974) calculated.

All outcome measurements were assessed before and immediately after 9 min of exercise.

Statistical analysis

For all parameters, descriptive analysis was performed. The mean of all pre- and post-training parameters was compared with Student's paired *t*-test and the *t*-value was used as a parameter of choice. The Statistics Package for Social Sciences (SPSS Inc., Chicago, IL, USA) was used and *P*-values <0·05 were considered statistically significant.

Results

Twenty subjects – eight women and 12 men – voluntarily participated in the study. Anthropometric data are shown in Table 1. The participants were physically active but did not engage in strength or strenuous power training. In general, they did not perform more than 8–9 metabolic equivalents (METs) (one MET is the metabolic requirement under basal conditions, which is equal to the metabolic rate) within 1 week.

Table 1 Anthropometric data (mean ± SD).

Variables	Female	Male
Number of subjects	8	12
Age (years)	28·5 ± 2·2	32·7 ± 3·3
Height (cm)	168·0 ± 6·4	178·5 ± 8·3
Weight (kg)	55·8 ± 6·2	77·0 ± 9·5

Heart rate values, systolic and diastolic blood pressures after exercise did not show a statistically significant change compared with baseline (HR: 87·6 ± 11·7 and 82·8 ± 9·4 beats min^{-1}, RR$_{syst}$: 122·0 ± 10·3 and 126·5 ± 11·6 mmHg, RR$_{diast}$: 79·5 ± 8·9 and 81·0 ± 7·7 mmHg, respectively).

In all of the exercising subjects a redish change in skin colour (erythema) of the foot and calf was subjectively visible. Figure 1(a) shows the number of distinctly visualized vessels with a diameter of at least 2 mm which were sonographically visualized immediately before and after the work out. Before and after the work out the Power Doppler Index (PDI) was 1·5 (0–6) [median (min–max)] and 3 (0–6) for the quadriceps muscle and 1 (0–3) and 2 (1–3) for the gastrocnemius muscle, respectively. The number of distinctly visualized vessels with a diameter of at least 2 mm depicted a statistically significant increase ($P = 0{\cdot}005$ and 0·0006 for the quadriceps and gastrocnemius muscles, respectively). Figure 1(b) shows the sonographically determined blush scores of these muscles. Pre- and post-exercise values of the PDI were 0·5 (0–2), 1 (0–2) and 0·5 (0–2), 1 (0–2) for the quadriceps muscle and the gastrocnemius muscle, respectively. Comparing the PDIs revealed statistically significant increases ($P = 0{\cdot}02$ and 0·0001 for the quadriceps and gastrocnemius muscles, respectively). For both parameters, the number of distinctly visualized vessels and the blush score, the *t*-value was higher for the gastrocnemius muscle indicating a higher difference between the values before and after the workout.

Table 2 shows the ultrasonic measurements of the popliteal artery. The systolic area of the popliteal artery remained unchanged. No statistically significant change in the maximal systolic and diastolic flow of the popliteal artery was found, but its mean speed of blood flow did show a statistically significant increase. On the other hand, the resistive index of the

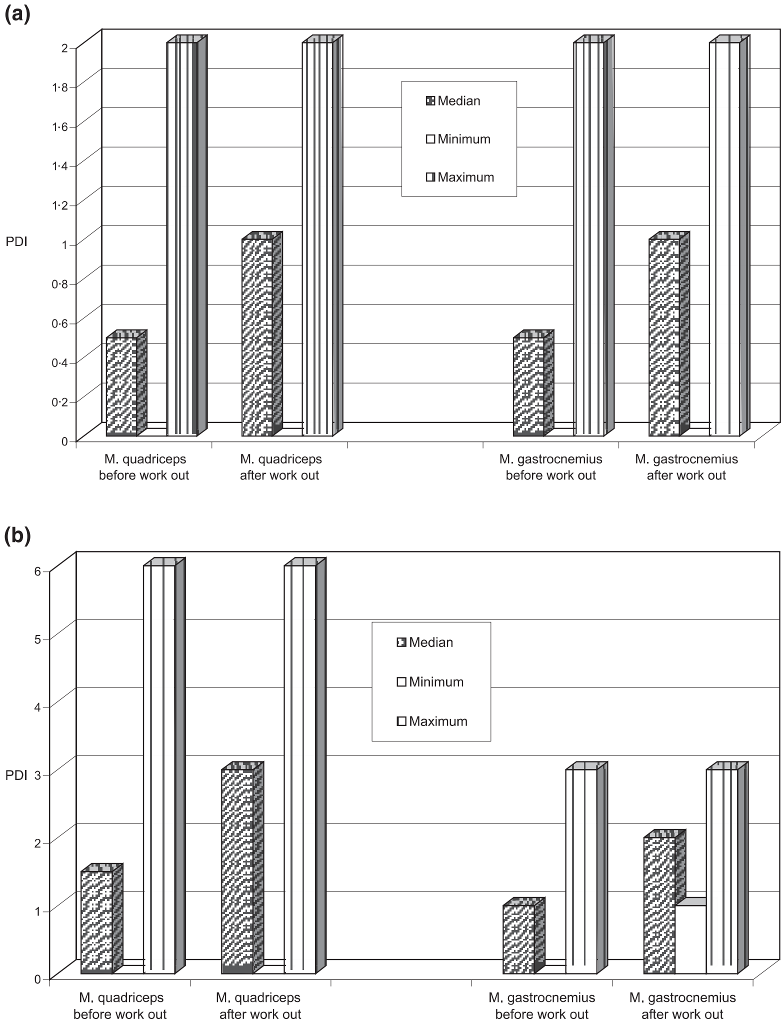

Figure 1 (a) Sonographically visualized vessels, (b) sonographically determined blush score.

Table 2 Ultrasonic measurements of the popliteal artery (mean ± SD).

Variables	Pre-exercise	Post-exercise	*t*-Value	*P*-value
Systolic vessel area (mm^2)	33 ± 10	37 ± 9	0·9	0·4
Maximum systolic velocity (cm s^{-1})	73 ± 11	89 ± 27	1·7	0·1
Maximum diastolic velocity (cm s^{-1})	−16 ± 14	−5 ± 18	6·1	0·17
Mean blood velocity (cm s^{-1})	7 ± 3	13 ± 3	5·1	0·0001
Resistive index	1·41 ± 0·9	1·23 ± 0·1	4·6	0·0002

popliteal artery yielded a statistically significant reduction.

Discussion

A few minutes lasting stance on a vibrating platform leads to an increase in the relative moving blood volume of quadriceps and gastrocnemius muscles. Mean blood flow in the popliteal artery was also increased and its resistive index decreased.

According to the authors' opinion, trying to attenuate the imposed vibration on the body evokes rhythmic muscle contractions. However, this supposed muscular exercise did not alter the heart rate or blood pressure. It induced changes in peripheral circulation. The increased number of visualized vessels with a diameter of at least 2 mm reflects the exercise-induced widening of small vessels. Widening of the capillaries in the quadriceps and gastrocnemius muscles facilitates the passage of more molecules and, therefore, the blush score of these muscles increased. These findings are in line with Rittweger *et al.* (2000) who reported that, even if performed to exhaustion, cardiovascular effects of vibration exercise are mild. The authors also found an increase in the foot and calf blood flow assessed with the cutaneous laser Doppler flow. In this study, however, the Newman's method measuring the relative moving blood volume of the capillary system was used. With this method a differentiation between arterial and venous capillary loop is not possible. However, this does not matter as the speed of blood flow is approximately the same in the whole capillary region.

As expected, the systolic area of a relatively large vessel, the popliteal artery, did not change. Also, the maximal systolic and diastolic speed of blood flow were the same, but the mean speed of blood flow in this vessel increased. The most reasonable explanation may be the following: widening of the small vessels in the muscles reduces the peripheral resistance, which may increase the mean speed of flow in the popliteal artery. Additionally, the effect of thixotropism, a reclotting phenomenon, may also play a role. Vibration might reduce the viscosity of blood and thereby increase the mean speed of blood flow in the popliteal artery. The reduction in peripheral resistance probably also is the reason for the reduction in the resistive index of the popliteal artery.

Previously reported results regarding peripheral circulatory function during exposure to vibration are conflicting. However, studies investigating the effect of hand-held vibrating tools showing a vasoconstriction following exposure to vibration did not take the effect of grasping into account (Bovenzi *et al.*, 1999). Our findings are in line with a vibration exposure test performed by Nakamura *et al.* (1995), who showed that the digital blood flow increased when the individual was exposed to vibration while grasping a handle compared with grasping alone. The authors thought that the negative correlation between digital blood flow and endothelin levels during vibration exposure suggested the following: a reduction in the release of the vasoconstrictor endothelin from smooth muscle into the vessel cavity during vibration leads to vasodilatation, possibly attributable to a local axon reflex.

Electromyography (EMG) studies revealed that exposure to seated 5 Hz sinusoidal vibrations increased the development of muscular fatigue in comparison with sitting alone. Whole-body vibration induced vibration-synchronous EMG activity in the erector spinae muscle, which exceeded the activity without whole-body vibration (Seidel, 1988; Seroussi *et al.*, 1989). These studies show that vibration induces muscle activation and therefore muscle training.

It has been suggested that muscle stimulation by vibration might improve the mechanical power of the lower limbs in elite athletes by means of neural adaptation (Bosco *et al.*, 1998). One minute of mechanical vibration applied during arm flexion in isometric conditions enhanced the average power of the arm in international level boxers (Bosco *et al.*, 1999a). In another investigation, Bosco *et al.* (1999b) showed that whole-body vibrations increased the average velocity, average force and average power in well-trained subjects.

The underlying mechanism of muscle activation via vibration may be that it activates Ia afferent fibres which are segmentally connected to the corresponding α-motor neurone (Rothmuller & Cafarelli, 1995). Additionally, it has been shown that the activation of the muscle spindle receptors is not only limited to the muscle the vibration is applied to, but also affects the neighbouring muscles (Kasai *et al.*, 1992).

Nevertheless, some published investigations report that vibration has a negative outcome on muscle strength. It has been found that the hand-grip force of vibration-exposed forest workers using chain saws was diminished in comparison with controls (Bovenzi *et al.*, 1991). In rats, vibration held at a constant frequency of 80 Hz and a constant acceleration of 32 m s^{-2}, 5 h daily, during five consecutive days led to different degrees of degeneration of muscle fibres in some muscles (Necking *et al.*, 1996). It was postulated that changes in the size of muscle fibres were the first indication of vibration-induced muscle injury.

The crucial points concerning a positive or negative outcome in vibration studies on peripheral circulation and muscle strength seem to be the frequency and amplitude of vibration as well as the duration of exposure. The results of the study indicate that a short-term exposure to whole-body vibration of 26 Hz does not have the negative effects known from long-term exposure to high frequency.

References

Bosco C., Cardinale M., Tsarpela O. *et al.* (1998) The influence of whole body vibration on the mechanical behaviour of skeletal muscle. *Biol Sport*, **15,** 157–164.

Bosco C., Cardinale M. & Tsarpela O. (1999a) Influence of vibration on mechanical power and electrcardiogram activity in human arm flexor muscles. *Eur J Appl Physiol*, **79,** 306–311.

Bosco C., Colli R., Introini E. *et al.* (1999b) Adaptive responses of human skeletal muscle to vibration exposure. *Clin Physiol*, **19,** 183–187.

Bovenzi M. & Griffin M. J. (1997) Haemodynamic changes in ipsilateral and contralateral fingers caused by acute exposures to hand transmitted vibration. *Occup Environ Med*, **54,** 566–576.

Bovenzi M., Zadini A., Franzinelli A. & Borgogni F. (1991) Occupational musculoskeletal disorders in the neck and upper limbs of foresty workers exposed to hand-arm vibration. *Ergonomics*, **34,** 547–562.

Bovenzi M., Lindsell C. J. & Griffin M. J. (1999) Magnitude of acute exposures to vibration and finger circulation. *Scan J Work Environ Health*, **25,** 278–284.

Fleckenstein J. L., Canby R. C., Parkey R. W. & Peshock R. M. (1988) Acute effects of exercise on MR imaging of skeletal muscle in normal volunteers. *AJR*, **151,** 231–237.

Hettinger T. (1956) Der Einfluss sinusförmiger Schwingungen auf die Skelettmuskulatur. *Int Z Angew Physiol*, **16,** 192–197.

Hirsch W., Bell D. S., Crawford D. C., Kale S. G., McCready V. R. & Bamber J. C. (1995) Colour Doppler imaging analysis for tissue vascularity and perfusion: a preliminary clinical evaluation. *Ultrasound Med Biol*, **21,** 1107–1117.

Issurin V. B., Liebermann D. G. & Tenenbaum G. (1994) Effect of vibratory stimulation training on maximal force and flexibility. *J Sports Sci*, **12,** 561–566.

Kasai T., Kawanishi M. & Yahagi S. (1992) The effects of wrist muscle vibration on human voluntary elbow flexion-extension movements. *Exp Brain Res*, **90,** 217–220.

Kattus A. *et al.* (1975) *Exercise Testing and Training of Individuals with Heart Disease or at High Risk for its Development. A Handbook for Physicians*, American Heart Association.

Lundström R. & Burstöm L. (1984) Vibrations in hand held tools. The Swedish National Board of Occupational Safety and Health. *Invest Rep*, **84,** 1–111 (in Swedish with an English summary).

Nakamura H., Ariizumi M., Okazawa T., Nagase H., Yoshida M. & Okada A. (1995) Involvement of endothelin in peripheral circulatory change induced by hand-arm-vibration. *Centr Eur J Public Health*, **3** (Suppl.), 27–30.

Necking L. E., Lundström R., Lundborg G., Thornell L. E. & Friden J. (1996) Skeletal muscle changes after short term vibration. *Scand J Plast Reconstr Hand Surg*, **30,** 99–103.

Newman J. S., Adler R. S. & Rubin J. M. (1997) Power doppler sonography: use in measuring alterations in muscle blood volume after exercise. *AJR*, **168,** 1525–1530.

Pena C. S., Mccauley T. R., Price T. B., Sumpio B., Gusberg R. J. & Gore J. C. (1996) Quantitative blood flow measurements with cine phase-contrast MR imaging of subjects at rest and after exercise to assess peripheral vascular disease. *AJR*, **167,** 153–157.

Pourcelot L. (1974) Applications cliniques de l'examen Doppler transcutane. In: *Velocimetrie Ultrasonore Doppler* (ed. Perroneau, P.), pp. 213–240. Inserm, Paris, France.

Rittweger J., Beller G. & Felsenberg D. (2000) Acute physiological effects of exhaustive whole-body vibration exercise in man. *Clin Physiol*, **20,** 134–142.

Rothmuller C. & Cafarelli E. (1995) Effect of vibration on antagonist muscle coactivation during progressive fatigue in humans. *J Physiol*, **485,** 857–864.

Rubin J. N., Adler R. S., Fowlkes J. B. *et al.* (1995) Fractional moving blood volume estimation using power Doppler imaging. *Radiology*, **197,** 183–190.

Seidel H. (1988) Myoelectric reactions to ultra-low frequency and low-frequency whole body vibraton. *Eur J Appl Physiol*, **57,** 558–562.

Seroussi R. E., Wilder D. G. & Pope M. H. (1989) Trunk muscle electromyography and whole body vibration. *J Biomech*, **22,** 219–229.

Whedon G. D., Deitrick J. E. & Shorr E. (1949) Modification of the effects of immobilization upon metabolic and physiologic functions of normal men by the use of an oscillating bed. *Am J Med*, **6,** 684–710.