Oxygen Uptake in Whole-Body Vibration Exercise: Influence of Vibration Frequency, Amplitude, and External Load

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Abstract

Vibration exercise (VbX) is a new type of physical training to increase muscle power. The present study was designed to assess the influence of whole-body VbX on metabolic power. Specific oxygen uptake (s$\dot{V}O_2$) was assessed, testing the hypotheses that s$\dot{V}O_2$ increases with the frequency of vibration (tested in 10 males) and with the amplitude (tested in 8 males), and that the VbX-related increase in s$\dot{V}O_2$ is enhanced by increased muscle force (tested in 8 males). With a vibration amplitude of 5 mm, a linear increase in s$\dot{V}O_2$ was found from frequencies 18 to 34 Hz ($p < 0.01$). Each vibration cycle evoked an oxygen consumption of approximately 2.5 µl × kg^{-1}. At a vibration frequency of 26 Hz, s$\dot{V}O_2$ increased more than proportionally with amplitudes from 2.5 to 7.5 mm. With an additional load of 40% of the lean body mass attached to the waist, s$\dot{V}O_2$ likewise increased significantly. A further increase was observed when the load was applied to the shoulders. The present findings indicate that metabolic power in whole-body VbX can be parametrically controlled by frequency and amplitude, and by application of additional loads. These results further substantiate the view that VbX enhances muscular metabolic power, and thus muscle activity.

Key words
Indirect calorimetry · exercise physiology · rehabilitation

Introduction

Vibration exercise (VbX) is a new type of exercise that is currently being used as a training device in sports, a therapeutic method in rehabilitation, and as a countermeasure to muscular atrophy and bone loss during immobilization and space flight [3,4,10]. Whole-body VbX and its mode of operation, as currently understood, have been described elsewhere [21–24]. In brief, the subject exercises on a platform which applies an anti-phase vibration to the two feet with zero amplitude directly over the central axis. It is assumed that this vibration evokes muscle contractions, probably via the monosynaptic stretch reflex [7,14].

The above concept has been questioned, stating that the vibration applied would elicit merely a passive, elastic deformation of the connective tissue and thixotropic properties of muscle, without evoking any muscular activation. Recent findings, however, indicate an increase in calf muscle blood volume and in metabolic power during VbX [16,22]. We have shown that during VbX at a frequency of 26 Hz and an amplitude of 6 mm, the specific oxygen uptake was increased by 4.5 ml × min^{-1} × kg^{-1}, independent of squatting that was performed simultaneously. The conclusion drawn from these results was that VbX increased energy metabolism, and in a way that was better predictable than in an exercise as simple as squatting.

Energy consumption in the muscle fibers can be broken down into two components, one which is "activation" related, and another which is related to the production of mechanical power [9]. Hence, if our interpretation is correct that VbX evokes muscular

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power output, one should expect the following: On the one hand, deflection of the leg, i.e. each vibration cycle, should elicit a single contraction and thus raise both the activity and the power-output-related energy consumption. In consequence, the total energy consumption should increase with the number of vibration cycles. On the other hand, an increase in the mechanical power output should be followed by an increase in energy consumption. Mechanical power output increases with force, velocity, or with the work performed per unit time. In VbX, this would mean an increase in pre-load to the muscles or vibration amplitude. We have summarised the above reasoning and generated the following hypotheses.

1. Metabolic power in VbX increases with vibration frequency (hypothesis H1).
2. Metabolic power in VbX increases with vibration amplitude (hypothesis H2).
3. Likewise, an increase in pre-load to the muscles is followed by an increase in metabolic power (hypothesis H3).
4. The greater the mass of activated musculature, the greater will be the VbX-related increase in metabolic power (hypothesis H4).

Material and Methods

Subjects and general set-up

To test the above hypotheses, three sets of experiments were performed. Each of them was in line with the Declaration of Helsinki of 1975 and had been approved by the local Ethical Committee. All subjects signed their written informed consent before inclusion to the study. All subjects regularly practised sports on a moderate to medium level (1–2 hours, 1–3 times per week) and were acquainted with the vibration device before the study.

The first study (FREQ) assessed the influence of vibration frequency on specific oxygen uptake ($s\dot{V}O_2$) in 10 male subjects with a mean age of 28.0 years (SD 4.1 years), height between 174 and 191 cm (mean 180.9 cm, SD 4.8 cm), and a mean weight of 74.2 kg (SD 7.6). The second study (AMP) tested the effect of vibration amplitude on $s\dot{V}O_2$ in 8-male subjects with a mean age of 28.1 years (SD 5.6), a height ranging between 174 and 185 cm (mean 179.9, SD 3.9 cm), and with a mean weight of 73.6 kg (SD 7.1). The third study (LOAD) assessed the effects of pre-loading different parts of the body's musculature on $s\dot{V}O_2$ by application of external loads. It was performed in the same subjects as the AMP study.

The vibration platform used in all three studies was a prototype of a device that has been commercialized under the name "Galileo 2000". In all three studies, the total duration of the experiment did not exceed 1.5 hours. The subjects performed warm-up exercises (10 minutes cycling at 50 Watt and stretching). The sequence of the different VbX exercise units was randomized between subjects. Before and after each VbX unit, standing for 3 minutes without vibration was recorded as a baseline control. VbX was performed in stance, with the knees almost extended (170°). Between the VbX units, the subjects were allowed to walk around slowly or to sit down for 10–15 minutes, as they preferred. Previously, we had found that in VbX most subjects depict a steady state in oxygen uptake after 3 minutes. This is in line with the finding that in cycling and treadmill running below the lactate threshold, the time constants of the oxygen uptake kinetics are shorter than one minute [6]. On the other hand it is difficult to maintain the same position on the vibration platform for more than five to seven minutes. Hence, each unit of VbX was maintained for 4 minutes.

FREQ-study

Below 15–18 Hz, many subjects make additional movements to stabilize their balance on the platform. Above 35 Hz, we observed a tonization of the musculature in a number of subjects, and it seems to be difficult to obtain a steady state of $s\dot{V}O_2$. Hence, the frequencies to be tested in the FREQ-study were defined as 18 Hz, 26 Hz, and 34 Hz. The foot distance was set at 20 cm, corresponding to an amplitude of 5 mm. The foot position was parallel to the neutral rotational axis, and the distance was measured between the axis and the heel (Table 1).

AMP-study

The rotational axis is at the center of the vibration platform between the feet. In consequence, the vibration amplitude increases linearly with the distance that the feet are put apart. The feet can be placed at a maximum of 30 cm from the central axis. In this position, the vibration amplitude is 7.5 mm. Besides the 30 cm position, we tested metabolic power in the AMP-study with 10 cm and 20 cm distance between center and feet, corresponding to vibration amplitudes of 2.5 mm and 5 mm. The vibration frequency was set at 26 Hz, a frequency used in a number of former studies [4,22] (Table 1).

LOAD-study

In the LOAD study, the basic muscular tension was augmented by the application of additional loads. The mass to be applied was calculated as 0.4 × lean body mass. The latter had been assessed before by the body impedance analysis (BIA), using the Body Composition Analyzer (Akern-Rcl BIA 101/S, Data Input, Frankfurt, Germany) [11]. The exact masses were rounded to the nearest kg. Three different conditions were tested: no load, load attached to the waist in the form of a diving belt, and load of two lead-filled sacks placed on the shoulders. The idea behind the testing of different positions was to pre-load different amounts of musculature (H3). All three load positions were tested at 18 and 34 Hz vibration frequency, with an amplitude of 5 mm (Table 1).

Table 1 Parameter settings of the three studies

Study	*Vibration Frequency*	*Vibration Amplitude*	*Additional Load (0.4 × lean body mass)*
FREQ	18/26/34 Hz in randomized order	5 mm	0
AMP	26	2.5/5/7.54 mm in randomized order	0
LOAD	18/34 Hz in randomized order	5 mm	none/on hip/on shoulder in randomized order

Data acquisition

In the AMP-study and in the LOAD-study, oxygen-uptake was assessed with the Metamax system (Cortex Biophysics, Leipzig, Germany). This system uses a mixed chamber, and the dedicated software averages over 10 seconds. It has a resolution of 15 ml and an accuracy of 1.5% for volume measurement. The zirconium oxygen sensor and the infrared CO_2-sensor have an accuracy of 0.1 Vol%. In the FREQ-study, oxygen-uptake was assessed using a Metalyser IIIb (Cortex Biophysics, Leipzig, Germany). This device has the same sensor system as the Cortex-system, but it allows breath-by-breath measurement.

Dividing the instantaneous O_2-uptake by the body weight yielded the specific O_2-uptake ($s\dot{V}O_2$). In all experiments and conditions, a plateau was reached by the third minute. Thus, the mean value of $s\dot{V}O_2$ during the entire third minute was chosen for further analyses.

Data analysis

Identical analyses were performed for the AMP-study, the LOAD-study, and the FREQ-study. Statistics were performed with the SPSS software in its PC version 9.0. Significance was assumed if $p < 0.05$. Differences between the baseline conditions were tested by ANOVA. Differences in $s\dot{V}O_2$ of the VbX conditions with their baseline values and differences between the different VbX conditions were tested with the paired t-test, applying the Bonferroni correction for multiple comparisons. Before the t-test or the multiple t-test was applied, variables were tested for normal distribution with the Kolmogorov-Smirnoff test and for homogeneity of variances with Bartlett's F-test.

To test for the linearity of the dependence of $s\dot{V}O_2$ on vibration frequency, the related delta ratios were computed, e.g. $\Delta 26/18\,Hz = s\dot{V}O_{2_{26Hz}} - s\dot{V}O_{2_{18Hz}}$. $\Delta 26/18$ Hz was then compared to $\Delta 34/26$ Hz with the t-test. The corresponding computations were performed to test the dependency on vibration amplitude for proportionality. The same computation was performed for the amplitude-related delta ratios.

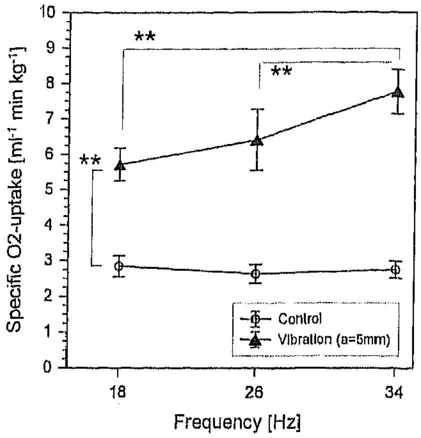

Fig. 1 $s\dot{V}O_2$ in vibration Exercise at 18, 26 and 34 Hz vibration frequency. Given are mean values±SEM during the third minute of exercise. The vibration amplitude was kept constant at 5 mm. Exercise values (solid triangles) were significantly greater than the control values during standing (open dots), and were further increased with increasing frequency ($p < 0.01$).

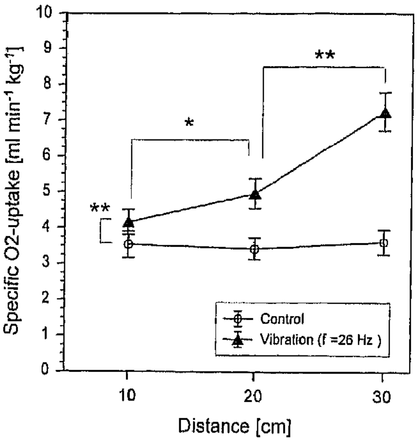

Fig. 2 Mean values±SEM of $s\dot{V}O_2$ in vibration exercise at different vibration amplitudes with a constant frequency of 26 Hz. A foot distance of 10 cm corresponds to 2.5 mm amplitude, 20 cm to 5 mm amplitude, and 30 cm to 7.5 mm, respectively. Exercise values (solid triangles) significantly increased with amplitude.

Results

In the FREQ-study, $s\dot{V}O_2$ under baseline conditions was 2.85, 2.63, and 2.74 ml × min^{-1} × kg^{-1} for the 18 Hz, 26 Hz and 34 Hz conditions, respectively (see Fig. 1). No significant difference was found between the three baseline conditions (ANOVA, $p > 0.25$). During 18 Hz vibration, $s\dot{V}O_2$ increased significantly to 5.72 ml × min^{-1} × kg^{-1} (paired t-test, $p < 0.01$). $s\dot{V}O_2$ during 26 Hz vibration was 6.41 ml × min^{-1} × kg^{-1}, which was not significantly greater than during 18 Hz vibration ($p > 0.05$), but significantly lower than the 7.76 ml/min/kg observed during 34 Hz vibration ($p < 0.01$).

Comparison of the frequency-related deltas $\Delta 26/18$ Hz and $\Delta 34/26$ Hz yielded no significant difference (paired t-test, $p > 0.2$), i.e. the increase in vibration-related metabolic power from 18 to 34 Hz could not be distinguished from a proportional one.

In the AMP-study, $s\dot{V}O_2$ during simple standing was 3.54, 3.43, and 3.62 ml × min^{-1} × kg^{-1} for the 10 cm, 20 cm and 30 cm position, respectively (see Fig. 2). No significant differences were discovered among these baseline conditions (ANOVA, $p > 0.25$). With vibration (frequency = 26 Hz) and the feet positioned 10 cm from the center, sVO2 increased significantly to 4.17 ml × min^{-1} × kg^{-1} (paired t-test, $p < 0.01$). Another significant increase in $s\dot{V}O_2$ was observed in the 20 cm position (4.97 ml × min^{-1} × kg^{-1}, $p < 0.05$), and also in the 30 cm position (7.26 ml × min^{-1} × kg^{-1}, $p < 0.01$).

Comparison of the amplitude-related deltas $\Delta 20/10$ cm and $\Delta 30/20$ cm yielded a significant difference (paired t-test, $p < 0.05$), i.e. the vibration-related increase in metabolic power was larger from 5 mm to 7.5 mm vibration amplitude than from 2.5 mm to 5 mm.

In the LOAD-study, no significant correlation was found between the lean component of body mass as assessed by BIA and $s\dot{V}O_2$. Hence, as in the FREQ- and AMP-studies, specific oxygen uptake was divided by body mass (and not lean body mass) to yield $s\dot{V}O_2$. Baseline $s\dot{V}O_2$ increased from 2.85 ml × min^{-1} × kg^{-1} without load to 3.28 ml × min^{-1} × kg^{-1} with the external load placed at the waist (paired t-test: $p < 0.05$, see Fig. 3). When the load was placed on the shoulders, an insignificant increase to 3.40 ml × min^{-1} × kg^{-1} was observed ($p > 0.2$).

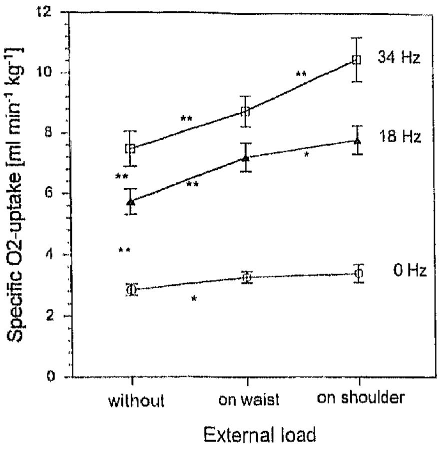

Fig. 3 Mean values±SEM of s$\dot{V}O_2$ in vibration exercise with an additional load of 40% of the lean body mass at a constant amplitude of 5 mm at 18 Hz and 34 Hz. Exercise values were greater than control values. They increased significantly with the load, particularly if the load was attached to the shoulders.

Without load, s$\dot{V}O_2$ increased significantly when vibration was on (both at 18 and 34 Hz), as was expected from the FREQ-study ($p < 0.01$). A further increase was observed when the external load was attached to the waist. This load-related increase in s$\dot{V}O_2$ amounted to 1.50 ml × min^{-1} × kg^{-1} in vibration with 18 Hz, and to 1.28 ml × min^{-1} × kg^{-1} in vibration with 34 Hz. Both of these increases were significantly greater than that during standing without vibration ($p < 0.05$). Moreover, s$\dot{V}O_2$ increased further when the external load was attached to the shoulders instead of the waist, namely by 0.57 ml × min^{-1} × kg^{-1} in 18 Hz vibration ($p < 0.05$) and by 1.71 ml × min^{-1} × kg^{-1} in vibration with 34 Hz ($p < 0.01$).

Discussion

We report here the results of three different studies undertaken to investigate the influence of amplitude, frequency and load on energy turnover in VbX, based on indirect calorimetry [17,19,25]. As expected from former studies, metabolic power increases during VbX [2,22,26], the increase being comparable to that in moderate walking [8,22]. We have shown here, moreover, that s$\dot{V}O_2$ in VbX can be parametrically controlled by frequency, amplitude and additional loads.

In the FREQ-study, s$\dot{V}O_2$ increased progressively with the vibration frequencies tested – 18, 26, and 34 Hz (hypothesis H1). The effect of vibration was indistinguishable from a proportional one. A simple calculation of the exercise-related oxygen uptake for each vibration cycle as

$$s\dot{V}O_2/(60 \times \text{frequency})$$

yields ~ 2.5 µl per kg body weight for each cycle with 5 mm vibration amplitude. Assuming a caloric equivalent of 20 Joule per ml oxygen, we get a rough estimate for the specific metabolic power of 50 mJoule per vibration cycle and kg.

Since these values appeared to be close to constant throughout the FREQ study, they support the view that each cycle of the vibration evokes a certain amount of muscular work. The permanent change between eccentric and concentric muscle work during VbX may of course elicit stretch activation, post activation potentiation and force depression following shortening in the muscle [5,12,13], but there is no indication that either of these phenomena influences muscle metabolic power.

A parametrical influence on metabolic power was also observed by vibration amplitude. Given the J-shaped force-length relationship of biological materials, one would expect that a larger amplitude increases the proportion of elastically stored energy [15,20] which should lead to a less than proportional increase in s$\dot{V}O_2$. Moreover, increasing the prestretch, the muscle's mechanical efficiency likewise increases [1], which should further diminish the expected s$\dot{V}O_2$ per unit amplitude.

In the AMP-study, however, the opposite was observed. As expected, s$\dot{V}O_2$ increased significantly with vibration amplitude (hypothesis H2). But quite unexpectedly, this increase was more than proportional with greater amplitudes. A possible explanation would be that spindle activation increases with the amplitude of vibration. This interpretation may be supported by the fact that in the tonic vibration response the vibration amplitude increases both the number and degree of activated primary afferents [7,18].

Finally, the LOAD-study has shown that the mild increase in metabolic power caused by application of external loads in mere standing is considerably augmented by whole-body vibration with 18 Hz and 34 Hz (hypothesis H3). Moreover, the increase in vibration-related metabolic power was greater when the musculature of the trunk was involved (load on the shoulders) than when only the musculature of the lower extremities was loaded (hypothesis H4). This indicates that pre-loading of certain muscles during VbX enhances the activation of these particular muscles.

In the studies reported here, we applied additional loads of 0.4 × body weight. This was done with the intention to generally demonstate the load effect on metabolic power. Different loads, however, and different places to attach are possible. In training studies with elite athetes, we currently work with loads as great as 1.0 × lean body mass. In another study, in contrast, in which we could demonstrate the effectiveness of VbX in chronic lower back pain (data are to be published elsewhere), we applied loads of only up to 10 kg to the shoulders and forearms. Generally, elder people tolerate smaller loads, as it is also the case in resistance exercise. In all these studies, we see the effect of VbX in that it elicits muscle contractions that are not entirely controlled voluntarily. The most promising fields of application for VbX hence are rehabilitation in patients with central and peripheral disorders, but also training to prevent muscle weakness and falls in the elderly.

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The data have partly been presented on the Annual Meetings of the German Physiological Society in 2000 and 2001. The experiments of the present publication were conducted in Berlin and are in line with the German laws on human subject testing.

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