

Jörn Rittweger · Hans Schiessl · Dieter Felsenberg

Oxygen uptake during whole-body vibration exercise: comparison with squatting as a slow voluntary movement

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Abstract In this study we investigated metabolic power during whole-body vibration exercise (VbX) compared to mild resistance exercise. Specific oxygen consumption ($\dot{V}O_2$) and subjectively perceived exertion (rating of perceived exertion, RPE; Borg scale) were assessed in 12 young healthy subjects (8 female and 4 male). The outcome parameters were assessed during the last minute of a 3-min exercise bout, which consisted of either (1) simple standing, (2) squatting in cycles of 6 s to 90° knee flexion, and (3) squatting as before with an additional load of 40% of the subject's body weight (35% in females). Exercise types 1–3 were performed with (VbX+) and without (VbX-) platform vibration at a frequency of 26 Hz and an amplitude of 6 mm. Compared to the VbX- condition, the specific $\dot{V}O_2$ was increased with vibration by $4.5 \text{ ml}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$. Likewise, squatting and the additional load were factors that further increased $\dot{V}O_2$. Corresponding changes were observed in RPE. There was a correlation between VbX- and VbX+ values for exercise types 1–3 ($r=0.90$). The correlation coefficient between squat/no-squat values ($r=0.70$ without and $r=0.71$ with the additional load) was significantly lower than that for VbX-/VbX+. Variation in specific $\dot{V}O_2$ was significantly higher in the squatting paradigm than with vibration. It is concluded that the increased metabolic power observed in association with

VbX is due to muscular activity. It is likely that this muscular activity is easier to control between individuals than is simple squatting.

Keywords Oxygen consumption · Whole-body vibration · Exercise · Perceived exertion

Introduction

It is generally accepted that sports and exercise are beneficial in many chronic diseases. The beneficial effects are not restricted to the motor system. In spinalized patients, for example, chronic electrical muscle stimulation increases muscle and bone mass as well as aerobic capacity (Belanger et al. 2000; Mohr et al. 1997a, b). This shows that patients may profit from muscular activation, even if their locomotor capacity remains unchanged.

Moreover, the example cited can increase the awareness for new therapeutic concepts based on artificially elicited muscle activity. There are many applications of this idea. For example, it may benefit immobilized and elderly patients with poor compliance or who are in a bad clinical state, and may help with the recovery from exhaustion and fatigue in athletes. The usefulness of electrical stimulation, however, is restricted because (1) electrodes have to be applied, (2) artificial stimulation neglects the processing of afferent information, and (3) it is painful in subjects with intact afferent pathways. Hence, one of the authors (Schiessl) has developed a device for whole-body vibration exercise (VbX) as a new mode of exercise (Schiessl 1997a, b), in which vibration is generated by rotational oscillations. Other machines that impose vibration as a translational oscillation to the whole body are already in existence (Fritton et al. 1997). These machines were built with the idea of stimulating bone formation through a specific "osteogenic" frequency. Indeed, increased bone formation in response to whole-body vibration has been demonstrated in animal experiments (Flieger et al. 1998; Fritton et al. 1997).

J. Rittweger (✉)
Institut für Physiologie, Freie Universität Berlin,
Arnimallee 22, 14195 Berlin, Germany
E-mail: ritmus@zedat.fu-berlin.de
Tel.: +49-30-84451696
Fax: +49-30-84451602

H. Schiessl
Novotec Maschinen GmbH, Durlacher Strasse 35,
75172 Pforzheim, Germany

D. Felsenberg
Zentrum für Muskel- und Knochenforschung,
Universitätsklinikum Benjamin Franklin,
Freie Universität Berlin, Hindenburgdamm 30,
12200 Berlin, Germany

With our vibration exercise device, however, the idea is to evoke muscle contractions, and we attribute the resulting increase in bone formation to an increase in muscle force. Objections have been made to this concept, stating that vibration causes only passive displacements of the skeleton, without any muscular response. If that is the case, one would expect that metabolic power, as measured by oxygen uptake ($\dot{V}O_2$), is not influenced by VbX. Recently, however, we have shown that VbX in combination with squatting performed until exhaustion increases $\dot{V}O_2$ to about 50% of the aerobic capacity (Rittweger et al. 2000).

In the present publication, this new vibration exercise device was tested, along with the hypothesis that VbX per se increases $\dot{V}O_2$, similar to the $\dot{V}O_2$ increase evoked by voluntary movements such as squatting with and without loads. In addition, we expect that the VbX-related $\dot{V}O_2$ has less inter-individual variability than the extra $\dot{V}O_2$ caused by a more complex voluntary movement such as squatting.

Methods

This study was approved by the Ethics committee of the Free University Berlin. Twelve subjects (8 female and 4 male) were recruited from our University campus. Before inclusion in the study, they provided their written informed consent to participate. The mean age of the subjects was 25.2 years, the mean (SD) height was 172.1 (7.8) cm, and the mean body mass was 66.0 (7.5) kg.

Three exercise types (1, standing; 2, squatting; 3, squatting with a load) were performed with (VbX+) and without vibration (VbX-). The six test conditions: mere standing (VbX+1), standing with vibration (VbX+1), mere squatting (VbX-2), squatting with vibration (VbX+2), mere squatting with additional load (VbX-3), and squatting with additional load plus vibration (VbX+3) were performed in randomized sequence for 3 min each. Every minute, the rating of perceived exertion (RPE) was assessed to monitor subjectively perceived exertion (Borg 1976). $\dot{V}O_2$ was assessed continuously with the Metamax system (Cortex Biophysik, Leipzig). The Metamax system has a resolution of 15 ml and an accuracy of 1.5% for volume measurement. The zirconium oxygen sensor and the infrared carbon dioxide sensor have an accuracy of 0.1% for volume. Dividing the instantaneous $\dot{V}O_2$ by the body mass yields the specific $\dot{V}O_2$ ($s\dot{V}O_2$).

As previous experiments have shown, in most persons during still stance, a clear plateau of $s\dot{V}O_2$ is reached in the 3rd min, while

after 5 min, most subjects feel uncomfortable if no change in posture is allowed. Thus, the mean value of $s\dot{V}O_2$ in the 3rd min was chosen for further analyses. Between the test conditions, the subjects relaxed on a chair for 10–15 min, until they subjectively felt recovered. By then, $s\dot{V}O_2$ had returned to initial values.

Before starting, the subjects warmed up (10 min bicycling at 50 W and stretching). Vibration exercise was performed on a prototype of a device that has been commercialized under the name "Galileo 2000". In all conditions, the frequency was set at 26 Hz, and the feet were placed 24 cm apart. Thus, the amplitude of vibration was 6 mm.

Contrasting with other devices in existence, with this device vibration is applied by rotational oscillation (see Fig. 1). The idea behind this device is primarily to evoke muscle contractions via the stretch reflexes. Like children on a seesaw, the subjects place their feet on either side of the rotation centre of the vibration platform. Each time the right leg is accelerated upward (push-phase), the left leg is accelerated downward (slack-phase). At the same time, the right leg is subjected to flexion, while the left leg undergoes extension. As a consequence, the pelvis is rotated upward on the right side, and downward on the left, which elicits flexion in the vertebral column (see Fig. 2). Thus, the seesaw oscillation is imposed on the pelvis, but with phase shift and damping.

These skeletal displacements are likely to evoke neuromuscular responses: during passive extension of the leg, the flexor muscles are

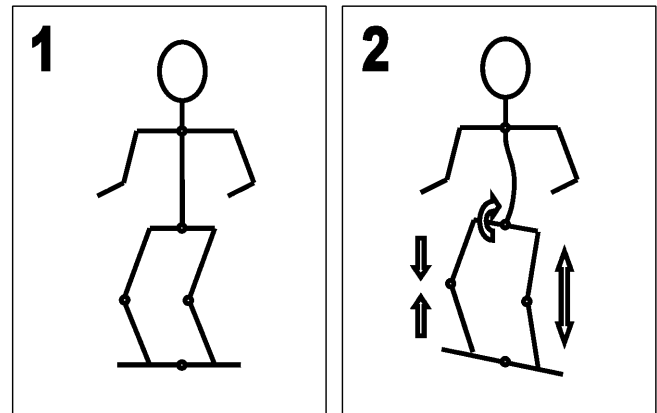


Fig. 2 Rotation of the vibration platform elicits passive elongation and flexion of the opposite legs, and rotation of the pelvis in the same direction as the platform (with delay and attenuation). Flexion of the vertebral column evokes rotation of the shoulders. All of these passive displacements are thought to evoke neuromuscular responses

Fig. 1 Whole-body vibration device. Vibration to the entire body is applied by alternating rotation around the centre of the platform. The amplitude increases with distance from the rotational centre. In our device, the maximum amplitude at the outer edges is 7.5 mm. The frequency can be freely chosen between 1 Hz and 35 Hz

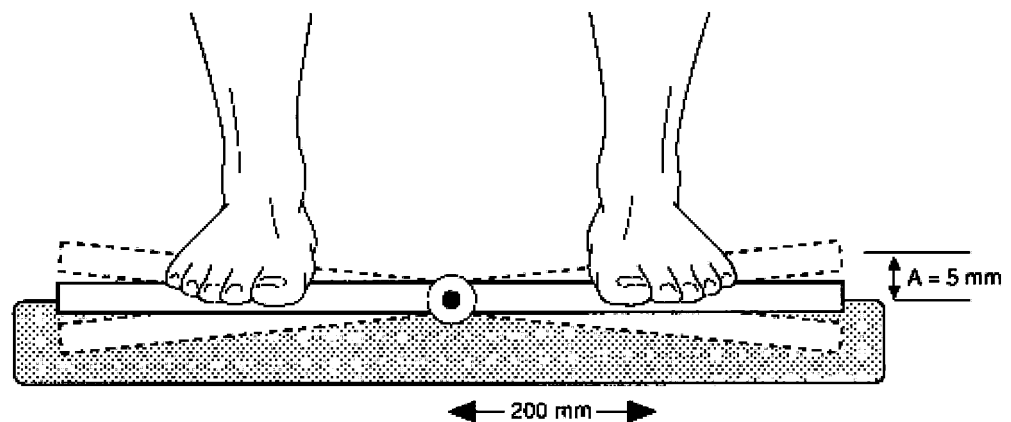


Table 1 Mean (SD) values of specific oxygen uptake ($\dot{V}O_2$) during the last minute of exercise under the six different test conditions. In general, $\dot{V}O_2$ was greater in the exercise condition with vibration (VbX+) than in that without vibration (VbX-), and squatting and a load yielded further increases ($P < 0.5$)

| Exercise type | VbX- | VbX+ |
|------------------|------------|------------|
| Standing (1) | 4.8 (0.9) | 10.2 (1.2) |
| Squatting (2) | 10.7 (3.3) | 14.0 (2.7) |
| Squat + load (3) | 12.1 (4.3) | 17.1 (3.8) |

activated, and during flexion, the extensors are activated. Likewise, repetitive rotation of the pelvis elicits alternating activation of the hip adductors and abductors of the iliopsoas muscles and the erector spinae muscles. Hence, similar to running, there is hardly any muscle that is not activated during vibration exercise. It is clear, therefore, that there are just as many concentric muscle contractions as eccentric ones. The physiological leg extensors work eccentrically during the push-phase, while at the same time the flexors work concentrically. The maximum acceleration (a_{\max}) of the platform depends on the amplitude, A (and thereby on the distance between the feet), and on the frequency, f . Because the movement of the seesaw platform itself is sinusoidal, the maximal acceleration, a_{\max} , is calculated as

$$a_{\max} = A \cdot \omega^2 = A \cdot (2\pi f)^2 \quad (1)$$

Thus, at a frequency of 30 Hz, $a_{\max} = A \cdot 35530 \text{ s}^{-2}$, and with $A = 5 \text{ mm}$, roughly $18 \times$ the gravitational acceleration on earth.

Squatting was performed from full extension to a knee angle of 90° . For each subject, the 90° knee angle was measured initially, and a hurdle was adjusted such that the buttocks of the subject touched the hurdle in 90° knee flexion. For the temporal control of the squatting exercise, a metronome was set at 1 Hz beats, and the subjects were instructed to move 3 s down and 3 s up as evenly as

they could. The exactness of the movements was controlled by the experimenter. Extra loads were placed in the form of a diving belt around the hips, in males 40% of the body weight, in females 35%.

Statistics were performed with SPSS software in its PC version 7.5.2. Significance was assumed if $P < 0.05$. Differences in $s\dot{V}O_2$ and in RPE between the different conditions were tested with the paired Wilcoxon test, applying the Bonferroni correction for multiple comparisons. Variances of different test conditions were compared with Bartlett's F -test. Values from the VbX+ and VbX- conditions were compared by correlation and regression analyses. The same analyses were performed with respect to squatting and non-squatting conditions.

Results

Mean (SD) values of $s\dot{V}O_2$ are given in Table 1. Individual values are depicted in Figs 3 and 4. In general, $\dot{V}O_2$ was greater in VbX+ than in VbX- conditions ($P < 0.05$). On average, the increase amounted to $4.5 \text{ ml} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$.

Likewise, $s\dot{V}O_2$ was increased by squatting without an added load (VbX-1 vs VbX-2 and VbX+1 vs VbX+2; $P < 0.05$), and application of the additional load appeared to further increase $s\dot{V}O_2$, although this was significant only for VbX+2 vs VbX+3. Interestingly, the variance was significantly lower in VbX+1 than in VbX-2 ($P < 0.05$; Bartlett F -test), although the mean values of these conditions did not differ ($P > 0.2$; t -test).

Similar to $s\dot{V}O_2$, the RPE values (Table 2) were significantly higher with vibration than without (e.g. 14.6

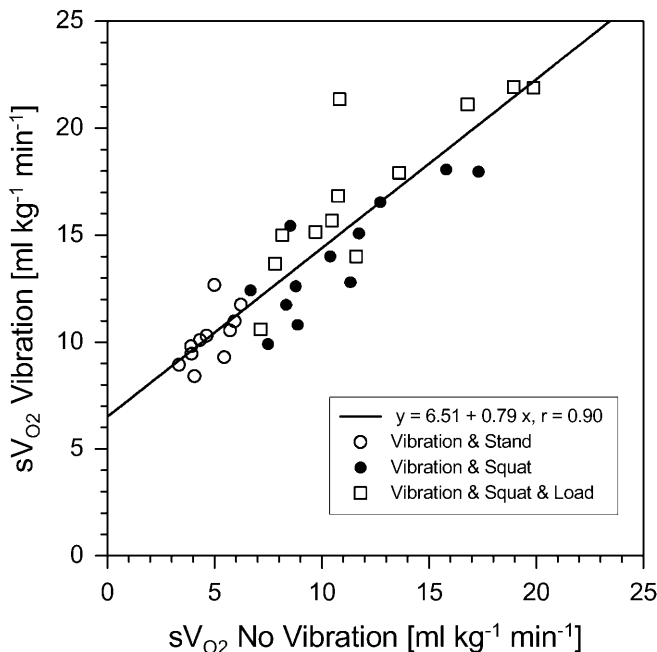


Fig. 3 Linear regression between specific oxygen uptake ($s\dot{V}O_2$) values from experimental conditions with and without vibration exercise (VbX+ and VbX-, respectively; $r^2 = 0.82$). Analysis was performed on data pooled from all three exercise types imposed (vibration + standing, open circles; vibration + squat, closed circles; vibration + squat + load, open squares)

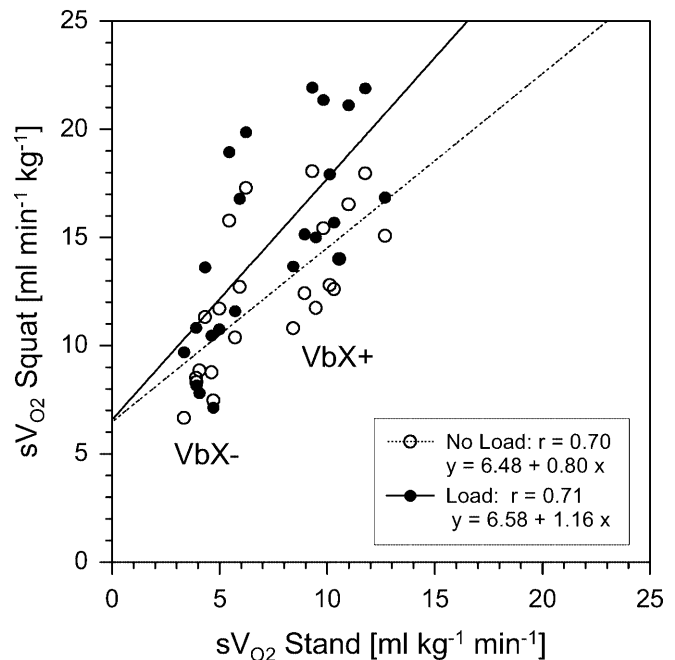


Fig. 4 Linear regression of exercise type 1 versus type 2 (standing vs squatting, open circles), and type 1 versus type 3 (standing vs squatting with load, closed circles). VbX+ and VbX- data were pooled and can be distinguished by the "gap" between $7 \text{ ml} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$ and $8 \text{ ml} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$ on the abscissa

Table 2 Mean (SD) values of the rating of perceived exertion (RPE) in the 3rd min of the six different test conditions. Similar to the case for $\dot{V}O_2$, the RPE was greater in the VbX+ than in the VbX- conditions, and squatting and load yielded further increases ($P < 0.5$)

| Exercise type | VbX- | VbX+ |
|------------------|------------|------------|
| Standing (1) | | 12.8 (2.3) |
| Squatting (2) | 10.4 (2.7) | 14.6 (2.3) |
| Squat + load (3) | 14.4 (2.2) | 16.8 (2.8) |

after 3 min VbX+2 vs 10.5 in VbX-2, $P < 0.01$, Wilcoxon test), and higher in squatting than in standing (12.8 after 3 min in VbX+1). Linear regression analyses for all $s\dot{V}O_2$ values in VbX+ with the values in VbX- for exercise types 1-3 yielded very similar coefficients, with no significant difference. Hence, one correlation analysis was performed with values from all exercise types 1-3 (see Fig. 3), yielding a positive correlation ($r = 0.90$). The regression line has an intercept of about 6.5 (0.70) $\text{ml kg}^{-1} \text{min}^{-1}$, and a slope of 0.79 (0.068).

The residuals were computed from the equation obtained from the regression. No correlation was found between the residuals of exercise types 1 and 2 (standing and squatting), but a significant positive correlation ($r = 0.71$, $P < 0.001$) was observed between the $s\dot{V}O_2$ residuals of exercise types 2 and 3 (squatting without and with load).

Similarly, a linear regression analysis was computed for exercise type 1 and type 2 $s\dot{V}O_2$ values, and for type 1 and 3 values (see Fig. 4). Separate analyses were performed for exercise types 2 and 3, with data pooled from VbX- and VbX+ conditions. For exercise type 2 (squat without load), a correlation coefficient of $r = 0.70$ was obtained, while for exercise type 3 (squat with load), $r = 0.71$. Variance around the regression lines shown in Fig. 4 was significantly greater than around the line shown in Fig. 3, as evidenced by the F -test performed on the residuals.

Discussion

If assessed during steady-state conditions, $\dot{V}O_2$ permits an estimation of energy metabolism of the organism (Margaria 1968; McArdle et al. 1991; Stegemann 1991). If resting values are subtracted, exercise-related metabolic power can be estimated. Normalizing to the body mass yields data that are comparable between individuals. Our data show that platform vibration with a frequency of 26 Hz increases $\dot{V}O_2$. This supports strongly the view that vibration elicits muscular activity, and that we are therefore dealing with a type of exercise rather than with passive vibration.

This notion is further substantiated by the fact that, like $\dot{V}O_2$, RPE increased with vibration (see Table 2). Moreover, heart rate has been shown to increase in whole-body VbX with $\dot{V}O_2$, as expected from other types of exercise such as bicycling, and likewise,

increases in blood lactate have been shown to be in the range expected for moderate exercise (Rittweger et al. 2000).

In our subjects and set-up, the $s\dot{V}O_2$ was increased by about $4.5 \text{ ml}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$. This increase was observed equally in all three exercise types, confirming our former conjecture that VbX is comparatively easily controlled. The absolute value of $s\dot{V}O_2$ gives a rough idea of the vibration-related metabolic power. Given an energy equivalent of oxygen of $20.9 \text{ J}\cdot\text{ml}^{-1}$, this amounts to $1.6 \text{ W}\cdot(\text{kg body mass})^{-1}$. Walking at a speed of $0.4 \text{ m}\cdot\text{s}^{-1}$ requires a metabolic power of $2.3 \text{ ml}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$ (Beneke and Meyer 1997; di Prampero 1986; Zamparo et al. 1992). Hence, we conclude that whole-body VbX at frequency of 26 Hz and an amplitude of 6 mm requires a level of energy metabolism comparable to that required by moderate walking (Zamparo et al. 1992). If desired, this amount could be augmented by increases in the frequency and amplitude of the vibration (Rittweger et al. 2000).

Interestingly, the VbX-related $\dot{V}O_2$ was correlated with the "control" values, measured without vibration (Fig. 3). This was also true under resting conditions, when merely standing. In simple terms: the higher the $\dot{V}O_2$ under "control" conditions, the greater the vibration-related metabolic power (Fig. 3). Surprisingly, the slope of the regression line in Fig. 3 is significantly less than 1, indicating that in our experimental set-up, VbX-related metabolic power decreases with increasing general metabolic cost. While this observation can not be explained categorically by these results, possible explanations would be either a greater proportion of eccentric muscle work or of elastic energy storage at higher pre-loads to the muscles. Of course, both eccentric exercise and elastic storage are crucial mechanisms with which to understand VbX, which becomes clear from the peak acceleration applied in our experiment (18 times the earth's gravitation). It is likely that eccentric muscle work at 26 Hz vibration elicits stretch activation of the muscle (Bosco et al. 1981). Further studies should focus on this question, which may turn out to be crucial for the application of VbX in athletes.

In several instances, our results indicate that metabolic power was better controlled by vibration than by a more complex, voluntarily performed task such as knee bending (squatting). At a comparable rate of metabolic power, the inter-individual variability was greater for squatting than for VbX. Moreover, the correlation between the VbX- and VbX+ conditions was significantly closer than between the squat/no-squat conditions. We attribute this observation to the fact that voluntary motor patterns employ complicated, individually typical central nervous programs, whereas VbX, which is currently believed to be effective through stretch reflexes, is based on comparatively simple and thereby predictable spinal circuits. This interpretation is supported by our finding that the residuals from the VbX+/VbX- regression were correlated between type 2 and type 3 exercises (squat and squat with load), but not between

type 1 and 2 exercises (standing and squatting). It would be interesting in future studies to further elucidate this inter-individual variability and compare it to other, simpler tasks such as cycling.

It has been shown in patients with central nervous lesions that the degree of motor impairment in patients for a given motor task (e.g. walking) is correlated with $\dot{V}O_2$ (Olgiati et al. 1986). Hence, VbX in combination with the assessment of $\dot{V}O_2$ and, possibly, in combination with other motor tasks, may be useful as a diagnostic tool in central nervous disorders.

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