Acute physiological effects of exhaustive whole-body vibration exercise in man

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Summary

Vibration exercise (VE) is a new neuromuscular training method which is applied in athletes as well as in prevention and therapy of osteoporosis. The present study explored the physiological mechanisms of fatigue by VE in 37 young healthy subjects. Exercise and cardiovascular data were compared to progressive bicycle ergometry until exhaustion. VE was performed in two sessions, with a 26 Hz vibration on a ground plate, in combination with squatting plus additional load (40% of body weight). After VE, subjectively perceived exertion on Borg's scale was 18, and thus as high as after bicycle ergometry. Heart rate after VE increased to 128 min^{-1}, blood pressure to 132/52 mmHg, and lactate to 3·5 mM. Oxygen uptake in VE was 48·8% of $\dot{V}O_{2max}$ in bicycle ergometry. After VE, voluntary force in knee extension was reduced by 9·2%, jump height by 9·1%, and the decrease of EMG median frequency during maximal voluntary contraction was attenuated. The reproducibility in the two VE sessions was quite good: for heart rate, oxygen uptake and reduction in jump height, correlation coefficients of values from session 1 and from session 2 were between 0·67 and 0·7. Thus, VE can be well controlled in terms of these parameters. Surprisingly, an itching erythema was found in about half of the individuals, and an increase in cutaneous blood flow. It follows that exhaustive whole-body VE elicits a mild cardiovascular exertion, and that neural as well as muscular mechanisms of fatigue may play a role.

Keywords: energy turnover, exercise physiology, osteoporosis, sports, training.

Introduction

Vibration exercise (VE) is a type of exercise that has recently been developed for the prevention and treatment of osteoporosis. It elicits neuromuscular training reflectorily, without much effort and in short periods. In ovariectomized rats, VE has been reported as a successful countermeasure against loss of bone mineral (Flieger *et al.*, 1998). Moreover, it is conceivable that, depending on the frequency of vibration, VE renders specific training of type II muscle fibres possible. At present, several chronic training studies are being conducted in various fields, including sports and training sciences, geriatrics and treatment of osteoporosis (Rubin *et al.*, 1998; Wilhelm *et al.*, 1998; Bosco *et al.*, 1999).

We currently work with a prototype, in which a platform vibrates around a horizontal rotation axis. Exercise is usually performed with both legs, the feet posed equidistant on either side of the rotation axis. Hereby, extensor and flexor contractions alternate continuously in the left and the right legs. There is no direct vertical acceleration to the body's centre of gravity. This reduces passive forces to the joints, but elicits reflexes to stabilize the body posture.

In previous experiments, we have ascertained that VE elicits muscle contractions by recording an electromyogram (EMG). Moreover, oxygen uptake and hence

metabolism typically increases during VE with 26 Hz by about 5 ml O_2 min^{-1} kg^{-1} body weight, as compared to squatting without vibration (unpublished data). The present study was performed to explore the limits, i.e. the exertion and fatigue effects of exhaustive VE, and how far these limits are reproducible in subsequent exercise sessions. As a comparison, aerobic capacity was determined by progressive bicycle ergometry. Variables of interest were (i) gas exchange and lactate, (ii) heart rate and blood pressure, and (iii) neuromuscular function and fatigue. In addition, skin blood flow was assessed, since in previous experiments some subjects developed an erythema over the activated muscles.

Materials and methods

Subjects and set-up

The study was approved by the ethics committee of the Freie Universität Berlin (signature: GALILEO\PHYSIO\AKUT). The subjects were recruited through our centre by announcements on the campus. All subjects gave written informed consent before inclusion to the study. They came for three visits, with at least 8 days in between.

Forty persons decided to participate. One person was excluded for medical reasons, and two subjects dropped out in the course of the study: 16 females and 21 males were therefore included. The mean age was 23·5 years (SD 2·7 years, no significant difference between sexes). The female subjects were on average 168·9 cm tall (SD 5·0) and had a weight of 60·6 kg (SD 6·5). The males were 181·4 cm tall (SD 5·3) and weighed 75·2 kg (SD 8·3).

First visit (BIC)

Subjects were clinically investigated. A bicycle ergometry was performed, with increasing steps of 50 W over 3 min until exhaustion. Before (CTRL), during, immediately after (POST), and after 15 min recovery (REC), the following parameters were measured:

1 arterial blood pressure (Riva Rocci) in sitting position (POST: 60 s after termination),
2 ECG and heart rate,
3 O_2 uptake and CO_2 delivery, sampled at 0·1 Hz (Metamax, Cortex Biophysik, Leipzig),
4 subjectively perceived exertion, assessed by Borg's scale (Borg, 1976), and
5 blood lactate concentration from the finger tip (Accusport, Boehringer; CTRL & POST only).

The Metamax system has a resolution of 15 ml and an accuracy of 1·5% for volume measurement. The Zirkonium oxygen sensor and the infrared CO_2 sensor have an accuracy of 0·1 vol%.

Second and third visit (VIB1 & VIB2)

On the second and third visits, exercise until exhaustion was performed on a vibration platform (Novotec, Pforzheim, Germany). The subjects stood on this platform with their feet at 15 cm distance from the rotation axis on either side. Vibration was with an amplitude $a_0 = 1{\cdot}05$ cm, a frequency of 26 Hz, and hence a peak acceleration of 147 m s^{-2}, or 15 *g*.

The subjects bore an additional load fixed around the waist (40% of body weight in males; 35% in females because of their higher total body fat mass). After 30 s of simple standing, they started squatting, i.e. bending their knees in a 6 s cycle, 3 s down and 3 s up, as smoothly as possible.

When exhausted, the weight was removed, and the post-exercise (POST) values were immediately assessed. These were, in addition to those of the BIC visit:

1 jump height in three trials with 5 s intervals, with both hands places on the hips, the knees bent to 90° when started, and extended while in the air,
2 cutaneous laser Doppler flow (LDF) over the calf and over the foot during a 20 s period (Periflux3, Perimed, Sweden), and
3 for a period of 10 s, maximal voluntary contraction (MVC) of the knee extensors on the dominant side, torque and EMG were recorded (2 min after termination).

Assessment of arterial blood pressure was not possible during VE.

Signal and data analysis

The ECG and the EMG over the vastus lateralis muscle were recorded continuously during the whole experiment. Together with the LDF, torque chair and jump pad signals they were sampled at 1000 Hz after low-pass filtering (cut-off 350 Hz). The resolution of the Analog–digital (AD) board was 12-bit. The EMG

was picked up with two Ag/AgCl electrodes (0·33 mm^2), positioned with 30 mm distance over the vastus lateralis at 66% of the distance between the knee joint cleft and the spina iliaca anterior superior of the dominant leg.

The mean blood lactate concentration before BIC, VIB1 and VIB2 visits was 1·69 mM (SD 0·50, no significant difference). Hence, a lactate concentration ≥3 mM was considered as elevated. From 3 min before the exercises (VIB1, VIB2 & BIC) until termination, O_2 uptake and CO_2 delivery were recorded. These signals yielded the resting and the peak values of O_2 uptake, peak CO_2 delivery and the respiratory quotient.

For the vastus lateralis EMG during MVC, spectral analysis (Hanning window) was conducted for periods of 200 ms with 100 ms overlapping period, yielding a power spectrum every 100 ms. From these spectra, the absolute power and the EMG median frequency were extracted (Kupa *et al.*, 1995). Torque, power and median frequency were averaged for every 2000 ms.

Statistics were performed with SPSS software (PC version 7·5.2). 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. Whenever data showed normal distribution, differences between groups were checked by one-way ANOVA and the *t* test with Bonferroni's correction for multiple comparisons. In all other cases, the Wilcoxon or Friedman tests were applied. Significance was assumed if $P<0·05$. Values for VIB1 and VIB2 sessions were compared by correlation analysis and regression analysis.

Results

All analyses were performed for females and males separately. For the sake of clarity, however, we detail gender differences only where they were significant.

The delay between squatting and the first POST jump was on average 10·9 s in VIB1 (SD 1·29) and 10·6 s in VIB2 (SD 1·26). The jump intervals were 4·87 s in VIB1 and 4·80 s in VIB2. No significant differences were found.

Exercise and cardiovascular data

Exercise and cardiovascular data are summarized in Table 1. Exercise time was 325 s in VIB1 and 362 s in VIB2. Subjectively perceived exertion was initially higher in VIB1 than in VIB2 (12·0 versus 10·6), and also higher in both VE sessions than in the BIC visit. At the termination of exercise, however, there was no difference, with a Borg value of about 18 meaning something between 'very hard' and 'very, very hard' exercise.

As shown in Table 1, heart rate increased significantly less in VE than in bicycle ergometry (127·5 and 128·6 versus 171·4 min^{-1}). Control values were higher before VE than before bicycle ergometry. No difference was found in the recovery values. Similar to heart rate, the O_2 uptake was significantly lower during VE than during bicycle ergometry (21·9 and

Table 1 Exercise data during bicycle ergometry (BIC), and the two sessions of vibration exercise (VIB1 & VIB2).

	BIC	VIB1	VIB2
Exercise time (s)	743 (172)	325* (125)	362* (123)
Borg's scale			
ExBeg	8·5* (1·5)	12·0* (1·9)	10·6*,† (2·1)
ExEnd	18·1 (1·3)	18·0 (1·1)	18·2 (1·1)
Heart rate (min^{-1})			
CTRL	77 (12)	98* (17)	84* (17)
POST	171 (16)	128* (22)	129* (23)
REC	99 (14)	95 (19)	90 (17)
Specific O_2 uptake (ml min^{-1} kg^{-1})			
CTRL	5·8 (0·9)	7·3* (1·5)	7·6* (1·3)
ExEnd	44·8 (7·9)	21·3* (4·0)	22·1* (4·1)
Lactate (mM)			
POST	7·7 (2·7)	3·5* (1·6)	4·4* (2·0)
Respiratory quotient			
CTRL	0·79 (0·04)	0·82 (0·05)	0·82 (0·05)
ExEnd	0·98 (0·05)	0·90* (0·08)	0·89* (0·07)
Systolic blood pressure (mmHg)			
CTRL	114 (11)	114 (11)	115 (9)
POST	148 (18)	132* (16)	135* (16)
REC	106 (13)	109 (11)	111 (7)
Diastolic blood pressure (mmHg)			
CTRL	70 (11)	68 (8)	70 (10)
POST	65 (15)	52* (14)	50* (20)
REC	65 (14)	69 (7)	70 (10)

Values are given at the beginning (ExBeg) and in the end before termination (ExEnd) of exercise, or before exercise (CTRL), immediately after termination (POST) and after 15 min recovery (REC), respectively. SD is given in parenthese. *Significantly different from BIC; †significantly different from VIB1 (two-sided *t* test with Bonferroni correction for multiple comparisons).

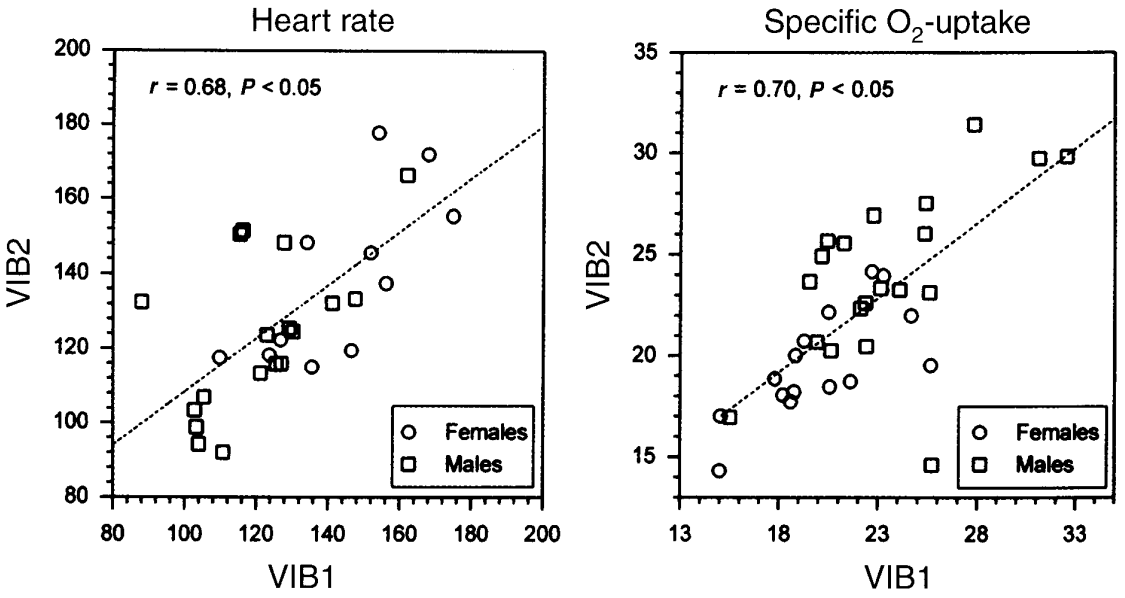

Figure 1 Heart rate and specific oxygen uptake at the termination of vibration exercise in two exercise sessions (VIB1 & VIB2). The correlations are significant, and indicate that exertion in vibration exercise has individually typical features.

22·1 versus 44·8 ml min^{-1} kg^{-1}). Again, control values were higher in VE. All subjects tested had a significant increase of lactate concentration after bicycle ergometry, indicating significant exertion. Hence, we identified the maximal specific O_2 uptake ($\dot{V}O_{2max}$): 48·8% of $\dot{V}O_{2max}$ was reached in VIB1, and 49·3% in VIB2 (Table 1). High values of up to 81·1% of $\dot{V}O_{2max}$ were observed in two former male Judoka. The mean lactate values after VE were significantly lower than during bicycle ergometry, but still 20 out of 37 had a lactate concentration higher than 3 mM in VIB1, and 27 in VIB2.

Systolic blood pressure increased significantly during bicycle ergometry and VE (Table 1). Again, the rise in VIB1 and VIB2 was not as large as in BIC (131·6 and 134·9 versus 147·6). Interestingly, the diastolic blood pressure was decreased after VE, but not after bicycle ergometry. Blood pressure returned to control values after 15 min recovery.

For individual subjects, heart rate and oxygen uptake values of the VIB1 and VIB2 sessions were correlated with each other (Fig. 1). The correlation coefficients of the end-exercise values of VIB1 and VIB2 were 0·68 for heart rate and 0·70 for $\dot{V}O_2$ (Fig. 1). No obvious relation was seen between the residuals of heart rate (VIB1/VIB2) and oxygen uptake (VIB1/VIB2).

The data for cutaneous LDF were not normally distributed. The Friedman test yielded a significant increase of the LDF signal after VE over both calf and foot (see Table 2). After recovery, the values had returned to normal. Without quantification, we report that a number of subjects, particularly women and particularly in the VIB1 visit, showed considerable erythema on their legs, often sharply delineated like stockings. In many cases, the erythema was paralleled by oedema over the foot and the tibia (see Fig. 2). Oedema and erythema also occurred independently of each other. Moreover, many subjects spontaneously reported itching of the leg (not the foot sole) after about 1–2 min of VE.

Neuromuscular data

Basal values of jump height differed significantly between females and males. In both groups, a reduction was observed after VE. This was more pronounced in males, where the first and second POST jumps were reduced by 10%. In females, only the first POST jump in VIB2 was significantly

Table 2 Laser Doppler flow (LDF) of the skin over the foot and over the calf, before VE (CTRL), immediately after termination (POST), and after 15 min recovery (REC).

Laser Doppler flow	VIB1	VIB2
Foot		
CTRL	3·66 (1·40)	3·86 (2·70)
POST	9·01* (11·4)	7·21* (7·11)
REC	5·84 (7·47)	4·43 (3·51)
Calf		
CTRL	3·03 (1·59)	2·87 (2·02)
POST	6·53* (6·47)	7·42* (9·02)
REC	3·39 (1·90)	4·02 (5·11)

LDF was increased after VE in females. Values are given in arbitrary units, unity is the calibration signal of the Periflux3. SD is gicen in parentheses. *Significant increase compared to CTRL.

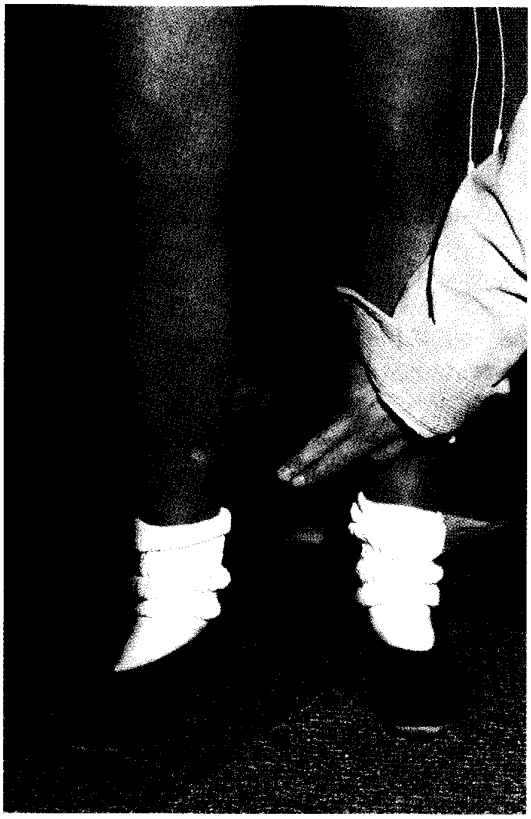

Figure 2 Erythema and oedema of the foot after vibration exercise were seen particularly in the first session, and particularly in women. Itching was reported frequently. These changes resolve rapidly if the subject walks around.

lowered (see Fig. 3). No reduction of jump height was found in the third jump.

Reduction of jump height (ΔJH) was computed as the mean jump height in CTRL minus first jump POST. A significant correlation was found between ΔJH in VIB1 and VIB2 ($r = 0{\cdot}67$, no significant offset, see Fig. 4). Multiple linear regression analysis did not reveal any relation between ΔJH_{VIB1} and POST blood lactate concentration, maximal specific O_2 uptake, duration of exercise, or CTRL mean jump height ($P > 0{\cdot}25$ in all cases).

After VE, a significant reduction of knee extension torque by about 10% was observed in the males during the first 2 s, but not during the last seconds (see Table 3). However, the EMG frequency in POST was increased in the first as well as in the last two seconds, if compared to CTRL and REC. In the females, the same tendency was observed without reaching the level of significance.

To account for the time course of torque and EMG median frequency during MVC, the differences between the 0–2 s and 8–10 s values were computed. These differences were significantly lower in POST than in CTRL in both sexes, i.e. torque and median frequency during MVC decreased less after VE than before ($P<0{\cdot}05$, ANOVA).

From the 0–2 s values of EMG median frequency and torque, the reduction (ΔMF and Δtorque) was calculated in the same way as for reduction of jump height (ΔJH). Δtorque was weakly correlated with ΔJH, and ΔMF with POST lactate. ΔMF showed a correlation to lactate, particularly at lower lactate levels.

Discussion

Treatment and prevention of osteoporosis by physical exercise is a new therapeutic concept (Calmels *et al.*, 1995). While several studies have demonstrated that it is applicable (Braith *et al.*, 1996; Heinonen *et al.*, 1996; Heinonen *et al.*, 1999), there definitely is potential for improvement. The present investigation was conducted to explore a novel method, vibration exercise, at its extreme.

Generally, the subjects became acquainted very rapidly with this exercise. By the second VE visit, they were standing confidently and safe on the platform. This is mirrored in the data: exercise time was longer

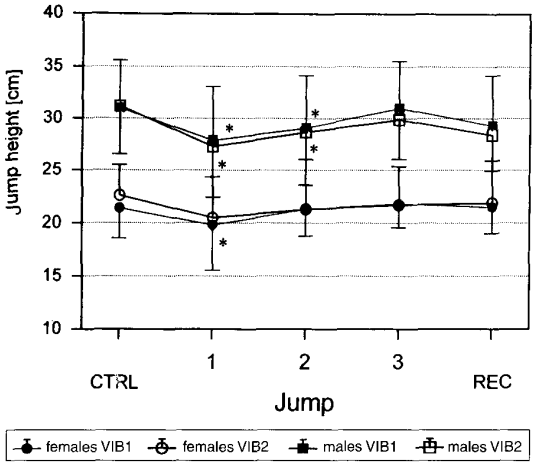

Figure 3 Jump height before vibration exercise (CTRL), immediately after termination in 5 s intervals (1, 2 & 3), and after 15 min recovery (REC). For CTRL and POST conditions, the average of three jumps is given. Jump height was decreased immediately after VE, but had recovered by the 3rd jump POST. *Significantly lower than mean of CTRL ($P<0{\cdot}05$).

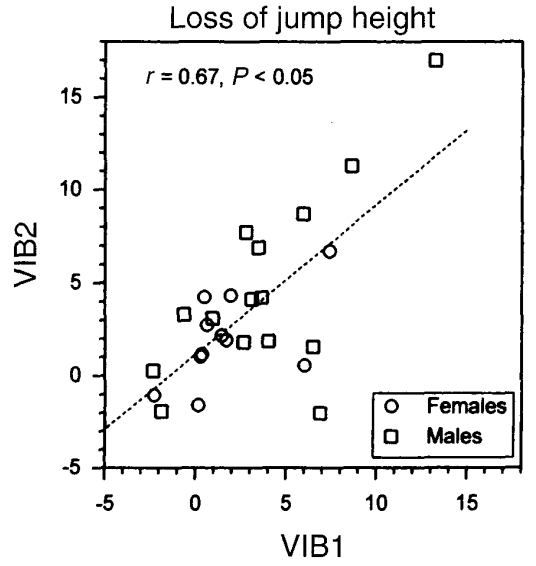

Figure 4 Reduction of jump height (ΔJH) after vibration exercise in sessions VIB1 and VIB2. Again, the significant correlation indicates individual typical patterns of fatigue. Note that some subjects even had an increased jump height after VE.

Table 3 Torque and EMG median frequency in VIB2: before VE (CTRL), immediately after termination (POST) and after 15 min recovery (REC).

	Torque (Nm)	EMG median frequency (Hz)
Females		
0–2 s		
CTRL	133 (30)	138 (47)
POST	128 (31)	149 (53)
8–10 s		
CTRL	131 (27)	124 (45)
POST	129 (27)	142 (48)
Males		
0–2 s		
CTRL	203 (62)	129 (19)
POST	182† (59)	132* (22)
8–10 s		
CTRL	195 (60)	124 (22)
POST	197 (47)	133* (20)

Depicted are the first and the last two seconds of maximum voluntary knee extension. In males, torque was decreased in the first two seconds after VE, whereas median frequency was elevated in the POST condition. *Significantly higher, †significantly lower than CTRL value ($P < 0{\cdot}05$, Wilcoxon). SD is given in parentheses.

in VIB2 than in VIB1, and the Borg values at the beginning of exercise were lower in VIB1 (approximately 12) than in VIB2 (approximately 10·5). At the termination of exercise, i.e. after about 5 min, the subjects appeared to be quite as exerted by VE as after 12 min bicycle ergometry (see Table 1).

O_2 uptake reached only about 50% of $\dot{V}O_{2max}$, almost uniformly in VIB1 and VIB2. Likewise, heart rate rose to about 130 in females, which is about the value expected for 50% of $\dot{V}O_{2max}$ (Rowell, 1971). This seems to rule out possible additional stimulating effects on the cardiovascular control system (McCloskey *et al.*, 1972; Schulz *et al.*, 1983). For technical reasons, CTRL heart rate and oxygen uptake in VIB1 and VIB2 were recorded while the subjects were standing, which accounts for their elevation compared to CTRL in BIC. Systolic arterial blood pressure, which could not be measured during VE, was found to have increased after it, but less so than after bicycle ergometry. In contrast, diastolic blood pressure had decreased only after VE.

The fatigue in VE therefore appears to be caused not by insufficiency of cardiac output (as in exhaustive bicycle ergometry), but rather occurs in the neuromuscular system. Lactate never increased in VE as much as in bicycle ergometry. But even if the blood

concentration was low, some parts of the musculature may accumulate lactate, which then is signalled via muscle metaboreceptors and leads to subjective exertion.

In both VE visits, a reduction of jump height (ΔJH) was observed 10 s after termination of VE, which was basically recovered from within 20 s. ΔJH was not dependent on initial jump height, POST VE lactate concentration, or peak specific O_2 uptake, and it was intra-individually stable in repeat visits. Therefore, ΔJH seems to express individually typical information. Similar r^2 values were found for VIB1 and VIB2 values of peak specific oxygen uptake and heart rate. The residuals of these regressions, however, were not correlated with each other. This indicates that different subjects depict different, but intra-individually typical response patterns, which is of importance for training regimes.

MVC was performed 2 min after termination of VE. Usually, the EMG frequency and force decline during sustained maximal voluntary contraction (Sandercock *et al.*, 1985). This was seen in CTRL, but not in POST, where EMG median frequency hardly decreased during MVC, and torque even showed a tendency to increase. In other words, in POST, less force was produced at a higher median frequency, but with less tendency to decline during sustained contraction.

Taking these findings together, it becomes clear that in VE, at least two mechanisms of fatigue play a role: a rapid one (evidence: recovery of ΔJH within 20 s), and a slow one (evidence: Δtorque and ΔMF in MVC). ΔMF was correlated with lactate and could be partly explained by muscle fatigue. The facts that (i) subjective fatigue could occur without increased lactate, (ii) correlation of ΔJH with lactate and ΔMF is poor or lacking, and (iii) the recovery time of 20 s, hint at neural causes of the fast-recovering fatigue mechanism, at peripheral, spinal or higher levels.

These findings and conclusions are in line with studies of fatiguing by the tonic vibration response (TVR). The TVR is elicited by vibrating devices applied either to the muscle bellies or tendons. It is transmitted by activation of Ia afferents (Hagbarth, 1973), which activate, via large α-motor neurones, mainly type II muscle fibres. It has been shown (i) that sustained TVR decreases voluntary force until 10–20 s after the end of vibration, (ii) that it is accentuated by preceding muscle exercise, and (iii) that it affects primarily the subject's ability to generate high firing rates in high-threshold motor units (Bongiovanni *et al.*, 1990). A pre-synaptic inhibition or a transmitter depletion of the Ia afferents have been postulated. Recently, Ribot-Ciscar *et al.* (1998) have shown a third mechanism, namely a 'fatiguing' of the Ia afferents themselves.

Some important differences between TVR and VE must be kept in mind: (i) in TVR, the usual frequencies applied are around 100 Hz or even higher, (ii) VE in this study was applied to the whole body and not to a single muscle, and (iii) VE was combined with slow, voluntary movements, which usually break the TVR.

An unexpected finding of interest is the reduced diastolic blood pressure after VIB1 and VIB2. Since heart rate and systolic pressure were higher than in CTRL, arterial vasodilation is the cause. It is not clear whether the diastolic hypotension emerges during VE, or only after it. In the latter case, vasodilation might occur in response to impeded muscular circulation, which in isometric contraction is known to occur above 60% maximal isometric force (Petrofsky & Hendershot, 1984).

It is another interesting question, whether the swelling and erythema are caused by vasodilation of supplying arteries via an increase of perfusion pressure. Interestingly, swelling and flare have also been observed after TVR at frequencies around 30 Hz, but not higher (Homma, 1973). Quantitatively, we assessed an increase in the LDF signal after VE. LDF measures blood flow, i.e. volume × speed. Increases of LDF were also observed without erythema, suggesting differential effects on cutaneous superficial and deeper arteries. Both, erythema and oedema were often limited to stocking-like areas, always starting at the bottom of the foot, i.e. closest to the vibrating platform. This renders a mechanic explanation likely. A well-known reaction of the skin to mechanical stimulation is dermographism: friction over the cutis leads to reddening and swelling (Wong *et al.*, 1984). Because so frequently observed, the reaction in our subjects is definitely distinct from the scarce vibratory angioedema (Lawlor *et al.*, 1989) and from acute pressure urticaria (Lawlor *et al.*, 1991).

In brief, vibration exercise is a new strategy in eliciting muscular contraction by reflexes. It therefore

may allow the combination of voluntary and involuntary muscle work. The present investigation has shown that, even if performed to exhaustion, cardiovascular effects of VE are mild. In young healthy subjects, heart rate rises to 130 min^{-1}, which corresponds to 50% of maximal oxygen uptake. Blood lactate rose to about 3·5 mM. Systolic blood pressure increased moderately up to 130 mmHg, but the diastolic pressure dropped to almost 50 mmHg. All parameters returned to normal values within 15 min of recovery. In consequence, the risk expected when VE is applied in the elderly is negligible. Surprising findings of this study were the itching erythema and oedema of the skin over the activated muscles, which have to be investigated by further studies, as well as the mechanisms of fatigue, which seem to bear neuronal and muscular components.

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