

# Acute changes in neuromuscular excitability after exhaustive whole body vibration exercise as compared to exhaustion by squatting exercise

Jörn Rittweger<sup>1,2</sup>, Marcus Mutschelknauss<sup>2</sup> and Dieter Felsenberg<sup>2</sup>

<sup>1</sup>Institut für Physiologie, Freie Universität Berlin, Arnimallee, Berlin, Germany, <sup>2</sup>Zentrum für Muskel- und Knochenforschung, Universitätsklinikum Benjamin Franklin, Freie Universität Berlin, Hindenburgdamm, Berlin, Germany

## Summary

### Correspondence

Jörn Rittweger, Institut für Physiologie, Freie Universität Berlin, Arnimallee 22, 14195 Berlin, Germany  
E-mail: ritmus@zedat.fu-berlin.de

### Accepted for publication

Received 15 July 2002;  
accepted 28 October 2002

### Key words

electromyographic; jumping test; patellar tendon reflex; perceived exertion; training; vibration exercise

The effects of hard squatting exercise with (VbX+) and without (VbX-) vibration on neuromuscular function were tested in 19 healthy young volunteers. Before and after the exercise, three different tests were performed: maximum serial jumping for 30 s, electromyography during isometric knee extension at 70% of the maximum voluntary torque, and the quantitative analysis of the patellar tendon reflex. Between VbX+ and VbX- values, there was no difference found under baseline conditions. Time to exhaustion was significantly shorter in VbX+ than in VbX- ( $349 \pm 338$  s versus  $515 \pm 338$  s), but blood lactate ( $5.49 \pm 2.73$  mmol l<sup>-1</sup> versus  $5.00 \pm 2.26$  mmol l<sup>-1</sup>) and subjectively perceived exertion (rate of perceived exertion values  $18.1 \pm 1.2$  versus  $18.6 \pm 1.6$ ) at the termination of exercise indicate comparable levels of fatigue. After the exercise, comparable effects were observed on jump height, ground contact time, and isometric torque. The vastus lateralis mean frequency during isometric torque, however, was higher after VbX+ than after VbX-. Likewise, the tendon reflex amplitude was significantly greater after VbX+ than after VbX- ( $4.34 \pm 3.63$  Nm versus  $1.68 \pm 1.32$  Nm). It is followed that in exercise unto comparable degrees of exhaustion and muscular fatigue, superimposed 26 Hz vibration appears to elicit an alteration in neuromuscular recruitment patterns, which apparently enhance neuromuscular excitability. Possibly, this effect may be exploited for the design of future training regimes.

## Introduction

Although present in many classical sports, vibration loads have been neglected until very recently (Issurin et al., 1994; Mester et al., 1999). Vibration exercise (VbX) is a new type of exercise, that has been designed with the idea of stimulating muscles via spinal reflexes. It is currently being tested in different fields, ranging from the training of elite athletes (Bosco et al., 1999) to the therapy of osteoporosis (Spitzenpfeil & Mester 1997; Rubin et al., 1998, 2001) and chronic low back pain (Rittweger et al., 2002b).

Some unexpected observations have been made in the application of vibration exercise. For example, the blood volume has been reported to increase (Kersch-Schindl et al., 2001), and an erythema may occur over the activated limbs (Rittweger et al., 2000). Another finding has been that of an increased electromyographic (EMG) median frequency in isometric contraction immediately after exhaustive vibration

exercise, which is in contrast to the general observation of a decreased EMG frequency in muscle fatigue (Hakkinen & Komi 1983).

It is evident that a better understanding of the physiological mechanisms involved in vibration exercise will help to identify the potential benefits of this technique. In this respect, an alteration in the neuromuscular functioning is of crucial interest. It was thus decided to investigate the acute neuromuscular effects of exhaustive whole body vibration in an integrative approach.

Muscle function is characterized by the production of force and power, but also by the capacity to maintain force and power over a given period of time (=endurance). Both central nervous and peripheral mechanisms contribute to these functions.

The maximum muscular power output can be observed after single jerks or jumps (Bosco et al., 1983b). In young healthy subjects, the power output during continuous maximum jumping is usually maintained over 10–20 s and then declines

as a function of fibre type composition and hence fatigability (Bosco et al., 1983a).

One mechanism of fatigue is due to the relative insufficiency in oxidative energy supply. As a result, lactate accumulates in the blood. Within the usual range, lactate efflux from the muscle is linearly related with the intracellular concentration and is inversely related to the slow twitch muscle fibre proportion (Bangsbo et al., 1993). During intense, dynamic exercise blood lactate may thus serve as an indicator of fast twitch muscle fibre fatigue.

During isometric maximum voluntary contraction (MVC) in healthy young subjects, the greatest part of the recruitable force is reliably elicited (Allen et al., 1995). In sustained contractions, the EMG frequency and the EMG power picked up over the working muscle typically decrease, both in concentric contractions and in isometric contractions (Tesch et al., 1983; Hakkinen & Komi 1983). This is due to changes in the recruitment patterns, as smaller motor units have a smaller conduction velocity (and hence EMG frequency) and amplitude (and hence EMG power) than larger units (Kupa et al., 1995). Thus, the analysis of EMG patterns serves as an indicator of central nervous recruitment patterns.

The stretch reflex is a pathway with one central nervous synapse, relaying information about length changes to the  $\alpha$ -motoneurone. Within this pathway, the Ia-afferent nerve fibres have a predominant effect on larger motor units, containing predominantly fast twitch muscle fibres. After demanding exercise the reflex amplitude is typically decreased (Avela et al., 2001; Zhang & Rymer 2001).

We have thus decided to investigate the influence of vibration exercise on neuromuscular force and power production and maintenance, as assessed by isometric contraction and the serial jumping test, and on the central nervous neuromuscular recruitment, as assessed by EMG analysis during isometric contraction and by quantitative stretch reflex analysis. We chose to test the frequency (26 Hz) that has been used by many other investigators including our own laboratory. From the experience in our laboratory and by reports from other colleagues, a vibration frequency below  $\sim 20$  Hz induces muscular relaxation (we have successfully applied 18 Hz vibration exercise in patients with chronic lower back pain), whereas there are reports that at frequencies above  $\sim 50$  Hz severe muscle soreness and even haematoma may emerge in untrained subjects.

## Methods

### Participants

Ten female and nine male subjects were recruited from the University campus. Before inclusion, written informed consent was obtained from all subjects (approval of the local ethical committee under signature Galileo/Physio/Elektrik). The female subjects had a mean age of  $21.8 \pm 2.7$  years, height of  $172.6 \pm 6.1$  cm, body mass of  $63.2 \pm 3.4$  kg and a body mass

index (BMI) of  $21.3 \pm 1.8$  kg m<sup>-2</sup>. The male subjects had a mean age of  $24.4 \pm 2.8$  years, height of  $181.8 \pm 5.5$  cm tall, body mass of  $75.3 \pm 6.4$  kg and a BMI of  $22.7 \pm 1.2$  kg m<sup>-2</sup>.

### Study design

A randomized cross-over study was designed, that compared neuromuscular effects of exhaustive exercise in squatting with (VbX+) and without (VbX-) whole body vibration. Three different neuromuscular measurements (i.e. serial jumping, isometric torque, and patellar stretch reflex) were performed separately before the exercise (Pre), and immediately after termination of the exercise (Post), and again after 10 min of recovery after termination (Rec). Hence, each subject performed six trials ( $3 \times 2$ ), with at least 3 days interval between visits. Each subject performed the different tests in random order.

### Measures

Neuromuscular testing comprised EMG during isometric knee extension, quantitative measurement of the patellar tendon reflex and serial vertical jumping. All tests were performed for 30 s.

Vertical serial jumping was performed on a resistive contact plate. The subjects were instructed to jump as high as they could, with the ground contact time as short as possible. During the whole time, the hands were placed on the hips.

Isometric torque typically declines after exhaustive vibration exercise (Rittweger et al., 2000). Experiments carried out for preparation of this study have shown that a level of 70% of the maximum isometric knee extension can be performed for 30 s even after exhaustive exercise. Hence, the isometric knee extension in this study was performed at 70% of MVC. Contractions were performed on a specially manufactured chair, with the knee angle set at  $100^\circ$  ( $0^\circ$  = full extension). The maximum isometric extension force was assessed in three trials with eyes closed and verbal encouragement by the experimenter. A 100% MVC was defined as the greatest torque value in these three trials. Two electrodes for EMG recordings were placed with 3 cm distance over the vastus lateralis muscle at one-third of the femur length from its distal part. For the testing conditions, the subjects were asked to elicit a torque of 70% of their maximum voluntary effort. They controlled the torque exerted on a computer screen on which the range between 65 and 75% was displayed.

The patellar tendon reflex was tested in the same chair as the isometric torque. The ankle was attached to a leg supporter with a velcro tape. The hanging foot exerted a negative torque under resting conditions, which was helpful in asserting the relaxation of the leg muscles. Stretch reflexes were elicited manually every second with a hammer bearing a strain gauge on its front. The hammer impact was controlled on-line.

Both the isometric knee extension and the patellar tendon reflex were tested on the non-dominant leg.

## Procedures

Before starting, the subjects warmed up (10 min bicycling at 50 W and stretching). Whole body vibration exercise was performed with a prototype of a commercially available product (Galileo 2000; NovoTec, Pforzheim, Germany). In brief, the device evokes platform oscillations around a central axis, that is located between both feet of the subject. Hence, the left and right leg are stretched and shortened alternately. The vibration amplitude was set to 6 mm (12 mm from top to bottom), and the frequency was set to 26 Hz.

During the exercise, squatting was performed from almost complete extension of the knee to an angle of 90°. An additional load of 40% of the body mass was applied via a string that was attached to a hip belt. The length of the string was adjusted so that the weight touched the ground at flexions greater than 90°, thus controlling the squatting range. For the temporal control of the squatting exercise, a metronome was set at 1 Hz, and the subjects were instructed to move 3 s down and 3 s up as evenly as they could. The precision of the movements was controlled by the experimenter confirming that the hanging weight almost touched the platform during each squat cycle.

Before and 2 min after all exercise bouts, the blood lactate was measured with the Accusport device (Roche Diagnostics, Mannheim, Germany), using capillary blood from the finger. During exercise, the rate of perceived exertion (RPE) was assessed every minute (Borg 1976). At the end of the exercise the subjects reported their level of fatigue. The load was then discharged by a quick release button and the subject was placed on the chair or on the jumping plate, respectively. Testing began exactly 10 s after termination of the exercise.

## Data analysis

Signals from the contact plate, the hammer strain gauge, knee extension torque, and the electromyogram of the m. vastus lateralis were amplified and digitized with a 12-bit resolution and a sampling rate of 1000 Hz. The neuromuscular test variables were averaged over epochs of 10 s, yielding three consecutive epochs for each test condition (10, 20, and 30 s).

For each jump, the time-in-air ( $t_{Air}$ ) and the ground contact time ( $t_{Ground}$ ) between jumps was assessed. The jump height was computed as  $h_{Jump} = 1.23t_{Air}^2 (m/s^2)$ .

During 70% MVC knee extension, the average torque was assessed. The EMG recordings of the m. vastus lateralis were analysed for the median frequency (Kupa et al., 1995; Rittweger et al., 2000). Power spectra were computed every 200 ms with 100 ms overlap and applying a Hanning window as described before (Rittweger et al., 2000). From these spectra, the median frequency was assessed.

The hammer beats were detected from the strain gauge recordings by a threshold algorithm. They were used to compute triggered averages of the torque signal. The reflex amplitude was assessed as the difference between the peak torque after the hammer beat and the torque at onset of the beat.

The reflex latency was computed as the time delay between the beat onset and the torque value of 25% of the reflex amplitude.

## Statistical analysis

Statistics were performed with the SPSS software in its PC version 10.0. The paired t-test was used to examine for differences in exercise time and RPE. A within subject repeated measures ANOVA with *post-hoc* simple contrasts was performed to examine for differences in blood lactate and reflex latency before and after VbX- or VbX+. Within subject repeated measures ANOVA was also performed to analyse effects of treatment (VbX- or VbX+) and epoch (10, 20 and 30 s) in torque, EMG frequency, EMG power, reflex amplitude, jump height and jumping ground contact time.

If not indicated otherwise, data are given as mean  $\pm$  standard deviation (SD). Significance was assumed if  $P < 0.05$ . Significance levels were adjusted for multiple comparisons applying Bonferroni's rule.

## Results

The exercise time was significantly shorter in VbX+ than in VbX- sessions. There were no significant differences in RPE between the two treatments (VbX+ and VbX-). Blood lactate increased after the exercise, but again there was no treatment related effect (see Table 1). A significant correlation was found between VbX- and VbX+ in values of exercise time ( $r = 0.67$ ,  $P < 0.001$ ), but not in RPE or blood lactate.

## Serial jumping

Under Pre conditions, jump height was decreased in the second and third 10 s epoch ( $P < 0.001$ ), but there was no treatment effect observed ( $P > 0.2$ ). Likewise, ground contact time was prolonged in the second and third epoch. Post exercise, the epoch effect on jumping height and on ground contact time was not present ( $P = 0.15$ , and  $P = 0.13$ , respectively). As before, there were no treatment effects on jump height ( $P = 0.60$ ) or ground contact time ( $P = 0.30$ ).

**Table 1** General descriptive data for exercise.

Measure	VbX+	VbX-
Exercise time (s)	349 (230)	515 (338) <sup>a</sup>
RPE last minute	18.1 (1.19)	18.6 (1.63)
Blood lactate Pre (mmol l <sup>-1</sup> )	1.80 (0.57)	1.92 (0.72)
Blood lactate Post (mmol l <sup>-1</sup> )	5.49 (2.73) <sup>b</sup>	5.00 (2.26) <sup>b</sup>

Exercise time: time to subjective exhaustion; RPE: rate of perceived exertion (Borg's value).

<sup>a</sup>Greater in squat than in VbX ( $P < 0.01$ ).

<sup>b</sup>Post greater than Pre ( $P < 0.001$ ), but comparable between treatments ( $P > 0.25$ ).

### Isometric knee extension

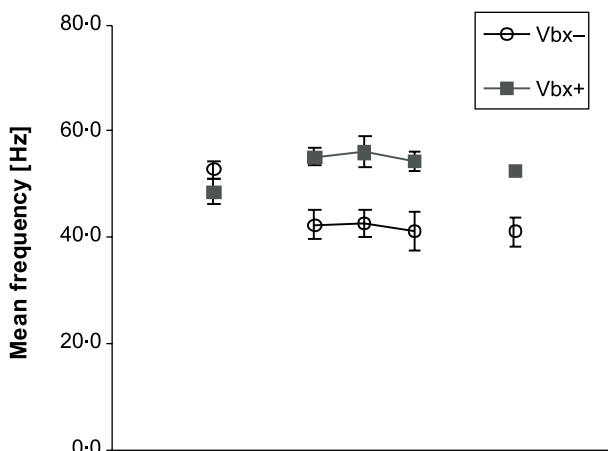
Pre exercise, there were no effects of epoch or treatment on the average torque, indicating that knee extension was equally maintained at 70% of the maximum voluntary torque. The m. vastus lateralis EMG median frequency decreased from the first to the third epoch (VbX- 52.7 ± 7.3 Hz versus 47.3 ± 5.3 Hz, and VbX+ 48.6 ± 11.6 Hz versus 41.9 ± 12.0 Hz), but it was comparable between treatments.

Post exercise, the torque declined significantly from the first epoch (VbX-: 121 ± 18 Nm, VbX+: 111 ± 29 Nm) to the second epoch (VbX-: 116 ± 21 Nm, VbX+: 105 ± 28 Nm). No significant treatment effect was observed. There were 12 subjects who discontinued the isometric contraction in the third 10-s epoch after VbX- exercise, and 10 after VbX+ exercise, reporting severe fatigue. The EMG frequency was greater in VbX+ than in VbX- ( $P < 0.001$ , for example 55.2 ± 5.8 Hz versus 42.4 ± 9.4 Hz in the first epoch). No significant epoch effect was found Post exercise (Fig. 1).

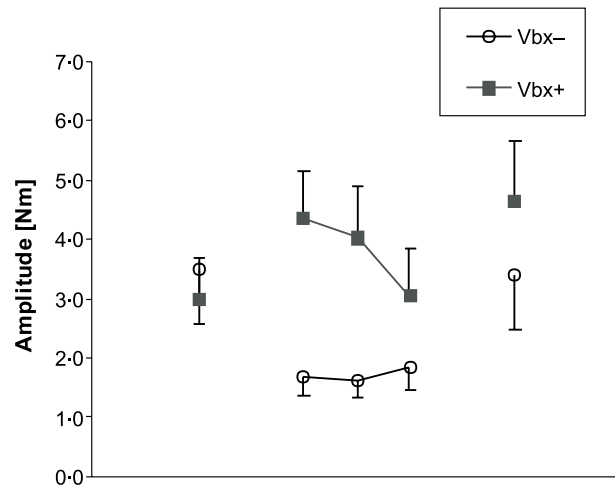
Under Rec conditions, there was no effect of epoch or treatment on torque, indicating that knee extension was again equally maintained. Although the EMG median frequency still appeared to be higher after VbX+ than after VbX-, the difference was no longer significant ( $P = 0.15$ ). No differences were observed in EMG power before or after exercise.

### Patellar tendon reflex

Reflex latency was comparable under Pre, Post and Rec conditions, and there was no treatment effect observed, indicating that evoking the reflexes was quite stable. No significant effect of treatment or epoch was found in reflex amplitude under Pre conditions. There was, however, a significant treatment effect on reflex amplitude in Post exercise ( $P = 0.005$ ), with an increase after VbX+, but a decrease after VbX- exercise (see Fig. 2). A weekly significant interaction



**Figure 1** EMG mean frequency picked up over the vastus lateralis muscle after exercise with (VbX+) and without vibration (VbX-). The mean frequency was significantly higher after VbX+ than after VbX-. This effect persisted after 10 min of recovery.



**Figure 2** Amplitude of the patellar tendon reflex after exercise with (VbX+) and without vibration (VbX-). The reflex amplitude was measured as torque on a specially designed chair. After VbX+, it was significantly greater than after VbX- ( $P < 0.01$ ). Compared with baseline conditions, it decreased after VbX- ( $P < 0.05$ ), but it increased insignificantly after VbX+ ( $P = 0.056$ ).

effect was observed between treatment and epoch ( $P = 0.043$ ), indicating that the greater reflex amplitude after VbX+ was most pronounced in the first and second 10-s epochs. During Rec, these effects were no longer observed.

### Discussion

The observed total exercise time, the changes in blood lactate and the RPE values suggest that a comparable degree of exhaustion and muscular fatigue was reached more rapidly with vibration than without. This becomes plausible when considering that whole-body vibration increases the oxygen consumption when applied in addition to the squatting exercise (Rittweger et al., 2001). A substantial correlation was observed between the individual exercise times with or without vibration, indicating a contribution of the individual resistance to fatigue for both types of exercise.

Comparable levels of fatigue were also observed in the serial jumping test, as demonstrated by the jumping height and ground contact time that were found to be reduced after the exercises and which no longer depicted a decline of power output over the subsequent epochs. Moreover, the neuromuscular capacity to maintain force over time was comparably disrupted after both types of exercise, as shown by the decline in torque in the second and third epoch after exercise and the inability of about 50% of the subjects to maintain 70% of the maximum voluntary torque over 30 s.

Both types of exercise produced comparable levels of exhaustion and neuromuscular fatigue and there were also differences observed in the neuromuscular function. First, and consistent with our former reports (Rittweger et al., 2000), the EMG median frequency increased over the vastus lateralis muscle during isometric contraction and was greater after exercise with

than without vibration. Although no effect of vibration was observed on EMG power, the difference in EMG frequency suggests a central nervous recruitment of predominantly large motor units.

Secondly, we found differences in the stretch reflex amplitude, which after exercise with vibration was comparable with baseline conditions or even increased, while it was clearly decreased after exercise without vibration. This is remarkable because the declines in muscular force and power output were comparable in both exercise types. Interestingly, the effect faded away after 10–20 s.

Considering that an attenuation of stretch reflex amplitude is a common finding after demanding exercise, the maintained (or even increased) stretch reflex amplitude observed after vibration exercise is most likely due to an enhanced central motor excitability, particularly with respect to the phasic (fast twitch) fibres and motor units. This view might find support in the reports by Torvinen *et al.*, (2002) who found an increase in jumping height and in isometric torque after non-exhaustive vibration exercise, possibly supporting the view of an increased neuromotor excitability.

The tonic vibration response, which is thought to be elicited via the spindle loop, causes a mitigation of reflex levels, probably due to presynaptic inhibition. This seems to be in contrast with the above interpretation. It should be remembered, however, that the tonic vibration response can be only elicited if the subject relaxes the limb to which the vibrator is attached. Voluntary movements disrupt the response. Vibration exercise, on the other hand, is in combination with slow voluntary movements (squatting), thus presumably counteracting the response in passive vibration.

Studies of oxygen uptake during non-exhaustive vibration exercise have shown that the energy turnover elicited by the vibration can be parametrically controlled by vibration amplitude, vibration frequency and by additional loads applied (Rittweger *et al.*, 2002a). Together with the known influence of passive vibration on muscle spindle activity (Ribot-Ciscar *et al.*, 1998), and with the neuromuscular findings presented here, we assume a substantial evidence for vibration exercise interacting with spinal reflex loops and possibly influencing these pathways.

Thus, the view may be emerging that vibration exercise is a means to alter central motor control patterns. It should be considered that the present observations have been made in healthy young adults of moderate levels of physical fitness. Moreover, they have been obtained after exercise until exhaustion with an additional load at one vibration frequency and amplitude. As indicated above, the vibration frequency plays an important role. Based on the observation that oxygen consumption increases fairly linearly between 18 and 34 Hz, the same might be expected for the neuromuscular effects. Yet the effects of exercise duration, vibration frequency, amplitude and load that are optimum to evoke the observed neuromuscular excitability remain to be clarified in young adults, but also in athletes or elderly subjects and patients, after acute and after

chronic application. Once explored, the mechanisms involved may be exploited for the application of vibration as a training method and for the design of training schedules.

## Acknowledgments

The authors are particularly grateful Nitert, to Dipl Ing Petsch, to Breuer and to Forster for their technical support. Boehringer Mannheim has kindly provided the lactate tests. The Siemens company has provided the bicycle ergometer, and Novotec has delivered a Galileo prototype. Special thanks to the 'Forschungskommission' of the Medical Faculty of the Free University of Berlin for the support regarding the physiological recording system and the torque chair. Last but not least, we are grateful to all our test subjects, whose selfless contribution has made this work possible.

## References

- Allen GM, Gandevia SC, McKenzie DK. Reliability of measurements of muscle strength and voluntary activation using twitch interpolation. *Muscle Nerve* (1995); **18**: 593–600.
- Avela J, Kyrolainen H, Komi PV. Neuromuscular changes after long-lasting mechanically and electrically elicited fatigue. *Eur J Appl Physiol* (2001); **85**: 317–325.
- Bangsbo J, Johansen L, Graham T, Saltin B. Lactate and H<sup>+</sup> effluxes from human skeletal muscles during intense, dynamic exercise. *J Physiol (Lond)* (1993); **462**: 115–133.
- Borg G. Simple rating methods for estimation of perceived exertion. In: *Physical Work and Effort* (ed. Borg, G) (1976), pp. 39–47. Pergamon Press, Oxford, New York.
- Bosco C, Colli R, Intorini *et al.* Adaptive responses of human skeletal muscle to vibration exposure. *Clin Physiol* (1999); **19**: 183–187.
- Bosco C, Komi PV, Tihanyi J, Fekete G, Apor P. Mechanical power test and fiber composition of human leg extensor muscles. *Eur J Appl Physiol* (1983a); **51**: 129–135.
- Bosco C, Luhtanen P, Komi PV. A simple method for measurement of mechanical power in jumping. *Eur J Appl Physiol* (1983b); **50**: 273–282.
- Hakkinen K, Komi PV. Electromyographic and mechanical characteristics of human skeletal muscle during fatigue under voluntary and reflex conditions. *Electroencephalogr Clin Neurophysiol* (1983); **55**: 436–444.
- Issurin VB, Liebermann DG, Tenenbaum G. Effect of vibratory stimulation training on maximal force and flexibility. *J Sports Sci* (1994); **12**: 561–566.
- Kersch-Schindl K, Grampp S, Henk C, Resch H, Preisinger E, Fialka-Moser V, Imhof H. Whole-body vibration exercise leads to alterations in muscle blood volume. *Clin Physiol* (2001); **21**: 377–382.
- Kupa EJ, Roy SH, Kandarian SC, De Luca CJ. Effects of muscle fiber type and size on EMG median frequency and conduction velocity. *J Appl Physiol* (1995); **79**: 23–32.
- Mester J, Spitzenfeil P, Schwarzer J, Seifriz F. Biological reaction to vibration—implications for sport. *J Sci Med Sport* (1999); **2**: 211–226.
- Ribot-Ciscar E, Rossi-Durand C, Roll JP. Muscle spindle activity following muscle tendon vibration in man. *Neurosci Lett* (1998); **258**: 147–150.
- Rittweger J, Beller G, Felsenberg D. Acute physiological effects of exhaustive whole-body vibration exercise in man. *Clin Physiol* (2000); **20**: 134–142.

- Rittweger J, Ehrig J, Just K, Mutschelknauss M, Kirsch K, Felsenberg D. Oxygen-uptake during whole body vibration exercise: influence of vibration frequency, amplitude and external load. *Int J Sports Med* (2002a); **23**: 428–432.
- Rittweger J, Just K, Kautzsch K, Reeg P, Felsenberg D. Treatment of chronic lower back pain with lumbar extension and whole-body vibration exercise—a randomized controlled trial. *Spine* (2002b); **27**: 1829–1834.
- Rittweger J, Schiessl H, Felsenberg D. Oxygen-uptake during whole body vibration exercise: comparison with squatting as a slow voluntary movement. *Eur J Appl Physiol* (2001); **86**: 169–173.
- Rubin C, Recker R, Cullen D, Ryaby J, McLeod K. Prevention of bone loss in a post-menopausal population by low-level biomechanical intervention. *Bone* (1998); **23**(5 Suppl.): 174 Abstract.
- Rubin C, Turner AS, Bain S, Mallinckrodt C, McLeod K. Anabolism. Low mechanical signals strengthen long bones. *Nature* (2001); **412**: 603–604.
- Spitzenpfeil P, Mester J. Carving and ski technique—aspects of biological regulation. *Sportverletz Sportschaden* (1997); **11**: 134–136.
- Tesch PA, Komi PV, Jacobs I, Karlsson J, Viitasalo JT. Influence of lactate accumulation of EMG frequency spectrum during repeated concentric contractions. *Acta Physiol Scand* (1983); **119**: 61–67.
- Torvinen S, Kannu P, Sievanen H. et al. Effect of a vibration exposure on muscular performance and body balance. Randomized cross-over study. *Clin Physiol Funct Imaging* (2002); **22**: 145–152.
- Zhang LQ, Rymer WZ. Reflex and intrinsic changes induced by fatigue of human elbow extensor muscles. *J Neurophysiol* (2001); **86**: 1086–1094.