Effect of a vibration exposure on muscular performance and body balance. Randomized cross-over study

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Summary

This randomized cross-over study was designed to investigate the effects of a 4-min vibration bout on muscle performance and body balance in young, healthy subjects. Sixteen volunteers (eight men, eight women, age 24–33 years) underwent both the 4-min vibration- and sham-interventions in a randomized order on different days. Six performance tests (stability platform, grip strength, isometric extension strength of lower extremities, tandem-walk, vertical jump and shuttle run) were performed 10 min before (baseline), and 2 and 60 min after the intervention. The effect of vibration on the surface electromyography (EMG) of soleus, gastrocnemius and vastus lateralis muscles was also investigated. The vibration-loading, based on a tilting platform, induced a transient (significant at the 2-min test) 2·5% net benefit in the jump height ($P = 0{\cdot}019$), 3·2% benefit in the isometric extension strength of lower extremities ($P = 0{\cdot}020$) and 15·7% improvement in the body balance ($P = 0{\cdot}049$). In the other 2-min or in the 60-min tests, there were no statistically significant differences between the vibration- and sham-interventions. Decreased mean power frequency in EMG of all muscles during the vibration indicated evolving muscle fatigue, while the root mean square voltage of EMG signal increased in calf muscles. We have shown in this study that a single bout of whole body vibration transiently improves muscle performance of lower extremities and body balance in young healthy adults.

Introduction

Mechanical stimulation in a form of vibration has recently aroused a great deal of interest in the fields of exercise physiology and bone research (Rubin & McLeod, 1994; Rubin *et al.*, 1995, 1998, 2001a, b; Flieger *et al.*, 1998; Bosco *et al.*, 1999a, b; Falempin & Albon, 1999; Rittweger *et al.*, 2000). It has been hypothesized that a low amplitude, high frequency mechanical stimulation of human body is a safe and efficient way to improve muscle strength, body balance and mechanical competence of bone.

Although the vibration stimulus is widely employed among athletes as a part of their training regimen and it may be a promising way to enhance muscle and bone characteristics simultaneously, only some experimental and clinical studies have investigated its actual effects (Flieger *et al.*, 1998; Bosco *et al.*, 1999b; Falempin *et al.*, 1999; Rubin *et al.*, 2001a, b). According to published peer-reviewed literature, a single vibration bout (10 min at the frequency of 26 Hz) has been shown to result in a significantly temporary increase in muscle strength of female volleyball players (Bosco *et al.*, 1999b), and a vibration stimulus has been shown to prevent ovariectomy-induced bone loss in rats (Flieger *et al.*, 1998).

Notwithstanding the preliminarily positive experimental and clinical results (Rubin *et al.*, 1994, 1995, 1998, 2001a, b; Flieger *et al.*, 1998; Bosco *et al.*, 1999a, b; Falempin *et al.*, 1999; Rittweger *et al.*, 2000), conclusive evidence regarding the efficacy and safety of vibration in humans is lacking. The purpose of this study was therefore to investigate with a randomized controlled, within-subject design the effects of a single, 4-min vibration bout on healthy, young volunteers' muscle performance and body balance.

Materials and methods

Subjects

Sixteen young healthy volunteers (eight men and eight women, 24–33 years of age) participated in the study. Their body mass ranged from 66 to 83 kg for males and from 51 to 70 kg for females and height ranged from 175 to 190 cm for males and from 156 to 178 cm for females. The exclusion criteria were: any cardiovascular, respiratory, abdominal, urinary, gynaecological, neurological, musculoskeletal, or other chronic diseases; pregnancy; prosthesis; medication that could affect the musculoskeletal system; menstrual irregularities and regular participation in impact-type exercise more than three times a week. All participants gave their informed written consent before enrolment to the study, and the protocol was approved by the Institutional Review Board and Ethics Committee of the UKK Institute.

Study setting

All subjects were familiarized with the whole body vibration protocol and all outcome measurements about 1 week before the actual study tests. The tests were shared between two different, consecutive days to avoid fatigue and thus possible contamination of the results, i.e. in all subjects both the vibration- and sham-interventions were carried out twice in conjunction with different outcome measurements (Fig. 1). In each subject, the distance between the vibration- and sham-interventions was 1–2 weeks.

At the beginning of each study test session, a 4-min warm-up was performed on a bicycle ergometer (workload in $W = 1{\cdot}2$ body weight in N). During the tests and interventions, subjects wore thin-soled gymnastic-type shoes. Four minutes of cooling down on the cycle ergometer also followed each test session (Fig. 1). Use of alcohol or strenuous physical activity were allowed neither during the day before the test session, nor the testing day.

All subjects thus received both the vibration intervention and sham intervention and were randomly assigned to start with either the vibration- or sham-intervention (Fig. 1) in order to eliminate the influence of a learning curve on the results. Both interventions were carried out in a standing position on the vibration platform (a prototype of Galileo, 2000, Novotec Maschinen GmbH, Pforzheim, Germany), with (vibration-intervention) or without (sham-intervention) the whole body vibration. The duration of both interventions was 4 min. While standing on the ends of the rigid lever arm of the platform (each foot kept 0·28 m away from the centre of the platform) the subjects repeated four times a 60-s light exercise programme according to instructions shown by the investigator. The rationale of the exercise programme was to guarantee a multidirectional, balanced vibration loading on the body and make the standing on the platform less monotonous. The programme comprised of light squatting (0–10 s),

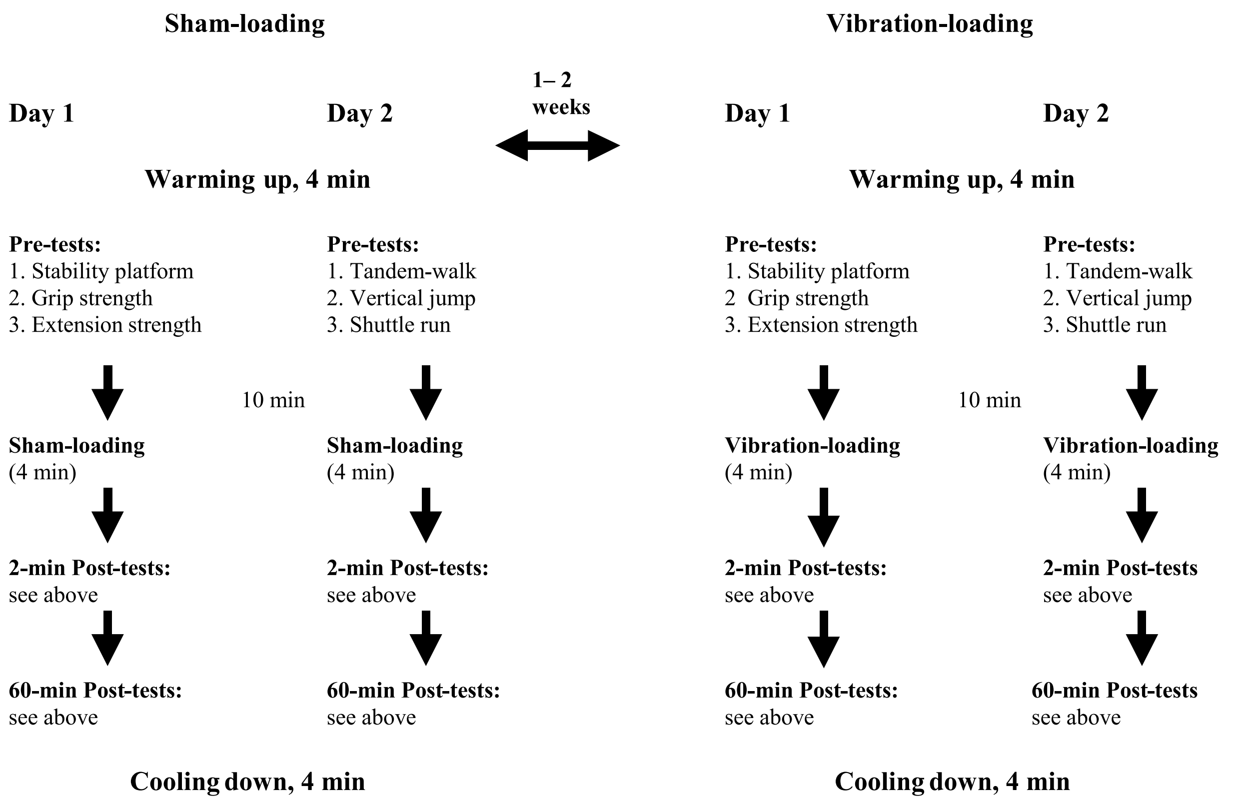

Figure 1 The study protocol.

standing in the erect position (10–20 s), standing in a relaxed position the knees in a slight flexion (20–30 s), light jumping (30–40 s), alternating the body weight from one leg to another (40–50 s), and standing on the heels (50–60 s). During the vibration intervention, the vibration frequency increased in 1 min intervals: 15 Hz for the first minute, 20 Hz for the second minute, 25 Hz for the third minute and 30 Hz for the last minute. The peak-to-peak amplitude of vibration at the end of the 0·72 m long tilting platform was 10 mm. Considering the amplitude at the 0·28 m site (where the feet were kept) and the sinusoidal nature of loading, the theoretical maximal acceleration was nearly 3·5 *g* (where *g* is the Earth's gravitational field or 9·81 m s^{-2}) with 15 Hz loading, 6·5 *g* with 20 Hz, 10 *g* with 25 Hz, and 14 *g* with 30 Hz, respectively.

Performance tests

The baseline performance measurements were started 2 min after the warm-up. Ten minutes after the baseline measurements, subjects were exposed to either the above-described vibration- or sham-intervention. The same performance measurements were done again at 2 and 60 min after the 4-min vibration- or sham-intervention (Fig. 1).

The performance tests were shared between 2 days to avoid potential contamination of results due to fatigue. On *day* 1, stability platform test, measurements of grip strength and isometric extension strength of lower extremities were carried out. On *day* 2, tests consisted of tandem-walk, vertical jump, and shuttle run tests. The measurements were always done in the same order. Day-to-day reproducibilities (expressed as a root-mean-square coefficient of variation $CV\%_{rms}$) of the performance tests were determined using the duplicate baseline data measured before the vibration- and sham-interventions and are given in the 'Results' section (see below).

A *postural sway platform* (Biodex Stability System, New York, NY, USA) was used to assess the body balance (Schmitz & Arnold, 1998). The subjects stood on a labile platform on both legs, eyes opened and arms beside the trunk. The platform provides eight different stability-levels: level 8 is virtually stable and level 1 is the most labile. As a test, we employed a 40-s protocol in successive 10 s intervals: level 5 (0–10 s), level 4 (10–20 s), level 3 (20–30 s), and level 2 (30–40 s). The system provides a numerical stability index, which reflects the body sway variation around the projection of the centre of gravity of the body (centre of foot pressure) so that the lower the score of the test the better the stability (Schmitz *et al.*, 1998). Each subject's feet position coordinates on the platform were recorded after the first stability measurement and the same coordinates were used throughout the study to obtain consistency between the tests. The mean value of two stability indices was used as the test score. Before each test, the subjects had one to two familiarization trials.

Grip strength was considered as a reference test that was expected not to be affected by the vibration- or sham-intervention. It was measured using a standard grip strength meter (Digitest, Muurame, Finland). The median value of three readings was used as a test score.

Maximal isometric strength of the leg extensors was measured with a standard leg press dynamometer (Heinonen *et al.*, 1994). The subjects sat on the dynamometer chair with their knees and ankles at an angle of 90° of flexion while pressing maximally against strain gauges (Tamtron, Tampere, Finland) under their feet. The isometric strength was recorded for three maximal efforts, and the median value of three readings was used as the test score.

A *tandem walk test* along a 6-m line was used to assess the dynamic balance (Nelson *et al.*, 1994). The subjects were instructed to place one foot behind the other, each time making sure that the tip of the foot was in contact with the heel of the other. The subjects were told to walk backwards as fast as possible while avoiding any mistakes. The time of a successful performance was measured with a stopwatch. The median value of three readings was used as a test score.

A *vertical countermovement jump test* (hands kept on the pelvis) was used to assess the lower-limb explosive performance capacity (Bosco *et al.*, 1983). The tests were performed on a contact platform (Newtest, Oulu, Finland), which gives the time the subject is on air in milliseconds. The obtained 'flight' time (t) was used to estimate the height of the rise of body centre of gravity (h) during the vertical jump, i.e. $h = gt^2/8$, where $g = 9{\cdot}81$ m s^{-2}. The median value of three measurements was used as a test score.

A *shuttle run test* over a 30-m course was used to assess the dynamic balance or agility (Baker *et al.*, 1993). The subjects were asked to run as fast as possible six times between markers placed 4 m apart and touch the floor after each 4-m run, and finally run a 6-m course over the goal line. A single performance was done and the running time was recorded with photoelectric cells in milliseconds.

Electromyography (EMG) measurements

Bipolar surface EMG from soleus, gastrocnemius and vastus lateralis (of the quadriceps) muscles was recorded by a dedicated differential amplifier (Myosystem 1008, Noraxon, Oulu Finland; input impedance >1 MΩ, gain 1000, and 3-dB bandwidth 20–350 Hz) during the 4-min bout of vibration-intervention. Disposable electrodes were located on the muscle bellies approximately in the midway between the centre of the innervation zone and the further tendon. Before attaching the electrodes, the skin was carefully shaved, rubbed and cleaned with alcohol. Good contact of electrodes was further secured with an adhesive tape.

The EMG signals were digitized at a sampling frequency of 1 kHz (DT2801 12-bit A/D-converter, Data Translation, Marlborough, MA, USA) during the 4 min periods and stored for further analysis with a dedicated software (NST, Noraxon, Oulu, Finland). A 1024-point Fast Fourier Transform was used to determine the power spectrum of given EMG signals. Four separate spectra were determined in 1 s intervals over a 4-s period in the middle of the relaxed standing phase (only stabilizing muscle activity present), and the average of these spectra was determined. The EMG signal quality was visually checked before the spectrum analysis. From this average spectrum, a representative mean power frequency (MPF in Hz) and root mean square voltage (RMS, in mV) of the EMG signal were calculated for each minute of intervention and these variables used as test outcomes.

Statistical analysis

Mean, standard deviation (SD), and 95% confidence interval (95% CI) are given as descriptive statistics.

The 2 and 60-min effects of whole body vibration on individual physical performance were defined as relative differences between the changes in the given test outcome observed after the vibration (V)- and sham (S)- interventions. The relative differences were achieved through log-transformation of the variables. The time-effect at 2 and 60 min was determined by one-way analysis of variance (ANOVA) with repeated measures.

Repeated measures ANOVA was also used to estimate the time-effect on EMG variables (MPF and RMS) during vibration-interventions.

The associations between the mean power frequency and root mean square minute-values were analysed by the Pearson's correlation coefficients.

Results

All subjects completed the study without any objective side-effects. Neither subjective adverse reactions nor exhaustive fatigue were reported after the 4-min vibration bout. Most of the subjects reported that the whole body vibration was 'stimulating' for the lower extremities.

As response to sham- or vibration intervention showed no gender differences, the data of women and men were pooled and analysed together.

Muscle performance and body balance

The day-to-day reproducibility ($CV\%_{rms}$) was 2·3% for the isometric extension strength of lower extremities, 2·5% for the vertical jump, 3·6% for the grip strength, 17·5% for the stability platform, 8·2% for the tandem walk and 1·8% for the shuttle run.

Strength tests

Isometric lower limb extension strength increased 2·0 kg at 2 min after the vibration-intervention as compared with a mean decrease of 3·4 kg after the sham-intervention resulting in a statistically significant 3·2% net benefit ($P = 0{\cdot}02$) for the vibration (Table 1 and Fig. 2a). At 60 min after the vibration-intervention the benefit diminished (2·4%, $P = 0{\cdot}11$).

The vertical jump height increased 0·7 cm at 2 min after the vibration-intervention as compared with an unchanged value after the sham-intervention resulting in a significant 2·5% net benefit ($P = 0{\cdot}019$) for the vibration (Table 1 and Fig. 2b). The effect disappeared completely by 60 min after the intervention.

As expected, no effect was observed in the grip strength at 2 and 60 min after the vibration-intervention (Table 1 and Fig. 2c). The responses were virtually identical after sham- or vibration-intervention.

Stability tests

The net benefit of the vibration was 15·7% in the score of the stability platform at 2-min test (vs. sham-intervention, $P = 0{\cdot}049$) (Table 1 and Fig. 2d). No effect was observed in the 60-min test nor in the other balance and performance-tests (Table 1 and Fig. 2e–f).

EMG

Mean power frequency

Mean power frequency of the soleus muscle activity decreased systematically during the 4-min vibration, the 4-min values being on average 18·8% lower than the 1-min values. The magnitude of decrease in MPF during vibration was also statistically significant ($P<0{\cdot}001$) (Table 2 and Fig. 3a). A similar pattern was observed in MPF of the gastrocnemius muscle activity. The MPF decreased throughout the vibration ($P<0{\cdot}001$) and the 4-min values were on average 18·3% lower than the 1-min values (Table 2 and Fig. 3b).

The decrease in the MPF of the vastus lateralis muscle activity was not so evident and systematic as that in the soleus and gastrocnemius muscles during the first 3 min, but during the last minute of vibration-intervention a rapid 8·6% decrease occurred ($P<0{\cdot}001$) (Table 2 and Fig. 3c).

Root mean square voltage

Root mean square voltage of the soleus and the gastrocnemius muscle EMG activity increased during the 4-min vibration-intervention, the 4-min values being on average 21·6% ($P<0{\cdot}001$) and 35·2% ($P = 0{\cdot}004$) higher than the 1-min values, respectively (Table 2 and Fig 3a, b). Root mean square voltage of the vastus lateralis EMG activity was quite stable over the entire 4-min vibration-intervention and showed no statistically significant time-effect (Table 2 and Fig. 3c).

For analysing the relationship between the mean power frequency and root mean square minute-values, Pearson's correlation coefficients were calculated for each subject, and a mean correlation coefficient was calculated. The mean of these individual correlation coefficients was –0·79 for the soleus-muscle, –0·83 for the gastrocnemius-muscle and –0·61 for the

Table 1 The performance test parameters after the 4-min sham- and vibration-interventions. Mean (SD) values and mean (95% CI and P-value) between-groups net differences for the relative change by time.

Variables	Sham-loading	Vibration-loading	Between-groups net-difference for the relative change by time (%)[a]	95% CI[a]	*P*-value[a]
Lower limb extension strength (kg)					
Baseline	185·1 (53·8)	182·9 (54·9)			
2 min	181·7 (53·0)	184·9 (53·8)	3·2	0·6 to 5·9	0·020
60 min	179·1 (53·1)	181·3 (55·5)	2·4	−0·6 to 5·5	0·11
Vertical jump (cm)					
Baseline	31·3 (9·2)	31·2 (9·1)			
2 min	31·3 (9·8)	31·9 (9·6)	2·5	0·5 to 4·6	0·019
60 min	30·6 (9·1)	30·6 (9·0)	0·1	−4·0 to 4·4	0·97
Grip strength (kg)					
Baseline	36·6 (13·0)	36·7 (13·3)			
2 min	36·3 (12·7)	36·4 (13·0)	0·2	−3·2 to 3·9	0·88
60 min	37·4 (13·5)	37·0 (12·5)	−0·1	−3·1 to 3·1	0·97
Stability platform (stability index)					
Baseline	2·4 (0·8)	2·6 (1·0)			
2 min	2·5 (0·8)	2·3 (1·1)	−15·7	−28·8 to −0·1	0·049
60 min	2·5 (1·0)	2·4 (0·8)	−8·8	−32·6 to 23·5	0·53
Tandem walk (s)					
Baseline	12·1 (3·3)	11·9 (3·4)			
2 min	11·2 (2·6)	11·2 (3·4)	0·5	−5·4 to 6·8	0·87
60 min	11·2 (2·6)	11·1 (2·6)	1·6	−6·0 to 9·9	0·67
Shuttle run (s)					
Baseline	10·5 (1·2)	10·5 (1·1)			
2 min	10·4 (1·3)	10·3 (1·2)	−1·1	−2·9 to 0·7	0·22
60 min	10·4 (1·4)	10·4 (1·2)	−0·5	−3·1 to 2·0	0·66

[a]One-way analysis of variance with repeated measures.

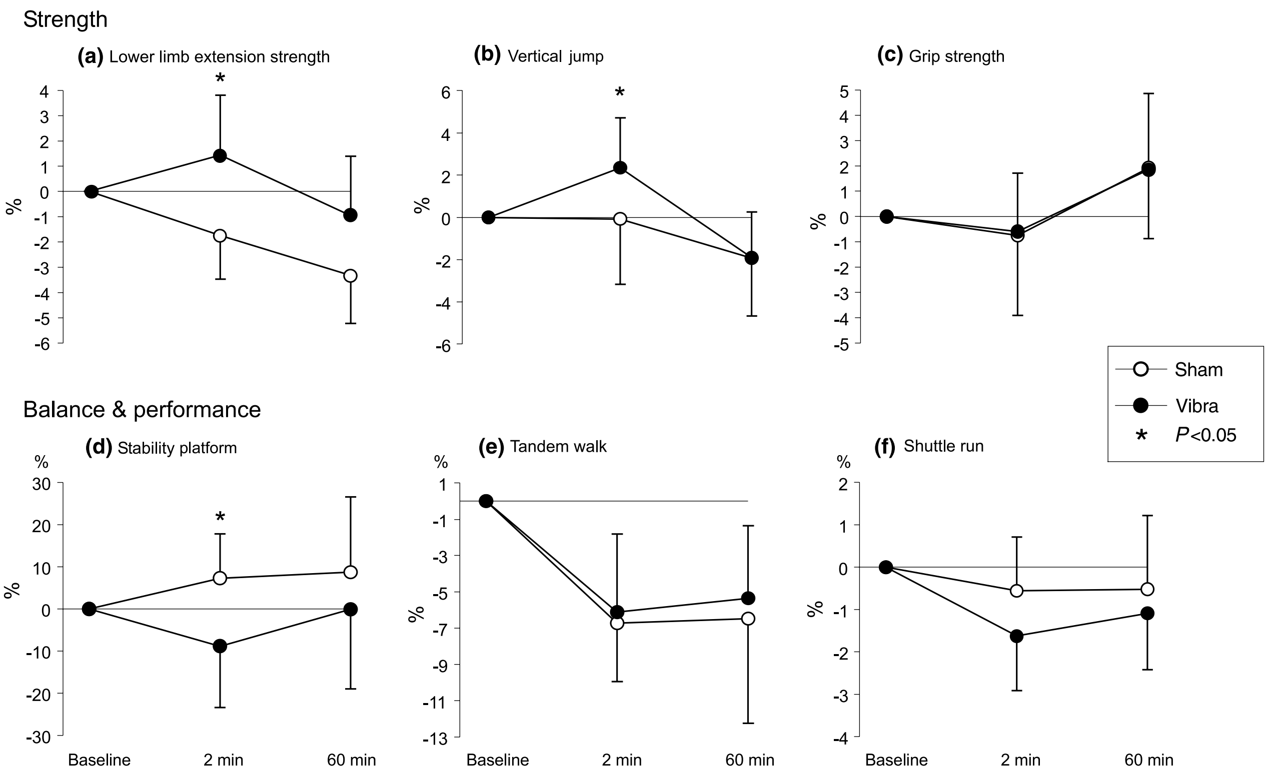

Figure 2 The percentage changes in the strength, balance, and performance test 2 and 60 min after the 4-min sham- or vibration-intervention. Mean and 95% confidence interval. *P<0·05.

Table 2 Mean power frequency (Hz) and root mean square voltage (mV) of the EMG signal of the soleus-, gastrocnemius- and vastus lateralis muscles as determined from the surface EMG during the 4-min vibration-loading. Mean (SD) and P-values.

	Soleus		Gastrocnemius		Vastus lateralis	
	Mean power frequency (Hz)	Root mean square voltage (mV)	Mean power frequency (Hz)	Root mean square voltage (mV)	Mean power frequency (Hz)	Root mean square voltage (mV)
1 min	97·6 (7·9)	1·3 (0·5)	100·6 (10·2)	1·3 (0·8)	89·3 (6·8)	1·3 (0·5)
2 min	88·2 (10·9)	1·4 (0·7)	94·1 (8·5)	1·3 (0·9)	85·7 (7·1)	1·2 (0·6)
3 min	84·5 (11·5)	1·5 (0·8)	87·4 (9·9)	1·5 (1·0)	86·2 (9·1)	1·2 (0·6)
4 min	79·3 (10·2)	1·5 (0·8)	81·8 (7·0)	1·5 (0·9)	78·6 (7·8)	1·3 (0·7)
	$P<0·001$	$P<0·001$	$P<0·001$	$P = 0·004$	$P<0·001$	$P = 0·137$
	$P_{linear\ trend}<0·001$	$P_{linear\ trend}<0·001$	$P_{linear\ trend}<0·001$	$P_{linear\ trend} = 0·002$	$P_{linear\ trend}<0·001$	$P_{linear\ trend} = 0·394$
	$P_{dev.\ from\ linear} = 0·034$	$P_{dev.\ from\ linear} = 0·078$	$P_{dev.\ from\ linear} = 0·92$	$P_{dev.\ from\ linear} = 0·32$	$P_{dev.\ from\ linear} = 0·047$	$P_{dev.\ from\ linear} = 0·070$

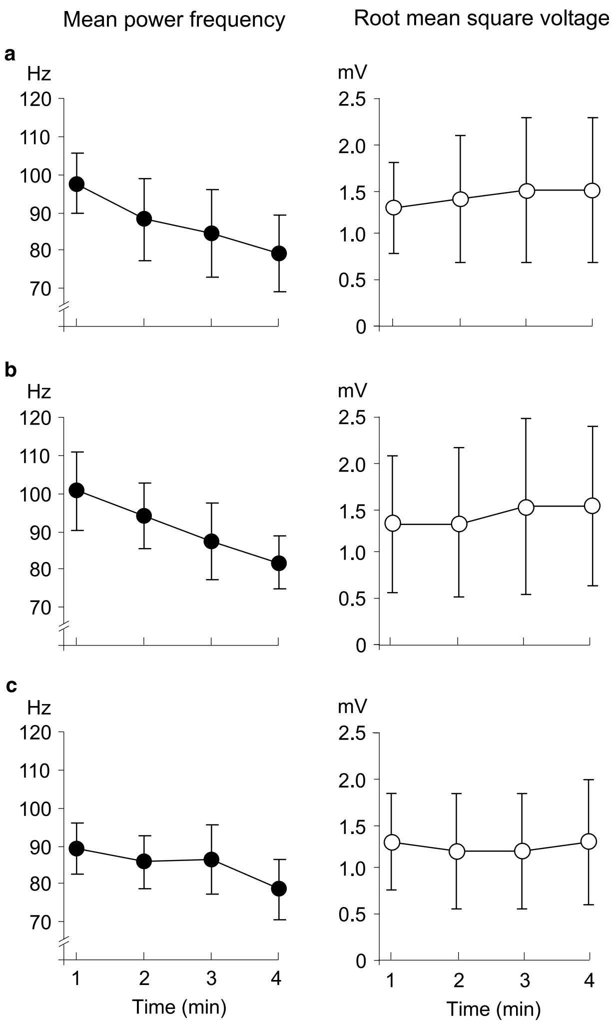

Figure 3 The changes in the mean power frequency (MPF) and root mean square voltage (RMS) values of the EMG recordings of the (a) soleus, (b) gastrocnemius, and (c) vastus lateralis muscles during the vibration-loading. Mean and SD. Trends in MPF values were linear ($P<0·001$) in all muscles, whereas linear trends in RMS were statistically significant in the soleus- and gastrocnemius-muscles ($P<0·001$ and $P<0·002$, respectively), but not in the vastus lateralis muscle (see Table 2).

vastus lateralis muscle. This indicated a remarkable negative correlation between MPF and RMS values during vibration.

Discussion

We showed in this randomized cross-over study that in healthy young adults a single, 4-min vibration-loading induced a significant, transient increase in the isometric extension strength of the lower extremities, jump height, and body balance. These effects were observed 2 min after the vibration, but had disappeared more or less completely 1 h later. Although the improvements in these performance parameters were quite small, the systematic nature of these responses was clear. Thus, it was evident that the immediate effects of a short-bout vibration were beneficial for physical performance.

It has been shown that mechanical vibration exert a tonic excitatory influence on the muscles exposed to it. Vibration applied directly to muscle belly or tendon (at the frequency of 10–200 Hz) or to whole body (1–30 Hz) has been shown to elicit a response named 'tonic vibration reflex' (TVR) (Hagbarth & Eklund, 1985, Seidel, 1988). The vibration-induced TVR involves activation of muscle spindles, mediation of the neural signal by 1a afferents (Hagbarth, 1973), and activation of the muscle fibres via large α-motor neurones. The TVR induced by the vibration is also capable of causing an increasing recruitment of motor units via activation of muscle spindles and polysynaptic pathways (De Gail *et al.*, 1966), which is seen as a temporary increase in the muscle activity. However, a long-term irritation of the muscle-spindles by vibration leads ultimately to muscle fatigue (Eklund, 1972; Martin & Park, 1997). This, in turn, is seen as a reduction of EMG activity, motor unit firing rates, and contraction force.

We initially anticipated that whole-body loading via vibration is fatiguing. However, the subjects experienced the vibration loading stimulating rather than fatiguing. This subjective opinion was also corroborated by the objective measurements (2 min performance tests). The improved strength and power of the lower extremities and the improved body balance after the vibration intervention (Fig. 2a, b, d) suggests that neurogenic adaptation may have occurred in the muscles of the lower extremities in response to vibration.

Although the participants did not subjectively experience the vibration fatiguing, and neither was any apparent fatigue-effect seen in the performance measurements, the EMG analysis showed a significant reduction of the MPF during the vibration-intervention. A reduction in MPF is generally considered a sign of muscle fatigue (Viitasalo & Komi, 1977; Petrofsky *et al.*, 1982; Dowling, 1997; Jurell, 1998). The muscle fatigue identified by the spectral analysis of EMG was more distinct in the calf muscles (soleus and gastrocnemius) than in the vastus lateralis of the quadriceps muscle (Fig. 3). In contrast to the reduction of the MPF in both calf and thigh muscles, the root mean square voltage of EMG increased in the former muscles during the vibration (Fig. 3). This finding suggests that it may have been necessary to recruit more motor units in the calf muscles to compensate the more pronounced fatigue present in these muscles during the vibration while in the thigh muscles such a response was not needed. Perhaps, a longer bout of vibration might have resulted in a similar response in the activity of the vastus lateralis muscle as well. These findings, improved results of the strength tests but the decreased EMG activity, suggest that our vibration stimulus was long enough to stimulate the muscles of the lower extremities, but too short to induce significant muscle fatigue. One may suspect whether this effect is specific for vibration stimulus only; that is, would it have been possible to get a similar effect by other forms of stimulating physical activity, such as a normal warming-up manoeuvre. In order to eliminate this possibility, the subjects performed exactly the same warm-up on a bicycle ergometer and performed the same exercise protocol while standing on the platform during both the vibration- and sham-interventions. It is also recalled that the order of these interventions was randomized so that the learning curve bias could be minimized.

When considering the possible effects of vibration loading on bone, it is possible that these effects are transferred to bone via vibration-induced muscle activity. Actually, according to the literature, it has been proposed that even extremely small strains induced by very low acceleration ($g = 0{\cdot}3$, much smaller than that used in our experiment) may be effective determinants of bone morphology (Rubin *et al.*, 2001a, b). On the other hand, our observations on the muscle fatigue are also of interest. The reduction in MPF indicated that in response to even a short bout of vibration, the muscles of the lower extremity tend to fatigue. This may indicate that with continuing vibration a larger proportion of the incident vibration energy is directed to bones, instead of being absorbed by muscle tissue (Yoshikawa *et al.*, 1994; Millgrom *et al.*, 1999).

The above noted findings suggest that vibration is a potentially efficient training stimulus and future studies should focus on evaluating the long-term effects of whole body vibration on body balance and muscle performance, and, as a broader objective, on bone structure and strength.

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References

Baker J, Ramsbottom R, Hazeldine R, Maximal shuttle running over 40 m as a measure of anaerobic performance. *Br J Sports Med* (1993); **27**: 228–232.

Bosco C, Luhtanen P, Komi PV, A simple method for measurement of mechanical power in jumping. *Eur J Appl Physiol* (1983); **50**: 273–282.

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

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

De Gail P, Lance J, Neilson P, Differential effects on tonic and phasic reflex mechanisms produced by vibration of muscles in man. *J Neurol Neurosurg Psych* (1966); **29**: 1–11.

Dowling J, The use of electromyography for the noninvasive prediction of muscle forces. *Sports Med* (1997); **24**: 82–96.

Eklund G, Position sense and state of contraction; the effects of vibration. *J Neurol Neurosurg Psych* (1972); **35**: 606–611.

Falempin M, IN-Albon S, Influence of brief daily tendon vibration on rat soleus muscle in non-weight-bearing situation. *J Appl Physiol* (1999); **87**: 3–9.

Flieger J, Karachalios T, Khaldi L, Raptou P, Lyritis G, Mechanical stimulation in the form of vibration prevents postmenopausal bone loss in ovariectomized rats. *Calcif Tissue Int* (1998); **63**: 510–514.

Hagbarth K, The effect of muscle vibration in normal man and in patients with motor disease. In: *New Developments in Electromyography and Clinical Neurophysiology* (1973); (ed. Desmedt, J), pp. 428–443. Karger, Basel.

Hagbarth K, Eklund G, Motor effects of vibratory stimuli. In: *Muscular Afferents and Motor Control. Proceedings of First Symposium* (1985); (ed. Granit, R). Almqvist and Wiksell, Stockholm.

Heinonen A, Sievänen H, Viitasalo J, Pasanen M, Oja P, Vuori I, Reproducibility of computer measurement of maximal isometric strength and electromyography in sedentary middle-aged women. *Eur J Appl Physiol* (1994); **68**: 310–314.

Jurell K, Surface EMG and fatigue. *Phys Med Rehab Clin North Am* (1998); **9**: 933–947.

Martin B, Park H, Analysis of the tonic vibration reflex: influence of vibration variables on motor unit synchronization and fatigue. *Eur J Appl Occup Physiol* (1997); **75**: 504–511.

Millgrom C, Finestone A, Ekenman I *et al.*, Tibial strain rate increases following muscular fatigue in both men and women. *Trans. ORS* (1999); **24**: (Abstract), 234.

Nelson M, Fiatarone M, Morganti C, Trice I, Greenberg W, Effects of high-intensity strength training on multiple risk factors for osteoporotic fractures. *JAMA* (1994); **28**: 1909–1914.

Petrofsky J, Glaser R, Phillips C, Evaluation of the amplitude and frequency components of the surface EMG as an index of muscle fatigue. *Ergonomics* (1982); **25**: 213–223.

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

Rubin C, McLeod K, Promotion of bony ingrowth by frequency-specific, low-amplitude mechanical strain. *Clin Orthop* (1994); **298**: 165–174.

Rubin C, Li C, Sun Y, Fritton C, McLeod K, Non-invasive stimulation of trabecular bone formation via low magnitude, high frequency strain. *Trans ORS* (1995); **20**: 548.

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** (Suppl.): S174 (Abstract).

Rubin C, Xu G, Judex S, The anabolic activity of bone tissue, suppressed by disuse, is normalized by brief exposure to extremely low-magnitude mechanical stimuli. *FASEB J* (2001a); **15**: 2225–2229.

Rubin C, Turner S, Bain S, Mallinckrodt C, McLeod K, Low mechanical signals strengthen long bones. *Nature* (2001b); **412**: 603–604.

Schmitz R, Arnold B, Intertester and intratester reliability of a dynamic balance protocol using the Biodex Stability System. *J Sport Rehabil* (1998); **7**: 95–101.

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

Viitasalo J, Komi P, Signal characteristics of EMG during fatigue. *Eur J Appl Physiol* (1977); **37**: 111–121.

Yoshikawa T, Mori S, Santiesteban A *et al.*, The effects of muscle fatigue on bone strain. *J Exp Biol* (1994); **188**: 217–233.