Ageing Research Reviews 7 (2008) 319–329

Contents lists available at ScienceDirect

Ageing Research Reviews

journal homepage: www.elsevier.com/locate/arr

Review

# Effects of whole body vibration on the skeleton and other organ systems in man and animal models: What we know and what we need to know

Rhonda D. Prisby [a,b,c,*], Marie-Hélène Lafage-Proust [a,b,c], Luc Malaval [a,b,c], Alain Belli [a,d,c], Laurence Vico [a,b,c]

[a] Université Jean-Monnet, Saint-Etienne F42023, France
[b] INSERM U890, Saint-Etienne F42023, France
[c] IFR 143, Saint-Etienne F42023, France
[d] Exercise Physiology Laboratory, Saint-Etienne F42023, France

ARTICLE INFO

*Article history:*
Received 30 March 2008
Received in revised form 22 July 2008
Accepted 23 July 2008

*Keywords:*
Whole-body vibration
Cartilage
Elderly
Hormones
Tissue perfusion
Parkinson's disease

ABSTRACT

Previous investigations reported enhanced osseous parameters subsequent to administration of whole body vibration (WBV). While the efficacy of WBV continues to be explored, scientific inquiries should consider several key factors. Bone remodeling patterns differ according to age and hormonal status. Therefore, WBV protocols should be designed specifically for the subject population investigated. Further, administration of WBV to individuals at greatest risk for osteoporosis may elicit secondary physiological benefits (e.g., improved balance and mobility). Secondly, there is a paucity of data in the literature regarding the physiological modulation of WBV on other organ systems and tissues. Vibration-induced modulation of systemic hormones may provide a mechanism by which skeletal tissue is enhanced. Lastly, the most appropriate frequencies, durations, and amplitudes of vibration necessary for a beneficial response are unknown, and the type of vibratory signal (e.g., sinusoidal) is often not reported. This review summarizes the physiological responses of several organ systems in an attempt to link the global influence of WBV. Further, we report findings focused on subject populations that may benefit most from such a therapy (i.e., the elderly, postmenopausal women, etc.) in hopes of eliciting multidisciplinary scientific inquiries into this potentially therapeutic aid which presumably has global ramifications.



## 1. Introduction

According to Wolff's law, bone mass adapts to the demands of mechanical loading in addition to metabolic influences. Much of our understanding of mechanically-induced osteogenesis comes from data collected on young and healthy individuals with little information in regards to bone remodeling in individuals who suffer from bone fragility. Bone remodeling patterns differ between young and elderly individuals and mechanical stimulation of the skeleton that is appropriate for one group may be ineffective for the other. Moreover, it has been shown that aging alters the responsiveness of skeletal tissue to mechanical loads (Rubin et al., 1992). Whole body vibration (WBV) has been utilized to deliver mechanical accelerations to the appendicular and axial skeleton (Rubin et al., 2003) to elicit increased bone mass. The attractiveness of such a therapy lies in its ability to be applied in a low-impact manner, which is critical for individuals with impaired mobility and attenuated muscle strength (i.e., the elderly or diseased individuals).

Currently, many companies advertise the use of WBV as an effective means by which muscle strength and bone mass (in addition to other physiological benefits) can be obtained. While some scientific evidence support these claims (e.g., accretion of bone mass), the recommended advertisements should be viewed with caution since appropriate standards for use of vibrating platforms have not been established and validated for any segment of the population. For example, Kiiski et al. (2008) reported subject discomfort when individuals were vibrated between 20 and 25 Hz at an amplitude of 0.5 mm or more. Further, site-specific peak accelerations (e.g., ankle, knee, etc.) were several time higher than the peak acceleration delivered from the vibrating platform and the sinusoidal waveform became distorted with vibration amplitudes greater than 0.05 mm (Kiiski et al., 2008). Despite the fact that there have been no reports of bone fracture reported with the

* Corresponding author at: INSERM 890, Faculté de Médecine, 15 rue Ambroise Paré, 42023 Saint-Etienne Cedex 2, France. Tel.: +33 4 77 42 14 42; fax: +33 4 77 57 55 72.
*E-mail address:* rhonda.prisby@univ-st-etienne.fr (R.D. Prisby).

1568-1637/$ – see front matter © 2008 Elsevier Ireland Ltd. All rights reserved.
doi:10.1016/j.arr.2008.07.004

**Table 1**
Summary of skeletal effects of whole-body vibration in animals and humans

| Target population | Wave type | Vibration protocol | Duration | Intensity (accelerations (g); amplitudes (mm); force (N)) | Frequency (Hz) | Outcome | Reference |
|---|---|---|---|---|---|---|---|
| Animal studies | | | | | | | |
| OVX Wistar rats (12 wks) | NR | 30 min/d, 5 d/wk | 12 wks | 2.0 g | 50 | Vibration: ↓ OVX-induced bone loss ↑ BMD | Flieger et al. (1998) |
| Female Sprague Dawley rats (6–8 mon) | NR | 10 min/d | 4 wks | 0.25 g | 90 | ↑ BFR and MS/BS with normalized BFR in vibration + HU group similar to CON | Rubin et al. (2001b) |
| C57BL, BALB/c, and C3H mice (age NR) | SIN | 10 min/d | NR | 0.25 g | 45 | ↑ BV/TV in C57BL only (85%); ↑ BFR/BS in BALBc (32%), ↔ in C3H | Judex et al. (2002) |
| OVX Wistar rats (1 yr) | NR | 30 min/d | 17 wks | 0.5 g | 17 | @ 45 Hz: ↑ periosteal BFR and ↓ OVX-induced endocortical resorption, ↓ declines in biomechanical properties | Oxlund et al. (2003) |
| | | | | 1.5 g | 30 | | |
| | | | | 3.0 g | 45 | | |
| Male mice (7 mon) | SIN | 15 min/d | 5 wks | 0.1 g | 45 | ↑ trabecular bone BV/TV in 0.1 and 1.0 g groups | Christiansen and Silva (2006) |
| Female mice (2 mon) | SIN | 15 min/d | 3 wks | 0.3 g | 45 | ↓ osteoclastic activity; ↑ BFR | Xie et al. (2006) |
| C57BL/6 mice (12 wks) | SIN carrier waveform | 3 d/wk | 4 wks | 2 N | ?0–50 | No effect of vibration on periosteal bone formation in the ulna | Castillo et al. (2006) |
| OVX Sprague Dawley rats (6–8 mon) | NR | 10 min/d<br>5 d/wk | 4 wks | 0.15 g | 45<br>90 | 90 Hz: ↑ BFR, BV/TV and TbTh | Judex et al. (2007) |
| HU female mice (4 mon) | SIN | 20 min/d, 5 d/wk | 3 wks | 0.6 g | 45 | ↓ unloaded-induced bone loss and ↓ deterioration of microarchitecture | Ozcivici et al. (2007) |
| Adult female C57BL/6J mice (19 wks) | SIN | 10 min/d | 3 wks | 0.3 g, 0.6 g | 45 | 0.3 g: 88% ↑ trabecular BFR/BS, ↑ MS/BS (64%); 0.6 g: 66% ↑ BFR/BS, 22% ↑ MS/BS, 8% ↑ epiphyseal cortical area and 8% ↑ thickness | Garman et al. (2007) |
| BALB/cByJ mice (8 wks) | NR | 15 min/d, 5 d/wk | 6 wks | 0.3 g | 45 | Proximal tibial metaphysis: ↑ MS/BS; cortical bone: ↑ BV, periosteal bone area, bone marrow area, cortical area and moment of inertia; ↑ soleus cross-sectional area | Xie et al. (2008) |
| OVX Sprague rats (3 mon) | SIN | 20 min/d, 5 d/wk | 8 wks | 0.6 g, 3.0 g | 30 | Longitudinal analysis: no differences in cortical or trabecular BMD by pQCT; cross-sectional analysis: no differences in histomorphometric analysis; *in vitro* analysis → vibration at 3 g increased total cortical and medullary areas and periosteal and endosteal perimeter in OVX rats | Rubinacci et al. (2008) |
| Human studies | | | | | | | |
| PMP (58–74 yrs) | SIN | 30 min, 3 times/wk | 24 wks | 2.28–5.09 g, 1.7–2.5 mm | 35–40 | ↑ hip BMD (0.93%); ↔ markers of bone remodeling; ↑ isometric (15%) and dynamic (16%) muscle strength | Verschueren et al. (2004) |
| Pre- or postpubertal disabled, children (4–19 yrs) | SIN | 10 min/d, 5 times/wk | 6 mon | 0.3 g | 90 | ↑ vTBMD proximal tibia (6%); vTBMD in control group ↓ 12% ↔ cortical BMD, ↔ muscle parameters | Ward et al. (2004) |
| PMP (57 yrs) | SIN | 2 × 10 min/d | 12 mon | 0.2 g | 30 | ↔ BMD hip, lumbar spine, ↑ spine BMD in compliant subjects | Rubin et al., 2004 |
| Osteoporotic PMP (55–88 yrs) | NR | 1 time/wk, 4 min | 12 mon | 0.7–4.2 mm | 20 | ↔ BMD lumbar spine, hip; ↔ markers of bone remodeling; ↓ chronic back pain | Iwamoto et al. (2005) |
| Low-BMD females w/ fractures (15–20 yrs) | SIN | 10 min/d | 12 mon | 0.3 g | 30 | 2.1% ↑ cancellous vertebral BV/TV, 3.4% ↑ femoral cortical bone, 5% ↑ cross-sectional area of paraspinous muscle | Gilsanz et al. (2006) |
| PMP (66 yrs) | NR | 3 times/wk WBV vs. walking | 8 mon | 3 mm | 12.5 | ↑ BMD femoral neck (4.3%) ↔ BMD lumbar spine ↑ balance (29%) | Gusi et al. (2006) |

OVX: ovariectomized; BV/TV: bone volume per tissue volume; NR: not reported; min: minutes; d: day; wk(s): week(s); mon: month; yr(s): years; BMD: bone mineral density; MS/BS: mineralizing surface to bone surface ratio; WBV: whole body vibration; HU: hindlimb unloaded; CON: control; SIN: sinusoidal wave; BFR: bone formation rate; BFR/BS: bone formation rate/bone surface; TbTh: trabecular thickness; PMP: postmenopausal women; distorted: distorted signal; vTBMD: volumetric trabecular bone mineral density; w/: with; ↑: increase; ↓: decreased; ↔: no change.

use of WBV, the authors recommend caution when subjecting the elderly to supra-G vibration (Kiiski et al., 2008). Vibration consists of three components (i.e., frequency, amplitude, and acceleration) which can be modified independent of one another. Therefore, WBV protocols utilizing various combinations of frequency, amplitude, and acceleration make comparison of results among the studies difficult. In addition, not all contraindications to vibration have been identified. In a case study, an athlete with asymptomatic nephrolithiasis suffered a bout of significant morbidity subsequent to 5 min of WBV (frequency: 30 Hz; amplitude: 4.5 mm) (Monteleone et al., 2007). Therefore, investigations examining all possible contraindications was recommended by the authors, since to date no medical prescription is necessary for WBV (Monteleone et al., 2007).

In addition, readers should be aware that many investigations have not been properly controlled and conclusions reached by the authors in support of vibration were derived from secondary statistical analysis of the data and were not the original research design. Further, while the literature is replete with scientific investigations examining the therapeutic adaptations of skeletal tissue to short duration WBV, fewer investigations have examined the impact of such a regimen on other organs and tissues. For instance, application of WBV similar to that which derived skeletal benefits decreased capillarity in the soleus muscle and therefore may prove deleterious to the peripheral vasculature (Murfee et al., 2005). Recently, 15 weeks of high frequency, low-acceleration vibration (i.e., 90 Hz and 0.2 g, respectively) in mice reduced adipogenesis and factors associated with the onset of type II diabetes (e.g., triglycerides and nonesterified free fatty acid) (Rubin et al., 2007). Further, several investigations have reported hormonal fluctuations (e.g., growth hormone, cortisol, and testosterone) following bouts of WBV (Bosco et al., 2000; Kvorning et al., 2006) which may have systemic effects throughout the body long after the vibratory stimulus has ended. It is well documented that bone metabolism is controlled by various factors (e.g., calciotropic hormones, muscle strain, the peripheral and central nervous systems, body mass, and fat mass) all of which are potentially affected by vibration.

It would be ill-advised to develop and characterize vibration protocols that augment skeletal integrity while having a detrimental impact on muscles, tendons and/or blood vessels, or that induce side effects in elderly patients. In contrast, non-pharmacological therapies are attractive alternatives for the treatment of osteoporosis, particularly in populations treated for various diseases or in whom the use of medication is difficult due to contra-indications (Jones et al., 2007; Semler et al., 2007). We have attempted to limit the scope of this review to investigations relevant to the effects of vibration on senescent and diseased individuals and/or tissues. However, due to the paucity of investigations regarding some of the subject headings presented herein (e.g., effects of vibration on hormones, tissue perfusion, and body composition, etc.), it was necessary to include data collected on young, healthy individuals, which provides evidence for the need for more investigations concerning the elderly. This review summarizes adaptations that occur with the application of WBV as well as the protocols utilized in several investigations (see Tables 1 and 2) in an attempt to determine the influence of such a treatment on other physiological systems and to illustrate the possible diverse applications of WBV.

## 2. The effects of vibration on skeletal tissue

Mechanical stimulation in the manner of WBV appears beneficial to the maintenance and/or enhancement of skeletal mass in individuals such as the elderly, postmenopausal women, and adolescents. Therefore, this may be an effective method by which therapy may be administered to mobility-limited individuals without the risks associated with high-impact exercise. WBV applied at increasing accelerations (0.1, 0.3, and 1.0 g) enhanced trabecular bone volume >30% in a non-dose-dependent fashion as assessed by histomorphometry in the proximal tibia of adult mice (Christiansen and Silva, 2006) while no effect was observed at other bone sites such as vertebrae or femur. Rubin et al. (2001a) demonstrated a marked 34% increase in femoral trabecular bone mass in adult ewes following 1 year of vibration as compared to controls (Rubin et al., 2001a). Trabecular bone formation rate to bone surface ratio (BFR/BS) and mineralizing surface to bone surface ratio (MS/BS) were enhanced in female mice following 3 weeks of vibration (Garman et al., 2007). These enhancements in BFR/BS and MS/BS were acceleration-dependent with higher BFR/BS and MS/BS with the 0.3 g treatment vs. 0.6 g treatment (see Table 1) (Garman et al., 2007). Interestingly, Judex et al. (2002) theorized that genetic variations may modulate the sensitivity of the skeleton to anabolic or catabolic stimuli. For example, 3-month-old C57BL, BALB/c, and C3H mice exhibit different bone mineral densities despite similar body masses (Judex et al., 2002). Subsequent to 10 min/d of vibration (frequency: 45 Hz; acceleration: 0.25g), variations in bone parameters were observed whereby bone volume to total volume (BV/TV) was enhanced 85% in vibrated C57BL mice, BFR/BS was enhanced 32% in BALB/c mice compared to controls while no changes were observed in C3H mice (Judex et al., 2002). This investigation suggests that some individuals may be more sensitive to mechanical vibration and may benefit more from such a treatment than those who may be genetically nonresponsive. In contrast to enhanced trabecular BV/TV observed in C57BL mice (Judex et al., 2002), vibration had no effect on periosteal bone formation in the ulna of the same strain (Castillo et al., 2006).

In addition, WBV has been examined in ovariectomized (OVX) young (Flieger et al., 1998; Rubinacci et al., 2008) and mature (Oxlund et al., 2003; Judex et al., 2007) animals; e.g., trabecular BFR/BS rose 159% following 28 days of WBV in 8-month-old OVX rats (Judex et al., 2007). Further, periosteal BFR was enhanced, endocortical resorption inhibited, and the decrements in maximum bending and compressive stress observed in non-vibrated OVX rats were partially alleviated in the vibrated group (Oxlund et al., 2003). Subsequent to 2 months of vibration (20 min/d, 5 d/week) at a frequency of 30 Hz and two different accelerations (0.6 and 3.0 g) in rats, no differences in cortical and trabecular BMD at the tibial metaphysis and diaphysis at 4 and 8 weeks were observed (Rubinacci et al., 2008). Further, histomorphometric analysis revealed no differences between OVX and the OVX-vibrated groups for neither the tibial metaphysis nor diaphysis (Rubinacci et al., 2008). However, *ex vivo* cross-sectional pQCT analysis subsequent to the protocol revealed that vibration at 3 g augmented total cortical and medullary areas in the tibial diaphysis and also enhanced periosteal and endosteal perimeters (Rubinacci et al., 2008).

In the growing skeleton, WBV attenuated trabecular osteoclastic activity and enhanced metaphyseal endocortical BFR/BS (Xie et al., 2006). In addition, cortical bone area, bone marrow area, periosteal area, polar moment of inertia, and maximum moment of inertia were all enhanced following 6 weeks of vibration in BALB/cByJ mice as compared to the control group (Xie et al., 2008). The potential benefits of vibration for sedentary individuals and astronauts were illustrated when hindlimb unloaded (HU) mice (Ozcivici et al., 2007) and rats (Rubin et al., 2001b) were subjected to vibration. In the latter study, vibration maintained bone remodeling parameters (i.e., BFR, mineralizing surface, and

**Table 2**
Summary of effects of whole-body vibration on various physiological systems in animals and humans

| Target population | Wave type | Vibration protocol | Intensity (accelerations (g); amplitudes (mm); force (N)) | Frequency (Hz) | Outcome | Reference |
|---|---|---|---|---|---|---|
| Skeletal muscle | | | | | | |
| Males (33 ± 5 yrs) | NR | 2 bouts (6 min) for 56 d during bed rest | 5–10 mm | 19–25 | Maintenance of max voluntary isometric plantar flexion force, conservation of myofiber pattern | Blottner et al. (2006) |
| Post-menopausal women (~64 yrs) | NR | 3 times/wk, 24 wks | 2.5–5.0 mm, 2.29–5.09 g | 35–40 | ↑ isometric dynamic knee extensor strength, speed of movement of knee extension, and countermovement jumps height in both WBV and strength trained groups | Roelants et al. (2004b) |
| Males RVE group: (31 yrs); CON group: (33 yrs) | NR | 2 sessions/d (5–10 min) of resistive vibration exercise (RVE) during bed rest (56 d) | 3.5–4 mm | 19–26 | Attenuation of multifidus muscle atrophy and augmented recovery from atrophy after bed rest | Belavy et al. (2008) |
| Males and females (66–85 yrs) | SIN | 8 wks (3 times/wk) of WBV + exercise or exercise alone | 5–8 mm | 26 | No difference in hip or knee, flexor and extensor strength and power; no difference in ankle doriflexor torque and power; ↑ ankle plantar flexor torque and power vs. EX group | Rees et al. (2008) |
| Cartilage | | | | | | |
| Culture chondrocytes | SIN | 8 hr/d for 3–15 d; continuous vibration for 96 hr | 1.4 g | 200, 300, 400, 800, 1600 | 300 Hz ↑ DNA synthesis with periodic and continuous vibration | Liu et al. (2001) |
| 3D cultured chondrocytes | Square | 2 wks | 0.5 nm | 100 | Synthesis of chondroitin 4- and 6-sulfate more abundant with vibration and hyaluronic acid administration | Takeuchi et al. (2006) |
| Rabbit annulus cells | SIN | 2, 4, 6, 8 hr | 0.1 × gravity | 6 | ↓ extracellular matrix and matrix metalloproteinase gene expression | Yamazaki et al. (2002) |
| Neurological responses | | | | | | |
| Parkinson's disease patients (44–79 yrs) | NR | Step-synchronized vibration for 6 min (walking) | 0.1–0.2 mm | 70 | Increased walking speed and improved stride variability | Novak and Novak (2006) |
| Parkinson's disease patients (69 yrs) | Random | 5 series of 60 s | 3 mm | 6 ± 1 | Improved postural stability during certain test conditions | Turbanski et al. (2005) |
| Rhesus monkeys (8–12 lbs) | SIN | 1 hr vibration, 3 hr vibration | 10 mm, 1 g | 6, 8, 10, 12 | Severe vibration (6 and 8 Hz) affected latency | Floyd et al. (1973) |
| Multiple sclerosis patients (31–64 yrs) | Vertical and horizontal oscillations | 5 series of 1 min | 3 mm | 2.0–4.4 | Time get up and go test scored reduced from 9.2 to 8.2 s | Schuhfried et al. (2005) |
| Parkinson's disease patients (62–84 yrs) | NR | 3 wks (5 d/wk) of 2 sessions of WBV (15 min each); control subjects received tilt board exercises | 7–14 mm | 25 | No differences between WBV and conventional physical therapy observed | Ebersbach et al. (2008) |
| Tissue perfusion | | | | | | |
| Healthy subjects (25–35 yrs) | NR | 9 min | 3 mm, 78 m $s^{-2}$ | 26 | Blood volume in quad and gastroc muscle ↑ and blood flow through popliteal artery ↑ | Kerschan-Schindl et al. (2001) |
| Healthy adults (18–43 yrs) | NR | Isometric exercise w/ or w/o vibration (60 s) or vibration only (3 × 60 s) | 5–6 mm, 7 g | 30 | Vibration only ↑ skin blood flow | Lohman et al. (2007) |
| Females (45–70 yrs) | SIN | During supine and 35° upright tilt | 0.2 g | 15, 45 | ↑ calf, upper leg–pelvic and thoracic blood flow and augmented lymphatic and venous drainage | Stewart et al. (2005) |
| Males and females: study 1: (20 yrs); study 2: (23 yrs) | NR | 10 min for the dominant arm | 5–6 mm, 7 g | 30, 50 | ↑ skin blood flow for both frequencies; augmented flow lasted for 9 min | Maloney-Hinds et al. (2008) |

| | | | | | | |
|---|---|---|---|---|---|---|
| Dogs (14–30 kg) | SIN | 1 min stages, 4–6 min rest between stages | 0.9 g | 9 | ↑ forearm vasodilation with increasing acceleration and displacement | Liedtke and Schmid, 1969 |
| | | | 1.2 g | 12 | | |
| | | | 1.6 g | 16 | | |
| Microstructural and mixture theory model of vertebral cancellous bone and body | SIN | NR | 1–15 μg | 30–80 | Vibration-induced shear stress on trabeculae are in range for bone stimulation; volumetric blood flow rates varied with frequency and strain amplitude | Dickerson et al. (2008) |
| 3D poroelastic finite element model of intravertebral discs | SIN | 1 hr | 1000 N | 0.5, 1, 2, 4 | Static loading: vertebral loads ↑ with time vertebral fluid flow and deformation were dependent upon loading frequency | Cheung et al. (2003) |
| Peripheral vasculature | | | | | | |
| Sprague Dawley rats (6 wks) | NR | 4 hr | 49 m $s^{-2}$ | 125 | ↑ $\alpha_{2c}$-adrenergic receptor mediated vasoconstriction | Krajnak et al. (2006) |
| BALB/cByJ (8 wks) | SIN | 15 min/d for 6 wks | 0.3 g | 45 | Vascular rarefaction in mouse soleus muscle | Murfee et al. (2005) |
| Hormonal responses | | | | | | |
| Males (~22 ± 3 yrs) | SIN | 10 sets of 60 | 4 mm, 3.5 g | 30 | ↔ salivary [testosterone] and [cortisol] | Erskine et al. (2007) |
| Males (25 ± 5 yrs) | SIN | 10 × 60 s | ±4 mm, 17 g | 26 | ↑ in plasma [testosterone] and [growth hormone] and ↓ [cortisol] | Bosco et al. (2000) |
| Elderly (± 70 yrs) | NR | Five 1-min sessions separated by 1-min rest periods | 4 mm | 30 | ↑ IGF-1 levels were higher with WBV immediately, 1 and 2 hr post-↑ cortisol levels immediately post-WBV; 1 and 2 hr post-treatment → ↓ cortisol levels with both conditions | Cardinale et al. (2008) |
| Males (39 yrs) | NR | 10 vibration series of 1 min duration (25 min total) | ±4 mm, 17 g | 30 | ↓ plasma glucose at 30 min; ↑ plasma NE at 60 min vs. control. No effect on serum GH, IGF-1, free or total testosterone, and plasma E | Di Loreto et al. (2004) |
| Males (~24 yrs) | NR | 9 wks squat + load; squat + load + vibration; squat + vibration | NR | 20, 25 | No ↔ in body mass; no ↔ maximal voluntary contraction: no differences among groups; no ↔ in testosterone after 9 wks; bisphasic response of GH and cortisol levels (↑ then ↓) during first training session; no ↔ in GH and cortisol levels during last training session | Kvorning et al. (2006) |
| Body composition | | | | | | |
| Males (~18 yrs) | SIN | 5 sets of 10 repetitions | 4 mm | 30 | ↑RER and EE with vibration | Da Silva et al. (2007) |
| Males | NR | 3 squatting exercises in cycles of 6, 4, 2 s | 4 mm | 30 | ↑oxygen consumption and energy expenditure | Garatachea et al. (2007) |
| Females (21 yrs) | NR | 24 wks | 2.5–5.0 mm | 35–40 | No ↔ in BW, subcutaneous or total body fat mass ↑ lean mass | Roelants et al. (2004a) |

NR: not reported; min: minutes; s: seconds; hr(s): hour(s); d: day; wk(s): week(s); yr(s): year(s); quad: quadriceps muscle; gastroc: gastrocnemius muscle; SIN: sinusoidal wave; w/: with; w/o: without; lbs: pounds; WBV: whole body vibration; RVE: resistive vibration exercise; EX: exercise; μg: microstrain; []: concentration; IGF-1: insulin-like growth factor; NE: norepinephrine; GH: growth hormone, E: epinephrine; RER: respiratory exchange ratio; EE: energy expenditure; BW: body weight; ↑: increase; ↓: decrease; ↔: no change.

mineral apposition rate) similar to ambulatory control rats (Rubin et al., 2001b). Interestingly, when vibrations were delivered to specific segments of the murine skeleton, bone anabolism was observed in the absence of weight-bearing (Garman et al., 2007). Similarly, vibration for 3 weeks in HU female mice enhanced mechanical properties by 31% in trabecular bone of the tibia in stimulated left hindlimbs vs. nonstimulated contralateral right hindlimbs (Ozcivici et al., 2007). Further, vibration attenuated the deterioration of trabecular metaphyseal microarchitecture in the left hindlimbs vs. nonstimulated right hindlimbs; however, vibration did not totally prevent the bone deterioration associated with HU (Ozcivici et al., 2007).

Various investigations have been conducted on human subjects. In young women with low bone mineral density (BMD), 12 months of daily WBV (10 min, 30 Hz, 0.3 g) resulted in enhanced cancellous bone in the spine and increased cortical bone area in the femur (Gilsanz et al., 2006). The subjects were described as healthy, given medical examinations prior to admittance to the study, and therefore, did not suffer from a pathology (e.g., osteogenesis imperfecta) which may have increased the fragility of the skeleton. The reader should note that a placebo effect may have biased the results of this investigation since the subjects were not blinded to the experimental conditions (i.e., vibration platforms were only installed in the homes of the vibrated subjects). In children with disabling conditions, 6 months of vibration increased tibial volumetric trabecular BMD (vTBMD) 6% above baseline measures, while vTBMD declined 12% below baseline measures in children who stood on placebo devices (Ward et al., 2004). Following 6 months of WBV in postmenopausal women, enhancements in hip density, muscle strength, and postural control were observed (Verschueren et al., 2004). Following 1 year of vibration at low frequency and acceleration (i.e., 30 Hz and 0.2 g, respectively) in 70 postmenopausal women, no differences in bone density were observed between the vibrated and control groups (Rubin et al., 2004). Post hoc observations revealed that women with lower body weight may benefit to a greater extent than those women with high body weight. Further, high compliance of the vibration protocol is an important factor for a beneficial response (Rubin et al., 2004). Eight months of WBV (3 sessions/week; frequency: 12.6 Hz; amplitude: 3 mm) improved hip BMD and postural balance above values observed in the walking group; however, no differences in lumbar spine BMD was observed (Gusi et al., 2006). The subjects in this investigation were divided into either a WBV or walking group, therefore comparisons with a control group were not conducted. Further, the combined treatment of WBV and alendronate for 12 months did not alter lumbar spine BMD nor markers of bone remodeling above those levels observed in postmenopausal women administered only alendronate; however, a reduction in chronic back pain was reported with combined treatment (Iwamoto et al., 2005). The experimental design of this investigation does not preclude the possibility of a placebo effect. Taken together, the discrepancies in results may reflect different frequencies, amplitudes, and type of mechanical signal delivered to the skeleton. The data provides evidence that certain subsets of the population (e.g., postmenopausal and low-BMD women, astronauts, and adolescents) may derive skeletal benefits from daily regimens of WBV, provided that the appropriate regimen is delivered to the skeleton.

## 3. The effects of vibration on articular cartilage

Osteoarthritis (OA) is positively associated with advancing age and is characterized by deterioration of articular cartilage, which causes joint pain, deformation, and loss of function (Martin and Buckwalter, 2002). Further, osteoarthritis contributes to a significant decline in physical activity with advancing age (Lawrence et al., 1998). The development of OA can be attributed to excessive mechanical forces, inflammatory mediators originating from the synovium, and factors derived from subchondrondal bone within the joint (Loeser, 2006). In addition, aging chondrocytes lose their ability to maintain or repair articular cartilage as a result of chondrocyte death, mechanical damage, and possible desensitization of chondrocytes to anabolic cytokines (Buckwalter and Mankin, 1998). Recently, the pathogenesis of OA is recognized as being more complex than merely a mechanically-related phenomenon (Buckwalter and Mankin, 1998; Loeser, 2004) and the relation between load and cartilage is complex. Within the joint, articular cartilage lines the surface of bone and during mechanical stress is responsible for bearing the load and distributing this load uniformly across the bone surface (Takeuchi et al., 2006). Mechanical loads are requisite for the normal functioning of joints and removal of these loads initiates cartilage deterioration (Liu et al., 2001). The interaction between biomechanical and proinflammatory mediators participates in the progressive decline of cartilage within the osteoarthritic knee (Guilak et al., 2004) and the intervertebral discs (Setton and Chen, 2004). However, *in vitro* evidence suggests that mechanical strain attenuates the deleterious effects of inflammatory molecules on chondrocytes (Liu et al., 2001) and may provide therapeutic means by which the symptoms of OA are alleviated.

Since WBV may modulate skeletal tissue through mechanical perturbation, such a regimen may improve the age-associated deterioration of articular cartilage, a tissue in direct contact with the underlying skeleton. Liu et al. (2001) demonstrated that in cultured chrondrocytes subjected to mechanical vibration $^{3}$H-thymidine uptake into DNA and $H_2{}^{35}SO_4$ incorporation into proteoglycans were augmented (Liu et al., 2001). The culture plates were affixed to the vibrating platform which provided an oscillating force to the chondrocytes (Liu et al., 2001). However, not all vibration frequencies enhanced uptake and incorporation of these compounds into DNA and proteoglycans, respectively; i.e., frequencies above 400 Hz attenuated these responses (Liu et al., 2001). Similarly, combined administration of hyaluronic acid (HA), a common local treatment for OA, and mechanical vibration to chondrocytes in three-dimensional matrices was effective in increasing the production of chondroitin-4 and -6 sulfate and augmenting the thickness of the chondrocyte layer in comparison to chondrocytes treated with HA alone (Takeuchi et al., 2006). Culture plates were secured to the vibration platform and vibration was applied to the cells at 100 Hz and 0.5 nm amplitude (Takeuchi et al., 2006). Conversely, vibration decreased both extracellular matrix and matrix metalloproteinase gene expression in rabbit annulus cells (Yamazaki et al., 2002). In this investigation, the culture plate was also secure to the vibration platform in which a vibratory jig provided the vibration stimulus (Yamazaki et al., 2002). Since alterations in organelle movement can affect cell behavior, the mechanical effects of vibration in these cell culture studies may have influenced cell behavior via these mechanisms. Taken together, these results suggest that a vibratory stimulus may be effective in maintaining or preventing the reduction of chondrocyte activity with advancing age. However, the beneficial effects have not been demonstrated *in vivo* nor has the appropriate vibratory stimulus been elucidated. Furthermore, the long-term effects of WBV on the articular cartilage remain to be determined, even though such a regimen may be osteogenic.

## 4. The effects of vibration on the neuromuscular system

*Skeletal muscle.* The application of WBV in recreational and therapeutic settings is being used to augment muscle strength and

athletic performance. Many investigations have been conducted on young, healthy, and athletic individuals (for an excellent review see Norlund and Thorsstensson, 2007) and will not be the focus of this section. A recent investigation reported increased total cross-sectional area of the soleus of 8-week-old BALB/cByJ mice (Xie et al., 2008). The authors argue that accretion of muscle and bone during "adolescence" may decrease the risk of osteoporotic fractures with advanced age (Xie et al., 2008). Fewer investigations have examined the effects of WBV in the elderly population or other subgroups (e.g., postmenopausal women) which may derive the largest benefits from such a therapy. Poor body balance and attenuated muscle strength in elderly individuals are risk factors for falls (Hausdorff et al., 2001), which may increase the risk of fracture. Exercise protocols (e.g., WBV) that improve balance, mobility, muscle strength, and attenuate the risk of falling (Bruyere et al., 2005; Kawanabe et al., 2007) drastically enhance the quality of life for these individuals in addition to reducing the medical cost associated with fall-related injuries.

Recent evidence suggests that WBV may be an effective and efficient treatment for these populations. For example, in subjects bed rested for 56 days, daily resistive-like vibration exercise (RVE) maintained isometric plantar flexion force, increased soleus muscle fiber size (type I and II), and prevented the slow-to-fast fiber type conversion that normally occurs in the soleus muscle following prolonged bed rest (Blottner et al., 2006). Additional data from the "Berlin Bed-Rest Study" demonstrated that RVE during bed rest attenuated atrophy in the multifidus muscle, a muscle in the lumbo-pelvic region of the human torso; however the cross-sectional areas of other muscles from the same region (e.g., psoas) remained similar between groups (Belavy et al., 2008). The vibration device utilized in the "Berlin Bed-Rest Study" involved placing the subjects' feet on the vibrating platform while in a supine position (Belavy et al., 2008; Blottner et al., 2006). By use of elastic straps, an axial force approximately 2 times the person's body weight was generated and delivered to the subject (Belavy et al., 2008; Blottner et al., 2006). In an institutional setting, 6 weeks of WBV applied to elderly subjects (mean age: 77 years) modestly improved some assessments of activities of daily living (Bautmans et al., 2005). The authors concluded that WBV, which appears beneficial for balance and mobility, is a feasible form of exercise for this group of individuals (Bautmans et al., 2005). Additionally, improvements in gait, muscle strength, balance, and motor capacity were observed in nursing home residents following 6 weeks of WBV and elicited improvements in risk factors associated with falling (Bruyere et al., 2005). Two months of WBV in addition to routine exercises (i.e., balance, muscle strengthening, and walking) improved walking ability in comparison to the group of elderly individuals who performed only the routine exercises (Kawanabe et al., 2007) and 3 months of high-frequency vibration enhanced balance in elderly women (Cheung et al., 2007).

Similarly, exercises supplemented with WBV (35–40 Hz) increased jump height, knee-extension isometric strength, dynamic strength, and speed of movement in older women following 24 weeks of treatment (Roelants et al., 2004b). A limitation to these findings is the lack of a proper control group; i.e., measurements were not taken in subjects performing only exercise without vibration. The authors do cite previous investigations from their laboratory whereby a portion of the observed strength gains were associated with the vibration stimulus (Roelants et al., 2004b). Subsequent to 1 year of vibration, gains in muscle strength and mass in elderly men were equivalent to gains observed in elderly men performing a fitness program (Bogaerts et al., 2007). Ankle plantar flexor strength and power was enhanced in elderly individuals (74 years) following 8 weeks of strength training supplemented with WBV vs. the exercise trained group; however, no differences were observed between groups in knee and hip flexor or extensor strength (Rees et al., 2008). In postmenopausal women (58–74 years), improvements in isometric strength (15%), dynamic strength (16.5%), and postural balance were observed following 6 months of WBV training in comparison to the control group (Verschueren et al., 2004). Similar improvements were observed in the resistance strength training group, indicating that WBV training is as effective as resistance training in modifying balance and muscle strength in this population (Verschueren et al., 2004). Therefore, WBV may be effective in enhancing muscle strength, balance, and mobility in individuals affected by age- and pathology-related declines in these parameters. Further, WBV may be successful in restoring the quality of life in these individuals whose mobility is limited.

*Neurological responses.* One proposed mechanism by which WBV affects muscular strength and performance is via increased neuromuscular efficiency (Bosco et al., 2000). Enhanced recruitment of motor units during WBV may be one mechanism by which neuromuscular atrophy associated with advanced age or disease is attenuated (Blottner et al., 2006). In addition, chemicals (e.g., oxygen, enzymes, and glucose) amplified during muscular activity have the ability to alter nerve axons and nerve conduction time (Floyd et al., 1973). Therefore, dependent upon the frequency and duration of the vibratory stimulus, WBV may be beneficial or detrimental to neuromuscular performance. Indeed, nerve conduction time in rhesus monkeys was altered during application of WBV at frequencies of 6, 8, 10, and 12 Hz (1.0 g) for 1 h (Floyd et al., 1973). The most dramatic decreases in nerve conduction time occurred at frequencies of 6 and 8 Hz while increased conduction time occurred at 12 Hz (Floyd et al., 1973). The authors concluded that long durations of low-frequency vibration may be detrimental for tasks requiring rapid response times (Floyd et al., 1973).

Whole body vibration administered in shorter durations may prove efficacious for individuals with postural instability and whose motor functions are impaired (e.g., the elderly and individuals with Parkinson's disease or multiple sclerosis) (Bautmans et al., 2005; Schuhfried et al., 2005; Turbanski et al., 2005; Novak and Novak, 2006; Cheung et al., 2007; Kawanabe et al., 2007). For example, patients suffering from Parkinson's disease (PD) have approximately double the risk of falling when compared to other elderly persons (Wood et al., 2002) and many patients have reported a worsening of postural stability with medication (Bronte-Stewart et al., 2002). Therefore, nonpharmacological therapies may be optimal in this patient population (Jöbges et al., 2004). Enhanced postural control in patients with PD was observed following random WBV at 6 Hz (5 series of 60 s); however, not all tests (e.g., narrow standing) indicated enhanced postural stability (Turbanski et al., 2005). Step-synchronized vibration delivered to PD patients with mild-to-moderate gait impairment associated with abnormal balance improved gait steadiness in these individuals (Novak and Novak, 2006). In this investigation, vibratory devices were implanted into the insoles of the shoes of PD patients. Vibration was delivered at 70 Hz during the stance phase of the step (Novak and Novak, 2006). The authors concluded that the results were not applicable to all PD patients and that the experimental design (i.e., short-term investigation, non-blinded conditions, and learning and placebo effects) may have limited the findings of the investigation (Novak and Novak, 2006). In contrast, 3 weeks of WBV did not enhance gait and equilibrium measures above those PD patients who received standard balance training (Ebersbach et al., 2008). In addition to the WBV or standard balance training treatment, all patients received three 40-min sessions per day of standard therapy (Ebersbach et al., 2008). Therefore, comparisons of gait and

equilibrium measures between subjects who received treatment and no treatment could not be made. In another investigation with multiple sclerosis patients, WBV (2.0–4.4 Hz) delivered in 5 series of 1 min each improved the Timed Get Up and Go test and may enhance postural control and mobility in these individuals (Schuhfried et al., 2005). A limitation of this investigation is a lack of a group that received no sensory input. The control group received Burst-transcutaneous electrical nerve stimulation (TENS) in lieu of vibration, which elicited muscle contractions and may therefore have affected the results of the study (Schuhfried et al., 2005). In totality, WBV may be a potential therapeutic aid for individuals suffering from many types of age- and disease-related motor impairments; however, more investigations should be conducted.

## 5. The effects of vibration on tissue perfusion and the peripheral vasculature

*Tissue perfusion.* A potential ubiquitous mechanism of vibration is its ability to alter tissue perfusion and modify the vascular network. However, the magnitude of this effect is tissue specific and depends upon the vibration regimen. The frequencies and durations of the vibratory stimulus in the occupational setting are higher in magnitude and duration than those utilized for therapeutic purposes and the literature is replete with studies examining the adverse consequences of occupational vibration (for an example, see Stoyneva et al., 2003). Further, industrial guidelines safeguarding the health of employees exposed to vibration have been implemented (see Nelson and Brereton, 2005). Attenuated tissue perfusion (e.g., impaired circulation to the fingers) is a well-recognized hazard associated with occupational vibration (Bovenzi et al., 2006). Reductions in finger blood flow occurred with 5 min of vibration (i.e., 31.5 and 125 Hz), whereby the greater reductions in blood flow were observed during the 125 Hz protocol (Bovenzi et al., 2006). The mechanism attributed to the reduction in blood flow was enhanced vasoconstriction in the digit (Bovenzi et al., 2006). In contrast, three bouts (60 s) of vibration at 30 Hz dramatically increased skin blood flow, which remained elevated for 10 min following the cessation of vibration (Lohman et al., 2007). Further, skin blood flow was augmented during vibration (10 min) to the dominant arm of males and females (Maloney-Hinds et al., 2008). Skin blood flow rose similarly with both frequencies (30 and 50 Hz) and remained augmented for at least 9 min (Maloney-Hinds et al., 2008).

WBV protocols that reported improvements in bone mass utilized frequencies and durations which ranged from 17 to 90 Hz and 9–30 min, respectively (Flieger et al., 1998; Rubin et al., 2001a; Oxlund et al., 2003; Christiansen and Silva, 2006; Gilsanz et al., 2006; Xie et al., 2006; Judex et al., 2007). Similar protocols have been used to determine the influence of vibration on tissue perfusion. For example, 9 min of WBV at 26 Hz enhanced the relative moving blood volume in skeletal muscle (i.e., quadriceps and gastrocnemius) and improved mean blood flow through the popliteal artery (Kerschan-Schindl et al., 2001). It must be noted that these indices were not measured in the absence of the vibratory stimulus. Plantar vibration and 35° upright tilt modulated calf blood flow (CBF) whereby vibration alleviated the orthostatically induced decrement in CBF (supine: $137 \pm 18$ ml min$^{-1}$; 35° upright tilt: $99 \pm 15$ ml min$^{-1}$; 35° upright tilt + 15 Hz: $131 \pm 31$ ml min$^{-1}$; 35° upright tilt + 45 Hz: $146 \pm 28$ ml min$^{-1}$) (Stewart et al., 2005). Further, plantar vibration augmented venous drainage and lymphatic fluid flow suggesting that enhanced blood and lymph flow as well as venous drainage within skeletal tissue may be a mechanism to modulate bone mass (Stewart et al., 2005). In dogs, vasodilation in the forelimbs varied inversely with the frequency (9, 12, and 16 Hz) and directly with the acceleration and the displacement of the vibration protocol (Liedtke and Schmid, 1969). The magnitude of vasodilation was greater in the neurally intact vs. denervated limbs, suggestive of a neurogenically-mediated vasodilator response to vibration (Liedtke and Schmid, 1969).

A poroelastic finite element model was used to analyze fluid flow in intervertebral discs and determined that following 1 h of vibration at 1 Hz or static compression at 1000 N, the loss of fluid in the discs was 20% and 5%, respectively (Cheung et al., 2003). When different vibration frequencies were applied for 10 min subsequent to 50 min of static compression, the rate of change of fluid volume within the discs transiently improved with increasing frequencies. Therefore, vibration may be beneficial for disc fluid exchange (i.e., enhanced nutrient transport and waste removal) but further investigations are needed to determine whether prolonged durations (e.g., 1 h) are detrimental to the biomechanical responses of the intervertebral disc (Cheung et al., 2003).

Similarly, a microstructural model of vertebral cancellous bone was utilized to predict shear stress and volumetric blood flow rate within the vertebrae during WBV (Dickerson et al., 2008). The model predicted that shear stresses perceived by trabeculae increased linearly with vibration frequency and reached levels similar to stresses that stimulate osteoblast *in vitro* (Dickerson et al., 2008). Further, peak volumetric blood flow rates escalated linearly with both increasing vibration frequency and macroscopic strain, which possibly may enhance nutrient transport within the vertebrae (Dickerson et al., 2008). Therefore, the alterations in tissue perfusion appear dependent upon the duration, frequency, and amplitude of the stimulus as well as the tissue of investigation. For example, reductions in finger blood flow occurred at 31.5 Hz (Bovenzi et al., 2006) while, in another investigation, moving blood volume in the quadriceps and gastrocnemius muscles and blood flow through the popliteal artery was enhanced at 26 Hz (Kerschan-Schindl et al., 2001). In general, these results indicate that vibration exposures of shorter duration and lower frequencies may be the most beneficial to enhance tissue perfusion. To date, the optimal duration, frequency, and amplitude have yet to be determined and further studies should be conducted.

*The peripheral vasculature.* Hand-arm syndrome can be characterized by neurological and vascular dysfunction (Juntunen and Taskinen, 1987) in limbs exposed to prolonged vibrational stimuli in the occupational setting. Excessive vibrational stimulation may damage endothelial and vascular smooth muscle cells (Curry et al., 2002, 2005; Govindaraju et al., 2006). While the pathology behind this syndrome has been studied extensively, the effects of short duration and low-frequency vibration on the peripheral vasculature have been under-investigated. Decrements in vessel number occurred in mouse soleus muscle following vibration exposure (45 Hz, 0.3 g) as brief as 15 min/d (Murfee et al., 2005). Slow-to-fast fiber type transition did not occur and muscle fibers per area and total muscle area were not altered, indicating that vascular rarefaction resulted from the protocol (Murfee et al., 2005). Vibration alters the functional properties of the peripheral vasculature as well. For example, a single exposure to vibration (4 h, 125 Hz) enhanced vasoconstriction via $\alpha_2$-adrenergic receptors and may have amplified sympathetic vasoconstriction in cutaneous arteries; however endothelial dysfunction and damage were not observed (Krajnak et al., 2006). These data correspond to diminished finger blood flow with acute (5 min) vibration (Bovenzi et al., 2006) and, on the contrary, enhanced skin blood flow with three bouts (60 s) of WBV (Lohman et al., 2007). To date, the effects of WBV on the peripheral vasculature and tissue perfusion remain obscure. Based upon the results summarized in this section, both

acute and chronic alterations in the peripheral vasculature occur with WBV. Acute and chronic stimuli alter vessel diameter via vasodilation, vasoconstriction, and vascular remodeling. Therefore, the divergent results presumably represent the consequence of the various acute and chronic WBV protocols as well as the vascular bed analyzed.

## 6. Hormonal responses to vibration

Whole-body vibration may augment skeletal mass through direct mechanical perturbation or modulation of tissue perfusion; however, this augmentation may also develop from vibration-induced fluctuations in hormones capable of modulating bone cell activity. Therefore, understanding the physiological responses of the endocrine system during acute and chronic vibratory protocols may be imperative when deciphering the mechanisms involved in enhanced bone remodeling. For example, cortisol has an inhibitory effect on bone formation and a stimulatory effect on bone resorption (Manelli and Giustina, 2000). Endogenous growth hormone is critical for the maintenance of bone mass in adults (Ueland, 2005) and aged individuals experience declines in circulating growth hormone levels (Sherlock and Toogood, 2007). Indeed, an acute bout of WBV resulted in enhanced levels of blood testosterone ($24.3 \pm 6.6$ nmol $l^{-1}$ vs. $22.7 \pm 6.6$ nmol $l^{-1}$) and growth hormone ($28.6 \pm 29.6$ ng $ml^{-1}$ vs. $6.2 \pm 16.2$ ng $ml^{-1}$) and attenuated levels of cortisol ($464 \pm 257$ nmol $l^{-1}$ vs. $682 \pm 255$ nmol $l^{-1}$) (Bosco et al., 2000). Enhanced production of growth-stimulating hormones and attenuated production of growth-inhibiting hormones possibly contribute to gains in skeletal tissue observed in other investigations (Flieger et al., 1998; Rubin et al., 2001a,b; Oxlund et al., 2003; Christiansen and Silva, 2006; Gilsanz et al., 2006; Xie et al., 2006; Judex et al., 2007).

Other reports indicate that hormonal fluctuations resulting from WBV vary considerably; i.e., serum concentrations of growth hormone, testosterone, and insulin-like growth factor were unaffected following an acute bout of WBV (Di Loreto et al., 2004). Likewise, subjects who underwent 9 weeks of WBV showed no change in testosterone levels when comparing the first and last training sessions (Kvorning et al., 2006). In the same experiment, growth hormone and cortisol levels rose and fell, respectively, subsequent to the vibratory stimulus applied during the first training session but did not change following 9 weeks of WBV, as was observed following the last training session (Kvorning et al., 2006). In addition, Erskine et al. (2007) found no change in salivary testosterone or cortisol levels immediately post-, 1 h post-, 2 h post- and 24 h post-vibration; however, there was a tendency ($p = 0.052$) for cortisol levels to rise across time in the vibrated group. The authors concluded that WBV consisting of accelerations of 3.5 g delivered to young, healthy individuals does not significantly stimulate the neuroendocrine system (Erskine et al., 2007). In a recently published manuscript, hormonal fluctuations were observed in elderly individuals following a single session of WBV (Cardinale et al., 2008). Insulin-like growth factor-1 (IGF-1) levels were elevated immediately-, 1 h-, and 2 h-post-WBV plus static squat (slight knee flexion) vs. levels observed with static squat alone (Cardinale et al., 2008). Immediately subsequent to the WBV session, cortisol levels were higher than those observed with static squat alone; however by 1 h- and 2 h-post-treatment, cortisol concentrations were reduced below pre-treatment levels with both WBV plus static squat and static squat alone (Cardinale et al., 2008). In contrast, no differences were observed between treatments in testosterone or growth hormone concentrations (Cardinale et al., 2008). To our knowledge, hormonal fluctuations subsequent to WBV have not been measured in other populations, such as postmenopausal women, who may benefit from vibration therapy.

## 7. Effects of vibration on body composition

One of the main advertising arguments for use of vibrating devices available on the market is that they promote weight loss or decrease fat mass; however, there is a lack of data in the literature to support these claims. Since body mass has a profound influence on body composition, weight loss associated with the use of the vibrating devices may indirectly modulate skeletal tissue (Roelants et al., 2004a). Twenty-four weeks of WBV (35–40 Hz, 2.5–5.0 mm) did not alter body weight, total body fat or subcutaneous fat mass, but slightly increased lean mass in previously untrained females (Roelants et al., 2004a). In young males, vibration in addition to exercise training, significantly increased energy expenditure during exercise and recovery (Da Silva et al., 2007). In a similar population, energy expenditure, carbohydrate and fat oxidation rate, and oxygen consumption were positively affected by vibration (Garatachea et al., 2007). Taken together, these data suggest that WBV modulates energy expenditure but are insufficient to determine whether chronic application of WBV alters body composition.

## 8. Conclusions

In summary, investigations in the literature provide some evidence of the effectiveness of WBV in enhancing skeletal mass in the elderly, in individuals with low-bone mineral density, and adolescents. The mechanisms by which this occurs may be related to tissue perfusion, fluctuations in systemic hormones, and/or occur via direct mechanical stimulation. The potential effects of WBV on several physiological systems may occur via direct or indirect mechanisms as illustrated in Fig. 1. Currently, the data are unclear as to how WBV affects systemic hormones, peripheral vascular morphology and function, and bone perfusion, especially in the elderly and in postmenopausal women and women with low-bone mineral density. In addition, experimental evidence

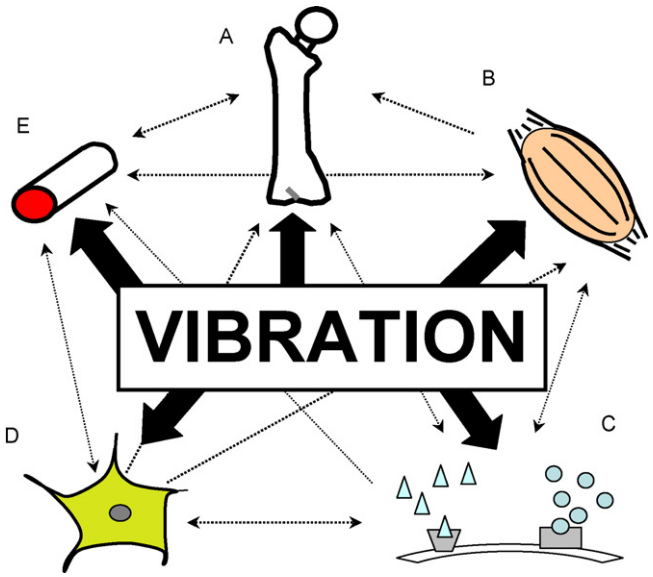


**Fig. 1.** The potential effects of WBV on physiological systems and the potential interplay among systems. WBV modulates the (A) skeletal, (B) muscular, (C) endocrine, (D) nervous, and (E) vascular systems, which may elicit secondary responses through interaction among the systems of which the figure presents only the most obvious.

indicates that WBV may be beneficial in restoring muscle strength, balance, and mobility in the elderly and diseased individuals and may potentially reduce the risk of falls and fall-related injuries. Prescription of an appropriate and still to be defined WBV regimen may prove fruitful for individuals suffering from OA by presumably attenuating the age-associated deterioration of articular cartilage. Decrements in bone mass, muscle strength, tissue perfusion, systemic hormones, and articular cartilage are common ailments in elderly individuals. Therefore, WBV training may be the most efficient and cost effective method to globally alleviate these deteriorations.

On the other hand, the use of WBV for therapeutic purposes is far from being standardized. Currently, the optimal threshold for a beneficial effect is undetermined and it is unknown whether such a threshold would be applicable to all tissues and organs of the body. The vibratory protocols (i.e., waveform, frequency, duration, and amplitude) reported in the literature summarized herein vary considerably, making definitive conclusions regarding the most effective protocol extremely difficult. In many cases, only the frequency and duration of the protocols are provided and many of the investigations fail to report the type of vibratory signal (i.e., sinusoidal, square, etc.). Therefore, future investigations should focus on determining the optimum frequency, duration, amplitude, and type of vibratory signal. In addition, the most appropriate WBV protocols will most likely depend upon the subject population; e.g., WBV protocols developed for young individuals may be inappropriate for the elderly. Additionally, many articles in the literature have faulty experimental designs and the reader is encouraged to carefully distinguish between results obtained from primary vs. secondary analysis of the data when the original hypothesis failed to yield significance. Lastly, multidisciplinary approaches are requisite in determining whether the application of WBV is beneficial for all physiological responses.

## References


Bautmans, I., Van Hees, E., Lemper, J.C., Mets, T., 2005. The feasibility of whole body vibration in institutionalised elderly persons and its influence on muscle performance, balance and mobility: a randomised controlled trial [ISRCTN62535013]. BMC Geriatr. 5 (17), open access.

Belavy, D.L., Hides, J.A., Wilson, S.J., Stanton, W., Dimeo, F.C., Rittweger, J., Felsenberg, D., Richardson, C.A., 2008. Resistive simulated weightbearing exercise with whole body vibration reduces lumbar spine deconditioning in bed-rest. Spine 33 (5), E121–E131.

Blottner, D., Salanova, M., Puttmann, B., Schiffl, G., Felsenberg, D., Buehring, B., Rittweger, J., 2006. Human skeletal muscle structure and function preserved by vibration muscle exercise following 55 days of bed rest. Eur. J. Appl. Physiol. 97 (3), 261–271.

Bogaerts, A., Delecluse, C., Claessens, A.L., Coudyzer, W., Boonen, S., Verschueren, S.M., 2007. Impact of whole-body vibration training versus fitness training on muscle strength and muscle mass in older men: a 1-year randomized controlled trial. J. Gerontol. A: Biol. Sci. Med. Sci. 62 (6), 630–635.

Bosco, C., Iacovelli, M., Tsarpela, O., Cardinale, M., Bonifazi, M., Tihanyi, J., Viru, M., De Lorenzo, A., Viru, A., 2000. Hormonal responses to whole-body vibration in men. Eur. J. Appl. Physiol. 81 (6), 449–454.

Bovenzi, M., Welsh, A.J., Della Vedova, A., Griffin, M.J., 2006. Acute effects of force and vibration on finger blood flow. Occup. Environ. Med. 63 (2), 84–91.

Bronte-Stewart, H., Minn, A.Y., Rodrigues, K., Buckley, E.L., Nashner, L.M., 2002. Postural instability in idiopathic Parkinson's disease: the role of medication and unilateral pallidotomy. Brain 125 (Pt 9), 2100–2114.

Bruyere, O., Wuidart, M.A., Di Palma, E., Gourlay, M., Ethgen, O., Richy, F., Reginster, J.Y., 2005. Controlled whole body vibration to decrease fall risk and improve health-related quality of life of nursing home residents. Arch. Phys. Med. Rehabil. 86 (2), 303–307.

Buckwalter, J., Mankin, H.J., 1998. Articular cartilage: degeneration and osteoarthritis, repair, regeneration, and transplantation. Instr. Course Lect. 47, 487–504.

Cardinale, M., Soiza, R.L., Leiper, J.B., Gibson, A., Primrose, W.R., 2008. Hormonal responses to a single session of whole body vibration exercise in elderly individuals. Br. J. Sports Med. April 15 (E-pub ahead of print).

Castillo, A., Alam, I., Tanaka, S.M., Levenda, J., Li, J., Warden, S.J., Turner, C.H., 2006. Low-amplitude, broad-frequency vibration effects on cortical bone formation in mice. Bone 39 (5), 1087–1096.

Cheung, J., Zhang, M., Chow, D.H., 2003. Biomechanical responses of the intervertebral joints to static and vibrational loading: a finite element study. Clin. Biomech. 18 (9), 790–799.

Cheung, W., Mok, H.W., Qin, L., Sze, P.C., Lee, K.M., Leung, K.S., 2007. High-frequency whole-body vibration improves balancing ability in elderly women. Arch. Phys. Med. Rehabil. 88 (7), 852–857.

Christiansen, B., Silva, M.J., 2006. The effect of varying magnitudes of whole-body vibration on several skeletal sites in mice. Ann. Biomed. Eng. 34 (7), 1149–1156.

Curry, B., Bain, J.L., Yan, J.G., Zhang, L.L., Yamaguchi, M., Matloub, H.S., Riley, D.A., 2002. Vibration injury damages arterial endothelial cells. Muscle Nerve 25 (4), 527–534.

Curry, B., Govindaraju, S.R., Bain, J.L., Zhang, L.L., Yan, J.G., Matloub, H.S., Riley, D.A., 2005. Evidence for frequency-dependent arterial damage in vibrated rat tails. Anat. Rec. A: Discov. Mol. Cell Evol. Biol. 284 (2), 511–521.

Da Silva, M., Fernandez, J.M., Castillo, E., Nuñez, V.M., Vaamonde, D.M., Poblador, M.S., Lancho, J.L., 2007. Influence of vibration training on energy expenditure in active men. J. Strength Cond. Res. 21 (2), 470–475.

Di Loreto, C., Ranchelli, A., Lucidi, P., Murdolo, G., Parlanti, N., De Cicco, A., Tsarpela, O., Annino, G., Bosco, C., Santeusanio, F., Bolli, G.B., De Feo, P., 2004. Effects of whole-body vibration exercise on the endocrine system of healthy men. J. Endocrinol. Invest. 27 (4), 323–327.

Dickerson, D., Sander, E.A., Nauman, E.A., 2008. Modeling the mechanical consequences of vibratory loading in the vertebral body: microscale effects. Biomech. Model. Mechanobiol. 7 (3), 191–202.

Ebersbach, G., Daniela, E., Kaufhold, O., Wissel, J., 2008. Whole body vibration versus conventional physiotherapy to improve balance and gait in Parkinson's disease. Arch. Phys. Med. Rehabil. 89, 399–403.

Erskine, J., Smillie, I., Leiper, J., Ball, D., Cardinale, M., 2007. Neuromuscular and hormonal responses to a single session of whole body vibration exercise in healthy young men. Clin. Physiol. Funct. Imaging 27 (4), 242–248.

Flieger, J., Karachalios, T., Khaldi, L., Raptou, P., Lyritis, G., 1998. Mechanical stimulation in the form of vibration prevents postmenopausal bone loss in ovariectomized rats. Calc. Tissue Int. 63 (6), 510–514.

Floyd, W., Broderson, A.B., Goodno, J.F., 1973. Effect of whole-body vibration on peripheral nerve conduction time in the rhesus monkey. Aerosp. Med. 44 (3), 281–285.

Garatachea, N., Jiménez, A., Bresciani, G., Mariño, N.A., González-Gallego, J., de Paz, J.A., 2007. The effects of movement velocity during squatting on energy expenditure and substrate utilization in whole-body vibration. J. Strength Cond. Res. 21 (2), 594–598.

Garman, R., Gaudette, G., Donahue, L.R., Rubin, C., Judex, S., 2007. Low-level accelerations applied in the absence of weight bearing can enhance trabecular bone formation. J. Orthop. Res. 25 (6), 732–740.

Gilsanz, V., Wren, T.A.L., Sanchez, M., Dorey, F., Judex, S., Rubin, C., 2006. Low-level, high-frequency mechanical signals enhance musculoskeletal development of young women with low BMD. J. Bone Miner. Res. 21 (9), 1464–1474.

Govindaraju, S., Curry, B.D., Bain, J.L., Riley, D.A., 2006. Comparison of continuous and intermittent vibration effects on rat-tail artery and nerve. Muscle Nerve 34 (2), 197–204.

Guilak, F., Fermor, B., Keefe, F.J., Kraus, V.B., Olson, S.A., Pisetsky, D.S., Setton, L.A., Weinberg, J.B., 2004. The role of biomechanics and inflammation in cartilage injury and repair. Clin. Orthop. Relat. Res. 423, 17–26.

Gusi, N., Raimundo, A., Leal, A., 2006. Low-frequency vibratory exercise reduces the risk of bone fracture more than walking: a randomized controlled trial. BMC Musculoskelet. Disord. 7, 92.

Hausdorff, J., Rios, D.A., Edelberg, H.K., 2001. Gait variability and fall risk in community-living older adults: a 1-year prospective study. Arch. Phys. Med. Rehabil. 82 (8), 1050–1056.

Iwamoto, J., Takeda, T., Sato, Y., Uzawa, M., 2005. Effect of whole-body vibration exercise on lumbar bone mineral density, bone turnover, and chronic back pain in post-menopausal osteoporotic women treated with alendronate. Aging Clin. Exp. Res. 17 (2), 157–163.

Jöbges, M., Heuschkel, G., Pretzel, C., Illhardt, C., Renner, C., Hummelsheim, H., 2004. Repetitive training of compensatory steps: a therapeutic approach for postural instability in Parkinson's disease. J. Neurol. Neurosurg. Psychiatry 75 (12), 1682–1687.

Jones, C., Wehrli, F., Magland, J.F., Rubin, C.T., Nihtianova, S.A., Leonard, M.B., 2007. Structural implications of low-magnitude mechanical stimulation in a pilot study of patients with renal osteodystrophy evaluated with the MRI-based virtual bone biopsy. J. Bone Miner. Res. S493.

Judex, S., Donahue, L.R., Rubin, C., 2002. Genetic predisposition to low bone mass is paralleled by an enhanced sensitivity to signals anabolic to the skeleton. FASEB J. 16 (10), 1280–1282.

Judex, S., Lei, X., Han, D., Rubin, C., 2007. Low-magnitude mechanical signals that stimulate bone formation in the ovariectomized rat are dependent on the applied frequency but not on the strain magnitude. J. Biomech. 40 (6), 1333–1339.

Juntunen, J., Taskinen, H., 1987. Pathogenic and clinical aspects of polyneuropathies, with reference to the hand-arm vibration syndrome. Scand. J. Work. Environ. Health 13 (4), 363–366.

Kawanabe, K., Kawashima, A., Sashimoto, I., Takeda, T., Sato, Y., Iwamoto, J., 2007. Effect of whole-body vibration exercise and muscle strengthening, balance, and walking exercises on walking ability in the elderly. Keio J. Med. 56 (1), 28–33.

Kerschan-Schindl, K., Grampp, S., Henk, C., Resch, H., Preisinger, E., Fialka-Moser, V., Imhof, H., 2001. Whole-body vibration exercise leads to alterations in muscle blood volume. Clin. Physiol. 21 (3), 377–382.

Kiiski, J., Heinonen, A., Järvinen, T., Kannus, P., Sievänen, H., 2008. Transmission of vertical whole body vibration to the human body. J. Bone Miner. Res. (E-pub ahead of print).
Krajnak, K., Dong, R.G., Flavahan, S., Welcome, D., Flavahan, N.A., 2006. Acute vibration increases α2C-adrenergic smooth muscle constriction and alters thermosensitivity of cutaneous arteries. J. Appl. Physiol. 100 (4), 1230–1237.
Kvorning, T., Bagger, M., Caserotti, P., Madsen, K., 2006. Effects of vibration and resistance training on neuromuscular and hormonal measures. Eur. J. Appl. Physiol. 96 (5), 615–625.
Lawrence, R., Helmick, C.G., Arnett, F.C., Deyo, R.A., Felson, D.T., Giannini, E.H., Heyse, S.P., Hirsch, R., Hochberg, M.C., Hunder, G.G., Liang, M.H., Pillemer, S.R., Steen, V.D., Wolfe, F., 1998. Estimates of the prevalence of arthritis and selected musculoskeletal disorders in the United States. Arthritis Rheum. 41 (5), 778–799.
Liedtke, A., Schmid, P.G., 1969. Effect of vibration on total vascular resistance in the forelimb of the dog. J. Appl. Physiol. 26 (1), 95–100.
Liu, J., Sekiya, I., Asai, K., Tada, T., Kato, T., Matsui, N., 2001. Biosynthetic response of cultured articular chondrocytes to mechanical vibration. Res. Exp. Med. 200 (3), 183–193.
Loeser, R., 2006. Molecular mechanisms of cartilage destruction: mechanics, inflammatory mediators, and aging collide. Arthritis Rheum. 54 (5), 1357–1360.
Loeser, R.J., 2004. Aging cartilage and osteoarthritis—What's the link? Sci. Aging Knowledge Environ. 29, pe31.
Lohman, E.B., Petrofsky, J.S., Maloney-Hinds, C., Betts-Schwab, H., Thorpe, D., 2007. The effect of whole body vibration on lower extremity skin blood flow in normal subjects. Med. Sci. Monit. 13 (2), CR71–CR76.
Maloney-Hinds, C., Petrofsky, J.S., Zimmerman, G., 2008. The effect of 30 Hz vs. 50 Hz passive vibration and duration of vibration on skin blood flow in the arm. Med. Sci. Monit. 14 (3), CR112–CR116.
Manelli, F., Giustina, A., 2000. Glucocorticoid-induced osteoporosis. Trends Endocrinol. Metab. 11 (3), 79–85.
Martin, J., Buckwalter, J.A., 2002. Aging, articular cartilage chondrocyte senescence and osteoarthritis. Biogerontology 3 (5), 257–264.
Monteleone, G., De Lorenzo, A., Sgroi, M., De Angelis, S., Di Renzo, L., 2007. Contraindications for whole body vibration training: a case of nephrolitiasis. J. Sports Med. Phys. Fitness 47 (4), 443–445.
Murfee, W., Hammett, L.A., Evans, C., Xie, L., Squire, M., Rubin, C., Judex, S., Skalak, T.C., 2005. High-frequency, low-magnitude vibrations suppress the number of blood vessels per muscle fiber in mouse soleus muscle. J. Appl. Physiol. 98 (6), 2376–2380.
Nelson, C., Brereton, P.F., 2005. The European vibration directive. Ind. Health 43 (3), 472–479.
Norlund, M., Thorsstensson, A., 2007. Strength training effects of whole-body vibration? Scan. J. Med. Sci. Sports 17 (1), 12–17.
Novak, P., Novak, V., 2006. Effect of step-synchronized vibration stimulation of soles on gait in Parkinson's disease: a pilot study. J. Neuroeng. Rehabil. 4 (3), 9.
Oxlund, B., Ortoft, G., Andreassen, T.T., Oxlund, H., 2003. Low-intensity, high-frequency vibration appears to prevent the decrease in strength of the femur and tibia associated with ovariectomy of adult rats. Bone 32 (1), 69–77.
Ozcivici, E., Garman, R., Judex, S., 2007. High-frequency oscillatory motions enhance the simulated mechanical properties of non-weight bearing trabecular bone. J. Biomech. 40 (15), 3404–3411.
Rees, S.S., Murphy, A.J., Watsford, M.L., 2008. Effects of whole-body vibration exercise on lower-extremity muscle strength and power in an older population: a randomized clinical trial. Phys. Ther. 88 (4), 462–470.
Roelants, M., Delecluse, C., Goris, M., Verschueren, S., 2004a. Effects of 24 weeks of whole body vibration training on body composition and muscle strength in untrained females. Int. J. Sports Med. 25 (1), 1–5.
Roelants, M., Delecluse, C., Verschueren, S.M., 2004b. Whole-body-vibration training increases knee-extension strength and speed of movement in older women. J. Am. Geriatr. Soc. 52 (6), 901–908.
Rubin, C., Bain, S.D., McLeod, K.J., 1992. Suppression of the osteogenic response in the aging skeleton. Calcif. Tissue Int. 50 (4), 306–313.
Rubin, C.T., Capilla, E., Luu, Y.K., Busa, B., Crawford, H., Nolan, D.J., Mittal, V., Rosen, C.J., Pessin, J.E., Judex, S., 2007. Adipogenesis is inhibited by brief, daily exposure to high-frequency, extremely low-magnitude mechanical signals. Proc. Natl. Acad. Sci. U.S.A. 104 (45), 17879–17884.
Rubin, C., Pope, M., Fritton, J.C., Magnusson, M., Hansson, T., McLeod, K., 2003. Transmissibility of 15-Hertz to 35-Hertz vibrations to the human hip and lumbar spine: determining the physiologic feasibility of delivering low-level anabolic mechanical stimuli to skeletal regions at greatest risk of fracture because of osteoporosis. Spine 28 (23), 2621–2627.
Rubin, C., Recker, R., Cullen, D., Ryaby, J., McCabe, J., McLeod, K., 2004. Prevention of postmenopausal bone loss by a low-magnitude, high-frequency mechanical stimuli: a clinical trial assessing compliance, efficacy, and safety. J. Bone Miner. Res. 19 (3), 343–351.
Rubin, C., Turner, A.S., Bain, S., Mallinckrodt, C., McLeod, K., 2001a. Anabolism: low mechanical signals strengthen long bones. Nature 412 (6847), 603–604.
Rubin, C., Xu, G., Judex, S., 2001b. The anabolic activity of bone tissue, suppressed by disuse, is normalized by brief exposure to extremely low-magnitude mechanical stimuli. FASEB J. 15 (12), 2225–2229.
Rubinacci, A., Marenzana, M., Cavani, F., Colasante, F., Villa, I., Willnecker, J., Moro, G.L., Spreafico, L.P., Ferretti, M., Guidobono, F., Marotti, G., 2008. Ovariectomy sensitizes rat cortical bone to whole-body vibration. Calcif. Tissue Int. 82 (4), 316–326.
Schuhfried, O., Mittermaier, C., Jovanovic, T., Pieber, K., Paternostro-Sluga, T., 2005. Effects of whole-body vibration in patients with multiple sclerosis: a pilot study. Clin. Rehabil. 19 (8), 834–842.
Semler, O., Fricke, O., Vezyroglou, K., Stark, C., Schoenau, E., 2007. Preliminary results on the mobility after whole body vibration in immobilized children and adolescents. J. Musculoskelet. Neuronal. Interact. 7 (1), 77–81.
Setton, L., Chen, J., 2004. Cell mechanics and mechanobiology in the intervertebral disc. Spine 29 (23), 2710–2723.
Sherlock, M., Toogood, A.A., 2007. Aging and the growth hormone/insulin like growth factor-1 axis. Pituitary 10 (2), 189–203.
Stewart, J., Karman, C., Montgomery, L.D., McLeod, K.J., 2005. Plantar vibration improves leg fluid flow in perimenopausal women. Am. J. Physiol. Regul. Integr. Comp. Physiol. 288 (3), R623–R629.
Stoyneva, Z., Lyapina, M., Tzvetkov, D., Vodenicharov, E., 2003. Current pathophysiological views on vibration-induced Raynaud's phenomenon. Cardiovasc. Res. 57 (3), 615–624.
Takeuchi, R., Saito, T., Ishikawa, H., Takigami, H., Dezawa, M., Ide, C., Itokazu, Y., Ikeda, M., Shiraishi, T., Morishita, S., 2006. Effects of vibration and hyaluronic acid on activation of three-dimensional cultured chondrocytes. Arthritis Rheum. 54 (6), 1897–1905.
Turbanski, S., Haas, C.T., Schmidtbleicher, D., Friedrich, A., Duisberg, P., 2005. Effects of random whole-body vibration on postural control in Parkinson's disease. Res. Sports Med. 13 (3), 243–256.
Ueland, T., 2005. GH/IGF-1 and bone resorption in vivo and in vitro. Eur. J. Endocrinol. 152 (3), 327–332.
Verschueren, S., Roelants, M., Delecluse, C., Swinnen, S., Vanderschueren, D., Boonen, S., 2004. Effect of 6-month whole body vibration training on hip density, muscle strength, and postural control in postmenopausal women: a randomized controlled pilot study. J. Bone Miner. Res. 19 (3), 352–359.
Ward, K., Alsop, C., Caulton, J., Rubin, C., Adams, J., Mughal, Z., 2004. Low magnitude mechanical loading is osteogenic in children with disabling conditions. J. Bone Miner. Res. 19 (3), 360–369.
Wood, B., Bilclough, J.A., Bowron, A., Walker, R.W., 2002. Incidence and prediction of falls in Parkinson's disease: a prospective multidisciplinary study. J. Neurol. Neurosurg. Psychiatry 72 (6), 721–725.
Xie, L., Jacobson, J.M., Choi, E.S., Busa, B., Donahue, L.R., Miller, L.M., Rubin, C.T., Judex, S., 2006. Low-level mechanical vibrations can influence bone resorption and bone formation in the growing skeleton. Bone 39 (5), 1059–1066.
Xie, L., Rubin, C., Judex, S., 2008. Enhancement of the adolescent murine musculoskeletal system using low-level mechanical vibrations. J. Appl. Physiol. 104 (4), 1056–1062.
Yamazaki, S., Banes, A.J., Weinhold, P.S., Tsuzaki, M., Kawakami, M., Minchew, J.T., 2002. Vibratory loading decreases extracellular matrix and matrix metalloproteinase gene expression in rabbit annulus cells. Spine J. 2 (6), 415–420.