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

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Abstract

Study Design. Experiments were undertaken to determine the degree to which high-frequency (15-35 Hz) ground-based, whole-body vibration are transmitted to the proximal femur and lumbar vertebrae of the standing human.

Objectives. To establish if extremely low-level (<1 g, where 1 g = earth's gravitational field, or 9.8 ms^{-2}) mechanical stimuli can be efficiently delivered to the axial skeleton of a human.

Summary of Background Data. Vibration is most often considered an etiologic factor in low back pain as well as several other musculoskeletal and neurovestibular complications, but recent *in vivo* experiments in animals indicates that extremely low-level mechanical signals delivered to bone in the frequency range of 15 to 60 Hz can be strongly anabolic. If these mechanical signals can be effectively and noninvasively transmitted in the standing human to reach those sites of the skeleton at greatest risk of osteoporosis, such as the hip and lumbar spine, then vibration could be used as a unique, nonpharmacologic intervention to prevent or reverse bone loss.

Materials and Methods. Under sterile conditions and local anesthesia, transcutaneous pins were placed in the spinous process of L4 and the greater trochanter of the femur of six volunteers. Each subject stood on an oscillating platform and data were collected from accelerometers fixed to the pins while a vibration platform provided sinusoidal loading at discrete frequencies from 15 to 35 Hz, with accelerations ranging up to 1 $g_{peak-peak.}$

Results. With the subjects standing erect, transmissibility at the hip exceeded 100% for loading frequencies less than 20 Hz, indicating a resonance. However, at frequencies more than 25 Hz, transmissibility decreased to approximately 80% at the hip and spine. In relaxed stance, transmissibility decreased to 60%. With 20-degree knee flexion, transmissibility was reduced even further to approximately 30%. A phase-lag reached as high as 70 degrees in the hip and spine signals.

Conclusions. These data indicate that extremely low-level, high-frequency mechanical accelerations are readily transmitted into the lower appendicular and axial skeleton of the standing individual. Considering the anabolic potential of exceedingly low-level mechanical signals in this frequency range, this study represents a key step in the development of a biomechanically based treatment for osteoporosis.

Osteoporosis is one of the most common complications of aging. 1 After the age of 50, bone mineral density (BMD) decreases at a rate as high as 3% per year in the postmenopausal female. 2-4 Among women age 80 years and older, 70% have bone density measurements less than 2.5 standard deviations of young normal values. 5 Certainly, in devising intervention strategies for this disease, slowing the loss of bone in the recent postmenopausal population, as well as reversing bone loss in the osteoporotic person, will have a significant and beneficial impact on reduction of fractures and associated morbidity and mortality.

While the bone tissue in osteoporotic individuals is normal and capable of repair, the overall loss of tissue ultimately reduces the effective strength of the skeleton. While manifestations of the disease (fractures) are focal in nature (hip and spine), the most accepted treatment protocols are administered systemically. 6 Further, the majority of pharmaceutical interventions approved by the FDA for osteoporosis work by inhibiting bone resorption. Increases in bone mass-related to antiresorptive therapy are restricted to the first 2 to 3 years of therapy, rarely normalize bone density in the most severely affected individuals, and may ultimately compromise structural properties of bone. 7

Therapies that increase bone formation are thus highly desirable. One readily recognized anabolic factor, is mechanical stimuli and indicates a nonpharmacologic strategy for enhancing bone mass and morphology. The mechanosensitivity of bone tissue is recognized within the orthopedic community as Wolff's Law, 8 in which the premise of form follows function is evidenced by many reports of a beneficial effect of exercise. 9-12 While there is great debate as to which specific aspects of exercise are responsible for increases in bone mass, recent evidence indicates that low-amplitude, high-frequency mechanical stimulation may represent a strongly osteogenic signal. 13 Thus, if such low-level mechanical signals can be effectively delivered to the axial and appendicular skeleton, perhaps through whole-body vibration, a unique biomechanical prophylaxis for osteoporosis may be possible. 14

Vibration, particularly in the frequency domain of 5 to 15 Hz in which resonance of the spine can occur, 15 is considered a key etiologic factor in low back pain, 16,17 as well as a causal factor in circulatory disorders such as Raynaud's syndrome. 18 Thus, the majority of research has focused on attenuating the transmissibility of whole-body vibration to the skeleton, with the widely held presumption that high-frequency vibrations are pathogenic to the musculoskeletal system. 19-21 In cases in which vibration is inevitable, 22 exposure limits have been recommended by agencies focused on occupational hazards, such as the National Institute of Occupational Safety and Health, (NIOSH), Centers for Disease Control (CDC), and the International Organization for Standardization (ISO). 20 Rarely, however, do these empirical studies investigate vibration more than 15 Hz, primarily because the energy in this higher-frequency domain is exceedingly small. 21,23

In contrast to the conclusion that vibration should only be considered deleterious to the musculoskeletal system, and thus avoided, recent animal studies 14,24 indicates that brief (<20 min) daily durations of extremely low-level (<0.5 g), high-frequency (15-90 Hz) vibration can be strongly anabolic to bone tissue. In essence, these studies suggest that the pathogenic consequences of long-duration, high-intensity vibrations 25 should not necessarily preclude the potential of extremely low-level mechanical stimuli as a treatment for musculoskeletal disease. With the osteogenic potential of mechanical stimuli long recognized in the orthopedic community, 26 and the growing concern for the consequences of long-term pharmaceutical treatment for osteoporosis, 27 it becomes critical to determine if these low-level mechanical signals can effectively reach the skeletal sites of greatest concern, and thus lay the groundwork for a unique noninvasive treatment for bone disease. The specific objective of this study is to determine the degree of transmissibility of high-frequency, low-magnitude mechanical signals, delivered through the plantar surface of the foot to the hip and spine, which are the regions of greatest concern in osteoporosis.