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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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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 $g_{peak\text{-}peak}$.

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. [Key words: spine, hip, osteoporosis, transmissibility, vibration, biomechanics, anabolic]
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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.

Table 1. Subject Gender, Height, and Mass, as Well as Pin Resonance, Measured for the Pins at the Lumbar Vertebrae and Trochanter.

Subject	Sex	Height (cm)	Mass (kg)	Pin Resonance L4	Pin Resonance Hip
1	M	174	72	50	35
2	F	170	56	113	75
3	F	171	65	89	73
4	F	170	52	95	75
5	F	162	63	68	*
6	F	168	66	92	60

Frequency response characteristics up to one-half the pin resonance were included in the transmissibility calculations. Because of subject concern, the trochanter pin was not placed in subject 5.

■ Materials and Methods

Subjects. Five females and one male volunteered for the study. Each participant was in good health, with no history of low back pain. They were aged between 23 and 33 years, ranged in mass from 52 to 72 kg, and were between 162 and 174 cm in height (Table 1). All subjects gave full informed consent to the protocols and the surgical procedure that had been approved by Göteborg University, in full accord with the Helsinki Accord for Human Experimentation.

Pin Implantation. Pin placement by the orthopedic surgeon (TH) was performed under aseptic conditions with the subject in the operating theater. The subjects lay on their side while one 2.3-mm K-wire was placed approximately 10 mm into the spinous process of the L4 vertebra (Fig 1A), and a second K-wire was placed in the greater trochanter of the left hip.

Under local anesthesia, each pin was first drilled and then tapped into place to ascertain rigid bone fixation. A fluoroscopic image was used to confirm the pin location, depth, and orientation. The pin insertion time was recorded (approximately 30 min), and the total experimental time was limited to 3 hours. Great care was taken to place the pins such that, when standing, the pins would be orthogonal to the spine and hip, and parallel with the ground. The position of each K-wire was confirmed by a goniometer to establish the horizontal and vertical angles in the sagittal plane in each of the test positions. Because the hip pin penetrates thick fascia, extreme care was taken to avoid hip flexion while moving from the lying to standing position. Trochanter pin placement was not considered in one subject (subject 5).

Instrumentation. Accelerometers (Endevco 7265A-HS) were mounted on aluminum fixtures and attached to the K-wires (Figure 1B). Hip assemblies had x-axis and z-axis accelerometers while spine assemblies had y-axis and z-axis accelerometers. The z-axis accelerometer attached to the spine was adjusted such that it was parallel to spinal segment L4, and the y-axis orthogonal to the spine. The hip accelerometer was aligned vertically.

The input acceleration of the vibrating platform was measured with accelerometers mounted at the center and back of the top platen. Static calibration of the accelerometers was achieved by placing the transducer on a horizontal surface, corresponding to a value of 1.0 g. The transducer was then rotated by 180 degrees to give the value of −1.0 g. The reso-

Figure 1. Pin placement in L4 (left) and the greater trochanter was performed under local anesthetic with the goal of placing the pins such that they were orthogonal to the bone under study. Accelerometers were then attached (right), and the pin "plucked" to determine resonance of the pin-bone system (L4 shown).

nance properties of the bone/pin/accelerometer system was determined after surgery, with the subject standing with erect posture and accelerometers fixed to the pins, and the pin being "plucked" to initiate vibration (Figure 1B) and thus verify rigid fixation.[28] Because of limitations of frequency analysis, only those pin-bone-accelerometer "systems" with a resonance more than double the ground-based vibration frequencies of interest could be used in the analysis.

Whole-Body Vibration. A unique vibration platform developed for use in a clinical setting was used to impose the whole-body vibration.[29] Each subject was instructed to stand in the center of the platform in each of three postures: erect with knees extended and locked, relaxed with knees straight, and knees flexed at 20 degrees (Figure 2). Angle of the spine pin to the horizontal was measured, posture adjusted to keep it within 5 degrees of horizontal, after which data were collected. The hand-held goniometer was susceptible to errors of approximately 10 degrees, which could establish an error of approximately 5%.

The platform was driven to provide a force of 36 N_{p-p} at all loading frequencies. Vibration data were recorded at 2-Hz intervals beginning at 15 Hz and ending at 35 Hz. In five subjects, the tests at the relaxed and knee straight posture were also repeated at half the force (18 N_{p-p}). All subjects were encouraged to report any unusual symptoms (*e.g.*, discomfort, queasiness) and the specific frequencies noted.

Signal Processing. Accelerometer signals were bridge amplified and filtered (Endevco), using the same gain in each test, because variations in signal level were small. An initial test session determined the maximum signal level. The signals from the multipurpose amplifier rack were fed to a Victor PC equipped with a Data Translation DT 2801 A/D-board. The A/D-board was configured as single ended with a range of ± 10 V. Sampling was accomplished using the software package ASYSTANT+ in the acquired/high-speed recorder mode. Data were sampled at 500 Hz for an acquisition time of 4 seconds. The signals were also recorded and stored with a DATA REC-E8 digital tape recorder.

The transmissibility transfer function (H) was calculated as the ratio of the vector sum of the two accelerometer outputs mounted on each pin to the acceleration recorded at the plate surface. A transmissibility of 100% would indicate the total energy of the ground-based acceleration was realized at the hip and/or vertebrae. For the spine data, the transmissibility was converted from local to global coordinates by correcting for the measured pin angle as: $H_v = H_z / \sin(90° - A)$

in which A is the angle in degrees of the spine pin with respect to horizontal. However, in all cases, pin angle did not vary from the horizontal by more than ± 10 degrees, and thus these corrections were exceedingly small (and would underestimate transmissibility). Transmissibility data were reported as a function of frequency, amplitude, and posture for both the spine and the hip.

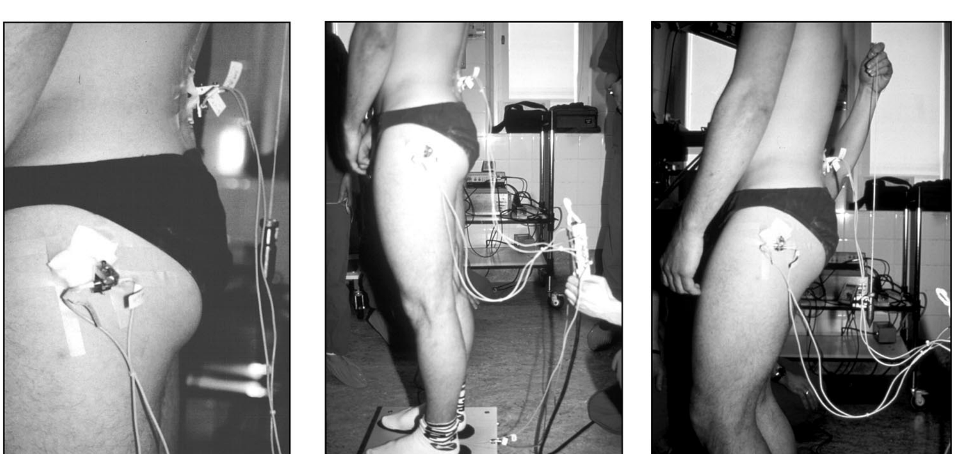

Figure 2. While standing erect on the oscillating plate (center), accelerometers attached to pins inserted into the spine and trochanter pins (left) were used to measure the transmissibility of ground-based vibrations. To determine the role of posture on transmissibility, data were also collected during relaxed standing and with 20 degrees of knee flexion (right).

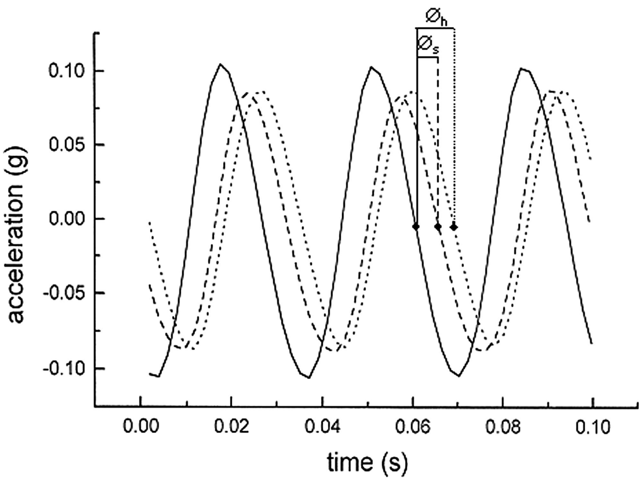

Figure 3. While subject 4 was in a relaxed standing position, 18 $N_{p\text{-}p}$ used to vibrate the plate at 30 Hz caused accelerations to approach 0.2 $g_{p\text{-}p}$, as measured at the surface of the plate (solid line), at L4 (dashed line), and at the trochanter (dotted line). Even at this exceedingly low force, transmissibility at both the hip and spine was approximately 85% of the ground-based vibration. A lagging phase-shift was observed at both the spine ($\varnothing_s$) and hip ($\varnothing_h$), indicating a compliant (deforming) structural system.

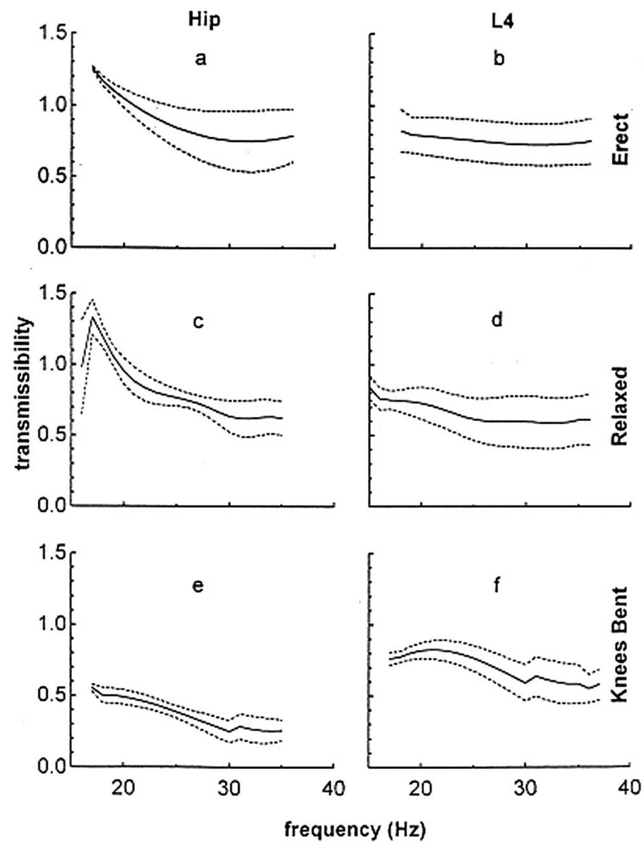

Figure 4. Transmissibility (±SD) of low-level, high-frequency, ground-based vibrations to the hip (left) and spine (right) of five volunteers. Measurements were made while standing erect (top), relaxed (middle), and with knees bent (bottom). Other than a resonance observed during relaxed standing in the hip at frequencies less than 20 Hz (**C**), there is little evidence that the transmissibility approaches 100%. With knees bent, the transmissibility decreases off to much less than 50% in the hip (**E**), yet remains at approximately 60% in the spine (**F**). A transmissibility of 1 indicates that acceleration measured at the hip or spine is equivalent to that at the oscillating platform.

■ Results

Of the six subjects in which pins were implanted, data from the first volunteer were excluded from the analysis because the pin-resonance of the hip (35 Hz) and spine (50 Hz) system, as indicated by the plucking calibration, dictated the pin-accelerometer-bone assemblies to be too low to permit analysis in the range of interest (Table 1). It should be noted that while this subject swung from a recumbent to an upright position, the pin actually bent, indicating that shearing by the superficial fascia caused the pin to loosen in the trochanter. In all follow-up subjects, the legs were supported as the subject moved from the recumbent to the upright positions. Because of concerns expressed by subject 5, the trochanter pin was not inserted. The pin-resonance frequencies for the remaining five subjects ranged from 60 Hz to 113 Hz.

Two subjects encountered ill effects at specific frequencies of whole-body vibration: a feeling of faintness at 27 Hz in one case and a seasick-like reaction at approximately 17 Hz in the other. These effects occurred at accelerations that well exceeded $0.5g_{p\text{-}p}$, and the symptoms quickly passed after each individual laid down.

Because a constant peak force was used to drive the vibrating platform, changes in driving frequency resulted in changes in peak platform accelerations because of the dynamic response of the body.[29] Accelerations of the platform, femur, and spinous process of L4 were found to increase exponentially with frequency in most subjects, for all postures, approaching $1g_{p\text{-}p}$ at the highest frequencies tested. An attenuation of the ground based-vibration was evident at the hip and spine at most frequencies tested, and this attenuation was consistently associated with a lagging phase shift (Figure 3). At the lumbar spine, for the erect stance posture, the phase lag increased monotonically from 15 through 35 Hz, from less than 40 degrees to greater than 70 degrees. X- and Y-axis recordings were much less than 10% of the Z-axis accelerations, and vector sums of the two orthogonal components were calculated to obtain the maximum accelerations for the transmissibility calculations.

Transmissibilities for the ground acceleration to the femur and to the lower lumbar spine were dissimilar and varied with frequency and posture. While standing erect, there was evidence of a resonance in the hip data at the lowest frequencies, because transmissibility exceeded 100% in this postural position (Figure 4A). However, at the lumbar spine, transmissibility remained relatively constant during erect posture (Figure 4B), at approximately 75% through 35 Hz.

In relaxed stance, transmissibility at the hip displayed a distinct resonance of almost 17 Hz (Figure 4C), resulting in a maximum transmissibility of 130%. This transmissibility decayed rapidly as a function of frequency,

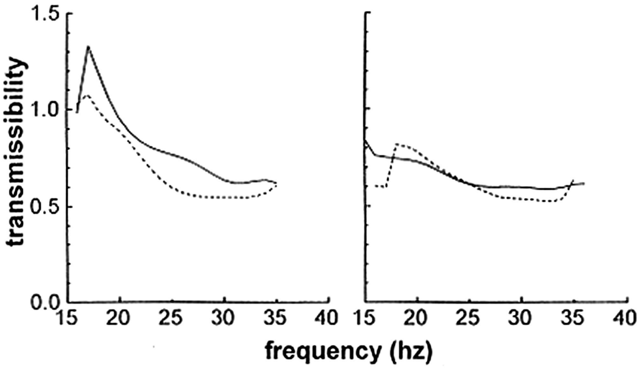

Figure 5. During relaxed standing, comparison of the transmissibility profile at the trochanter (left) and L4 (right), relative to vibration induced at the plantar surface, for two driving amplitudes, 36 $N_{p\text{-}p}$ (solid), and one-half the driving force, or 18 $N_{p\text{-}p}$ (dashed). Transmissibility functions were essentially identical for these two conditions, particularly at frequencies well-removed from the body's resonance, indicating that there is little attenuation, even at extremely low-level accelerations, to the hip and spine.

decreasing to a level close to 60% at 35 Hz. There was also a plateau in the response characteristics in the 25 to 30 Hz range, suggesting the existence of a damped resonance in this range. Transmissibility to the L4 segment closely followed the hip data, with a decrease from approximately 80% at 15 Hz to 60% at 25 Hz, after which the response was essentially flat (Figure 4 days). There was no indication that the spine was subject to the 25-Hz resonant behavior observed in the hip data.

The lowest level of transmissibility occurred during bent knee posture. At the hip, transmissibility never exceeded 50%, even at frequencies as low as 15 Hz (Figure 4E), and continued to decrease through 35 Hz, at which transmissibility was less than 30%. Unlike the cases of erect and relaxed posture, transmissibility at the spine, in the bent knee posture, exceeded that in the hip at all frequencies evaluated. A slight peak in the response, in which a maximum transmissibility value of 80% was achieved, occurred near 21 Hz. The response then decayed with frequency but stayed above 50%, to a frequency of 35 Hz. (Figure 4F).

For all postures, transmissibility to the hip was found to be essentially linear with amplitude. Comparison of the transfer functions in the relaxed posture position for full (36 $N_{p\text{-}p}$) and half (18 $N_{p\text{-}p}$) drive force demonstrated largely overlapping curves (Figure 5). The exceptions to this linear response occur in the hip data at the two apparent resonances, at approximately 17 Hz and 25 Hz. Transmissibility was preserved in the spine, with the degree of attenuation at each loading level overlapping everywhere except at the two lowest frequencies evaluated (15 & 17 Hz).

■ Discussion

High-frequency vibration is most often considered deleterious to the musculoskeletal system. Long-term exposure to whole-body vibration has been determined to be a central etiologic factor in low back pain,[17] neurovestibular disorders,[30] and Raynaud's syndrome,[18] and thus industries such as transportation and construction,[31] as well as the military,[32] are working toward minimizing occupational exposure to potentially noxious mechanical stimuli.

Considering the potential pathology these signals may cause to physiologic systems, it should not be surprising that far lower doses of mechanical signals may actually be biologically beneficial to tissues such as bone or muscle, perhaps by enhancing tissue perfusion or amplifying regulatory signals.[33] Indeed, recent animal work has shown that high-frequency (15–90 Hz), extremely low-magnitude (<0.4 g) stimuli, inducing strains far less than 10 microstrain, are strongly anabolic to trabecular bone,[14] increasing bone mineral density, trabecular width and number in the weight-bearing skeleton,[24] and that these signals can effectively inhibit disuse osteopenia.[34] Importantly, these higher frequency mechanical signals, although small, are physiologic in nature, as they arise from the contractions of adjacent musculature,[35] and thus signify a persistent low-level, dynamic mechanical signal to the bone tissue.[36] Considering the anabolic nature of low-level vibration, determining if such signals can be delivered *via* whole body vibration to the appendicular and axial skeleton would represent a noninvasive means of treating musculoskeletal disorders, rather than necessarily causing them.

If whole body vibration in the 10- to 50-Hz range is to be applied as a clinical modality, it must be determined whether muscle action, modification by fluid in the joint spaces, and any soft tissue covering of the vertebral bodies effectively dampens any significant axial acceleration, as well as determining that any potential resonances in the system are avoided, to minimize the chance of unintended amplification. In fact, *ex vivo* and modeling studies of the transmissibility and impedance response of the spine have shown that a distinct single motion segment resonance may arise at approximately 25 Hz.[15,37] Assuming the whole spine resonance would scale in inverse proportion to its length, a one-segment resonance extrapolates to a whole spine resonance in the range of 4 to 8 Hz, a response consistently observed in human studies.[21] However, as few transmissibility studies have investigated frequencies more than 20 Hz, the magnitude of intrinsic one-segment motion when driven near resonance was previously untested.[38]

In the study reported here, transmissibility of ground-based vibrations at the hip is decidedly different than at the spine, at least at the lowest frequencies evaluated in this study. In both erect standing and relaxed posture, transmissibility in the hip exceeded 100% at frequencies less than 20 Hz. While whole-body resonances near 5 Hz are well-known,[15,39] the data presented here, particularly during relaxed standing, suggest a distinct resonance near 17 Hz in the hip. This resonance has not been previously reported, and it is interesting that the resonance does not arise at the spine. The frequency of this resonance, and the conditions under which it is observed, suggests an interaction with the postural control system, perhaps a coupling through muscle spindles into the reflex arc.[40] In relaxed standing, a minimal number of muscles are activated (typically only the soleus),[35] and so this condition presents a simple reflex arc which may be quite susceptible to external perturbations.[41] That high transmissibility is not measured at the spine indicates that this resonance reflects a rotational motion of the pelvis.

It is important to emphasize that this study was performed on healthy, young adults, and fails to identify, specifically, the transmissibility of low-level mechanical signals in an osteoporotic population. As described, slight changes in posture can have significant influence on the degree to which a plantar-based mechanical signal is actually delivered to the spine or hip, and thus it is likely that the signal would be attenuated with the inevitable changes in stance which occur with aging and osteoporosis.[42] However, it is also possible that, with less bone tissue per unit area, the actual physical signal that is realized by the bone cell population would actually be greater, as for a given load the stress and strain (and their byproducts) would increase.[43] Of course, these extremes were not addressed specifically here, but the possibility that the signal would be lesser—or greater—as dependent on posture and bone architecture is certainly very real.

Resonance caused by vibration must be considered as a possible source of undesirable side effects of using whole body vibration as part of a prevention strategy for osteoporosis. A large body of research has demonstrated a broad range of pathologic responses to high magnitude ($>1\ g_{rms}$) vibration,[23] and between 0.2 g_{rms} and 1 g_{rms}, there is some evidence of vibration contributing to back pain after extended exposure.[22] However, there is little or no evidence of any permanent effects of vibration exposure below 0.2 g_{rms}, corresponding to sinusoidal accelerations of 0.56 $g_{p\text{-}p}$. In fact, for short duration exposures (up to one-half hour), ISO 2631 establishes a level of $0.3g_{rms}$ (0.8 $g_{p\text{-}p}$) as the discomfort level for vibration in the 30-Hz range.[44] The acute discomfort appears to arise largely from induced alterations in visual perception and tracking. As early as 1938, Coermann[45] reported discontinuities in visual activity between 25 and 40 Hz for whole body vibration less than 1 g. In addition, he noted that at some acceleration levels, vibrations more than 20 Hz temporarily diminished patellar reflexes, a finding that has since been confirmed by Goldman,[46] Seidel,[30] and Roll *et al*.[47] Dupuis and Hartung[48] reported a physical resonance of the eyeball at 20 to 21 Hz, and, correspondingly, that visual perception time is affected during vibration exposure at 5 to 8 Hz, and again at approximately 25 Hz. It is entirely possible that the two subjects who experienced discomfort during the higher-amplitude (approaching 1 g) vibration were sensing such vestibular/ocular resonance, perhaps exacerbated by a local anesthetic (and the environment of an operating theater), but it should also be pointed out that in several preliminary trials with humans,[49–51] each at 0.3 g or less, no adverse effects were observed. Nevertheless, it is clear that vibration that approaches 1 g, even at these higher frequencies, should be studiously avoided considering the demonstrated risk to so many physiologic systems. Toward that end, a recent report on humans, using 30-Hz signals at 8.0 to 14.0 g, indicates no anabolic response in the skeleton, while at the same time exposing these individuals to perhaps toxic levels of mechanical signals.[52]

In conclusion, this study presents the first direct evidence of a high level of transmissibility of ground-based vibration to the hip and spine of the standing human in the frequency range of 15 to 35 Hz. Even at fractions of earth's gravitational field ($\ll 1g_{p\text{-}p}$), it appears that transmissibility from the ground to the hip and spine approaches 80% during erect and relaxed standing, but decreases significantly with bent knee posture. Further, these data indicate that whole body vibration at frequencies up to 35 Hz can be safely introduced into the appendicular skeleton without concern for coupling with the intrinsic resonances predicted to occur in spinal motion segments.[15] Because numerous animal studies have indicated that accelerations at these levels, for even brief daily exposures, are capable of initiating new bone formation[14] as well as inhibiting the bone loss of disuse,[34] inhibition or reversal of osteopenia in the clinic, through exposure to whole body vibration may be possible. Preliminary results in children with cerebral palsy,[49] girls with extremely low bone density,[50] and women who have recently undergone menopause[51] indicate that this unique biomechanical intervention may provide a noninvasive nonpharmacologic means of treating osteoporosis.[53]

Vibration, most typically considered noxious to the musculoskeletal system, may indeed provide useful biologic information to regulate bone mass and morphology. In retrospect, considering that many physiologic systems that perceive and respond to exogenous stimuli, such as sight, touch, and hearing, are most sensitive to frequency, and while large signals may cause damage, lower-level signals are central to survival.

■ Key Points

- High frequency (15–35 Hz), low-level mechanical signals are effectively transmitted to the hip and spine.
- The degree of transmissibility is dependent on stance with bent knees greatly attenuating the mechanical signals.
- Considering the anabolic potential of these low-level signals, and that they can be delivered to sites at greatest risk of fracture, this finding provides a key step in the development of a noninvasive, nonpharmacologic intervention for osteoporosis.

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