

Transmission of Vertical Whole Body Vibration to the Human Body

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ABSTRACT: According to experimental studies, low-amplitude high-frequency vibration is anabolic to bone tissue, whereas in clinical trials, the bone effects have varied. Given the potential of whole body vibration in bone training, this study aimed at exploring the transmission of vertical sinusoidal vibration to the human body over a wide range of applicable amplitudes (from 0.05 to 3 mm) and frequencies (from 10 to 90 Hz). Vibration-induced accelerations were assessed with skin-mounted triaxial accelerometers at the ankle, knee, hip, and lumbar spine in four males standing on a high-performance vibration platform. Peak vertical accelerations of the platform covered a range from 0.04 to 19 in units of G (Earth's gravitational constant). Substantial amplification of peak acceleration could occur between 10 and 40 Hz for the ankle, 10 and 25 Hz for the knee, 10 and 20 Hz for the hip, and at 10 Hz for the spine. Beyond these frequencies, the transmitted vibration power declined to 1/10th–1/1000th of the power delivered by the platform. Transmission of vibration to the body is a complicated phenomenon because of nonlinearities in the human musculoskeletal system. These results may assist in estimating how the transmission of vibration-induced accelerations to body segments is modified by amplitude and frequency and how well the sinusoidal waveform is maintained. Although the attenuation of vertical vibration at higher frequencies is fortunate from the aspect of safety, amplitudes >0.5 mm may result in greater peak accelerations than imposed at the platform and thus pose a potential hazard for the fragile musculoskeletal system.

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INTRODUCTION

EXPERIMENTAL STUDIES HAVE shown that low-amplitude high frequency vibration is anabolic to trabecular bone,^(1–4) and it can prevent ovariectomy-induced structural weakening of the rat femur.⁽⁵⁾ This kind of nonpharmacological intervention, with apparent osteogenicity and feasibility, was embraced as a novel means to prevent osteoporosis and related fragility fractures.^(6,7) Thereafter, several randomized clinical intervention trials using whole body vibration for bone training have been carried out.^(8–15)

Significant treatment effects of vibration on bone have been observed only in one half of the clinical studies,^(8,10,12,14) and the magnitude of effects has varied. Apparently, inconsistent results are at least partly attributable to vibration training protocols, which have differed markedly in terms of vibration amplitudes, frequencies, durations, type and repetition rate of vibration, target group, and the total duration of the intervention. However, according to the theoretical peak acceleration of the vibration, clinical vibration interventions can be divided either into sub-G studies^(8–10) (platform peak acceleration <1 G,

where G denotes Earth's gravitational constant, or 9.81 m/s² at sea level) or supra-G studies^(11–15) (platform acceleration >1 G, reaching 10 G or more).

Exposure to occupational whole body vibration, typically long term in nature, has been comprehensively evaluated,⁽¹⁶⁾ whereas the exposure to short-term whole body vibration used for bone training is not yet clear-cut. Only a few studies^(17–21) are relevant to bone training, which is typically performed in a standing position on a vibrating platform and at frequencies >10 Hz. However, none of these studies have systematically dealt with the whole range of applicable vibration amplitudes and frequencies.

This study was therefore carried out to explore the whole body vibration introduced to the body over a wide range of vibration amplitudes (from 0.05 to 3 mm) and frequencies (from 10 to 90 Hz); the very ranges of amplitudes and frequencies pertinent both to clinical studies and to commercial vibration devices. Because the vibration-induced accelerations can augment at frequencies <20 Hz because of body segment resonances,^(17–20,22) we also sought amplitudes and frequencies that together could substantially amplify the acceleration and create a potential hazard for fragile skeleton. This safety information is considered essential when whole body vibration training is used among elderly and osteoporotic persons.

The authors state that they have no conflicts of interest.

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TABLE 1. DESCRIPTIVE SUBJECT DATA

Subject	Age (yr)	Weight (kg, lbs)	Height (m, ft)
1	31	87, 192	1.81 5.94
2	24	69, 152	1.78 5.84
3	47	83, 183	1.81 5.94
4	43	100, 220	1.83 6.00

MATERIALS AND METHODS

Subjects

Four clinically healthy male volunteers, free from apparent contraindications to whole body vibration training,⁽²³⁾ participated in the study. Descriptive subject information is given in Table 1. Each subject gave an informed consent, and the study was approved by the Ethics Committee of Tampere University Hospital District. A physician (TJ) was attending the measurement sessions, and the subjects were asked to report immediately any unusual symptoms or discomfort and to stop the vibration with an emergency button, if necessary.

Vibration system

A massive (total mass ~2300 kg) high-performance (electrical power, 60 kW) servo-controlled electromagnetic vibrator (954 LS; Ling Dynamic Systems, Royston, UK), equipped with a rigid expander (used as the vertically vibrating platform) and handrails (for safety), was used (Fig. 1). The frequency and amplitude (the vibration amplitude denotes the peak displacement of the platform [in mm] from its middle position) of the vibrator were adjustable from 5 to 3000 Hz and from 0 to 19 mm, respectively. For sinusoidal vertical motion, the vibrator was capable of producing maximum 36 kN force and 2 m/s speed, and without additional load, the peak acceleration of the platform could be as high as 100 G; for a 40-kg load, it was ~50 G.

Obviously, the mechanical capacity of the used vibrator exceeded the feasible and safe range of vertical accelerations that may be applied in vibration training. The vibrator was regularly used for testing of high-tech instrumentation (e.g., for aeronautics), and its performance was under regular strict quality control. Because of the reasons above, the vibration system provided an ideal means to explore the transmission of vertical vibration to the body over the whole applicable range of frequencies and amplitudes, without being restrained by potentially limited mechanical capacity of commercial training devices.

A uniaxial accelerometer was firmly attached to the vibration platform to provide accurate data on its acceleration. This reference signal denoted the platform vibration signal and its frequency denoted the nominal frequency to which the measured acceleration signals from different body sites were compared.

Assessment of site-specific acceleration

Triaxial accelerometers were specifically made for this study of two light, orthogonally fixed biaxial accelerometers (ADXL210E; Analog Devices; dimensions, 5 × 5 × 2 mm;

mass ≤ 1 g). The accelerometer boxes containing the electronics (total mass, ~20 g; dimensions, 24 × 24 × 14 mm) were adhered to the ankle, knee, hip, and spine regions using double-sided contact tape (see the exact anatomic sites below). To further secure the attachment, the boxes and cables were tightly bound by elastic bandages.

The accelerometers were located on the skin above the left medial malleolus of the tibia (ankle), left tuberositas tibia (knee), left greater trochanter (hip), and processus spinosus of the third lumbar vertebra (spine), except for subject 3. For this subject, the spine accelerometer could not be firmly adhered to the lumbar region because of lumbar lordosis and prominent paraspinal muscles, but it was located at the processus spinosus of the ninth thoracic vertebra.

Vibration protocol

When subjected to vibration, the subjects were instructed to stand with normal erect position (knees slightly bent) on the platform (Fig. 1). The subjects wore no shoes and used similar cotton socks to avoid external between-subject variance in damping.

To cover the vertical vibration training protocols described in the literature,^(1-5,8-15) vibration amplitudes of 0.05, 0.5, 1, and 3 mm and frequencies from 10 to 90 Hz in 5-Hz increments were used (Table 2; Fig. 2). Each frequency level was sustained for 5 s, and thereafter the frequency was smoothly increased to the next level within some seconds. These procedures were programmed in the control system of the vibrator.

The subjects stood on the vibration platform no more than 30–60 s at a time, while the acceleration data of three to five consecutive frequency levels at a given vibration amplitude were recorded. To avoid fatigue of the subjects, these short measurement sessions were always intermitted by 3- to 4-min rest periods.

Data acquisition

Acceleration data were acquired through a 12-bit AD-converter (Model DI-420; DATAQ Instruments, Akron, OH, USA) onto a microcomputer for further analysis. Sampling frequency was 1000 Hz. The ±5-V output range of the accelerometer amplifier corresponded to accelerations from -10 to 10 G. The zero voltage corresponded to the situation when standing still (i.e., 1 G).

The *x,y,z*-directions of the accelerometers were calibrated against the accurate reference accelerometer over a range from no acceleration to 6.4 G. For the calibration, the accelerometers were attached to the vibrating platform using the double-sided contact tape, and the acceleration signals were collected during one vibration cycle at 1.0-mm amplitude and 40-Hz frequency. This procedure was repeated for each *x,y,z*-direction. The correlation between the actual platform acceleration and measured acceleration was always better than 0.95. The resultant of calibrated *x,y,z*-accelerations denoted the vibration signal for each accelerometer.

All the above-mentioned combinations of vibration amplitude and frequency could be successfully recorded, ex-



FIG. 1. Vibration system and the typical posture of the subject on the vibration platform.

cept the 0.05-mm amplitude and 10-Hz frequency for all subjects (because of unsatisfactory performance of the vibrator), and the 0.5-mm amplitude and 45-Hz frequency for subject 3 (because of a temporary technical error). Also,

TABLE 2. VIBRATION AMPLITUDES AND FREQUENCIES

Amplitude (mm)	Frequency (Hz)	Theoretical* peak acceleration (in G)
0.05	-, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90	0.04–1.63
0.5	10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65	0.20–8.49
1	10, 15, 20, 25, 30, 35, 40, 45, 50	0.40–10.05
3	10, 15, 20, 25, 30, 35, 40	1.21–19.30

* $a_{\text{peak}} = 4\pi^2 \times f^2 \cdot A$, where f is the frequency of sinusoidal vertical vibration and A is the vibration amplitude.

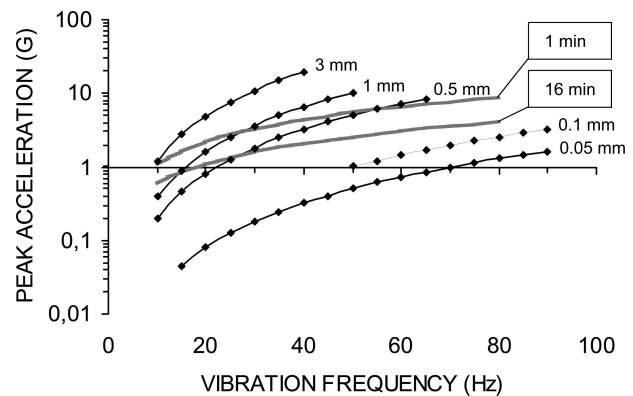


FIG. 2. Measured peak accelerations of the vibration platform at different amplitudes and frequencies. Daily vibration exposure limits (gray curves) indicated in the ISO 2631-1 standard are given for 1- and 16-min durations. Note that acceleration data are given also for the 0.1-mm vibration amplitude above 50-Hz frequency. Because of unexpected resonance of the vibrator at frequencies <50 Hz, all measurements could not be done, and the complete site-specific data for the 0.1-mm amplitude were not obtained and were thus not shown in the results.

because of high (>10 G) peak accelerations, the ankle accelerometer was released when the 3-mm amplitude was used at frequencies >25 Hz to prevent the device from damaging.

Data analysis

A 1-s period of acceleration data from the latter one half of the 5-s period was analyzed for each vibration amplitude and frequency. These periods, comprising data from 10 to 90 vibration cycles, were considered to adequately describe the site-specific acceleration signal at the given amplitude and frequency of the vibration platform.

Vibration signals were analyzed both in time and frequency domains using data analysis software (FlexPro 7; Weisang, St Ingbert, Germany). First, the transmissibility of vibration to the body sites was determined as the ratio of the root-mean-square-power (rms-power) of the site-specific vibration signal to the rms-power of the platform vibration signal. Second, the power spectra of the site-specific vibration signals were determined using fast-Fourier transform analysis with a Hamming window. From these spectra, the proportion of signal power within ± 1 Hz

of the nominal frequency was calculated to evaluate the purity of waveform (i.e., how well the sinusoidal waveform of the site-specific acceleration signal was maintained at the given vibration amplitude and frequency).

RESULTS

As a rule, none of the subjects felt the consecutive vibration sessions particularly fatiguing or stressing. However, it is noted that every subject felt some discomfort specifically between 20- and 25-Hz vibration frequencies when the amplitude was 0.5 mm or greater (the platform peak acceleration was between 0.8 and 7.5 G). In addition, subject 1 had numbness in his feet at the 3-mm amplitude and 40-Hz frequency (the platform peak acceleration was 19 G), but the symptoms subsided immediately after cessation. Subject 3 reported mild heel pain in the evening of the measurement day, but the pain disappeared in 2 days without any medical treatment.

Measured peak accelerations of the vibration platform are shown in Fig. 2 as a function of frequency and amplitude. These values were in full agreement with the theoretical peak accelerations. For the safety assessment of different vibration protocols, the daily vibration exposure limits indicated in the ISO 2631-1 standard⁽²⁴⁾ are also provided in Fig. 2.

Transmission of vertical vibration to the ankle, knee, hip and spine over the studied vibration frequency and amplitude ranges are shown in Figs. 3–6. Substantial amplification of peak acceleration could occur between 10 and 40 Hz for the ankle, 10 and 25 Hz for the knee, 10 and 20 Hz for the hip, and at 10 Hz for the spine. This means that the site-specific peak accelerations can be multiple to that imposed at the vibration platform. Beyond these frequencies, the transmitted vibration power declined to 1/10th–1/1000th of the power delivered by the vibrating platform. In general, the transmitted accelerations were least attenuated at the ankle and most at the spine. Differences in transmissibility between subjects could be 10:1 or even more for some conditions, but for certain amplitudes and frequencies, the transmissibility was rather similar in all subjects (Figs. 3–6).

The purity of waveform of site-specific acceleration signals is evaluated in Table 3. Sinusoidal waveform was rather well maintained with the 0.05-mm vibration amplitude at all frequencies (the spine excluded). With amplitudes of 0.5 mm or more, the site-specific acceleration signal was generally more distorted irrespective of the vibration frequency, with some exceptions (Table 3). Distortion means that higher frequency components (multiples of the nominal vibration frequency) were introduced to the site-specific acceleration signal, its waveform was changed from the sinusoidal acceleration delivered by the platform, and as a result, high peak accelerations appeared (Fig. 7).

DISCUSSION

Human body is a complex biomechanical apparatus, and analysis of its response to whole body vibration is challenging and subject to several confounding factors. In addition

to substantial differences in individual transmissibility,^(18,22,25) the transmissibility of vibration is affected by body posture,^(17–19,21,25) muscle activity,^(26,27) body segment weights, and their biomechanics.^(28–30) Accordingly, the propagation of whole body vibration is markedly influenced by nonlinearities in the body biomechanics, and it is not possible to infer the peak value of the site-specific acceleration from the amplitude and frequency of sinusoidal vertical vibration using the simple theoretical relationship (i.e., $a_{\text{peak}} = 4\pi^2 \times f^2 A$). Note that it is not known either, whether a single, specific frequency (i.e., a pure sinusoidal vibration) is central to osteogenic response, and if so, which frequency would be most effective.

Strengthening the skeleton is one of the clinical goals of whole body vibration training. Whereas the osteogenic response to loading seems to saturate after ~40 consecutive high loads⁽³¹⁾ and the vibration training at amplitudes >0.5 mm can generate tens of clearly supra-G accelerations in seconds, we speculate that the majority of such vibration is delivered in vain. In principle, a sufficient daily stimulus with supra-G vibration could be received in seconds only. However, clinical supra-G studies with significant bone effects have comprised single training sessions that have lasted several minutes.^(12,14) Judged from the reported vibration protocols and actual vertical peak accelerations of the platform, subjects in these supra-G studies might have received ~4500 high loads (~6 G at 3 mm and 12.6 Hz)⁽¹²⁾ or even 48000 high loads (~5 G at 2.5 mm and 40 Hz)⁽¹⁴⁾ during a single session three times a week for 8 or 6 mo, respectively; the corresponding net effects on bone were 4.3% (femoral neck BMD) and 1.5% (total hip BMD). Similarly positive effects on bone may be obtained with sub-G vibration training comprising tens of thousands low loads (<0.3 G at ~0.05 mm and 30 or 90 Hz) per session.^(8–10) With such a low-amplitude and high-frequency vibration, an effective stimulus may be safely and feasibly delivered within ~10 min of daily training.⁽³²⁾

Safety of whole body vibration training is crucial.^(17,20,21,23,32,33) In this study, high peak accelerations, not inferable from theoretical calculations, occurred. Apparently this amplification of acceleration arises from the complex interaction of body segment resonances.^(17–19,26–30) Additionally, when the vibration platform reaches supra-G levels, the body gets out of phase and is impacted tens of times per second, depending on frequency. It is noted that in a quasi-static compressive testing, the failure load of an osteoporotic lumbar vertebral body can be as low as 1300 N⁽³⁴⁾—only two to three times body weight (i.e., 2–3 G) of a frail individual. On the other hand, the vibration-induced impacts, although high in magnitude, are very short in duration (~10 ms), and may as such, not transfer enough energy to damage the vertebrae in their natural biomechanical environment. However, the mere possibility that the supra-G vibration induced impacts could endanger fragile bones warrants concern. In particular, given the large number of repetitive high loads received during a typical vibration session, fatigue damage to the bone may not be totally excluded. Besides possibly jeopardizing fragile bones, influence of supra-G vibration on aged cartilage tissue and other organs is not known.

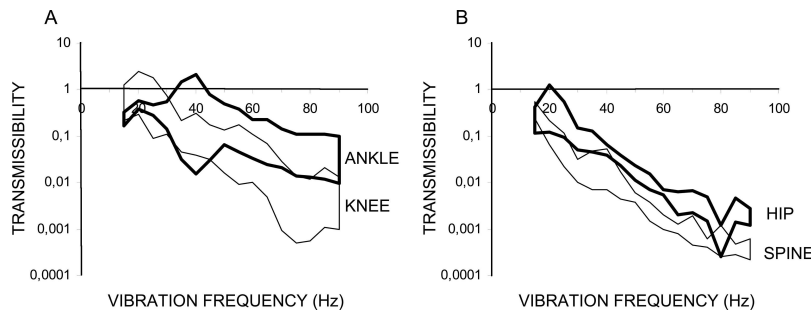


FIG. 3. Range of transmissibility of vertical whole body vibration power at the 0.05-mm vibration amplitude to the ankle and knee (A) and to the hip and spine (B) as a function of frequency.

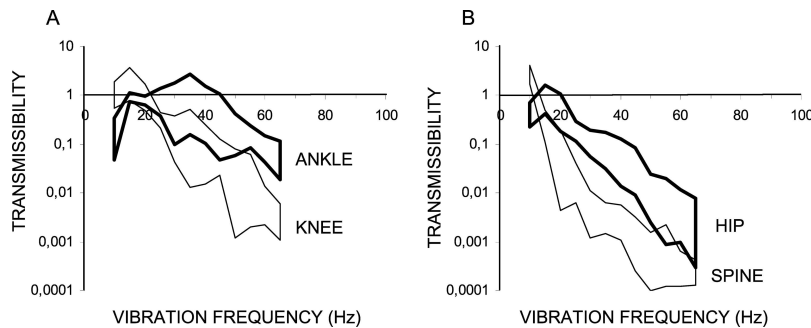


FIG. 4. Range of transmissibility of vertical whole body vibration power at the 0.5-mm vibration amplitude to the ankle and knee (A) and to the hip and spine (B) as a function of frequency.

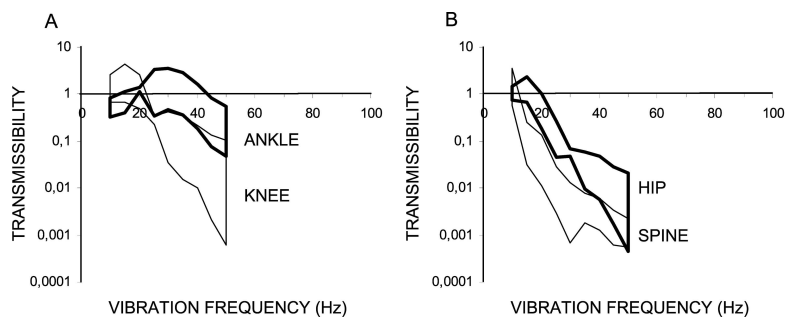


FIG. 5. Range of transmissibility of vertical whole body vibration power at the 1-mm vibration amplitude to the ankle and knee (A) and to the hip and spine (B) as a function of frequency.

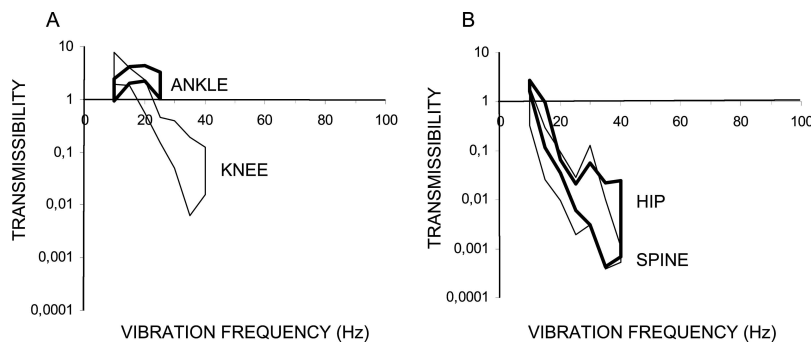


FIG. 6. Range of transmissibility of vertical whole body vibration power at the 3-mm vibration amplitude to the ankle and knee (A) and to the hip and spine (B) as a function of frequency.

Thus far, no fractures or adverse effects have been reported in clinical vibration trials of elderly or osteoporotic subjects.^(12,14,15,32,35-40)

Regarding the safety further, the transmissibility of vibration to the upper body is known to increase with fully straight knees,^(17-19,21,25) and whereas enhancing the stimulus for sub-G vibration devices, this posture may increase the risk for supra-G devices. Obviously, high transmission of vibration to the head should be avoided. According to previous studies of vertical vibration,^(18,20,25) accelerations

to the head may augment at frequencies below ~20 Hz, depending on posture. As the clinical experience with vibration training is yet scarce, Griffin's recent statement "estimates of what is likely to be safe or unsafe will benefit from experience of the various conditions and not blind reliance on formulae: is relevant."⁽¹⁶⁾ Whereas the occupational exposure to whole body vibration (several hours per day over many years) is associated with increased risk of low back pain, sciatic pain, and degenerative changes in the spine, the evidence for a dose-response relationship is

TABLE 3. MEAN (SD) PROPORTION* OF SITE-SPECIFIC ACCELERATION SIGNAL POWER WITHIN ±1 Hz OF THE NOMINAL FREQUENCY FOR DIFFERENT VIBRATION AMPLITUDES AND FREQUENCIES

Site/amplitude (mm)	Frequency (Hz)								
	10	20	30	40	50	60	70	80	90
Ankle									
0.05	—	94 (2)	96 (2)	92 (12)	95 (3)	97 (2)	98 (2)	98 (3)	98 (2)
0.5	70 (35)	91 (6)	83 (13)	79 (18)	65 (18)	70 (28)	—	—	—
1	80 (21)	68 (7)	35 (28)	38 (24)	38 (30)	—	—	—	—
3	43 (28)	57 (20)	—	—	—	—	—	—	—
Knee									
0.05	—	98 (2)	96 (4)	96 (2)	93 (7)	95 (5)	86 (18)	88 (18)	94 (4)
0.5	96 (1)	69 (29)	87 (5)	84 (13)	95 (7)	96 (2)	—	—	—
1	79 (16)	40 (27)	70 (19)	64 (16)	83 (21)	—	—	—	—
3	34 (22)	41 (20)	35 (12)	23 (14)	—	—	—	—	—
Hip									
0.05	—	91 (8)	92 (5)	96 (1)	85 (9)	89 (5)	91 (7)	93 (4)	94 (2)
0.5	67 (37)	73 (20)	81 (26)	89 (11)	94 (5)	96 (4)	—	—	—
1	64 (22)	63 (25)	78 (19)	92 (3)	92 (4)	—	—	—	—
3	39 (13)	53 (20)	54 (26)	61 (29)	—	—	—	—	—
Spine									
0.05	—	84 (13)	44 (38)	66 (6)	59 (11)	48 (22)	41 (24)	31 (18)	33 (32)
0.5	96 (3)	84 (27)	73 (22)	78 (12)	71 (19)	71 (19)	—	—	—
1	78 (28)	91 (2)	50 (33)	75 (13)	61 (40)	—	—	—	—
3	56 (23)	52 (27)	60 (35)	56 (36)	—	—	—	—	—

* Bold data indicate that >80% of vibration power was maintained within ±1 Hz of the nominal frequency in all subjects ($p < 0.05$).

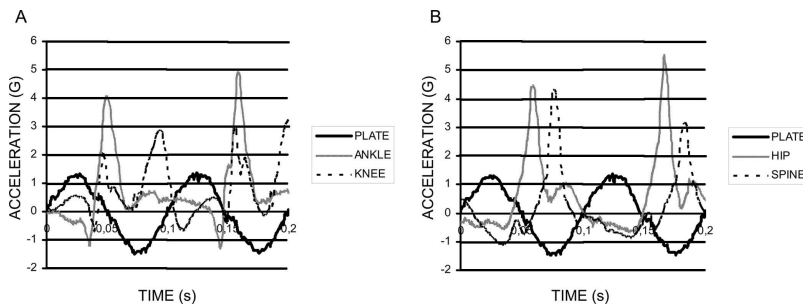


FIG. 7. An example of potential safety issue caused by supra-G vibration-induced impacts. For the 3-mm amplitude and 10-Hz frequency, the peak acceleration of the platform was 1.3 G, but the site-specific peak accelerations could be clearly augmented both at the ankle and knee (A) and also at the hip and spine (B), reaching even 6-G peak accelerations (data from subject 1). Other subjects showed similar responses, particularly at the ankle, knee, and hip sites (data not shown).

rather weak.⁽¹⁶⁾ In this light, the short daily exposures to vibration training seem reasonably safe, particularly if the high vibration-induced impacts can be avoided. The safety limits given in ISO 2631-1⁽²⁴⁾ may be taken as a guideline in settling vibration amplitudes and frequencies and the duration of a single training session in any vibration intervention.

The major strengths of this study are the comprehensive coverage of single vibration frequencies (from 10 to 90 Hz) and amplitudes (from 0.05 to 3 mm) used in clinical intervention trials with commercial training devices,^(8–15,35–40) and the site-specific assessment of transmission of vibration to the body over a wide range of vertical peak accelerations of the platform (from 0.04 to 19 G). In previous studies, the transmission of vertical vibration to the human body has been evaluated with single frequencies from 15 to 35 Hz⁽¹⁷⁾ or from 10 to 40 Hz⁽²⁰⁾ using a vertical vibration platform with constant force input (measured peak accelerations < 0.5 G) or using a vertical vibration platform producing random vertical acceleration with frequency spectrum from 0.25 to 25 Hz at rms-acceleration of ~0.2 G,⁽²⁵⁾ from 0.5 to

30 Hz at rms-accelerations from ~0.01 to 0.2 G,⁽¹⁹⁾ or from 4 to 300 Hz at rms-accelerations of ~0.4 G.⁽¹⁸⁾ Straight comparisons between the present transmissibility curves and those obtained with bone-mounted accelerometers⁽¹⁷⁾ or with skin-mounted accelerometers^(18,19) were not appropriate because of different vibration protocols; however, similarities were apparent.

This study has limitations that need to be taken into account. Above all, bone-mounted accelerometers would have been the most accurate way to measure actual site-specific accelerations.⁽¹⁷⁾ However, given the large number of measurements per subject and spending two working days in an industrial environment, invasive implantation of accelerometer pins to four bone sites was considered unfeasible because of safety and ethical issues. Noninvasive skin-mounted accelerometers can provide reasonable estimates of actual acceleration during vibration and impulsive motion after complex individualized transfer-function corrections and at frequencies below ~30 Hz.^(22,41–43) In this study, frequencies >30 Hz were also assessed, and corrections were not performed. Without the transfer-function

correction, skin-mounted accelerometers can overestimate the actual peak acceleration by 10–20% on average, modify the waveform of acceleration signal, and increase the between-individual variance.^(41,42)

Also, previous workers have assessed the transmission of vibration-induced accelerations to the head with a bite-bar accelerometer in regards to safety of whole body vibration,^(18,20,21,25) whereas in this study, head accelerations were not assessed. Furthermore, because of extreme peak accelerations and potential risks, this study was carried out with a small group of young healthy men. Therefore, the results may not be directly translated to describe vibration-induced accelerations among elderly people, for whom the transmission of vibration can vary because of less compliant joints, stiffer tendons and muscles, and declined muscle activity. Finally, these findings based on vertical vibration may not be directly applicable to whole body vibration generated by a seesaw-type vibrating platform.^(21,23)

Although these data obtained with skin-mounted accelerometers can be considered indicative only, the observed trends and ranges show the transmission of vertical whole body vibration to the human body. In particular, these data may help in estimating how the transmission of vibration-induced accelerations to body segments is modified by amplitude and frequency, and how well the sinusoidal waveform is maintained. Whereas the attenuation of vertical vibration at higher frequencies is fortunate from the aspect of safety, amplitudes >0.5 mm may result in greater accelerations than imposed at the platform and thus pose a potential hazard for fragile bone and cartilage tissue. Despite no reported adverse effects thus far, the safety of whole body vibration should be carefully considered before devising any specific training regimen.

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