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Platform accelerations of three different whole-body vibration devices and the transmission of vertical vibrations to the lower limbs

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ABSTRACT

Physical whole-body vibration (WBV) exercises become available at various levels of intensity. In a first series of measurements, we investigated 3-dimensional platform accelerations of three different WBV devices without and with three volunteers of different weight (62, 81 and 100 kg) in squat position (150° knee flexion). The devices tested were two professional devices, the PowerPlate and the Galileo-Fitness, and one home-use device, the PowerMaxx. In a second series of measurements, the transmission of vertical platform accelerations of each device to the lower limbs was tested in eight healthy volunteers in squat position (100° knee flexion). The first series showed that the platforms of two professional devices vibrated in an almost perfect vertical sine wave at frequencies between 25–50 and 5–40 Hz, respectively. The platform accelerations were slightly influenced by body weight. The PowerMaxx platform mainly vibrated in the horizontal plane at frequencies between 22 and 32 Hz, with minimal accelerations in the vertical direction. The weight of the volunteers reduced the platform accelerations in the horizontal plane but amplified those in the vertical direction about eight times. The vertical accelerations were highest in the Galileo (∼15 units of g) and the PowerPlate (∼8 units of g) and lowest in the PowerMaxx (∼2 units of g). The second series showed that the transmission of vertical accelerations at a common preset vibration frequency of 25 Hz were largest in the ankle and that transmission of acceleration reduced ∼10 times at the knee and hip. We conclude that large variation in 3-dimensional accelerations exist in commercially available devices. The results suggest that these differences in mechanical behaviour induce variations in transmissibility of vertical vibrations to the (lower) body.

1. Introduction

Because physical condition reduces with age, regular endurance training exercises are advised. It has been demonstrated that these exercises have profound benefits to prevent atrophy of muscles [1], functional impairment [2], obesities [3], cardiovascular diseases [4] and fragility fractures among elderly population [5]. Moreover, the assessment of overall physical fitness has become part of pre-operative screening in patient management. Traditional lower limb training methods like progressive resistive exercise (PRE), proprioceptive neuromuscular facilitation (PNF) and cycling exercises [6,7] may preserve or improve lower muscle strength. However, the effectiveness of these methods is reduced in elderly patients with balance or vestibular disorders [8]. A relatively new method to recruit muscles is whole-body vibration (WBV). A subject stands or sits on a vibration platform. The vibrations are induced via this platform and control and safety handles provide stability [9,10]. WBV training can be done at home, which reduces therapeutic cost and patient travel expenses.

Recently, effects of WBV training on muscle strength [11–16], bone density [9,17], cardiovascular parameters [18] and body balance have been investigated [19,20]. One proposed physiological impact of WBV on muscle performance is activation of the Tonic Vibration Reflex (TVR) [9]. Some reflexes, i.e. Hoffmann and Tendon reflexes, as well as tendon vibration response are substantially depressed when specific vibration patterns were applied to the body or to the legs of seated human subjects [21,22]. It might be that vibrations first stimulate primary muscle spindle (Ia) fibres, which subsequently result in a reflex at the level of spinal cord. It was shown that high platform accelerations are associated with high muscle activity levels [23], but it is still unclear to what extent WBV induces these reflex muscle activations and how this would lead to improved muscle performances.

Work on human responses to (whole body) vibration dates back from almost half a decade ago [24,25]. Biomechanical models

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[26,27] and human physiological measurements in sitting [28–31] and standing posture [32–36] have addressed the transmission of whole-body vibration to various body segments. Most studies that related to exposure of vibrations in sitting postures had a special focus on the prevention of low back problems. Besides different postures and the variability in activity levels of the subjects studied, the differences between effects of WBV may also be related to the variability in the vibration devices presently on the market. Mostly, WBV is induced using either a Power Plate or a Galileo. Although some of the technical specifications of these commonly used devices on vibration frequency are available, it is not fully investigated whether body mass might influence for example vibration platform accelerations. A recent study investigated gravitational forces at the vibration surface of the Galileo 2000 [32]. At present, simple and very cheap home-use vibration devices, i.e. the PowerMaxx, have become available as well. The platforms deliver different types of vibration. The PowerPlate induces vertical vibrations, the Galileo induces seesaw vibrations and the PowerMaxx induces vibrations in the horizontal plane. The purpose of the present study was to compare the mechanical behaviour of three different WBV devices in “unloaded condition” and “loaded condition”. The aims of the present study were:

1. To study the 3-dimensional (horizontal (X, Y) and vertical (Z) direction) platform accelerations of two commonly used professional WBV devices (PowerPlate and Galileo) and that of one simple home-use device (PowerMaxx) under different loading conditions.
2. To study the transmission of vertical platform accelerations of all three devices to the lower limbs at the lowest common preset frequency.

We expected to find no differences in platform frequency and only small differences in platform acceleration under different loading conditions with respect to the PowerPlate and the Galileo. With respect to the PowerMaxx, we expected rather large changes in platform acceleration values under loading conditions. Based on these expectations, we hypothesised to find large differences in transmission of vertical vibrations between the devices at the level of the ankle, knee and hip at one common platform frequency.

2. Materials and methods

In the present study, the PowerPlate (PowerPlate International, The Netherlands), the Galileo-Fitness (Novotec Medical GmbH, Germany) and the PowerMaxx (DS-produkte GmbH, Germany) were tested, see Fig. 1 for a schematic drawing. The two professional devices, the PowerPlate and the Galileo, could be set at vibration frequencies between 25–50 and 5–40 Hz, respectively. No frequency specifications were given for the PowerMaxx; 9 levels of vibrations were indicated (S1–S9). Two electro motors, each provided with an eccentric mass, controlled the platform vibrations of the PowerPlate. The platform could be set in two different modes: ‘low’ or ‘high’ implying a low or high platform displacement to alter the level of intensity workout. The Galileo platform oscillated around a central axis. A crankshaft principle on each side of the platform translated the rotating motion of the electro motor into a vertical displacement, inducing a seesaw vibrations. Depending on the position of the feet on the platform, the displacement is either small (feet near the axis) or large (feet near the edge of the platform). The vibrations of the PowerMaxx platform were controlled by an eccentric mass that was connected to one electro motor. This mass induced horizontal platform vibrations. In each device, a control panel allowed presetting the vibration frequencies.

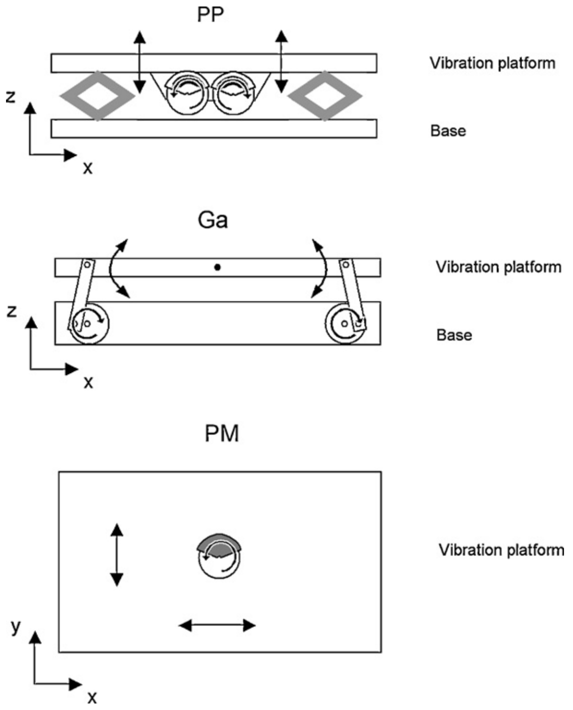

Fig. 1. A schematic drawing of the vibration directions of the three WBV devices tested: the PowerPlate (PP), the Galileo-Fitness (Ga) and the PowerMaxx (PM). Indicated are the vertical (Z) and the two horizontal (X, Y) directions.

2.1. Measurement setup

To measure the acceleration in the horizontal (X, Y) and vertical (Z) direction, three piezo-resistive accelerometers (ICSensors 3021-005-P, max. $\pm 50\,\mathrm{m/s^2} \sim 5\,\mathrm{g}$) were placed in a custom made PVC container. A fourth accelerometer (Analog Devices ADXL150JQC, max. $\pm 500\,\mathrm{m/s^2} \sim 50\,\mathrm{g}$) was placed in the container to measure accelerations exceeding 5G in vertical direction. The container with the accelerometers was fixed in the centre of the PowerPlate and PowerMaxx platform using two bolts. It was fixed at 185 mm from the rotating axis of the Galileo platform. The signal of each ICSensor was electronically amplified and together with the signal of the ADXL fed to a 14 bit A/D convector (National Instruments DAQmx USB-6009). The signals were sampled with a frequency of 1000 Hz and stored on a standard PC. Each accelerometer was calibrated on the basis of a two point calibration by applying zero gravity and the earth’s gravity of 1 g (9.81 $\mathrm{m/s^2}$). An offset equal to earth’s gravity was subtracted from all acceleration signals in vertical direction to make all signals start at 0 $\mathrm{m/s^2}$. A custom written LabVIEW program calculated of each 1000 samples the maximum acceleration, $a_{\max}$, and the root mean square value of the acceleration, a_{RMS}, in each direction. The corresponding frequency component, f_{out}, was calculated from the FFT transformed acceleration signal. We selected the lowest frequency; higher harmonic frequencies were not selected for further analysis. At each preset f_{in}, platform accelerations were measured for 10 s starting with the lowest f_{in}. After 10 s, f_{in} was increased in the same recording and the platform accelerations were again measured for 10 s. The first 2–3 s of each measurement was the response time to this stepwise increase of the frequency. We therefore took the last 5 s for further analysis. After 60 s, a measurement was ended and a new measurement was done. The average and standard deviation of the a_{RMS} and f_{out} values were derived from the set of a_{RMS} and f_{out} values calculated in each second of the last 5 s. In a pilot run, we fitted a sine function through test acceleration signals of each (unloaded) device at a low preset frequency and a high preset frequency. We found very small fit errors

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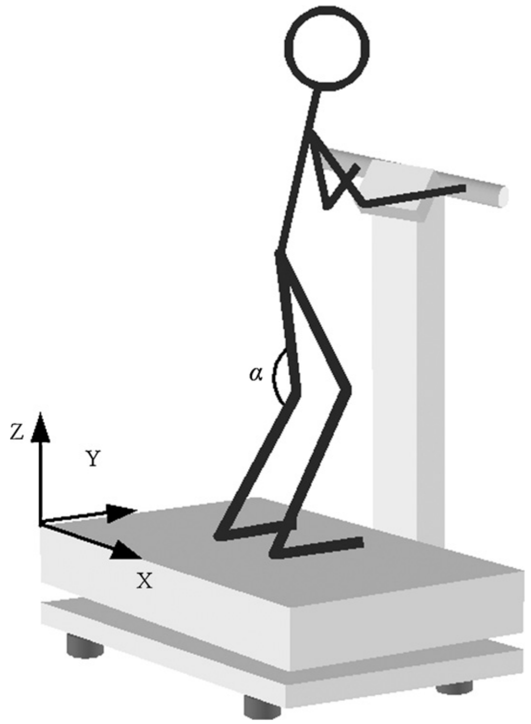

Fig. 2. A schematic drawing of a healthy subject standing in squad position with knee angle α on a WBV device. Indicated are the vertical (Z) and the two horizontal (X, Y) directions.

for the PowerPlate and the Galileo and for the PowerMaxx at low frequency (S1) of less than 0.5%. At high frequency (S9), the fit error for the PowerMaxx increased, but was still less than 2%. Based on these small errors, we assumed sinusoidal platform motions for each device and calculated the maximum platform displacement, $d_{\max}$, at the location of the accelerometer using the following set of equations:

$$d(t) = A \cdot \sin(\omega \cdot t) \tag{1}$$

$$a(t) = d''(t) = \frac{\partial^2 A \cdot \sin(\omega \cdot t)}{\partial t^2} = -\omega^2 \cdot A \cdot \sin(\omega \cdot t) = -\omega^2 \cdot d(t) \tag{2}$$

$$d(t) = -\frac{1}{\omega^2} \cdot a(t) = -\frac{1}{f_{\text{out}}^2 \cdot 4\pi^2} \cdot a(t) \tag{3}$$

$$d_{\max} = \left| -\frac{1}{f_{\text{out}}^2 \cdot 4\pi^2} \cdot a_{\max} \right| \tag{4}$$

where $d(t)$ is the displacement in time, A is the amplitude, ω is the angular frequency (=$2\pi f_{\text{out}}$) and $a(t)$ is the acceleration.

2.2. First measurement series: 3-dimensional platform accelerations

In the first series of measurements, a_{RMS} and f_{out} were determined for preset vibration frequencies, f_{in}, of each device without and with a weight placed on each platform. Initial tests to apply passive weight (masses of 10 kg each up to 80 kg) to each platform failed due to movement of the weights. An additional test using sand bags of 10 kg each failed as well, despite the fact that we tried to stabilise this load with large belts. Therefore, we asked two experienced vibration platform user (62 and 81 kg) to test each platform in squat position (knee angle α of 150° measured with a manual goniometer) and a third experienced vibration platform user of 100 kg for additional testing the PowerMaxx, see Fig. 2. In this way, the platforms were equally "loaded" and a squat position was chosen to prevent excessive head oscillations. The f_{in} of the PowerPlate was preset at 25 Hz and stepwise increased in steps of 5 Hz to its maximum of 50 Hz in "high" as well as "low" amplitude mode. The f_{in} of the Galileo was preset at 5 Hz and also stepwise increased with 5 Hz to its maximum of 40 Hz. All volunteers were asked to take of shoes and socks. Each volunteer placed their feet on the prescribed Galileo platform position (at 185 mm left and right from the central axis) to warrant the same induced platform accelerations. The PowerMaxx had prescribed settings starting from S1 to S9; the magnitude of f_{in} was neither specified on the display nor in the manual. Acceleration values measured in the "unloaded condition" were reported in units of gravitational force (1 g = 9.81 m/s^2). The acceleration and vibration frequency values measured in the "loaded condition" were normalized by dividing them by the values measured in the "unloaded condition". The ratio of f_{out} values was denoted as f_{ratio}.

2.3. Second measurement series: transmission of vertical accelerations

In the second measurement series, we studied in eight healthy volunteers (age 34 (12) years and body weight 76 (15) kg; mean (SD)) the transmission of the vertical platform accelerations of each device to the lower limbs. The accelerations of three different body locations: ankle, knee and hip were measured in each volunteer. He or she was instructed to maintain a fixed squad position for at least 10 s, head straight forward and 20 s of recovery between trials. The feet had to be placed 30 cm apart. This distance was indicated with markers on each platform to warrant a reproducible position, especially important or the Galileo. Using this device, both feet were placed 150 mm from the central axis. The f_{in} of each device was set at 25 Hz, the lowest common preset frequency in all devices (calculated on the basis of the first measurement series). Now, a knee angle α of 100° was chosen, which is a typical lower limb training posture: the body weight on the front feet and the back upright. The Analog Devices ADXL150JQC accelerometer was used to measure the accelerations in the vertical direction. This accelerometer was in random order placed on the malleolus lateralis, a relatively flat part of ankle, the epicondylus lateralis, a relatively flat part of the lower part of the thighbone and finally on the spinailiaca anterior superior, the edge of the hipbone. We attached the accelerometers to each site using rigid foam tape (Kushionflex Padding tape of approximately 100 mm × 25 mm (length × width)) to ensure that the position of the sensor was secure. We did not take any potential errors of skin movement into account nor did we correct raw data. Alignment of the accelerometer with earth gravity was on the basis of the sensor's output during the calibration procedure. During the vibration measurement, we visually inspected the direction of the foam tape with respect to the vertical direction. Transmission of vibrations in vertical direction was calculated as a percentage of the measured accelerations at a given location divided by the unloaded platform acceleration at 25 Hz, i.e. PowerPlate 'high mode' 32 m/s^2, Galileo 150/185 × 60 m/s^2 = 48.6 m/s^2 and PowerMaxx 1.4 m/s^2.

3. Results

3.1. Subjects

None of the subjects reported any side effects to the exposed vibrations, such as hot feet, vertigo, dizziness, itching in the legs, cramp or calf pain.

3.2. 3-Dimensional platform accelerations

3.2.1. PowerPlate

Fig. 3, top panel, shows an example of the unloaded platform accelerations in X, Y and Z direction with f_{in} preset at 30 Hz. The

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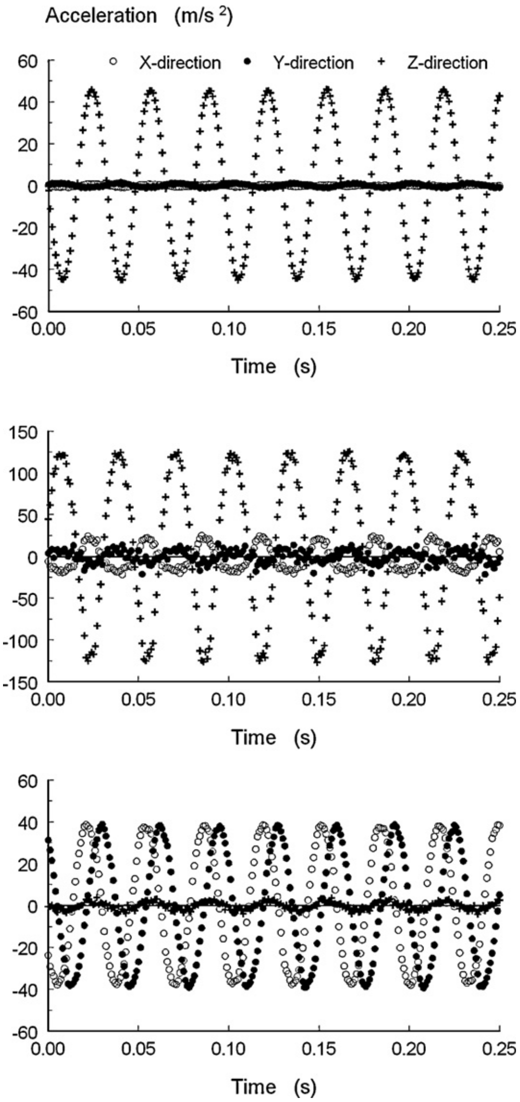

Fig. 3. Top panel: example of the PowerPlate unloaded platform acceleration against time t showing accelerations in X-direction (open circles), Y-direction (closed circles) and Z-direction (plusses) with f_{in} set at 30 Hz. The platform induced mainly vibrations in vertical direction. Middle panel: example of the Galileo unloaded platform accelerations against time with f_{in} also set at 30 Hz. This platform also induced highest vibrations in vertical directions, and some in the horizontal plane. Lowest panel: example of the PowerMaxx unloaded platform accelerations against time set at 30 Hz. The accelerations of this platform were mainly in the horizontal plane. Note the differences in y-axis scaling.

acceleration was mainly in vertical direction and described an almost perfect sine wave. Table 1 summarises the accelerations a_{RMS} in both “high” and “low” amplitude mode and the frequencies f_{out} at each preset f_{in}. The f_{out} values were within 3% comparable to the preset f_{in} values. The a_{RMS} values in the horizontal plane were less than 0.2 units of g. The a_{RMS} values in vertical direction measured in “low” amplitude mode, up to 3.8 units of g, were half of those measured in “high” amplitude mode at the same preset f_{in}. In “high” mode, the maximum vertical platform displacement, $d_{\max}$ was 2.2 (0.1) mm peak-to peak (mean (SD)); in “low” mode $d_{\max}$ was 1.2 (0.05) mm peak-to-peak. It only decreased ~0.2 mm when the preset f_{in} increased from 25 Hz up to 50 Hz in both “high” and “low” mode. Loading the platform did not affect the f_{out} values and the a_{RMS} values in vertical direction changed less than 10% when the preset f_{in} increased from 25 up to 50 Hz.

Table 1
3-Dimensional “unloaded” and “loaded” platform accelerations (a) and vibration frequencies (f_{out}) of the PowerPlate at preset vibration frequencies between 25 and 50 Hz. In the “unloaded condition”, the root mean square values of the accelerations (a_{RMS}) were expressed in units of g (9.81 m/s^2) in all directions. In the “loaded condition”, two volunteers with body weight 62 and 81 kg stood in squat position on this platform in ‘low mode’. The a_{RMS} and f_{out} values were normalized by dividing them by the a_{RMS} and f_{out} values measured in the “unloaded condition”. Thus f_{ratio} was defined as f_{out} (loaded condition) divided by f_{out} (unloaded condition).

f_{in} (Hz)	a_{RMS} (in units g)			f_{out} (Hz)
	X-direction	Y-direction	Z-direction	
“Unloaded condition”				
‘High’				
25	**0.0**	**0.1**	**2.5**	**25**
30	**0.0**	**0.1**	**3.3**	**31**
35	0.0	0.1	4.3	36
40	0.1	0.1	5.3	41
45	0.1	0.2	6.5	45
50	0.1	0.2	7.7	50
‘Low’				
25	**0.3**	**0.0**	**1.2**	**26**
30	**0.2**	**0.0**	**1.6**	**31**
35	0.2	0.1	2.1	36
40	0.2	0.1	2.6	41
45	0.2	0.1	3.3	45
50	0.2	0.1	3.8	50
‘Low’	a_{RMS}			f_{ratio}
	X-direction	Y-direction	Z-direction	
“Loaded condition”				
62 kg				
25	**0.6**	**2.5**	**0.9**	**1.0**
30	**0.3**	**2.2**	**1.0**	**1.0**
35	0.5	1.6	0.9	1.0
40	0.5	1.0	1.0	1.0
45	0.9	0.6	0.9	1.0
50	0.7	0.7	1.0	1.0
81 kg				
25	**0.2**	**3.6**	**0.9**	**1.0**
30	**0.2**	**2.7**	**1.0**	**1.0**
35	0.3	1.8	0.9	1.0
40	0.3	1.1	1.0	1.0
45	0.4	0.6	1.0	1.0
50	0.4	0.6	1.0	1.0

3.2.2. Galileo

The middle panel of Fig. 3, shows an example of the unloaded platform accelerations in X, Y and Z direction with f_{in} preset at 30 Hz. Again, the acceleration in vertical direction, the most prominent acceleration, described a sine wave. Table 2 summarises the overall findings of this platform. In the unloaded situation, the f_{out} values were up to 30 Hz within 1% accurate. Between 30 and 40 Hz, the f_{out} values decreased with 5% at f_{in} of 40 Hz. The accelerations in the horizontal X- and Y-direction increased to about 2 and 1 units of g, respectively. The accelerations in vertical direction ranged between 0.3 and 14.7 units of g (f_{in} values from 5 to 40 Hz). Note that the maximum accelerations were location dependent: the accelerations were linearly related to the distance between the rotating axis and the location of the accelerometers. The maximum vertical platform displacement, averaged over all measurements from 5 to 40 Hz, was 3.5 (0.1) mm peak-to-peak. Loading the platform did not affect the f_{out} values nor the maximum platform displacements. However, the platform accelerations in vertical direction at f_{in} values between 30 and 40 Hz reduced ~12% respectively 7% when loaded by a body weight of 62 kg respectively 81 kg. This might have been caused by some resonance above 30 Hz, which decreased the maximum platform displacement and thus the vertical accelerations.

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Table 2
3-Dimensional "unloaded" and "loaded" platform accelerations (a) and vibration frequencies (f_{out}) of the Galileo-Fitness at preset vibration frequencies between 5 and 40 Hz. In the "unloaded condition", the root mean square values of the accelerations (a_{RMS}) were expressed in units of g (9.81 m/s^2) in all directions. In the "loaded condition", two volunteers with body weight 62 and 81 kg stood in squat position on this platform. The a_{RMS} and f_{out} values were normalized by dividing them by the a_{RMS} and f_{out} values measured in the "unloaded condition".

f_{in} (Hz)	a_{RMS} (in units g)			f_{out} (Hz)
	X-direction	Y-direction	Z-direction	
"Unloaded condition"				
5	0.1	0.1	0.3	5
10	0.2	0.1	1.0	10
15	0.3	0.1	2.2	15
20	0.7	0.2	3.9	20
25	**1.0**	**0.3**	**6.1**	**25**
30	**1.3**	**0.6**	**7.9**	**30**
35	1.7	0.8	10.4	34
40	2.1	0.7	14.7	38
f_{in} (Hz)	a_{RMS}			f_{ratio}
	X-direction	Y-direction	Z-direction	
"Loaded condition"				
62 kg				
5	1.0	0.8	1.0	1.0
10	1.0	0.8	1.0	1.0
15	0.7	0.9	1.0	1.0
20	0.6	1.0	1.0	1.0
25	**1.1**	**1.4**	**1.0**	**1.0**
30	**0.9**	**1.3**	**0.9**	**1.0**
35	0.8	1.6	0.8	1.0
40	1.0	1.6	0.9	1.0
81 kg				
5	1.0	0.8	1.0	1.0
10	1.0	0.9	1.0	1.0
15	0.6	1.3	1.0	1.0
20	0.7	0.7	1.0	1.0
25	**1.2**	**1.6**	**1.0**	**1.0**
30	**1.1**	**0.8**	**1.1**	**1.0**
35	0.9	1.3	0.9	1.0
40	0.9	1.7	0.9	1.0

Table 3
3-Dimensional "unloaded" and "loaded" platform accelerations (a) and vibration frequencies (f_{out}) of the PowerMaxx at preset settings S1–S9. In the "unloaded condition", the root mean square values of the accelerations (a_{RMS}) were expressed in units of g (9.81 m/s^2) in all directions. In the "loaded condition", three volunteers with body weight 62, 81 and 100 kg stood in squat position on this platform. The a_{RMS} and f_{out} values were normalized by dividing them by the a_{RMS} and f_{out} values measured in the "unloaded condition".

f_{in}	a_{RMS} (in units g)			f_{out} (Hz)
	X-direction	Y-direction	Z-direction	
"Unloaded condition"				
s1	1.5	1.7	0.1	22
s3	**1.9**	**1.8**	**0.1**	**25**
s5	2.4	2.2	0.1	28
s7	**2.8**	**2.8**	**0.2**	**31**
s9	3.3	3.4	0.2	33
	a_{RMS}			f_{ratio}
	X-direction	Y-direction	Z-direction	
"Loaded condition"				
62 kg				
s1	0.7	0.6	2.1	1.0
s3	**0.9**	**0.6**	**2.9**	**1.0**
s5	0.9	0.6	4.3	1.0
s7	**0.9**	**0.7**	**7.2**	**1.0**
s9	0.9	0.7	7.6	1.0
81 kg				
s1	0.7	0.4	2.1	1.0
s3	**0.7**	**0.5**	**2.9**	**1.0**
s5	0.7	0.5	4.3	1.0
s7	**0.8**	**0.6**	**8.9**	**0.9**
s9	0.8	0.6	8.1	1.0
100 kg				
s1	0.5	0.6	2.1	1.0
s3	**0.7**	**0.5**	**2.9**	**1.0**
s5	0.8	0.5	3.6	1.0
s7	**0.8**	**0.6**	**5.0**	**0.9**
s9	0.9	0.7	7.6	1.0

3.2.3. *PowerMaxx*

The bottom panel of Fig. 3 shows an example of the platform accelerations at a preset setting S7. This setting corresponded to an f_{out} of 31 Hz. The overall findings of this device are listed in Table 3. The platform vibrated in the horizontal (*XY*) plane between 22 Hz (S1) and 32 Hz (S9). The a_{RMS} values in the vertical direction, between 0.1 and 0.2 units of g, were small compared to those in the horizontal *XY*-plane, between 1.5 and 3.4 units of g. The average platform displacement was in the *X*-direction 2.2 (0.01) mm peak-to-peak, in *Y*-direction 2.0 (0.05) peak-to-peak and in *Z*-direction 1.2 (0.02) mm peak-to-peak. When our volunteers of 62, 81 and 100 kg loaded this platform, the f_{out} values were within 6% comparable to those measured in the unloaded condition. However, the a_{RMS} values in vertical direction increased about eight times at preset S9, while the a_{RMS} values in the horizontal plane decreased. This was confirmed in the total displacement values: displacement in the *X*-direction decreased to 1.8 (0.1) mm peak-to-peak, in *Y*-direction to 1.4 (0.1) mm peak-to-peak and increased in *Z*-direction to 0.6 (0.1) mm peak-to-peak. The decrease in accelerations was thus more pronounced in *Y*-direction (up to 40%) than in *X*-direction (up to 25%). The magnitude of these changes seemed not to depend on the weight of the volunteers.

3.3. *Second measurement series (transmission of accelerations)*

Table 4 summarises the percentage of platform accelerations in vertical direction transmitted to the ankle, knee and hip joints of eight healthy volunteers who stood in squad position on each of the three tested devices. The platforms generated in unloaded condition vertical accelerations of 32 m/s^2 (PowerPlate (PP) "high" mode), 48.6 m/s^2 (Galileo (Ga)) and 1.4 m/s^2 (PowerMaxx (PM)). We calculated that the PowerPlate and Galileo transmitted 55 and 85% of the vibrations to the ankle, 9 and 8% to the knee and only 3 and 2% to the hip, respectively. Thus, the platform accelerations were 1.8 and 4.2 units of g at the ankle, respectively and less than ~0.45 units of g at the knee and ~0.15 units of g at the hip. Loading the PowerMaxx resulted in amplification of the accelerations in vertical direction, see also Table 3. We calculated that the vertical accelerations were at the ankle ~1 unit of g, at the knee ~0.2 units of g and at the hip ~0.1 units of g.

4. Discussion

4.1. *3-Dimensional platform accelerations*

Overall finding of the "unloaded condition" was that with increasing platform frequency, a large increase in vertical platform accelerations was measured in the PowerPlate (up to 8 units of gravitational force g) and in the Galileo (up to 15 units of g) and modest increase in horizontal platform accelerations in the PowerMaxx (up to 3.5 units of g). When we compare the three test devices at two common preset frequencies (25 and 30 Hz; printed bold in Tables 1–3), the Galileo is capable of producing the highest a_{RMS} values. Its magnitude, however, depends on the platform location, since it rotates around a central axis inducing pelvis and lumbar spine oscillations. This result, however, is different from

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Table 4
The percentage of vertical accelerations transmitted from the PowerPlate, Galileo and PowerMaxx platforms at 25 Hz to the ankle, knee and hip joints of eight healthy volunteers. The volunteers were instructed to maintain a fixed squad position with the feet 30 cm apart and the knees flexed at an angle α of 100° for at least 10 s. Summarised are the accelerations measured in vertical direction as a percentage of the "unloaded" platform acceleration at 25 Hz (PowerPlate 'high mode' 32 m/s^2, Galileo 48.6 m/s^2 and PowerMaxx 1.4 m/s^2).

nbr	Body weight (kg)	Ankle			Knee			Hip		
		PP	Ga	PM	PP	Ga	PM	PP	Ga	PM
a_{RMS} in vertical direction (%)										
1	63	59	101	610	11	6	90	2	2	60
2	80	23	41	360	8	10	140	3	2	90
3	63	52	70	890	6	6	130	3	2	100
4	75	67	111	980	9	6	190	3	4	60
5	100	89	113	1230	6	6	60	2	4	50
6	80	53	97	390	7	8	70	2	1	40
7	90	56	84	400	19	12	210	3	2	60
8	55	44	66	710	10	10	170	3	2	110
Mean	76	55	85	700	9	8	130	3	2	70
SD	15	19	25	320	4	2	60	1	1	25

PP = PowerPlate, Ga = Galileo-Fitness, PM = PowerMaxx.

the gravitational forces measured in a similar device, the Galileo 2000. It was shown, that increase in platform amplitude (1.25, 3 and 5.25 mm) only resulted in slight increase in g forces in vertical direction at platform frequencies of 10, 20 and 30 Hz, i.e. 9.67 units of g at 1.25 mm displacement and 10 Hz up to 10.88 units of g at 5.25 mm and 30 Hz [33] (Table 1). We firmly attached our accelerometers between foot position 3 and 4, at which the platform displacement was 3.5 mm. At this location, vertical accelerations ranged between 1 unit of g (10 Hz) and 7.9 units of g (30 Hz). We were not able to pinpoint the cause of these differences. It might be caused by differences in the linear accelerometers used (their 10 g versus our 50 g sensor), data analysis (their 6 Hz low pass Hamming filter versus our FFT analysis procedure) or measurement setup, but information on accelerometer attachment on the platform surface was missing. Our Galileo test device showed some resonance, but that was above 30 Hz. Platform displacement reduced and as a result the magnitude of the vertical accelerations. This device also showed moderate vibrations (~1–1.5 units of g) in the *X*-direction. The PowerPlate, on the other hand, induced very stable vibration patterns, i.e. its platform completely moved in vertical direction and showed very little horizontal vibrations. In the "high" amplitude mode, the a_{RMS} value was about half of that measured in the Galileo at a preset frequency of 25 Hz. The platforms of both these professional WBV devices mainly vibrated in vertical direction and loading both platforms did not influence their performance. The performance of the 'unloaded' PowerMaxx, however, was completely different from the two professional ones. The main accelerations (up to 3.5 units of g) were mainly in the horizontal plane. The a_{RMS} values in vertical direction were about a factor 7 less than that of the Galileo at comparable preset frequency. Loading this platform, however, altered vibrations primarily in the horizontal plane to vertical vibrations. It was suggested that this change in vibration direction is most likely caused by changes in the dynamics of the eccentric drive of the PowerMaxx and the added eccentricity of the body weight of the three volunteers. These altered properties, however, seemed not to depend on their weight. As we expected, each device has its specific properties, mainly in terms of accelerations (displacements).

4.2. Transmission of accelerations

It was previously shown that the magnitude of acceleration of the lumbar spine depended on the knee angle [10]. The highest accelerations of hip and lumbar spine were measured in upright position (knee in full extension), but these accelerations did not exceed 50% of the induced accelerations of the platforms with both knees in just 20° flexion. In that study, the accelerations were measured invasively. Others reported significantly greater vertical accelerations in squad position compared to standing postures [33]. It was speculated that greater muscle activation in this posture may increase total muscle stiffness, thereby enhancing the force transmission. We found in squat position that the transmission of vertical accelerations at a preset vibration frequency of 25 Hz was largest in the ankle and that transmission reduced ~6–10 times at the knee and hip. We calculated that the PowerPlate and Galileo transmitted 1.8 and 4.2 units of g at the ankle, respectively and less than ~0.45 units of g at the knee. Although loading the PowerMaxx resulted in amplification of the accelerations in vertical direction, the vertical accelerations were at the ankle ~1 unit of g and at the knee ~0.2 units of g. This indicates that storage of the vibration energy was mainly limited to the lower legs. This damping effect at frequencies >20 Hz has been reported by many others as well [32,33,18,36]. It was also shown that the transmission of vibration to the head, expressed as a transmissibility factor, decreased rapidly for frequencies >15–20 Hz [18]. These results suggest that no enhancement of muscle power can be expected in the upper body. A special point of concern is whether the head is free from vibrations or not during a WBV exercise. Although accelerations are small, it may induce high gain vestibular responses that alter visual perception and/or balance [37]. Especially in elderly, this might negatively influence the fall risk during or shortly after a WBV exercise. From a safety point of view, it has been suggested that the frequencies in vibration training for various groups should be higher than 20 Hz to avoid vibration of the head by resonance frequencies of the human body [18,33]. Furthermore, typical WBV training regimens (30 Hz, 10 min per day) exceed the recommended daily vibration exposure as defined by ISO 2631-1 and is thus potentially harmful to the human body [35,38]. Potential hazard for the fragile human musculoskeletal system may also exist at amplitudes greater than 0.5 mm due to great peak accelerations [36]. The results of the present study suggest that short training sessions on a PowerMaxx would comply with most of these safety rules stated. Its minimum vibration frequency is 22 Hz, its platform displacements are ~0.6 mm and its (vertical) acceleration are within 2 units of g. Potential hazard of this device, however, could be the large accelerations in the horizontal plane (up to 3 units of g). More research needs to be done to test the impact of these vibrations on the human musculoskeletal system. Finally, it was reported that transmission of vibration to the human body is a complicated phenomenon due to nonlinearities in the musculoskeletal system, meaning that sinusoidal waveform in terms of amplitude and frequency is modified at higher body segments [36]. We were able to partly confirm these findings in our data set. The vibration frequencies at the level of the ankle, knee and hip were within 5% comparable to the preset frequency of 25 Hz in all test persons on each tested device. However, the fit errors cal-

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culated by fitting a sine function through the vertical accelerations signals increased from ∼4% at the level of the ankle to ∼30% at the level of the hip, even regardless of the test device used, confirming this nonlinear behaviour past the knee. It should be noted that the platforms may induce substantial rotational vibration as well, especially the PowerMaxx may induce these vibrations around the vertical axis, although the vibrations along the translational axes alone were characterized. The human muscles response, however, also to rotational vibrations. Although the effects of rotational vibrations are not known, whether beneficial or detrimental, these may also have contributed to activation of some of the muscles in the lower and upper legs and pelvis region.

4.3. Study limitations

We measured rather high accelerations (maximum of ∼15 units of g) using a 50 g accelerometer. Calibration of this sensor, however, was based on a two point calibration procedure, i.e. zero gravity and only 1 unit of g, which places the correctness of the measured acceleration under debate. The large accelerations in the first measurement series were measured with the sensors placed in the container that could be perfectly aligned to the platform's surface in all three dimensions, allowing sensitive and correct calibrating of the individual sensors. In a previous report using a vertical vibration platform (similar to the PowerPlate we used), it was shown that given a peak-to-peak amplitude of a vertical vibration of 2 mm, the theoretical maximal accelerations would be ∼2.5 units of g at 25 Hz, 3.6 units of g at 30 Hz, 4.9 units of 9 at 35 Hz and 6.4 units of g at 40 Hz [19]. These theoretical values are ∼15% higher at $f_{out} > 30$ Hz than we measured at the PowerPlate platform. We calculated, however, not the maximum acceleration values but the root mean square acceleration values. In addition, the peak-to-peak displacements of the PowerPlate platform were calculated ∼10% higher (2.2 mm versus 2.0 mm), which presumably caused higher accelerations in the PowerPlate, see also Eq. (4). When we take these aspects into account, we conclude that the absolute magnitude of the accelerations might be a bit too high compared to theoretically expected values but accurate enough for comparison between the devices. Vertical alignment of the accelerometer to the ankle, knee and hip was much more complicated in the second series of measurements. No doubt that the two point calibration a these locations was less accurate, but the maximum accelerations measured in this series did not exceed 4 units of g.

It has been reported that measurement of acceleration with skin mounted accelerometers can be subject to inaccuracy as well, because of the movement of skin and soft tissues [28]. Probably, the foam tape to securely attach the sensor to the skin reduced the amplitude of the displacement and thus the acceleration to some extend. Not only reliable mounting of the accelerometer, but also inter-subject variability is expected to have substantial impact on the measurements accuracy, as shown by others [29,32,36]. The measurements were not repeated within each subject for a test–retest analysis to avoid an ‘overload’ of WBV. Indeed, the results in our subject did show rather large variations too. When realizing that individual responses may be large, we must be careful in prescribing unified physically tolerable protocols for WBV. One of our future aim is training of lower limb muscles. We therefore altered the knee angle α of 150° in the first measurement series (small head oscillations) to a knee angle of 100°. This position is known to be optimum for triggering and training of the main lower leg muscle, i.e. Quadriceps Muscle [34,39]. It could be that the outcome of the second series might change when squat position (thus knee angle) of each subject is altered. Position, however, was not directly related to our main research question. Based on the presented results, we think that posture only slightly influences platform properties of the PowerPlate and the Galileo. These two devices have shown robust mechanical properties. The platform properties of the PowerMaxx, however, may depend to some extend to differences in posture, but more research is needed to test this property.

We conclude that large variation in 3-dimensional accelerations exist in commercially available devices. The results of the present study suggest that these differences in mechanical behaviour induce variations in transmissibility of vertical vibrations to the (lower) body. We too support the call for biomechanical and/or biological markers that may determine correct timing of a vibration overload stimulus for assisting safe and effective use of WBV as a rehabilitation and training tool [33].

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Conflict of interest statement

All authors disclose any financial and personal relationships with other people or organisations that inappropriately influence (bias) this work.

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