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Transmission of Whole Body Vibration – Comparison of Three Vibration Platforms in Healthy Subjects

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Abstract

The potential of whole body vibration (WBV) to maintain or enhance musculoskeletal strength during ageing is of increasing interest, with both low and high magnitude WBV having been shown to maintain or increase bone mineral density (BMD) at the lumbar spine and femoral neck. The aim of this study was to determine how a range of side alternating and vertical WBV platforms deliver vibration stimuli up through the human body.

Motion capture data were collected for 6 healthy adult participants whilst standing on the Galileo 900, Powerplate Pro 5 and Juvent 100 WBV platforms. The side alternating Galileo 900 WBV platform delivered WBV at 5-30Hz and amplitudes of 0-5mm. The Powerplate Pro 5 vertical WBV platform delivered WBV at 25 and 30Hz and amplitude settings of 'Low' and 'High'. The Juvent 1000 vertical WBV platform delivered a stimulus at a frequency between 32-37Hz and amplitude 10 fold lower than either the Galileo or Powerplate, resulting in accelerations of 0.3g. Motion capture data were recorded using an 8 camera Vicon Nexus system with 21 reflective markers placed at anatomical landmarks between the toe and the forehead. Vibration was expressed as vertical RMS accelerations along the z-axis which were calculated as the square root of the mean of the squared acceleration values in g.

The Juvent 1000 did not deliver detectable vertical RMS accelerations above the knees. In contrast, the Powerplate Pro 5 and Galileo 900 delivered vertical RMS accelerations sufficiently to reach the femoral neck and lumbar spine. The maximum vertical RMS accelerations at the anterior superior iliac spine (ASIS) were 1.00g ±0.30 and 0.85g ±0.49 for the Powerplate and Galileo respectively. For similar accelerations at the ASIS, the Galileo achieved greater accelerations within the lower limbs, while the Powerplate recorded higher accelerations in the thoracic spine at T10.

The Powerplate Pro 5 and Galileo 900 deliver vertical RMS accelerations sufficiently to reach the femoral neck and lumbar spine, whereas the Juvent 1000 did not deliver detectable vertical RMS accelerations above the knee. The side alternating Galileo 900 showed greater attenuation of the input accelerations than the vertical vibrations of the Powerplate Pro 5. The platforms differ markedly in the transmission of vibration with strong influences of frequency and amplitude. Researchers need to take account of the differences in transmission between platforms when designing and comparing trials of whole body vibration.

Key Terms

Whole Body Vibration, Osteoporosis, Powerplate Pro 5, Galileo 900, Juvent 1000, Transmission

Abbreviations

Anterior Superior Illiac Spine (ASIS), Bone Mineral Density (BMD), Customary Strain Stimulus (CSS), Root Mean Squared (RMS), Whole Body Vibration (WBV), World Health Organisation (WHO)

Conflicts of Interest

The authors L.S., L.Y., J.M.W. and E.V.M. have no conflicts of interests to declare.

1. Introduction

Low bone mineral density (BMD) is the characteristic feature of osteoporosis and contributes to fracture occurrence in ~50% of women and ~20% of men after the age of 50 [1]. Skeletal fragility can result in 'low energy' fractures, quantified by the World Health Organization (WHO) as those due to forces equivalent to a fall from a standing height or less. This is especially true in the hip or vertebra, where fractures in turn result in increased mortality and morbidity [2]. As age is an independent risk factor for osteoporosis [2], the ageing population seen in developed and developing countries presents a public health challenge. As such, increasing BMD in older age is essential to attenuate osteoporotic onset. The most widely prescribed pharmaceutical therapies reduce overall fracture risk by less than 50%, and therefore alternative or complementary treatment approaches are required [3,4].

Increased physical activity has been proposed as a potential intervention to prevent osteoporotic fracture [5], however, the optimum osteogenic mechanical stimulus is yet to be defined. The use of whole body vibration to deliver low magnitude, high frequency loading has shown some promise as an intervention for osteoporosis [6]. If these vibrations prove osteogenic, this is an attractive prospect for use as an intervention for people at risk of fragility fracture, as the magnitude of the force exerted on the skeleton (and subsequent fracture risk) can be kept minimal whilst providing a novel, osteogenic stimulus.

Transmission of WBV has been shown to be inversely related to knee flexion angle and frequency of vibration[7–9] , with reduced transmission to the torso compared to that at input and in the lower body [10–12].However, WBV signals have been recorded at the level of the femoral neck and lumbar spine or above, supporting the notion that low magnitude WBV can provide a novel mechanical stimulus at sites where BMD increase would be beneficial to osteoporotic patients [7,8,10–13].

Initial small cohort studies have shown changes in BMD from baseline at the femoral neck and spine to be achieved through application of WBV at accelerations <0.3 g, with BMD increases between 2-2.17% at the femoral neck and 1.5-4.77% at the lumbar spine [14–16]. Similarly, higher magnitude vibration at a similar frequency to the aforementioned studies, also indicated an improvement in BMD at the lumbar spine (+6.2%) and femoral neck (+4.9%) in postmenopausal osteoporotic women [17] and there are indications that higher magnitude vibration prevents bone loss due to unloading and in postmenopausal cohorts [18,19]. Randomised control trials of WBV have also support musculoskeletal benefits, including increased BMD, along with improved strength and balance in postmenopausal populations [20–22].

However, the studies to date have generally been performed on small samples and have used different platforms, frequencies and amplitudes, generating different accelerations.

With differing protocols and outcome measures, comparison and concrete conclusions on the efficacy of WBV are difficult to draw [6].

The data generated in this study aims to inform future protocols used to deliver WBV to skeletal sites of interest in the treatment of osteoporosis, using a safe approach with osteogenic potential. It is envisaged this will form the basis for future trials of WBV as a healthcare intervention, allowing greater alignment of protocols and a critical mass of data to support development of suitable treatment regimes.

This study aims to present proof of concept that motion capture systems can provide sensitive detection of WBV and provide preliminary data of transmission throughout the human body by three commonly studied WBV platforms. Whilst previous studies have focused on the effect of posture on transmission of WBV, this study will compare the vertical transmission of WBV of different frequencies and amplitudes without prescribed joint angle, as may be expected if WBV were used in a clinical setting. We hypothesise that transmission of WBV will decrease as frequency of WBV increases, as has previously been reported using accelerometer data. In addition, given the previous reports of increased BMD at the femoral neck and lumbar spine in response to WBV, we expect detection of accelerations at the level of the anterior superior iliac spine and sacrum, used as surrogates for this region.

2. Method

2.1 Participants

Ethical approval was granted by the University of Sheffield ethics panel along with health research authority approval from Leeds (East) Research Ethics Committee.

Informed consent was obtained from six healthy male participants aged between 18 and 50 years (mean ± SD = 29 ± 12 years) who were recruited through advertisement across University of Sheffield and Sheffield Teaching Hospitals NHS trust sites.

Participants were excluded from the study if they had a history of disease affecting the skeletal system, prior fractures in the spine, hip, leg or foot, or use of medications known to affect the skeletal system. Exclusion criteria also included being diabetic, having cancer within 5 years, epilepsy, conditions affecting vision or balance, alcohol or drug abuse, or sensitivity to antibiotics or anaesthetic.

2.2 WBV Platforms

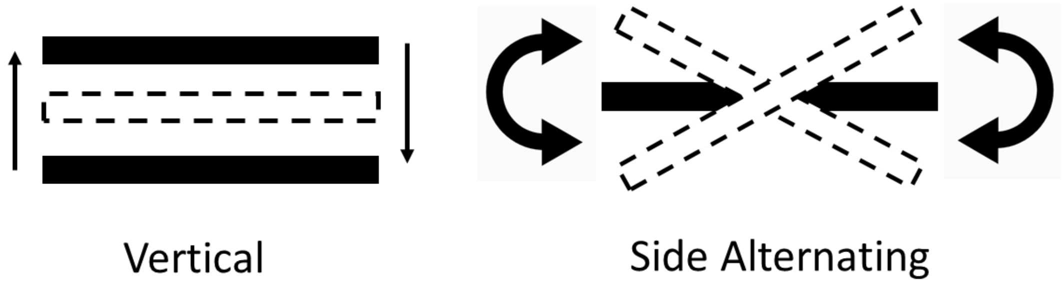

Figure 1: Types of Whole Body Vibration (WBV). Vertical WBV comprises vertical motion of the platform whilst side alternating WBV comprises alternating vertical left and right motion above/ below a fixed starting position.

Transmission of vertical root mean squared (RMS) accelerations along the z-axis, delivered by three different WBV platforms, was analysed. The Galileo 900 platform delivered side alternating (Figure 1) WBV at amplitudes of 0, 1, 3 and 5 mm and frequencies of 5-30 Hz at increments of 5 Hz. To achieve the different amplitudes the participant changed the spacing of their feet on the platform to align with marked increments of amplitude. The Powerplate Pro 5 platform delivered vertical WBV at amplitudes defined by the manufacturer as ‘Low’ (measured to be smaller than the 0.6 mm threshold of our system) and ‘High’ (measured to have a mean of 1.09 mm) and frequencies of 25 Hz and 30 Hz. Both the amplitude and frequency were changed using the electronic platform settings. The Juvent 1000 platform delivered vertical WBV at amplitudes 10 fold lower than either the Galileo 900 or Powerplate Pro 5, at a frequency between 32 Hz and 37 Hz. The outcome was an acceleration of 0.3 g.

All recordings were made with participants maintaining a bilateral stance with knees slightly bent. Knee angle was at the discretion of the participant and the stance adopted was directed to be ‘comfortable’ for the participant, observationally all participants adopted a stance with knee angle between 0-90 degrees.

2.3 Measuring vibration transmission

The Vicon motion capture system used for this study was set up to record gait in patients attending the Northern General Hospital Sheffield. It comprised 8 MX-F40 cameras, designed to capture light reflected from anatomical markers, positioned around the gait laboratory at the Northern General Hospital covering a capture volume of 77 m^3. Calibration of the system required 3000 data points to be captured by each camera during dynamic calibration using a calibration wand with reflective markers designed for this purpose. Data acquisition was made using Vicon Nexus software recording at a rate of 300 Hz with a minimum of three cameras required to start a trajectory and two to continue a trajectory.

Frequency (Hz)	Mean Vertical RMS Acceleration (g)	Standard Deviation	Significance in between session ANOVA (P)
5	0.36	0.015	S1 vs S5 P=0.034 S3 vs S5 P=0.034
10	1.38	0.056	S1 vs S5 P=0.024 S2 vs S5 P=0.032 S3 vs S5 P=0.040
15	3.13	0.096	S1 vs S5 P=0.005 S2 vs S5 P=0.008 S3 vs S5 P=016 S4 vs S5 P=0003 S6 vs S5 P=001
20	5.62	0.291	No significant differences P=0.150
25	8.67	0.319	S1 vs S5 P=0.017 S3 vs S5 P=0.021 S4 vs S5 P=0.037 S6 vs S5 P=0.033
30	12.02	0.491	No significant differences P=0.631

Table 1: Repeatability of measures using the Vicon motion capture system. Recordings made from a single marker attached to the moving base of the Galileo 900 during vibration at 5, 10, 15, 20, 25 and 30Hz. Recordings were made in 6 separate sessions each of different days, with four repeats made during each of the first 5 sessions and three in the sixth session due to technical difficulties in the 4th recording resulting in artefact. S1=session 1, S2 = session2, S3 = session 3, S4 = session 4, S5 = session 5, S6 = session 6. Significance between session determined using a One-way ANOVA with Dunnett's T3 with significance level P<0.05.

Reliability of data were considered, with recording of accelerations at a given marker required in a minimum of 3 out of 6 participants for inclusion in analysis.

The motion capture system measured displacements repeatably, showing small standard deviations and repeatability across most sessions, only showing significant difference in vertical RMS accelerations generated at the platform between session 5 and several other sessions (Table 1). The motion capture technique was accurate to 0.6 mm as confirmed through analysis of differences in distances between markers in a fixed position (Table 2). Data for inclusion was determined based on this 0.6 mm limit, with peak-to-peak displacements smaller than this being attributed to system noise and removed before analysis.

	Marker Pair 1	**Marker Pair 2**	**Marker Pair 3**	**Marker Pair 4**
Average Distance Between Markers (mm)	0.50	0.45	0.53	0.50
Maximum Distance Between Markers (mm)	0.55	0.55	0.6	0.50
Standard Deviation	0.02	0.05	0.03	0.01

Table 2: The change in distance between markers during Galileo 900 movement. Marker pair 1: markers on 1mm left and right positions. Marker pair 2: markers on 2mm left and right positions. Marker pair 3: markers on 4mm left and right positions. Marker pair 4: markers on 5mm left and right positions. Recordings of each pairing were made at 5, 10, 15, 20, 25 and 30Hz. The average greatest change in distance between the markers, standard deviation of the average greatest change and maximum change in distance between the markers across all recordings are reported here.

9mm reflective markers, mounted on a base which was 14mm in diameter and 2mm in depth, were attached using double sided tape to 21 anatomical landmarks throughout the body which are required under normal use for assessment of gait in patients (Figure 2).

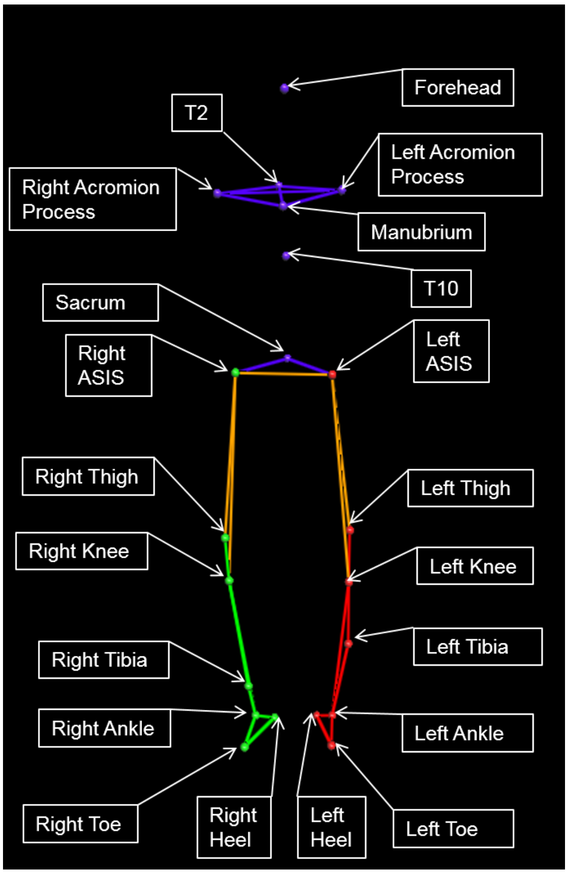

Figure 2: Reflective marker locations: Positions of the 21 reflective motion capture markers placed at anatomical landmarks throughout the body. ASIS = Anterior Superior Iliac Spine. T2 and T10 refer to the second and tenth thoracic vertebrae respectively.

Markers were grouped for discussion into lower limb (referring to all markers from the heels up to the anterior superior iliac spine (ASIS)) or torso (markers from the sacrum up to the forehead). Raw trajectories were exported to an excel spreadsheet (Microsoft 2010). Data for each marker were then filtered in Matlab 2007b using a bandpass filter, with cut-offs dependent upon frequency (Table 3).

Freq. Input	Freq. 1 (Hz)	Freq. 2 (Hz)
5Hz	2.2	25
10Hz	4.5	35
15Hz	8	48
20Hz	11	60
25Hz	15	70
30Hz	18	80

Table 3: Specification of the Bandpass Butterworth filters for each input frequency. The Bandpass Butterworth filter cut off frequencies (Freq.1 = Frequency cut off 1, Freq. 2= Frequency cut off 2) are shown for each frequency at input (Freq. input = Frequency of Input whole body vibration).

Filtered data were cropped to encompass only a period of recording at which the WBV was at a consistent frequency and amplitude.
The cropped data files were imported into Matlab 2007b and the maximum and minimum points of each vibration cycle were determined using an in house program.

Peak to peak displacements which show the distance moved by the marker along the z-axis for each vibration cycle were determined using the minimum and maximum points of the trajectories (Equation 1).

***Equation 1**: The Peak to Peak Displacement of a given vibration cycle:*

$$P2P\ Displacement = Maximum\ point\ \ of\ trajectory - minimum\ point\ of\ trajectory$$

Vertical accelerations along the z-axis were calculated as the second derivative of the marker position data (Equation 2). Accelerations were converted from meters per second squared to gravitational acceleration (g) through division by 9.81 m/s^2. The accelerations in g were squared, the mean squared value for each recording session was calculated and square root of these values used to report Root-mean-square (RMS) accelerations for each platform setting./

***Equation 2:** Calculating Acceleration*

$$First\ Derivative\ (velocity, m/s) = \frac{\Delta d}{t}$$

$$Second\ Derivative\ (acceleration, m/s^2) = \frac{\Delta v}{t}$$

(t=time in seconds, d=distance moved by the marker between data capture points, v=velocity) Root-mean-square (RMS) acceleration along the z-axis was calculated as the square root of the mean of the squared acceleration values in g.

Statistical analysis was performed using IBM SPSS 23. Differences in vertical RMS acceleration along the z-axis were analysed using One-Way ANOVA with Dunnett’s T3 post hoc test. Alpha was set *a priori* at P<0.05. Effect size is reported as Cohen’s d and was calculated using the RStats MOTE effect size calculator [23].

3. Results

3.1 Demographics

Six male participants aged between 18 and 50 years (mean ± SD = 29 ± 12 years) at the consent visit, were recruited to the study. Participants were ambulatory, generally healthy (as assessed by medical history and physical examination) and were physically willing and able to undergo all study procedures. All participants had a BMD measured by DXA (T score mean ± SD = -0.73 ± 0.46 at the spine and 0.35 ± 0.38 at the hip) within the young normal range and had a BMI less than 30kg/m^2 (Table 3).

Participant	BMI (kg/m^2)	T-Score Spine	T-Score Hip
1	21.7	-1.3	-0.4
2	24.2	-0.9	0.6
3	28.9	-0.3	0.3
4	22.1	-1.3	-0.3
5	21.4	-1.2	-0.5
6	22.5	-0.2	0.5

Table 4: BMI and BMD values of the six participants enrolled on the study.

The Powerplate Pro 5 delivered vertical RMS accelerations at the level of the platform between 1.64 g and 3.39 g. The Juvent 1000 low magnitude WBV delivered a vertical RMS acceleration of 0.34 g at input and the Galileo 900 which is capable of delivering a range of low to high magnitude WBV delivered vertical RMS accelerations of between 0.09 g and 10.59 g at input.

3.2 Maximum accelerations at the Sacrum and Anterior Superior Iliac Spine

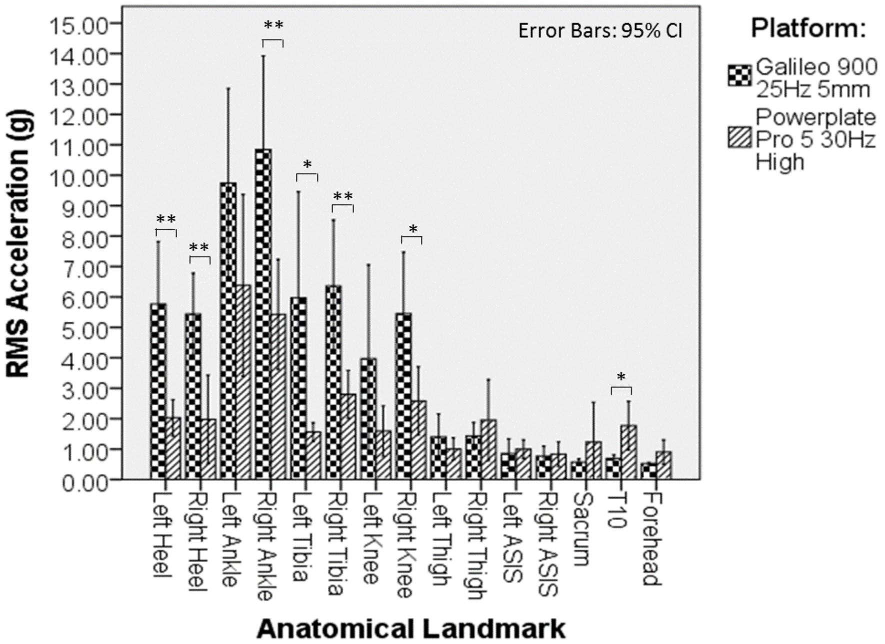

Figure 3: Galileo 900 and Powerplate Pro 5 Maximum vertical RMS Accelerations at the ASIS and Sacrum. Vertical RMS accelerations throughout the body at platform settings which generate the greatest vertical RMS accelerations at the Anterior Superior Iliac Spine and Sacrum using the Galileo 900 and Powerplate Pro 5. Differences in vertical RMS acceleration analysed using One-Way ANOVA with Dunnett's T3 post hoc test, P<0.05*, P<0.01**, P< 0.001***.

There was no significant difference in the maximum vertical RMS acceleration delivered to the ASIS or sacrum when comparing the maximum vertical RMS accelerations delivered by the Powerplate Pro 5 and Galileo 900 (Figure 3) (Left ASIS P= 0.567, Cohen's d= -0.39, Right ASIS P=0.724, Cohen's d= -0.24, Sacrum P=0.206, Cohen's d = -1.30). However, the vertical RMS accelerations at input used to achieve the maximum vertical RMS accelerations at the sacrum and ASIS are different, with the Powerplate Pro 5 at 30Hz High generating input vertical RMS accelerations of 3.39 g and the Galileo 900 at 25 Hz 5mm generating input vertical RMS accelerations of 10.59 g. This is reflected by significantly greater accelerations at the heel (Left Heel P=0.04, Cohen's d=2.59, Right Heel P=0.001, Cohen's d=2.81) observed using the Galileo 900 and also results in greater vertical RMS accelerations experienced in the lower limb when using the Galileo 900 to generate maximum accelerations at the ASIS and sacrum compared to the Powerplate Pro 5 (Figure 3) (Right Ankle P=0.003, Cohen's d=2.25, Left Tibia P=0.023, Cohen's d=1.77, Right Tibia P=0.003, Cohen's d=2.29, Right Knee P=0.01, Cohen's d=1.84).

In the torso, vertical RMS accelerations were only observed at T10 and the forehead when platform settings delivered the maximum vertical RMS accelerations at the ASIS and sacrum. These vertical RMS accelerations were significantly greater at T10 when using the Powerplate Pro 5 rather than the Galileo 900. At the forehead there was no significant difference between vertical RMS accelerations delivered by either platform using these settings.

3.3 Platform settings generating similar accelerations at input

Platform Settings (Galileo 900 vs Powerplate Pro 5)	Galileo 900 Vertical RMS Acceleration (g)	Powerplate Pro 5 Vertical RMS Acceleration (g)
20Hz0mm vs 25Hz Low	1.39	1.64
20Hz1mm vs 30Hz Low	2.26	2.03
15Hz5mm vs 25Hz High	2.90	3.12
30Hz0mm vs 30Hz High	3.42	3.39

Table 5: Powerplate Pro 5 and Galileo 900 platform settings which produce similar input accelerations.

Similar accelerations at input could be achieved using the Galileo 900 and Powerplate Pro 5 at the settings outlined in Table 5.

Few differences in accelerations at any marker were observed when input accelerations were similar on the Powerplate Pro 5 or Galileo 900. Where there was a significant difference, this tended to be due to higher accelerations observed in the lower limb when the Galileo 900 was set to 15Hz5mm (Left Thigh P=0.002, Cohen’s d= 2.85, Right Thigh P=0.0001 Cohen’s d= 3.57), or at the ASIS and T10 in participants stood on the Powerplate Pro 5 (20Hz1mm vs 30HzLow: Left ASIS P=0.01, Cohen’s d=-0.34, T10 P=0.008, Cohen’s d= -2.69, 15Hz5mm vs 25HzHigh : T10 P=0.003, Cohen’s d= -0.89, 30Hz0mm vs 30HzHigh: T10 P=0.031 , Cohen’s d= -2.04) (Figure 4, Figure S4).

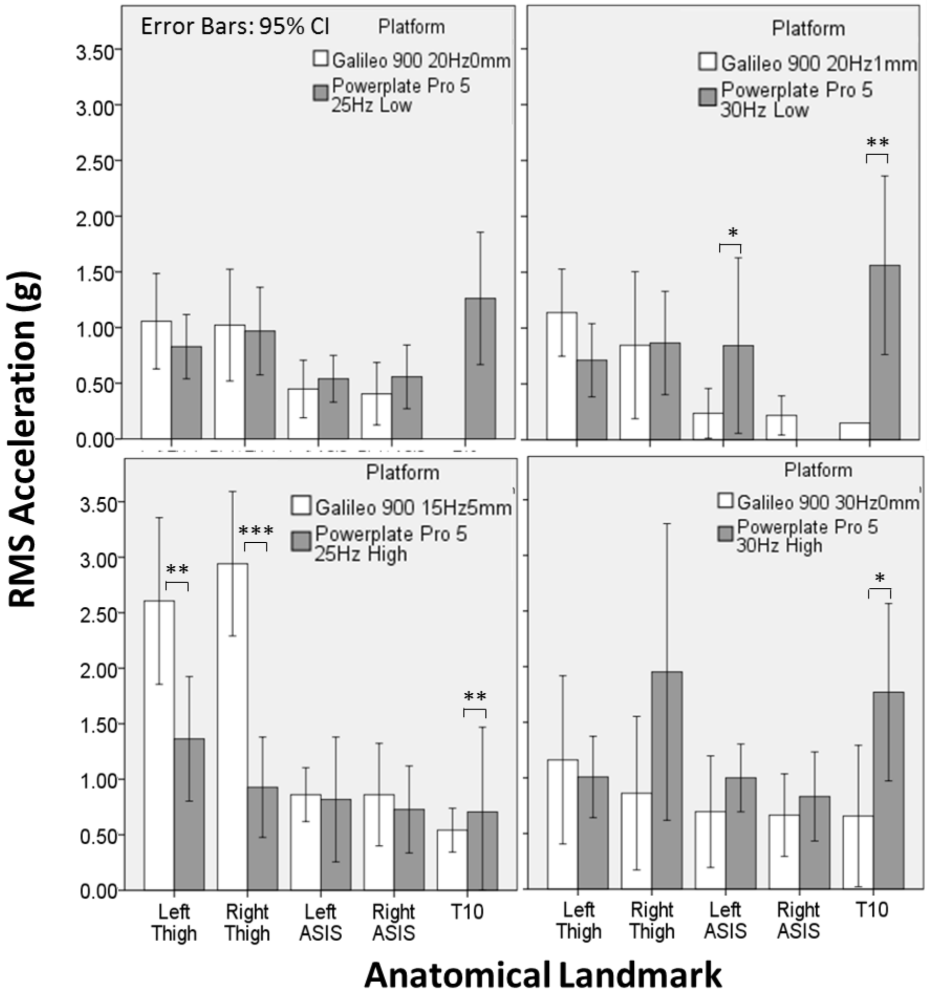

Figure 4: Comparison of Galileo 900 and Powerplate Pro 5 Accelerations. Vertical RMS accelerations delivered to the Thigh, Anterior Superior Iliac Spine (ASIS) and T10 when similar input accelerations are achieved using the Galileo 900 and Powerplate Pro 5. Missing bars represent anatomical locations where no data was recorded on one of the platforms. Few significant differences are seen at 'Low' amplitude and input accelerations. When the Powerplate Pro 5 setting is 'High', greater accelerations at the thigh are seen using the Galileo 900 with similar input, whereas greater accelerations at ASIS and T10 are observed using the Powerplate Pro 5. Differences in vertical RMS acceleration analysed using One-Way ANOVA with Dunnett's T3 post hoc test, P<0.05*, P<0.01**, P< 0.001***.

Occasional differences were seen in the lower limb with the Powerplate Pro 5 generating greater vertical RMS accelerations (20Hz0mm vs 25Hz Low: Left Ankle P=0.018, Cohen's d= -1.38, Right Tibia P=0.01, Cohen's d=-1.66, Right Knee P=0.008, Cohen's d=-1.73, 30Hz0mm vs 30Hz High: Right Knee P=0.04, Cohen's d= -1.36) (Figure S4). In the torso, accelerations are observed more frequently and tend to be greater when delivered using the Powerplate Pro 5, suggesting vertical WBV transmits accelerations further through the body than side alternating WBV (Figure S4).

In contrast to the above, greater accelerations are observed in the lower limb and torso using the Galileo 900 at 15 Hz 5 mm, compared to the similar input of the Powerplate Pro 5 at 25 Hz High (Left Heel: P=0.013, Cohen's d=1.64, Left Tibia: P=0.006, Cohen's d= 1.91, Left

Knee: P=0.001, Cohen’s d=2.65, Right Knee: P=0.05, Cohen’s d=1.22, Left Thigh: P=0.002, Cohen’s d=2.85, Right Thigh: P=0.0001, Cohen’s d=3.57) (Figure 4, Figure S4), with the exception of accelerations at the ASIS and sacrum where no difference was observed.

3.4 Juvent 1000 and Galileo 900 (5Hz5mm, 10Hz0mm)

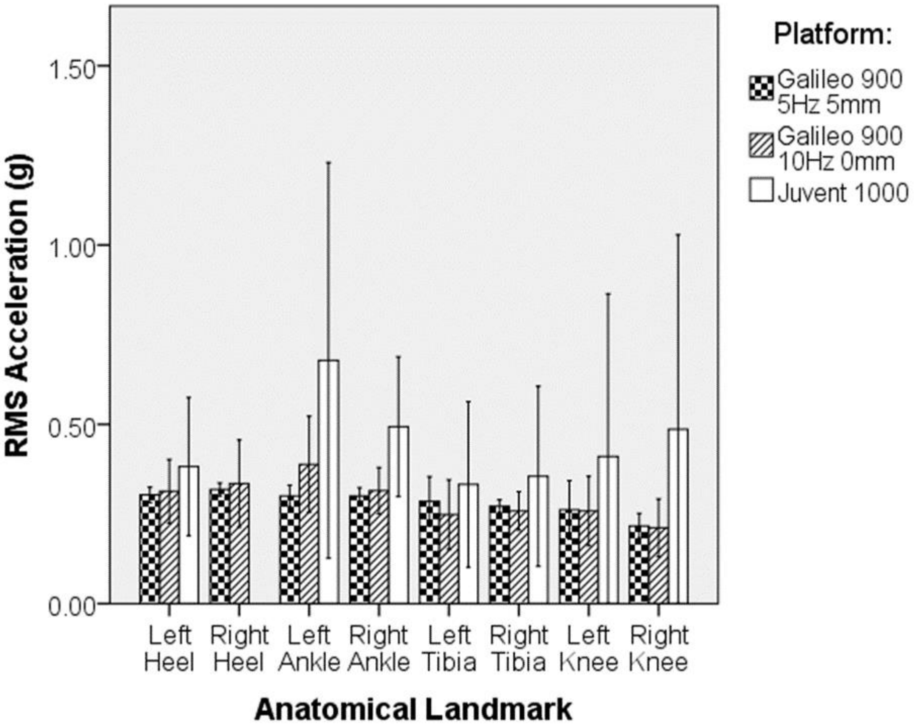

Figure 5: Comparison of Galileo 900 and Juvent 1000 Accelerations. Vertical RMS Accelerations delivered by the Juvent 1000 and Galileo 900 at similar input accelerations. Differences in vertical RMS acceleration analysed using One-Way ANOVA with Dunnett’s T3 post hoc test.

When vertical RMS accelerations at input are similar for the Juvent 1000 and Galileo 900 (0.34 g and 0.3 g respectively), vertical RMS accelerations were not detected reliably above the knee, however at the Ankle, Tibia and Knee, vertical RMS accelerations were recorded between 0.21g -0.68 g (Figure 5). Accelerations in the lower limb do not differ significantly between the platforms or settings. The low magnitude WBV delivered by the Juvent 1000 was not reliably detected as vertical RMS accelerations at the level of the ASIS or sacrum.

3.5 The outright maximum accelerations throughout the body

Platform	Frequency (Hz)	Amplitude	Maximum vertical RMS Acceleration (g)	Anatomical Landmark
Galileo 900	5	5mm	12.87	Right Ankle
Powerplate Pro 5	30	‘High’	6.38	Left Ankle
Juvent 1000	32-37	10 fold lower than Galileo/ Powerplate	0.68	Left Ankle

Table 6: Maximum vertical RMS acceleration recorded at any landmark using any frequency and amplitude available on each of the Galileo 900, Powerplate Pro 5 and Juvent 1000.

The maximum vertical RMS accelerations at any anatomical landmark were recorded at the Ankle, with the Galileo 900 generating the greatest value (Table 6). The greatest acceleration generated by the Galileo 900 was twice that generated by the Powerplate Pro 5. The greatest acceleration generated by the Juvent 1000 was ten fold smaller than that generated by the Powerplate Pro 5.

4. Discussion

Increased physical activity has been proposed as a potential intervention to prevent osteoporotic fracture[5]. Novel forces experienced by the skeleton affect bone modelling, altering the bone surface shape and strengthening bone to withstand load[24]. Forces can be considered novel in magnitude, frequency of mechanical load, number of cycles of loading, duration of loading, and rest between cycles of loading, each component contributing to the osteogenic potential of a given mechanical load [25–31].This study shows the Powerplate Pro 5 and Galileo 900 deliver vertical RMS accelerations with osteogenic potential to areas at risk of osteoporotic fracture (represented by markers at the thigh, ASIS, sacrum and T10), while the Juvent 1000 may deliver accelerations to these areas indirectly or at a level below the detection threshold of our system.

Both the Powerplate Pro 5 and Galileo 900 achieved maximum accelerations at the ASIS and sacrum that did not differ significantly (Figure 3). However, greater transmission of accelerations throughout the body, in particular to the torso, were generally seen using the Powerplate Pro 5 when input frequencies for each platform were similar (Figure 4, Figure S4). Similarity in maximum vertical RMS accelerations could be explained by greater input accelerations but lesser transmission of the side alternating Galileo 900 WBV to these sites, as one of the aims of designing the Galileo 900 to replicate human gait is to minimise vertical transmission along the z-axis to the spine and head [32,33].

In contrast to the above, greater accelerations are observed in the lower limb and torso using the Galileo 900 15Hz 5mm, compared to the similar input of the Powerplate Pro 5 at

25 Hz High (Figure 4, Figure S4), with the exception of accelerations at the ASIS and sacrum where no difference was observed.

This could be explained by differences in platform performance between unloaded platforms used to determine input accelerations and loaded platforms during participant data collection, however the small number of differences observed at the other input settings suggests this is unlikely or at least inconsistent. A second explanation could be differences in calibration between days of data collection, however this would be expected to affect all platforms, negating any significant differences between platforms. Finally, the greater accelerations could be due to the frequency of the vibration delivered. Resonant frequencies of the human body have been reported in the range of 5-16 Hz [34–36] however, many of these studies have been conducted with participants in a seated position and measurements have not been specific to the lower limb, concentrating on the neck and head in some cases. The 15 Hz value reported here does lie within this range and was the only frequency at which participants reported discomfort, suggesting a difference in accelerations delivered at this frequency. However, it is equally likely that the discomfort felt may have caused adjustment of foot position which determines the amplitude of vibration on the Galileo 900, thus resulting in input accelerations greater than those measured with markers placed on the platform or those delivered by the Powerplate Pro 5.

In the case of the Juvent 1000, platforms delivering WBV at similarly low magnitudes have been shown to increase or maintain BMD in both pre and postmenopausal populations [14–17]. However, vertical RMS accelerations were not detected at the ASIS or sacrum in this study (Figure 5), a potentially confounding result if WBV is required to directly stimulate the bone in order to have an osteogenic response.

This finding is likely a limitation of the motion capture system which was found to have a limit of 0.6mm for accurate detection of movements. The Juvent 1000 is expected to produce peak to peak displacements in the region of 0.1 mm in order to generate peak accelerations of 0.3 g at a frequency between 32-37 Hz, therefore it is possible that transmission to these sites is below the level of detection. An alternative method to detect accelerations would be the use of accelerometers, however the limit of detection of the most commonly used accelerometers to collect data on locomotor activities are accelerations at 25 Hz as they use a sampling frequency of 50 Hz [37–39].This would not encompass the frequency of the accelerations detected during this study and whilst it is possible to increase the sampling rate when recording for shorter periods to capture higher frequencies[40], motion capture allows collection of data from multiple landmarks more readily than the alternative of using wired accelerometers, at the expense of sensitivity to the lowest magnitude WBV such as that generated by the Juvent 1000.

Alternatively, this could be a true representation of the transmission of low magnitude WBV to the ASIS and sacrum. Vertical RMS accelerations were detected at the Ankle, Tibia and Knee, therefore stimulation of the femur, for which no direct measure was made, could have been elicited by muscles which originate at the femur but insert in the regions surrounding the ankle, tibia and knee. The quadriceps muscles, biceps femoris, popliteus, gastrocnemius and plantaris are all candidates for transmission of a stimulus to the femur, potentially of small enough magnitude to be below detection on the surface of the skin at the ASIS and sacrum. Small magnitude accelerations may be sufficient, even at a distance from the neck of the femur, to promote bone remodelling [14–17].

In young populations, peak accelerations of 4 g have been suggested as the threshold to define 'high impact' loads, in older populations this threshold is lowered to 1.5 g [37–39]. It is suggested that above this threshold, loads may be of a great enough magnitude to be osteogenic, however work is ongoing to confirm the osteogenic potential of loads generating peak accelerations over 1.5 g in older populations.
A peak vertical acceleration of 1.5 g equates to a RMS acceleration of 1.06 g, therefore, with the exception of the sacrum on the Galileo 900, this puts the maximum vertical RMS accelerations seen at the ASIS and sacrum above this threshold, suggesting that the Galileo 900 and Powerplate Pro 5 have potential to improve BMD in older populations. This is especially true given the previous observation that lower impact loads may be osteogenic at high frequencies [6,14–16].

Whilst not the focus of this article, it should be noted that over exposure to whole body vibration may cause conditions affecting the musculoskeletal system[41].
According to the ISO2631 safe exposure limits for WBV, 1.5 g delivered at 5 Hz, 15 Hz, 25 Hz and 30 Hz as reported in this paper, should only be delivered via WBV for a maximum of up to a minute per day [40]. Considering the settings which generate accelerations greater than 1.5g at the ASIS and sacrum, vertical RMS accelerations at input are much greater than 1.5g on both the Powerplate Pro 5 and Galileo 900, placing exposure limits firmly in the 'less than one minute per day' bracket.
In contrast, the maximum acceleration delivered by the Juvent 1000 allow a greater exposure time of between 1 and 30 minutes per day (Table 6), at the expense of detection of vertical RMS accelerations at the ASIS and sacrum. Using the Galileo 900, a compromise may be found between vertical RMS accelerations being directly transmitted to regions of osteoporotic fracture and low enough vertical RMS accelerations to allow time for protocols to be performed.
This study gives indications of the accelerations generated and transmitted by WBV platforms commonly used in research into osteoporosis interventions, however this data is not without limitations. There are only a small number of participants for which a single recording at each platform setting was made during this study. Based on previous studies of WBV transmission, the sample size of six allowed concurrent strain data collection, which

required invasive attachment of sensors and is reported elsewhere[42]. Six participants were deemed sufficient to collect preliminary data on WBV transmission and determine the sensitivity of motion capture technology when collecting this data, whilst minimising risks of WBV exposure to participants [7,9–11,40]. However, this has limited the strength of the data, resulting in several large confidence intervals and Cohen's d values suggesting a large effect size when statistical significance is not seen. Additional motion capture data recorded and processed using the same protocol would enhance the findings reported and allow firmer conclusions to be drawn.

In this small study, the Powerplate Pro 5 (set to 30 Hz High) and Galileo 900 (set to 25 Hz 5 mm) appear to deliver vertical RMS accelerations to the level of the ASIS and sacrum of sufficient magnitude to suggest they may have osteogenic potential. At these settings, very short durations (<1min per day) align with ISO regulations on WBV exposure, whereas WBV at 5-15Hz, whilst generating lower accelerations, may allow development of protocols of more extended duration [40].

The side alternating Galileo 900 showed greater attenuation of the input accelerations than the vertical vibrations of the Powerplate Pro 5, with the exception of the Galileo 900 platform set to 15Hz 5mm. This suggests the Galileo 900 may be of use in preventing excessive exposure of internal organs to vertical accelerations along the z-axis with potential for a compromise being found between magnitude of vertical RMS accelerations directly transmitted to regions of osteoporotic fracture and low enough vertical RMS accelerations to allow time for protocols to be performed.

The maximum acceleration delivered by the Juvent 1000 allows a greater exposure time of between 1 and 30 minutes per day (Table 6), at the expense of detection of vertical RMS accelerations at the ASIS and sacrum, however the Juvent 1000 reliably delivered vertical RMS accelerations as far as the knee. While previous studies show the promise of platforms such as the Juvent 1000 in prevention of bone loss, further investigation is warranted to determine the mechanisms underlying the impact of low magnitude vibrations on bone.

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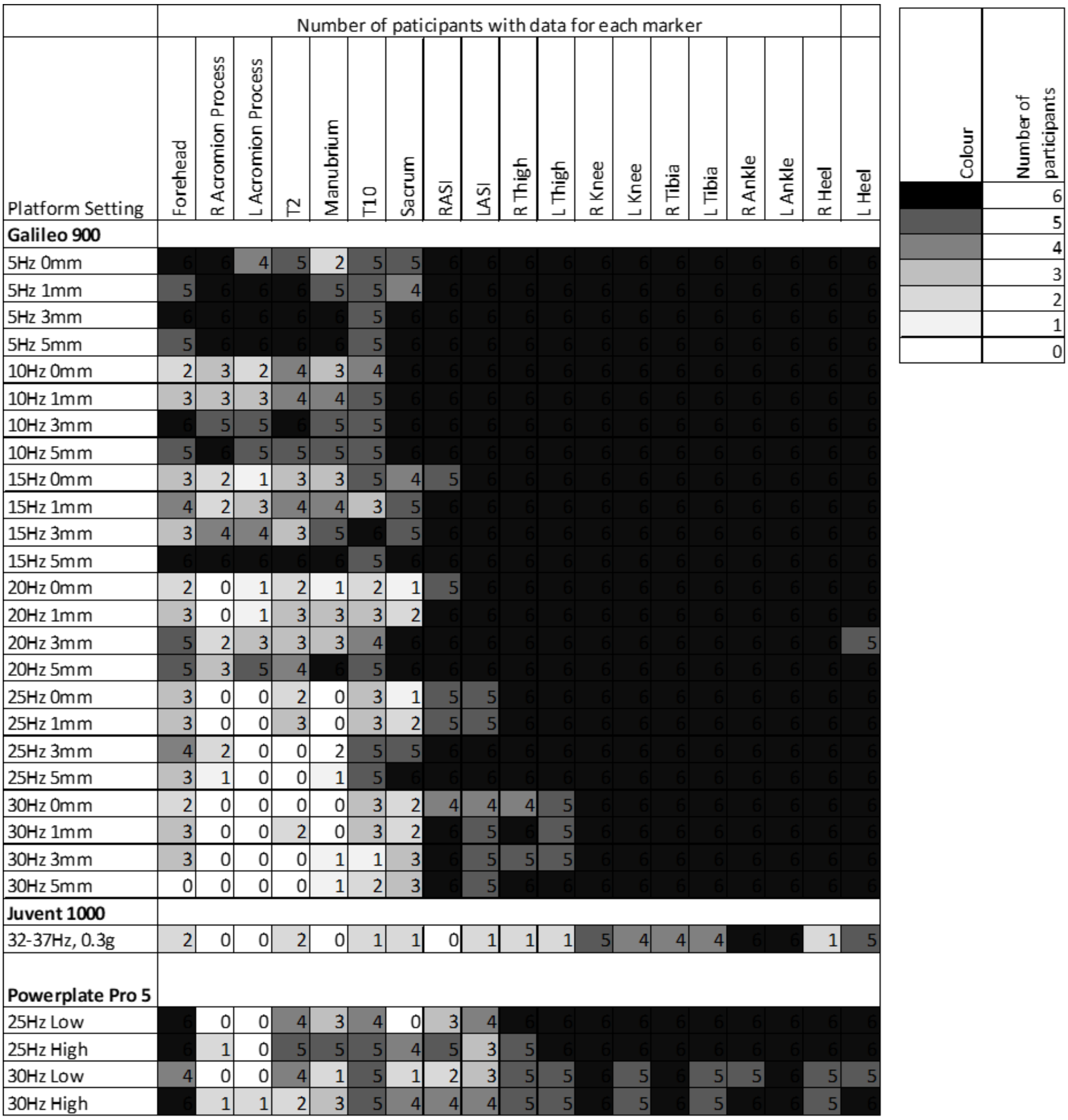
Supplementary Data

Threshold of Detection using Motion Capture

Data for inclusion was determined based on this 0.6 mm limit, with peak-to-peak displacements smaller than this being attributed to system noise and removed before analysis. A summary of the data included in analysis can be seen in Figure S1.



	Number of paticipants with data for each marker																		
Platform Setting	Forehead	R Acromion Process	L Acromion Process	T2	Manubrium	T10	Sacrum	RASI	LASI	R Thigh	L Thigh	R Knee	L Knee	R Tibia	L Tibia	R Ankle	L Ankle	R Heel	L Heel
Galileo 900																			
5Hz 0mm	6	6	4	5	2	5	5	6	6	6	6	6	6	6	6	6	6	6	6
5Hz 1mm	5	6	6	6	5	5	4	6	6	6	6	6	6	6	6	6	6	6	6
5Hz 3mm	6	6	6	6	6	5	6	6	6	6	6	6	6	6	6	6	6	6	6
5Hz 5mm	5	6	6	6	6	5	6	6	6	6	6	6	6	6	6	6	6	6	6
10Hz 0mm	2	3	2	4	3	4	6	6	6	6	6	6	6	6	6	6	6	6	6
10Hz 1mm	3	3	3	4	4	5	6	6	6	6	6	6	6	6	6	6	6	6	6
10Hz 3mm	6	5	5	6	5	5	6	6	6	6	6	6	6	6	6	6	6	6	6
10Hz 5mm	5	6	5	5	5	5	6	6	6	6	6	6	6	6	6	6	6	6	6
15Hz 0mm	3	2	1	3	3	5	4	5	6	6	6	6	6	6	6	6	6	6	6
15Hz 1mm	4	2	3	4	4	3	5	6	6	6	6	6	6	6	6	6	6	6	6
15Hz 3mm	3	4	4	3	5	6	5	6	6	6	6	6	6	6	6	6	6	6	6
15Hz 5mm	6	6	6	6	6	5	6	6	6	6	6	6	6	6	6	6	6	6	6
20Hz 0mm	2	0	1	2	1	2	1	5	6	6	6	6	6	6	6	6	6	6	6
20Hz 1mm	3	0	1	3	3	3	2	6	6	6	6	6	6	6	6	6	6	6	6
20Hz 3mm	5	2	3	3	3	4	6	6	6	6	6	6	6	6	6	6	6	6	5
20Hz 5mm	5	3	5	4	6	5	6	6	6	6	6	6	6	6	6	6	6	6	6
25Hz 0mm	3	0	0	2	0	3	1	5	5	6	6	6	6	6	6	6	6	6	6
25Hz 1mm	3	0	0	3	0	3	2	5	5	6	6	6	6	6	6	6	6	6	6
25Hz 3mm	4	2	0	0	2	5	5	6	6	6	6	6	6	6	6	6	6	6	6
25Hz 5mm	3	1	0	0	1	5	6	6	6	6	6	6	6	6	6	6	6	6	6
30Hz 0mm	2	0	0	0	0	3	2	4	4	4	5	6	6	6	6	6	6	6	6
30Hz 1mm	3	0	0	2	0	3	2	6	5	6	5	6	6	6	6	6	6	6	6
30Hz 3mm	3	0	0	0	1	1	3	6	5	5	5	6	6	6	6	6	6	6	6
30Hz 5mm	0	0	0	0	1	2	3	6	5	6	6	6	6	6	6	6	6	6	6
Juvent 1000																			
32-37Hz, 0.3g	2	0	0	2	0	1	1	0	1	1	1	5	4	4	4	6	6	1	5
Powerplate Pro 5																			
25Hz Low	6	0	0	4	3	4	0	3	4	6	6	6	6	6	6	6	6	6	6
25Hz High	6	1	0	5	5	5	4	5	3	5	6	6	6	6	6	6	6	6	6
30Hz Low	4	0	0	4	1	5	1	2	3	5	5	6	5	6	5	5	6	5	5
30Hz High	6	1	1	2	3	5	4	4	4	5	5	6	5	6	5	6	6	5	6

Colour	Number of participants
■	6
▓	5
▒	4
░	3
░	2
░	1
□	0

Figure S1: Number of participants with accelerations detected at each anatomical landmark at each of the frequencies and amplitudes of vibration studied. R- right, L- left, RASI – right anterior superior iliac spine, LASI – left anterior superior iliac spine.

Bandpass Butterworth Filters

Elements of unwanted background noise can have substantial bearing on the interpretation of recorded motion (Wood, 1982). Within this study, suitable filters for motion capture data collected during WBV were designed, with the aim of achieving the greatest roll off possible whilst keeping pass band ripple maximally flat.

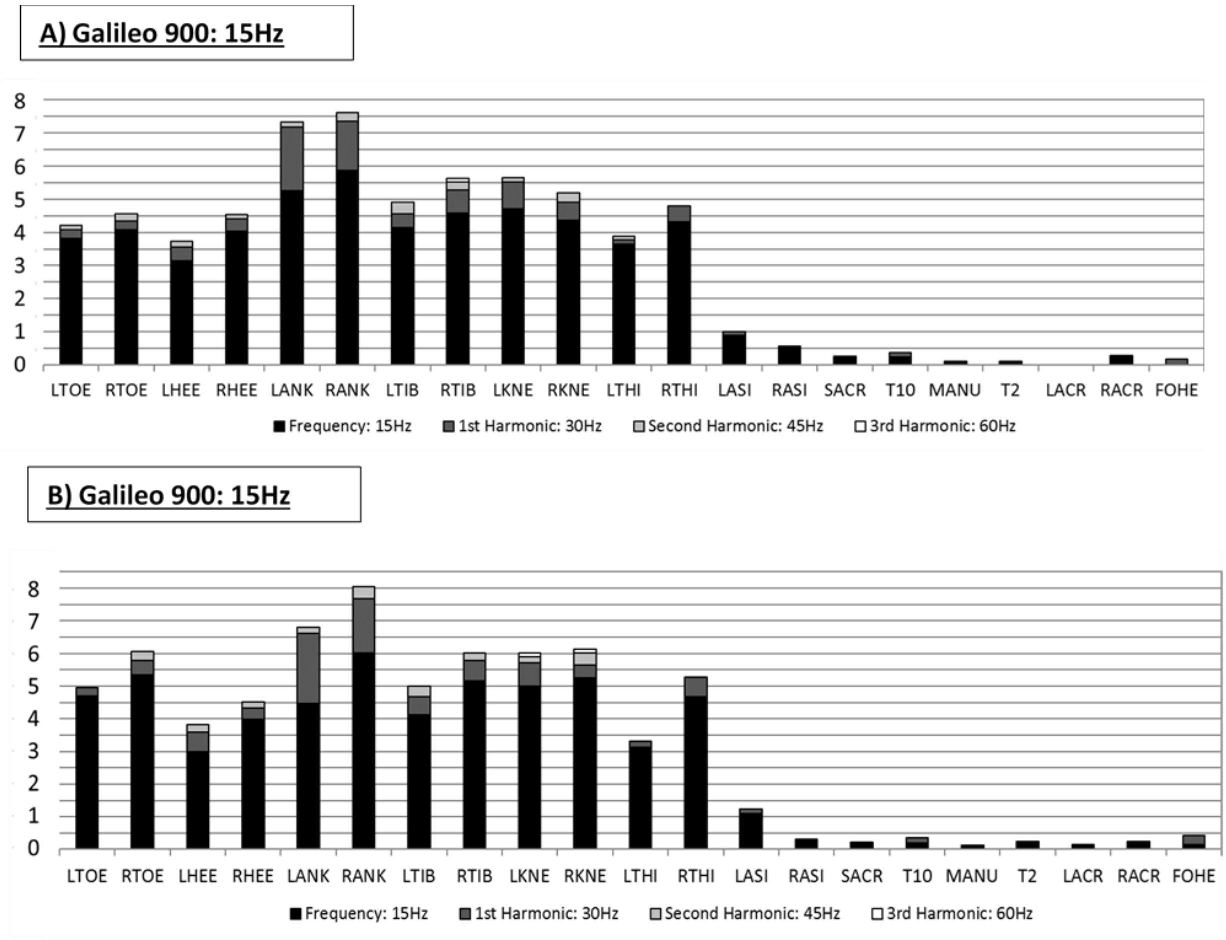


Figure S2: The contribution of the first three harmonics to the overall signal. Fast fourier transform (FFT) signal at anatomical landmarks from the toe to the forehead when the Galileo 900 platform was set to A) 15Hz 3mm and B) 15Hz 5mm. Black = FFT at frequency of input, dark grey =1st Harmonic, light grey = 2nd harmonic, white = 3rd harmonic. In both A &B, by the second harmonic the contribution to the overall signal is at least tenfold lower than that of the input. This is true for all frequencies and amplitudes studied.

Given the small contribution of the second harmonic and above to the overall signal (Figure S2), bandpass Butterworth filters centred on the frequency of input were designed to include the input frequency and first harmonic.

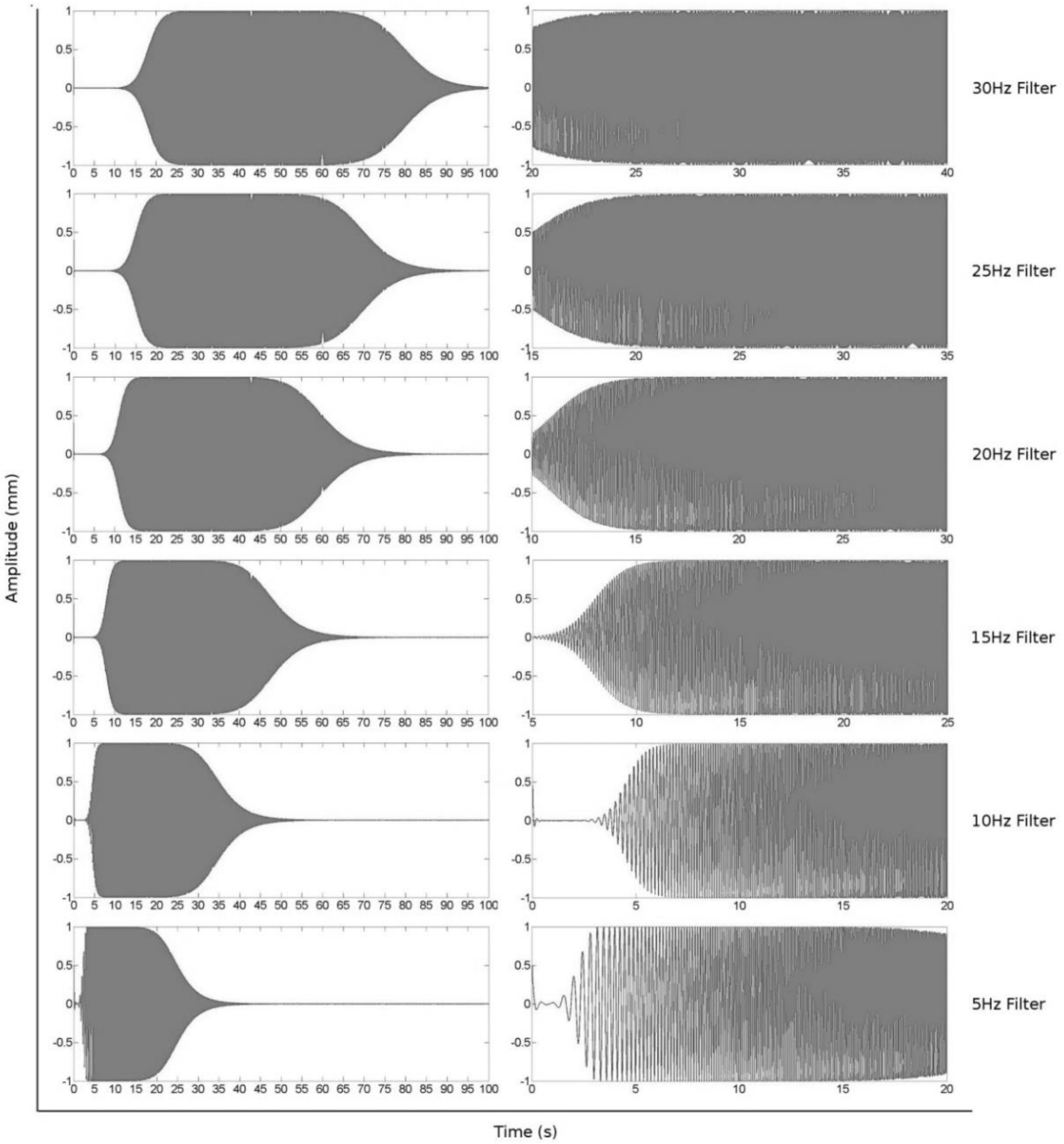


Figure S3: Filtered Chirps: Chirp signals filtered with the Butterworth filters specified in Table 3. Attenuation of the amplitude of the signals indicates the frequency response of each filter. The left column shows the frequency response between 0 and 100Hz. The right column shows the frequency response at the input frequency and first harmonic in more detail. For each filter, the amplitude at the input frequency and first harmonic are not attenuated.

When each filter was applied to a chirp (Figure S3), the input frequency and first harmonic are not attenuated. The amplitude of the signal is attenuated to 50% by the cut off frequencies. Frequency cut off one has a greater roll off than frequency cut off two, with roll off beginning approximately 2Hz above frequency cut off one and 10-25Hz below frequency cut off two. There is no substantial pass band ripple in any of the filters.

Galileo 900 and Powerplate Pro 5 with Similar Input Accelerations

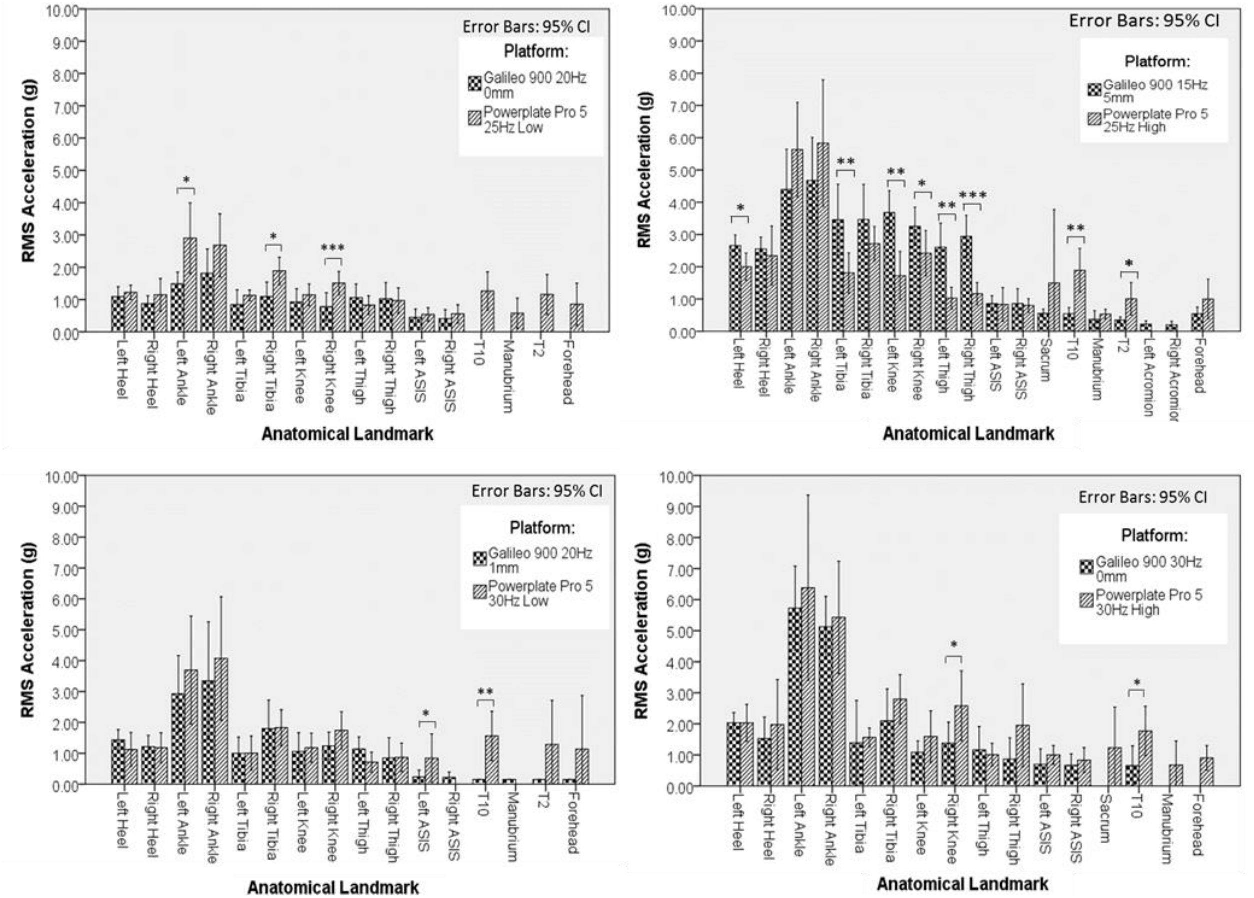


Figure S4: Accelerations delivered to markers throughout the body when similar input accelerations are achieved using the Galileo 900 and Powerplate Pro 5. P<0.05*, P<0.01**, P< 0.001***.

Few significant differences between vertical RMS accelerations at the anatomical markers are seen at ‘Low’ amplitude and input accelerations using the Galileo 900 and Powerplate Pro 5 (Figure S4). When the Powerplate Pro 5 setting is ‘High’, greater accelerations in the lower limb are seen using the Galileo 900 with similar input, whereas greater accelerations in the torso are observed using the Powerplate Pro 5, demonstrating differences between the side alternating and vertical whole body vibration modes (Figure S4).

Duration of Exposure According to ISO-2631

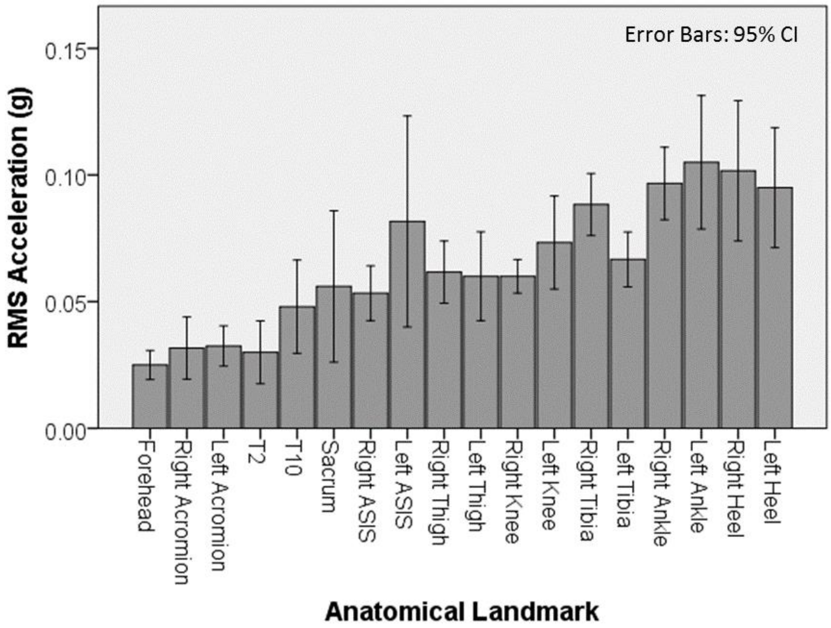


Figure S5: Accelerations delivered throughout the body using the Galileo 900 at 5Hz 0mm. This setting delivers the smallest 'maximum' acceleration at the level of the Ankle whilst delivering vertical RMS accelerations to landmarks in the lower limb and torso. According to ISO guidelines, human exposure to vertical accelerations of this magnitude at 5Hz is safe for durations of over 1hr per day.

The Galileo 900 is capable of delivering accelerations throughout the body at a small enough magnitude to allow minutes to hours of exposure (Figure S5, Table S1).

Frequency of Input (Hz)	Amplitude of Input (mm)	Vertical RMS Acceleration at Input (g)	Exposure Limit/ Day
5	0	0.09	4 hrs
5	1	0.12	1 hrs
5	3	0.25	30 mins
5	5	0.30	30 mins
10	0	0.30	30 mins
10	1	0.52	<1 min
15	0	0.69	<1 min

Table S1: Vertical RMS acceleration at input recorded on the Galileo 900 and corresponding exposure limits according to ISO2631.

The Powerplate Pro 5 at 25Hz Low delivers the smallest 'maximum' accelerations and accelerations at input, however the exposure limit according to ISO2631 remains <1 minute per day (Figure S7). The maximum acceleration delivered by the Juvent 1000 allow a greater exposure time of between 1 and 30 minutes per day, at the expense of detection of vertical RMS accelerations at the ASIS and sacrum.

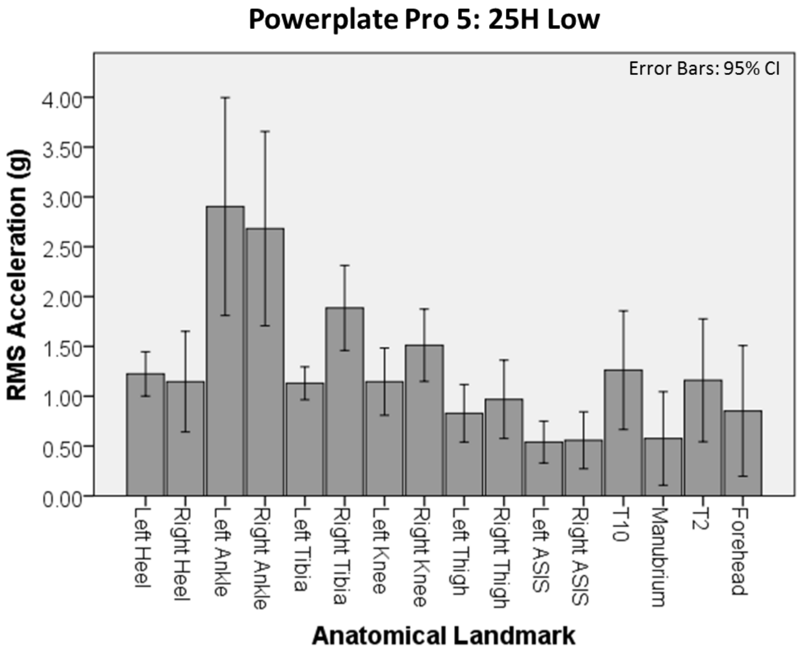


Figure S6: Accelerations delivered throughout the body using the Powerplate Pro 5 at 25Hz Low. This setting delivers the smallest 'maximum' acceleration at the level of the ankle whilst delivering vertical RMS accelerations to landmarks in the lower limb and torso. According to ISO guidelines, human exposure to vertical accelerations of this magnitude at 25Hz is only safe for durations of over <1minute per day.

In the case of the Powerplate Pro 5, the setting which delivers the lowest accelerations, whilst delivering ample accelerations to the areas at risk of osteoporotic fracture, still falls within the limit of 'less than one minute per day' according to ISO-2631 (Figure S6) (Muir *et al*, 2013). In contrast, The Galileo 900 at 5 Hz 0 mm delivered vertical RMS accelerations throughout the lower limb and into the torso, whilst sitting in the exposure bracket of over 1 hour per day (Table S1).

The accelerations generated by the Galileo 900 at 5 Hz 0 mm are well below 1.5 g, however investigations into the effects of the 'low magnitude' vibration settings of the Galileo 900 may benefit bone whilst establishing safe protocols for clinical practice.

Maximum RMS accelerations up to ~0.25 g at 5 Hz and ~0.45 g at 30 Hz would allow 30 minutes of exposure per day, raising to 0.45 g at 5 Hz and ~0.9 g at 30 Hz if exposure is only up to 1 minute (Muir *et al*, 2013). These values can be achieved on the Galileo 900, allowing 30 minutes exposure at 5Hz 0, 1 and 3 mm settings and 1 minute exposure at 5 Hz 5 mm, 10 Hz 0 & 1mm and 15 Hz 0 mm.

Whilst lower than the 'high-load' threshold for accelerations, these values may allow sufficient delivery of vertical RMS accelerations to the femoral neck and lumbar spine to be osteogenic, as with higher frequency of load than habitual locomotor activities, the osteogenic threshold may turn out to be lower for accelerations delivered by WBV (Skerry, 2006).

Future studies should discuss the safety of the duration of exposure used when delivering WBV and consider whether exposure is suitable. The ISO-2631 guidelines are developed in industry where exposure could be expected daily. As WBV exposure in this context is not often daily, these guidelines may need developing for use in clinical settings.