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Gravitational forces and whole body vibration: implications for prescription of vibratory stimulation

Blair Crewther*, John Cronin, Justin Keogh

Division of Sport and Recreation, Sport Performance Research Centre, Auckland University of Technology, Private Bag 92006, Auckland 1020, New Zealand

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Abstract

The purpose of this study was to determine the gravitational forces (g-forces) associated with different postures (standing single leg, standing double leg, semi-squat), amplitudes (1.25, 3.0, 5.25 mm), frequencies (10, 20, 30 Hz) and at different anatomical sites (tibial tuberosity, greater trochanter, jaw). Twenty-three subjects underwent whole body vibratory stimulation on a teetering platform that oscillated about a sagittal shaft (Galileo™ 2000). The analysis involved collapsing all the data into four categories (frequency, amplitude, posture, damping) and investigating the g-forces within each category. The 20 Hz frequencies resulted in significantly greater g-forces (2.05g) than 10 and 30 Hz (1.83 and 1.76g, respectively). As amplitude increased so to did the g-forces (1.25 mm, 1.6g; 3.0 mm, 1.85g; 5.25 mm, 2.2g; $P < 0.05$). G-forces associated with the semi-squat (2.34g) were significantly greater ($P < 0.001$) than the standing postures. Significant damping was observed as the vibratory stimulation was transmitted to the proximal segments (tibial tuberosity, 3.91g; greater trochanter, 1.26g and jaw, 0.34g). Findings were discussed in terms of safe, progressive and effective prescription of vibratory stimulation.

Keywords: Gravitational forces; Vibration; Damping

1. Introduction

Vibration has been widely used as a tool for rehabilitation, enhancing physical performance and stimulating bone development. Vibration has been used in the treatment of patients with spasmodic torticollis (Karnath et al., 2000), the rehabilitation of neck muscles following spatial neglect (Schindler et al., 2002) and in the treatment of pain (Lundeberg, 1984; Lundeberg et al., 1987a,b). Although, these studies involved the direct application of vibration, recent research has shown that whole body vibration (WBV) interventions may also be an effective rehabilitation tool. Two months WBV has been shown to improve lower limb neuromuscular function, as demonstrated by improved co-ordination and balance of 35 elderly subjects performing a standardised chair-rising test (Runge et al., 2000). Well-controlled WBV may also assist in the treatment of lower back pain (Rittweger et al., 2002) and in the treatment of patients with spinal chord injuries (Gianutsos et al., 2000).

There is a growing body of evidence both anecdotal and scientific, which suggests that WBV can be used as a performance-enhancing tool. Many studies have examined the influence of WBV upon physical performance (Bosco et al., 1998a,b, 1999a,c, 2000; Rittweger et al., 2000; Torvinen et al., 2002a,b; Warman et al., 2002). In most cases, vibration has been shown to positively influence maximal strength and force output (Bosco et al., 1999c; Warman et al., 2002), power output (Bosco et al., 1998b, 1999c, 2000) and vertical jump height (Bosco et al., 1998a, 2000; Torvinen et al., 2002a). In general, research in this area is characterised by frequencies of 25–50 Hz and amplitudes ranging from 1 to 10 mm, resulting in g-forces of 3–7g.

The application of WBV for bone development is another area gaining considerable interest. The use of WBV has been found effective in the prevention of bone loss and/or increasing bone density within various animal models (Rubin et al., 1995, 2001, 2002; Flieger et al., 1998; Judex et al., 2001, 2002). Considering its stimulatory effect upon bone this tool may be a potential treatment for osteoporosis and other related bone disorders. Rubin et al. (1998) investigated the ability of WBV to

* Corresponding author. Tel.: +649-917-9999x7119; fax: +649-917-9960.
E-mail address: blair.crewther@aut.ac.nz (B. Crewther).

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inhibit post-menopausal osteopenia. Thirty-one women underwent mechanical vibration of the lower body for 12 months (20 min/day). Loss of bone mineral density (BMD) of the trochanter region of the hip was significantly less in the treated group (-0.8%) as compared to the placebo group (-3.3%). Ward et al. (2001) also reported a net increase in tibial BMD (18.2 mg/ml) and spinal BMD (3.8 mg/ml) among cerebral palsy children, after 6 months vibration treatment. A recent study by Pitukcheewanont et al. (2002) reported significant increases in cancellous BMD (5.95%) and cortical BMD (1.21%) after only 8 weeks of vibration treatment. Research investigating the stimulatory effects of WBV upon bone have employed vibration frequencies in the range of 30–90 Hz and accelerations of 0.25–2*g*.

The frequency and amplitude of vibration, duration of exposure and the posture adopted during WBV are all factors that need to be considered when prescribing WBV, as the interaction of these factors affects will determine the magnitude of the *g*-forces and thus nature of the training stimulus. The application of WBV also has many potential side effects. Though mechanical vibration may not elicit those negative effects commonly associated with occupational vibration, various ill effects such as itching, erythema and oedema have been reported (Pope et al., 1996; Rittweger et al., 2000). A recent study investigated the effects of WBV (frequency, 26 Hz; amplitude, 6 mm, 6*g*) upon muscle stiffness (Cronin, Oliver and McNair, unpublished data). This study replicated an intervention cited previously (Bosco et al., 1999a), that is, 5×60 s of unilateral vibratory stimulation with 60 s rest between interventions. During and/or following treatment a number of the subjects experienced pain in the jaw, neck, and lower extremity, particularly tibialis anterior, some of these injuries requiring physiotherapy treatment. It was suggested that more research be conducted on the effects of different WBV protocols and a dose-response model formulated. Such an analysis would provide valuable information in terms of the forces developed and transmission of forces under different vibration conditions, thereby assisting in the development of both safe and effective protocols. Therefore, the aim of this study is to investigate the *g*-forces associated with sinusoidal WBV and the influence of amplitude, frequency and posture upon the development and transmission of these forces.

2. Methodology

2.1. Participants

Twenty-three subjects (11 males and 12 females) volunteered to participate in this study. Subject mean age and mass were (26.1 ± 5.4 years) and (69.6 ± 12.2 kg), respectively. Subjects were screened to ensure that they were free from the following conditions: pregnancy, acute thromboses, acute inflammations, implants, fractures, acute tendinopathies, kidney or bladder stones and gallstones (as per manufacturers instructions). All subjects signed an informed consent form prior to involvement in this research. The Human Subject Ethics Committee, Auckland University of Technology, approved all the procedures undertaken.

2.2. Equipment

Subjects were exposed to vertical sinusoidal WBV using the Galileo™ 2000 (Novotec GmbH, Germany). In effect, the Galileo is a mechanical teeterboard, that is, the teetering surface oscillates about a sagittal shaft (Fig. 1). The Galileo™ 2000 has a vibration range of 0–30 Hz and an amplitude range of 1.0–5.2 mm. A 10*g* linear accelerometer (Sensotec, Ohio), instrumented with an on-line amplifier (± 5 V), was used for data collection. Data was sampled at 1000 Hz with a custom-made data acquisition and analysis program (LabView™). Data was filtered using a low pass Hamming filter (cut-off frequency 6 Hz) and full-wave rectified prior to data analysis.

2.3. Procedure

Subjects completed a standardized warm-up prior to testing. This consisted of a 3-min cycle (60 rpm) followed by light stretches for the quadriceps, hamstrings and calf muscle groups, with each stretch held for 15 s. The accelerometer was then attached to the tibial tuberosity, greater trochanter and jaw of each subject (via an ice block stick clenched between the jaw). To prevent excessive oscillation at the head, subjects were required to look directly forward throughout testing. The accelerometers were aligned vertically, so as to record the vertical accelerations at each site. Attachment of the accelerometer to the lower limb sites was accomplished using industrial strength tape, then reinforced with strapping tape to ensure the accelerometer was secure.

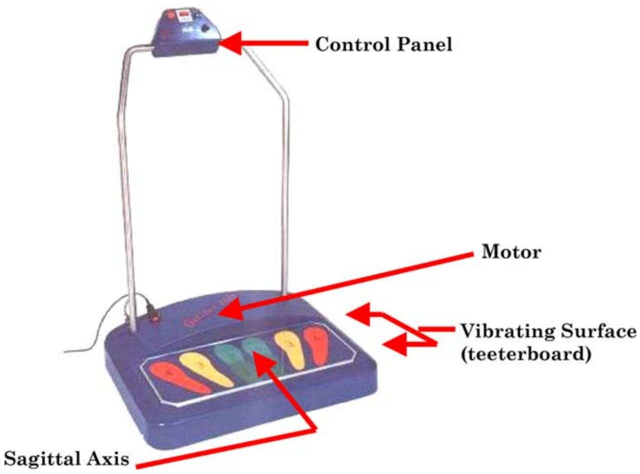

Fig. 1. Whole body vibration device (Galileo™ 2000).

Subjects were assessed in three postures: standing double leg (SDL), standing single leg (SSL) and a semi-squat (SS). The SDL required subjects to stand in a relaxed position with knees slightly flexed (i.e. 3–5° from lockout). The SSL required subjects to adopt the SDL before taking their bodyweight on their right limb. In the SS subjects adopted a squat position with their knees flexed at 120°, measured with a manual goniometer. All postures were performed with the trunk in a vertical position. Each posture was assessed at three separate foot positions (2–4) on the teeterboard, equating to distances of 5, 15 and 25 cm, respectively, from the sagittal axis. Thus, amplitude associated with the different foot positions also increased (2–1.25 mm, 3–3.0 mm, 4–5.25 mm). Heels remained in contact with the vibration surface throughout all assessments. Each posture and position was further assessed at three different vibration frequencies (10, 20 and 30 Hz). Trials were randomised to negate any order effects, with data collected for a period of 5 s with 20 s recovery between trials. Subjects were allowed to use the machine handrails but only to maintain their balance. Any unusual reactions or side effects to testing were also reported. Suitable footwear was worn for all the assessments. Acceleration data was also collected from the surface of the vibration machine at the different foot positions (× 3) and vibration frequencies (× 3).

2.4. Statistical analysis

Data was collapsed into four categories for analysis: (1) frequency effect, 10, 20 and 30 Hz vibration frequencies; (2) amplitude effect, foot positions 2–4; (3) posture effect, double leg standing, single leg standing and a semi-squat; and (4) damping effect, tibial tuberosity, greater trochanter and jaw. Mean values within each of these categories were analysed using a repeated measure ANOVA. F ratios were considered significant at $P < 0.05$. If significant interactions were present Tukey post-hoc comparisons were conducted.

3. Results

Data was collapsed to explain each effect (frequency, amplitude, posture or damping). For example, frequency data was determined from the combined values of amplitude (× 3), posture (× 3) and site (× 3). The g-forces measured at the surface of the vibration machine are depicted in Table 1.

Table 1
Gravitational forces (vibration surface) associated with different vibration frequencies and different foot positions

	10 Hz	20 Hz	30 Hz
2 (1.25 mm)	9.67	9.76	9.91
3 (3 mm)	9.71	9.95	10.38
4 (5.25 mm)	9.74	10.14	10.88

Table 2
Gravitational forces associated with different vibration frequencies

	10 Hz	20 Hz	30 Hz
Mean (g-force)	1.83	2.05[a]	1.76
SD	0.37	0.32	0.40
SEM	0.08	0.07	0.09
Range	1.20–2.50	1.40–2.60	0.90–2.60

[a] Significantly greater than the 10 and 30 Hz frequencies ($P < 0.05$).

Table 3
Gravitational forces associated with different foot positions

	2 (1.25 mm)	3 (3 mm)	4 (5.25 mm)
Mean (g-force)	1.60	1.85[a]	2.20[b]
SD	0.29	0.35	0.41
SEM	0.06	0.08	0.09
Range	1.10–2.20	1.00–2.50	1.50–3.10

[a] Significantly greater than position 2 ($P < 0.05$).
[b] Significantly greater than position 2 and 3 ($P < 0.05$).

An increase in amplitude (from position 2 to 3 to 4) resulted in a slight increase in g-forces at the lowest vibration frequency (9.67–9.74g). This increase became more prominent as frequency increased from 20 Hz (9.76–10.14g), with a further increase noted at 30 Hz (9.91–10.88g).

The g-forces associated with three different vibration frequencies can be observed in Table 2. A significant main effect ($F = 6.64$, $P = 0.003$) was noted with the g-forces associated with 20 Hz vibrations being significantly greater than that found at 10 or 30 Hz. The power of the performed test with $\alpha = 0.050$ was 0.843.

The g-forces related to the different foot positions are shown in Table 3. A significant main effect was observed ($F = 31.2$, $P < 0.001$). Post-hoc comparisons revealed that greater g-forces were experienced with increasing distance from the central axis of the teeterboard. The power of the performed test with $\alpha = 0.050$ was 1.00.

The g-forces related to the different postures are detailed in Table 4. A significant main effect for posture ($F = 43.4$, $P < 0.001$) was noted, with the g-forces associated with the SS significantly greater than both the standing postures. The power of the performed test with $\alpha = 0.050$ was 1.00.

The g-forces associated with the different positions that the accelerometer was attached, can be observed in Table 5.

Table 4
Gravitational forces associated with different postures

	Standing	Single leg	Semi-squat
Mean (g-force)	1.62	1.69	2.34[a]
SD	0.38	0.27	0.40
SEM	0.08	0.06	0.09
Range	0.90–2.20	1.20–2.20	1.69–3.20

[a] Significantly greater than standing and single leg postures ($P < 0.05$).

Table 5
Gravitational forces associated with different body positions

	Jaw	Greater trochanter	Tibial tuberosity
Mean (g-force)	0.34	1.26[a]	3.91[b]
SD	0.13	0.65	0.59
SEM	0.03	0.13	0.13
Range	0.14–0.55	0.70–3.20	2.50–5.20

[a] Significantly greater than the jaw ($P < 0.05$).
[b] Significantly greater than the jaw and the greater trochanter ($P < 0.05$).

The g-forces decreased with increasing distance from the vibrating platform ($F = 283.7$, $P < 0.001$). The power of the performed test with $\alpha = 0.050$ was 1.00.

4. Discussion

4.1. Frequency effect

The g-forces associated with 20 Hz vibrations (2.05g) were significantly greater than both the 10 Hz (1.83g) and 30 Hz (1.76g) frequencies (Table 2). A reduction in force transmission above frequencies of 16–20 Hz has been previously reported (Harazin and Grzesik, 1998; Mester et al., 1999). Harazin and Grzesik (1998) found that the vibration magnitudes being transmitted by the hip, shoulder and head decreased with an increase in frequency above 16–20 Hz. Mester et al. (1999) proposed that with increasing vibration frequency the onset of active damping might be observed with a decrease in force transmission. Thus, at higher frequencies (i.e. >20 Hz) the transmission of vibratory-induced forces would decrease, hence the lower g-forces occurring at 30 Hz. Resonant frequencies up to 20 Hz have been identified for the organs, head and the eyeballs, therefore, active damping may occur to prevent excessive acceleration at these sites (Mester et al., 1999). In response to greater vibration frequencies, coupled rotational motions about the hip joint (Matsumoto and Griffin, 1998), body sway (Mester et al., 1999) or greater muscle activation (Mester et al., 1999) may also affect the transmission of vibratory-induced forces. As exposure to WBV elicits other neural, biological and biomechanical responses (Seidel and Griffin, 1998; Bosco et al., 1999b) determining the exact mechanism of the frequency effect (i.e. greater g-forces at 20 Hz) remains difficult. It would seem, however, that frequencies of approximately 20 Hz result in maximal g-forces. In terms of exercise prescription it would seem that lower (10 Hz) and/or higher frequencies (30 Hz) should be used with novice or untrained individuals due to the lower g-forces associated with these frequencies. Utilisation of WBV at 20 Hz is more likely to induce injury and should be used with individuals that are conditioned to tolerate higher g-forces.

4.2. Amplitude effect

A significant main effect was observed in relation to the different foot positions (Table 3). That is, greater mean g-forces were experienced with increasing distance from the central axis of the teeterboard from position 2 (1.6g) to positions 3 (1.85g) and 4 (2.2g), respectively. In terms of prescribing WBV it would seem prudent to use foot position 2 (amplitude 1.25 mm) as an initial training stimulus due to the significantly lower g-forces associated with this position. As familiarity and adaptation occurs, the vibratory stimulus may be progressively overloaded by moving the foot positions distally from foot position 3 (3.0 mm) to foot position 4 (5.25 mm), thereby progressively increasing the associated g-forces. However, we can only speculate as when best to progressively overload frequency and amplitude as research investigating the overloading of these factors appears non-existent. Biological or biomechanical markers that indicate the individuals readiness for WBV overload need to be identified and should be the subject of future research.

4.3. Posture effect

The g-forces associated with the semi-squat (2.34g) were significantly greater than the standing postures (Table 4). It is speculated that greater muscle activation in this posture would increase muscular stiffness, thereby enhancing the transmission of vibratory forces throughout the body. Greater force transmission may also result when a structure is vibrated at or near its resonance frequency (Seidel and Griffin, 1998), though such notion is limited in this context given that the g-forces occurring at each frequency was combined to provide absolute values for each posture. Nonetheless, the results of this study suggest enhanced force transmission in the semi-squat compared to the single and standing postures. Previous research has indicated that a bent knee position attenuates force transmission into the hip and upper body (Lanyon, 1992; Pope et al., 1996; Matsumoto and Griffin, 1998). The different findings may be attributed to methodological differences between studies (i.e. skin vs. skeletal accelerometer, accelerometer position, vibration protocols). The discrepancy found with previous authors may be further explained by the fact that heels remained in contact with the teeterboard. Given that only one previous study used a teeterboard-vibrating machine (Pope et al., 1996) as per this study and that study assessed only a small sample size ($n = 5$), determining the influence of posture upon force transmission remains difficult. The findings of this study would suggest, however, that a continuum of postures beginning with bilateral standing and progressing to unilateral standing and bilateral semi-squatting would be the safest manner in which to progress WBV.

4.4. Damping effect

As expected, greater forces were observed at the sites located closer to the vibration surface (Table 5). The g-forces measured at the lowest site ($3.91g$) also revealed a large damping effect from those forces developed at the vibration surface (Table 1). Though, the propagation of vibratory forces throughout the body is largely determined by the damping effect of the soft tissues and body parts, other factors add to the complexity of this issue. Exposure to sinusoidal WBV is believed to induce various neural responses that may subsequently influence force transmission (Lundstrom and Holmlund, 1998; Seidel and Griffin, 1998). A vibrated muscle may undergo an active contraction, which is known as the tonic vibration reflex (Bosco et al., 1999b; Mester et al., 1999). Vibrating a muscle may also depress the excitability of motor neurons innervating the antagonist muscles or suppress the monosynaptic stretch reflexes of the vibrated muscles (Bishop, 1974). Recent work on human postural control during leg vibration also indicates that vibration modulates postural responses (i.e. body tilt, leaning), thereby influencing the propagation of forces throughout the body (Polonyova and Hlavacka, 2001; Tjernstrom et al., 2002). Other factors may also contribute to the transmission of vibratory-induced forces (i.e. posture, gender and bodymass). Nonetheless, the results of this study indicate that the greatest g-forces are found in the lower leg with significant damping occurring at the more superior sites. This in part explains the injuries reported by Cronin et al. (unpublished data) and the reason for pre-screening for conditions such as acute inflammations, fractures, and acute tendinopathies as recommended by the manufacturers of the Galileo vibration machine.

It should be noted that collapsing data as per this study and analysing the mean responses to vibratory stimulation does in no manner give any indication of the interaction between frequency, foot position posture and body site nor individual responses. This study, as with previous research, has indicated large variations in the individual responses to WBV (Pope et al., 1996; Lundstrom and Holmlund, 1998; Matsumoto and Griffin, 1998; Mansfield and Griffin, 2000). For example, the g-forces experienced at the tibial tuberosity whilst squatting (frequency, 30 Hz; amplitude, 1.25 mm; foot position 2) was 6.98 for one subject whereas it was 2.17 for another. Though some recommendations have been made in terms of progressive overload based on the findings of this study, it should be realized that individual responses to WBV differ. With this in mind one must be careful in prescribing vibratory stimulation based on the mean response as some individuals may or may not be able to tolerate such loading.

4.5. Implications for physical activity and health

4.5.1. Bone development

The application of WBV has been shown to positively influence bone development (i.e. BMD, bone formation rate) within various animal models (Rubin et al., 1995, 2001, 2002; Flieger et al., 1998; Judex et al., 2001, 2002) and within humans (Rubin et al., 1998; Ward et al., 2001; Pitukcheewanont et al., 2002). These studies are characterised by higher frequencies (30–90 Hz) but somewhat lower g-forces ($0.2–2g$) than that observed in this study. Thus, the g-forces observed under the various conditions in this study ($0.34–3.91g$) appear to be of sufficient magnitude to provide an effective stimulus for bone development. However, the responsiveness of bone to vibratory stimulation may be in some way constrained by the bone's stiffness, strength and architecture (Jiang et al., 1999). If a stimulus 'threshold' exists then low magnitude loading may be ineffective regardless of the number of cycles (frequency) or exposure period. It may be that a combination of these factors (i.e. magnitude, frequency) and the unusual distribution of a vibratory stimulus that facilitates the greatest osteogenic responses (Lanyon, 1992; Jiang et al., 1999). The responsiveness of bone to mechanical stimuli may also depend upon genetic variations. Judex et al. (2002) found that subtle genotypic variation among mice had a significant effect upon trabecular bone quality and quantity after exposure to mechanical vibration. Extrapolating these results to humans suggests that the response to vibration loading may also be subject dependent. Considering the complex nature of prescribing vibration and indeed the complexity of the human response to vibration, establishing the optimal dose-response relationship remains difficult.

4.5.2. Performance/health

Many studies have found WBV to positively influence various performance measures such as strength, force output, power output and vertical jump performance (Bosco et al., 1998a,b, 1999c, 2000; Torvinen et al., 2002a; Warman et al., 2002). These studies are characterised by similar frequencies (25–50 Hz) and amplitudes (1–10 mm and 3–7 g) to that used in this study. It is speculated that the development of some of these qualities may further improve the quality of movement and life in the injured or aged. For example, improving muscular strength, co-ordination and balance would reduce the risk of falling and the risk of fractures in osteoporotic bones (Heinonen et al., 1999; Runge et al., 2000). Two months of WBV training (6 min exposure at 27 Hz, 7–14 mm) has been shown to improve lower limb neuromuscular function as demonstrated by the improved co-ordination and balance of 35 elderly subjects performing a standardised chair-rising test (Runge et al., 2000). However, the majority of research in this area has used athletes or trained subjects. As the adaptations occurring within non-athletic or untrained populations may differ considerably to that seen in trained populations, it is suggested that further research investigate the adaptations and responses of these populations (i.e. injured, aged) to WBV interventions. These studies should also seek to establish safe and effective loading parameters for these populations.

4.5.3. Ill effects

Chronic exposure to occupational vibration has many side effects including vertigo, haemodynamic alterations, low back pain and visual impairment (Seidel and Griffin, 1998; Mester et al., 1999). Although, sinusoidal WBV may not induce these effects, 17 subjects from this study reported some type of ill effect. Two subjects withdrew from the study, one due to severe discomfort in the hip region and the other due to severe head motion (i.e. excessive shaking). The most common ill effects were hot feet ($n = 6$) and itching in the lower limbs ($n = 5$). An increase in vibration frequency and hence a higher rate of foot contacts, is the likely explanation for the high temperatures reported at the feet. Previous research has also reported itching in the lower limbs after exposure to sinusoidal WBV (Pope et al., 1996; Rittweger et al., 2000), though the mechanism for this response remains unknown. Other reported effects include nausea, cramp, calf pain and lower back discomfort. These findings may be compounded by the fact that heels were required to be in contact with the vibration surface. Nonetheless, the effects reported in this study, as with other research, have generally occurred at frequencies of 30 Hz and above. Thus, the application of WBV should be used with caution at higher frequencies (>30 Hz), higher amplitudes and hence higher *g*-forces, particularly among populations more susceptible to injury (i.e. elderly, untrained). It would also seem prudent to monitor the duration of vibration exposure at higher frequencies considering the effects reported in this study and the exposure period at 30 Hz (<2 min).

6. Conclusion

The use of WBV as a tool for improving functional performance (flexibility, strength, power, balance, etc.) and health (improving bone density) remains an exciting area for further study. However, the research within these areas is in its infancy. Much research is still needed on the optimal frequencies, amplitudes, *g*-forces and stimulation durations to improve each of these factors. Furthermore, knowledge as to how many sessions per day and/or per week as well as when to progressively overload vibratory stimulation is practically non-existent. The results of this study indicate that altering the frequency and amplitude of WBV as well as posture can significantly alter the resulting *g*-forces throughout the body. However, it is still unknown how best to determine when an individual is ready for an increase in frequency or amplitude, and/or for a change in posture. Biomechanical and/or biological markers need to be determined that assist in decision making as to the correct timing of the overload stimulus. Such an approach will greatly assist in the safe and effective use of WBV as a rehabilitation and training tool. With this in mind one should remain cognizant of the limitations that exist in the interpretation of the current research findings and the need for further research in this field.

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