Vibration Exercise: The Potential Benefits

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Abstract

The aim of this review was to examine the physiological effects of vibration exercise (VbX), including the cardiovascular indices and to elucidate its potential use for those with compromised health. VbX has long been acknowledged as a potential modality in sport, exercise, and health sectors. Muscle force and power have been shown to increase after VbX for athletes, the aged and those with diseases, where neural factors are thought to be the main contributor. Further, similarities to the tonic vibration reflex have been used to propose that the muscle spindle plays a role in activating the muscle which could benefit those with compromised health. There is strong evidence that acute VbX can enhance upper and lower-body muscle power, and there is some indication that longer-term VbX can augment muscle power of upper and lower body extremities, although this is less convincing. It is not conclusive whether VbX increases force attributes. This has been fraught by the type and parameters used for various muscle contractions, and the different sample populations that have varied in chronological age, experience and training status. VbX provides an insufficient stimulus to enhance cardiovascular indices, where VbX cannot increase heart rate to the same extent as conventional aerobic exercise. But when conventional aerobic exercise is not possible, for example, in aged, cardiovascular compromised persons, VbX could be implemented at an early stage because it could provide a safe induction of a slight elevation of cardiovascular function indices while providing neural and myogenic benefits. In conclusion, VbX is a safe modality to increase physiological responses of reflex and muscle activity, and muscle function, for athletes, the aged and compromised health. However, further research should focus on the optimum dose relationship of frequency, amplitude and duration for the various populations.

Introduction

Vibration exercise (VbX) is currently enjoying popularity as an alternative exercise modality for enhancing muscle activity, force and power [1,12,60,105,108] while others have found little or no effect [36,40,41]. VbX has been suggested as an attractive and efficient complement to traditional forms of exercise for athletes, the aged and health compromised individuals. The muscle performance benefit supposedly occurs via neurogenic potentiation involving spinal reflexes and muscle activation, which is based on the tonic vibration reflex [21,103]. It has been purported that neural factors are responsible for the increases in muscle function, which are similar to those neural changes seen after several weeks of conventional resistance and power training [13,14]. Further, it has been purported that VbX augments muscle spindle activity that causes a stretch-reflex response and elicits a rapid but small change in muscle length [21], which is of importance to those with diseased tissue or neurological problems. The change in muscle activity is likely to evoke a small increase in oxygen uptake, which suggests muscle energy turnover exists where VbX may have a beneficial effect for cardiovascular indices, such as blood pressure, blood flow and heart rate.

Despite its wide use in sport, exercise and health the physiological responses of VbX remain equivocal because a number of studies have used various protocols, of different methods of application, vibration parameters, training duration and exercises performed with vibration. Some recent VbX reviews have been conducted on specific population groups such as trained [22, 133], and untrained [97] but they have not integrated acute, short- and long-term effects of VbX on reflex muscle activity, cardiovascular responses and muscle function for various populations of healthy, and compromised health. Therefore, the purpose of this review was to critically examine the physiological effects of VbX, namely reflex activity, muscle function, and cardiovascular indices and to elucidate its potential use for those with compromised health where safety aspects and loading parameters of VbX are also discussed.

Method

A search was conducted using electronic databases Medline, PubMed, ISI Web of Knowledge and Scopus using key words of vibration and whole-body vibration, in combination with exercise, training, power, force, strength, cardiovascular, blood flow, heart rate, reflex, electromyography, Multiple Sclerosis, stroke, Parkinson's Disease, postmenopausal and elderly. Articles were checked for relevant content and were included from the following 1. published in English; 2. examined acute (single session), short-term (multiple sessions performed up to 2 months), and long-term (multiple sessions greater than 2 months) effects; 3. Status of participants included healthy, trained, untrained and specific health ailments and Conference abstracts and proceedings were not included.

Vibration exercise

Types of vibration exercise

VbX has taken on many different forms. Small vibratory units have been placed directly on the muscle or tendon [62, 132] and larger custom built units have been constructed for flexibility training [112, 113]. Vibrating units have also been attached to resistance training equipment to elicit vibration transmission through the cables of various machines [59]. Currently, there are 2 commercial forms of vibration platforms manufactured for the health and fitness industry. The first type of platform (e. g. Galileo®) has a teeterboard that produces side-alternating vertical sinusoidal vibration (SV) to the body. It rotates around an antero-posterior horizontal axis, so when the feet are further from the axis it results in a larger vibration amplitude (**Fig. 1**).
The side-alternating movement is asynchronous where the unilateral vibration is applied alternately to the left and right foot. The other commercial machines (Power Plate®, Nemes®, Vibra Pro®, Vibrafit®, Fit Vibe®, Pneu-vibe®, Vibrogym®, Soloflex®, Bodypulse®, Juvent 1 000®) produce vertical synchronous vibration (VV) where both legs are vibrated as the platform moves predominately in the vertical direction. This results in simultaneous and symmetrical movement of both sides of the body during the exposure (**Fig. 1**). Hand-held powered vibrating dumbbells have also been commercially manufactured for exercising the upper-body (Galileo TOP®, Mini-VibraFlex®) where the central handle piece of the dumbbell rotates and produces oscillatory movements to the body of varying frequencies (0–30 Hz).
The debate over which platform is superior is currently equivocal. Research performed by Abercromby *et al.* [1] reported that the lower limb extensors (vastus lateralis and gastrocnemius) were activated significantly more during SV than VV from an acute exposure; however, the activation of the tibialis anterior was significantly greater during VV than SV. Furthermore, during dynamic (from 10° to 35° of knee flexion, at a tempo of 4 s up 4 s down) and static squatting (18.5° knee flexion), SV produced a greater activation of the lower limb muscles compared to VV. In a later study, the same authors [2] reported that across different knee angles (5–35°) vibration transmitted to the upper-body and head was 71–189% greater during VV than SV. The authors concluded that during SV the pelvis damps the vibration energy more than the VV. Earlier, Rittweger *et al.* [104] had proposed a similar hypothesis: in SV the feet are alternated between up and down positions, causing rotation of pelvis and flexion of the spinal column, which decreases the vibration

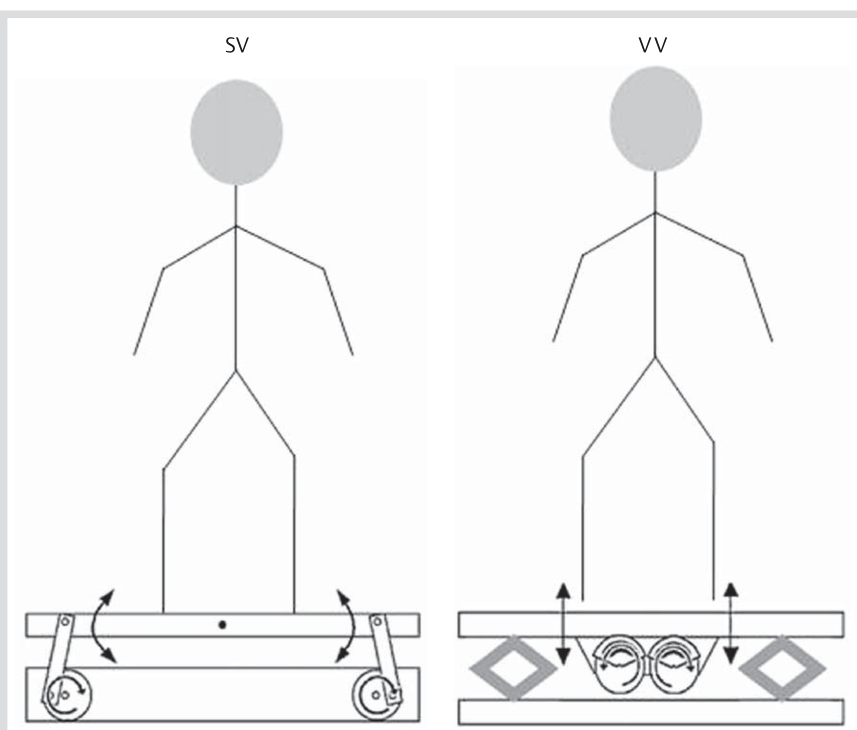

Fig. 1 The 2 different types of commercially manufactured vibrating platforms: SV and VV. (Adapted from Pel et al. [18]). The SV oscillates around a central axis, where a crankshaft on each side of the platform translates to a rotating motion of the electro-motor into a vertical displacement, inducing a seesaw motion, of which the amplitude is either small, closer to axis or larger near the edge of the platform. For VV 2 electro-motors with an eccentric mass induce vertical vibrartions where the amplitude has 2 predetermined settings: low or high.

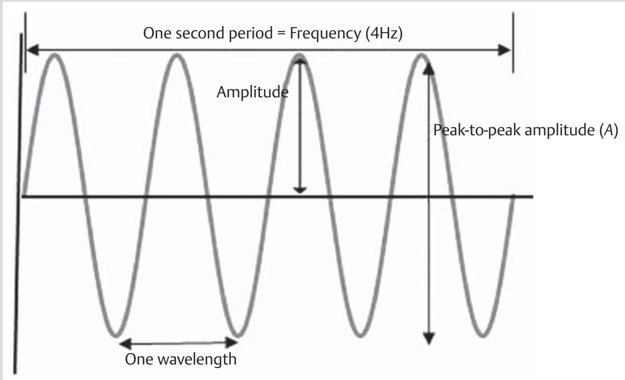

Fig. 2 Parameters of sinusoidal oscillation.

transmission to the head. However, no kinematic analyses have been performed on SV and VV to validate this claim. It should be noted that in Abercromby *et al.*'s [1] acute study the dynamic squat was only performed through a limited range of knee flexion (10–35 °).

Transmission of vibration exercise

The majority of contemporary vibration machines produce periodic sinusoidal oscillations, where energy is transferred from the vibratory machine to the human body. The vibratory load is dependent on 4 parameters: frequency, amplitude, acceleration, and duration. The number of cycles of oscillation determines the frequency; the amplitude refers to the displacement of the oscillatory motion (**Fig. 2**); the acceleration (m/s^2 or *g*) determines the magnitude; and duration refers to the exposure time. Normally, VbX is administered in the range of 0–45 Hz, amplitude of 0–12 mm (peak-to-peak amplitude) and peak acceleration of 0–18 *g*.

The motion of vibration training is sinusoidal. The acceleration transmitted to the body is based on the principle of peak acceleration (*a*) being the product of angular frequency (ω) squared and peak-to-peak amplitude (*A*), where *A* is converted from mm to m. (Equation 1)

$$a_{peak} = \omega^2 A \qquad (m/s^2) \qquad \text{Eq. 1}$$

$$\omega = (2\pi f) \qquad (Hz) \qquad \text{Eq. 2}$$

Angular frequency (ω) is the product of 2 π and vibration frequency (*f*) (Eq. 2). Where *f* is the number of vibratory cycles per unit of time. Therefore, 1/*f* provides the duration of a single cycle, Hz, which is equivalent to cycle per s. Thus, ω is proportional to *f* as given by 2π*f*, Hz, which is equivalent to cycle per s. For example, a vibration frequency of 26 Hz and peak-to-peak amplitude of 6 mm would produce a peak acceleration of 160 m/s^2 (16.3 *g*). Changes in vibration frequency or amplitude will determine the changes in acceleration transmitted to the body. The greatest acceleration (or gravitational load) is high when both frequency and peak-to-peak amplitude are at their maximum. For example, a vibration frequency of 26 Hz, at a peak-to-peak amplitude of 6 mm, will produce a peak angular acceleration of 160 m/s^2 or 16.3 *g*. The vibration frequency and amplitude can be manipulated to determine the desired peak acceleration; however, only a few studies have investigated the dose relationship on neuromuscular and performance aspects. Damping and stiffness adjustments are 2 other factors that need to be considered when vibration is transmitted from the vibratory device to the human body. Wakeling *et al.* [131] have reported that vibration is likely to be damped by tissues and fluids where the mechanical energy is absorbed by structures, leading to heat generation.

Anecdotal reports claim that standing erect, as opposed to squatting, evokes a stronger transmission of the vibration to the head, and shifting body weight to the forefront of the foot will reduce the vibration transmission. Lafortune *et al.* [70] confirmed this, reporting that when the knees were extended the vibration frequency above 10 Hz was more effective in transmitting to the hip compared to a frequency of less than 5 Hz. Rubin [109] found that at low vibration frequency the vibration transmission to the hip was dissipated; however, when the frequency was raised to 15–35 Hz, a higher response at the hip was evident. A scientific model [134] has been used to describe the transmission of vibration; however, this model has lacked the inclusion of the 3 lower limb joints (ankle, knee and hip) and the researchers have not considered the effect of the range of joint motion on vibration transmission. Abercromby *et al.* [1] stated that the damping of mechanical energy by the legs depends not only on the compliance of ankle, knee, and hip joints, but also on the modulation of leg muscle activation. These researchers found that the greatest mechanical impedance (as determined by a decrease in joint compliance and an increase in the absorption of vibration energy) occurred at a knee angle of 10–15 °. They also found that acceleration of the head decreased as knee angle increased from 10 to 30 °, and was greater in acute VV than SV (*f* = 30 Hz, *A* = 4 mm). The authors concluded that squatting at a knee angle of 26–30 ° dissipated head vibration and that the use of small knee flexion angles during VbX increased the likelihood of negative side effects as the greatest mechanical energy is likely to be transmitted to the upper-body and head and should, therefore, be avoided.

Parameters of vibration exercise

Frequency

Prior to the inception of commercialised VbX, vibration studies focused on high vibration frequency; vibratory units were applied directly to the muscle or tendons of animals or humans for a very short duration. McCloskey *et al.* [80] applied direct acute vibration of 100–200 Hz to the hindlimb of a cat's tricep surae muscle, and Bongiovanni and Hagbarth [11] applied 2 min of direct vibration of 150 Hz to human tendon ankle dorsiflexors to stimulate the tonic vibration reflex (TVR). It is not exactly known how the scientific merit of low frequency vibration was validated, but Nazarov and Spivak [86] may have had a part in determining it. They used an arbitrary frequency of 23 Hz because they feared that the vibration would disappear during transmission in the tissue if a higher frequency was selected. Another explanation states that from a natural frequency lower limb muscles respond between a range of 5–65 Hz [87]. There is little scientific documentation on the appropriate vibration frequency (*f*); however, Bosco *et al.* [13] exposed handball and waterpolo athletes to 10 days of intermittent vibration (*f* = 26 Hz, SV, Galileo) and reported an increase in vertical jump height by 12 %, but gave no rationale as to why 26 Hz was selected. In a follow-up study, Bosco *et al.* [14] confirmed their earlier findings that acute vibration performed at 26 Hz on an SV (Galileo) platform had a positive effect on muscular performance by shifting the force-velocity and power-force relationship to the right, enhancing average force, velocity and power in a sample size of

Table 1 Summary of vibration frequency, amplitude and acceleration.

Author	Type of Study	Participants	Condition	Exercise Type	Frequency (Hz)	Amplitude (mm)	Acceleration	Duration	Results
Abercromby *et al*. [1]	randomised cross-over	16H (9♂, 7 ♀)	VV, SV	DS (10–35°),	30	4 p-p	NR	30 s	EMG activity of the leg extensors were significantly greater during SV than VV.
			VV, SV	SS (18.5°)	30	4 p-p	NR	30 s	During SS EMG activity was greater than or equal to responses during DS.
Abercromby *et al*. [2]	randomised	16H (9♂, 7♀)	VV, SV	DS	30	4 p-p	NR	15 s	Head acceleration was greater during VV than SV, and during VV and SV varied inversely with knee angle. The effect of knee angle on head acceleration was different for SV and VV.
Adams *et al*. [3]	randomised	20UT (11♂, 9♀)	VV	SS (2.27 rad)	30, 35, 40, 50	2–4; 4–6	NR	30,45,60 s	High frequencies were more effective when combined with high displacements, and low frequencies were more effective in conjunction with low displacements for improving CMJ.
Bazett-Jones *et al*. [8]	randomised	44UT (33♂, 11♀)	VV	SS (90°)	0, 30, 35, 40,	2–4; 4–6	9.8 m/s^2, 21.2 m/s^2, 27.5 m/s^2, 47.8 m/s^2, 57.2 m/s^2.	9×5 s	No significant differences in CMJ for the different vibration frequencies and amplitudes.
Bosco *et al*. [13]	randomised	14 RA	SV	standing, SS, lunge	26	10	54 m/s^2	5×90 s (10 days)	VbX increased continuous mean jump height (5 s) by 12%.
Bosco *et al*. [14]	randomised	6 EL♀	SV	SS (100°)	26	10	54 m/s^2	10×60 s	Leg press velocity-force and power-force relationship shifted to the right after VbX.
Cardinale & Lim [25]	randomised	16 EL♀ volleyball	VV	SS (100°)	30, 40,50	10 p-p	NR	4×60 s	30 Hz elicited the highest muscle activity (EMGrms) response in the vastus lateralis muscle.
Cardinale *et al*. [24]	randomised	9 RA♂	NR	SS	30	1.5, 3	26.5 m/s^2, 53 m/s^2	10×60 s	30 Hz and amplitudes of 1.5 and 3 mm did not significantly increase serum testosterone and insulin growth factor-1 levels.
DaSilva *et al*. [39]	randomised	31♂	VV	NR	20, 30, 40	4	NR	6×60 s	30 Hz increased CMJ, strength, and power parameters more than 20 & 40 Hz.
Delecluse *et al*. [42]	randomised	18UT ♀	VV	SS, lunge	35–40	2.5–5	22.6–50 m/s^2	1–3×2–6×30–60 s (3×/wk; 12 wks)	VbX with SS increased EMGrms of the rectus femoris and medial gastrocnemius compared to the placebo condition
		19UT ♀	placebo	SS, lunge	NR	NR	3.9 m/s^2	1–3×2–6×30–60 s (3×/wk; 12 wks)	
		18UT ♀	resistance	cardio + knee & leg extensor strength	NA	NA	NA	3×/wk; 12 wks	
		19UT ♀	control	no training					
Di Giminian *et al*. [44]	randomised	RA 9 (4♂, 5♀)	VV – individualised	SS (90°)	20–50	2	1.1–53.6 m/s^2	10×1 min (3×/wk; 8 wks)	Individualised vibration frequency increased vertical jump performance (11%) compared to fixed vibration frequency (3%) and control (2%).
		10 (5♂, 5♀)	VV – fixed	SS (90°)	30	2	1.1–53.6 m/s^2	10×1 min (3×/wk; 8 wks)	
		11 (5♂, 6♀)	control	SS (90°)	0	0	NA	10×1 min (3×/wk; 8 wks)	

Table 1 Continued.

Author	Type of Study	Participants	Condition	Exercise Type	Frequency (Hz)	Amplitude (mm)	Acceleration	Duration	Results
Lythgo *et al.* [76]	randomised	9 H♂	SV	SS (90°)	5, 10, 15, 20, 25, 30	2.5, 4.5	NR	60 s	Leg blood flow increased with higher vibration frequencies.
Pel *et al.* [91]	randomised	NR	VV	SS (150°)	25–50	low (1.2)	24.5–75.5 m/s^2	10 s	Frequencies between 25–50 and 5–40 Hz, for VV and SV vibrated at a near identical vertical sine wave. SV produced higher vertical acceleration than VV. Body mass reduced platform accelerations in the horizontal plane but amplified those in the vertical direction.
						high (2.2)	11.8–37.2 m/s^2	10 s	
			SV	SS (150°)	5–40	3.5	2.9–144 m/s^2	10 s	
Rittweger *et al.* [102]	randomised	10 RA ♂	SV	SS (170°)	18, 26, 34	5	NR	4 min	VO_2 increased linearly from 18 to 34 Hz. At a fixed vibration of 26 Hz, VO_2 increased more proportionally with greater amplitudes.
		8 RA ♂	SV	SS (170°)	26	2.5, 5, 7.5	NR	4 min	

UT = Untrained; **EL** = Elite; **H** = Healthy; **RA** = Recreationally active; **SV** = Side alternating vibration; **VV** = Vertical vibration; **DS** = Dynamic squat; **SS** = Static squat; **p-p** = peak-to-peak; **NR** = Not Reported; **NA** = Not Applicable; **VbX** = Vibration exercise; **CMJ** = Countermovement jump; **EMGrms** = Electromyography root mean square; **CMJ** = Countermovement jump

6 elite volleyball players. Akin to their previous study, no rationale was given for the selection of the vibration frequency.

It took Cardinale and Lim [25] to provide some insight on the optimal vibration frequency. Using electromyography (EMG) to validate the vibration frequency, these authors found that the EMG response of the vastus lateralis, as analysed by the root mean square (rms) was significantly higher in acute 30 Hz compared to 40 and 50 Hz when standing in a half squat position (knee angle 100°) on a VV (Nemes) platform for 60 s (**Table 1**). Delecluse *et al.* [43] also reported that standing in a static half squat position on a vibrating platform (f = 35 Hz, Amplitude (A) = 5 mm, acceleration (a) = 3.9 g) increased EMG_{rms} of the rectus femoris and medial gastrocnemius muscles compared to the placebo condition (a = 0.4 g) after 12 weeks of VbX. However, both Delecluse *et al.*'s [43] and Cardinale and Lim's [25] studies were conducted on a VV platform, with no comparison being made to a SV machine.

Recently, a number of studies (**Table 1**) have examined whether a dose relationship exists between different vibration frequencies and muscular performance, where the majority have used vertical jump (VJ) height as the performance measure. Da Silva *et al.* [39] found that an acute intermittent vibration protocol performed at a frequency of 30 Hz (A = 4 mm) increased VJ height and leg power compared to 20 Hz and 40 Hz. However, this study lacked a control condition; the body posture during vibration was not described; and no measures of EMG were collected. Likewise, Bazett-Jones *et al.* [8] reported a significant increase of 9 % and 8.3 % in VJ height in young untrained women when acutely exposed to 40 Hz and 50 Hz compared to the control condition, but there was no increase inVJ height for the untrained men. However, the small sample size (n = 11) of the women compared to the men (n = 33) may have incurred a type I error, and the vibration exposure time of 45 s may have been insufficient to elicit the required neuromuscular responses for the males.

VbX is like any other form of training – every individual will have a response to an optimal intensity, and/or training load. In physical conditioning, most fitness programmes consider individual responses, and are tailored to suit the individual; however, in VbX there has been a tendency for one vibration frequency to be used by all. Until recently, this was the status quo; however, Di Giminiani *et al.* [44] observed that after 8 weeks (3x/week) of training with the vibration frequency individualised by determining the EMG_{rms} activity of the vastus lateralis performed in a half squat position, the mean power of squat jump and jump height from a continuous rebound jumping test increased 11 % and 18 % respectively in comparison to the fixed (30 Hz), or no vibration groups. These results clearly indicate that vibration frequency should be individualised to fully maximise the benefits of vibration training. Just as other fitness and resistance programmes are individualised for the client, vibration training should follow suit. However, it is unknown if EMG_{rms} is the most appropriate measure to individualise each person's optimal vibration frequency. It may not be practical, as EMG equipment is often expensive, and may not be affordable or readily available in practical settings, such as clinics and gyms. It also requires a certain level of expertise. Further, it should be noted that in Di Giminiani *et al.*'s [44] study only one site (vastus lateralis) was used to record EMG activity. Other muscles, such as the triceps surae and hamstring group, need to be analysed before a conclusion can be reached that the use of one particular muscle will provide the optimum vibration frequency.

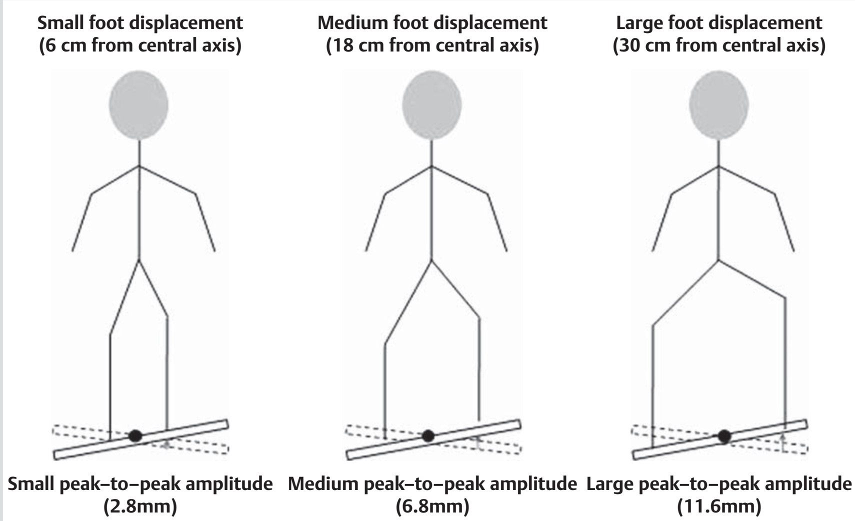

Fig. 3 Illustration of the different foot positions and the corresponding peak-to-peak amplitudes of SV (Galileo, Sport) performed at 26 Hz.

Amplitude

Amplitude is defined as the maximum displacement of a vibration point from a mean position, compared to peak-to-peak amplitude (*A*), which is referred to as the height from the lowest to highest vibration wave (▶ **Fig. 2**). For SV, the amplitude is dependent on where the feet are placed on the platform. When the feet are close to the middle of the platform it equates to a small peak amplitude (~3 mm). A wide stance equates to a greater amplitude (~12 mm) (▶ **Fig. 3**). This differs to VV, where foot placement is independent of amplitude and has a pre-setting of 0–2 mm or 4–6 mm. Using an acute intermittent vibration protocol Cardinale *et al.* [24] found no differences in insulin growth factor 1 (IGF-1) and testosterone levels when participants were exposed to high amplitude (A=3 mm), low amplitude (A=1.5 mm) and zero amplitude (A=0 mm) at a fixed vibration frequency (f=30 Hz). The authors failed to document the type of vibration platform; therefore, if a VV was used the selection of a small amplitude may not have elicited the required response. Using a SV (Galileo) platform where participants stood in an upright stance (10° knee flexion) at a fixed frequency of 26 Hz, Rittweger *et al.* [102] reported that acute VbX increased the oxygen cost increased in all 3 amplitudes (2.5, 5, 7.5 mm) compared to baseline levels, with the highest amplitude (7.5 mm) having the greatest oxygen cost (7.3 ml/kg/min compared to resting 3.6 ml/kg/min). For muscular power, Adams *et al.* [3] showed that acute high vibration frequency (50 Hz, VV, [Power Plate]) with high amplitude (4–6 mm), and low frequency (30 Hz) with low amplitude (2–4 mm) were effective for increasing VJ power. Moreover, Lythgo *et al.* [76] observed that low vibration amplitude ranging from 2.5 mm to 4.5 mm (SV) was able to elicit an increase in mean blood cell velocity by 27 %, when acute vibration frequency was progressively increased from 5 to 30 Hz.

To date, no study has directly compared the different amplitudes between the VV and SV platforms. As discussed earlier, the placement of the feet determines the amplitude in SV, which may affect the transmission of vibration to the various regions of the body. There has been some speculation that different body masses may alter the amplitude of vibration platforms; a heavier mass may decrease the amplitude of the platform. This presumption has been challenged based on recent evidence from Pel *et al.* [91] who reported no change in amplitude when SV (Galileo) and VV (Power Plate) platforms were loaded with 2 different body masses. The authors observed that the acceleration (*g*) from acute vibration in the vertical direction of the SV platform was reduced when vibration frequency was increased from 30 to 40 Hz. However, only 2 different body masses (62 kg and 81 kg) were used in this study and the authors did not consider that many athletes and overweight individuals that use VbX would be outside this body mass range. Consequently, the range is insufficient to critically discuss the effect of body mass on the frequency of VbX. Additionally, the interaction of body mass and stance (knee angle) on amplitude requires further investigation. A current criticism of the literature is that most studies do not provide such details on how amplitude is calculated to whether it is measured by an accelerometer or computed by a mathematical equation. Much confusion surrounds the terms amplitude, peak-to-peak amplitude, and displacement because they are used interchangeably and standardisation of terminology is required. It is advised that a consensus be established in an attempt to gain consistency between research protocols. Lorenzen *et al.* [73] recommended that the term 'peak-to-peak amplitude' be used, and for vibrating platforms an anatomical landmark, such as the middle toe of the foot, be used to standardise the amplitude measurement, which needs be measured and reported.

Acceleration

VbX generates mechanical vibration resulting in acceleration, which is the product of angular velocity $(2\pi f)^2$ and amplitude (*A*), where it has also been coined magnitude and the unit is either expressed as m/s^2 or as multiples of terrestrial gravitation in g (where $1 g = 9.81 m/s^2$). Acceleration is proportional to the force applied. Therefore, increasing acceleration relies on changing the frequency and amplitude to increase acceleration of vibration being transmitted to the body [26], which is similar to adding extra load in conventional resistance training ($F = m a$). VbX relies on increasing acceleration to increase force, where the force is likely to be the primary stimulus to promote changes within the body. However, as the vibrations travel through the body the effect of the force is likely to be damped by muscles, tissues and fluids [131]. A high level of acceleration can be potentially harmful but with careful measurement the optimal training stimulus can be monitored, which is important for making comparisons with other studies.

A large number of acute, short- and long-term VbX studies have reported acceleration but have not documented how they measured or calculated it [14, 15, 23, 24, 48, 59, 67, 101, 110, 123, 124] . A few studies that have directly measured the acceleration source by securing accelerometers to vibration platforms [8, 42–44, 76, 91, 105], and have reported mean accelerations of 2.2 *g* (*f* = 30 Hz, *A* = 2–4 mm, VV), 5.8 *g* (*f* = 50 Hz, *A* = 2–4 mm, VV) [8] 2.5 *g* to 7.7 *g* (*f* = 25–50 Hz, *A* = high, VV), 0.3 *g* to 14.7 *g* (*f* = 5–40 Hz, *A* = high, SV) [91], and 0.1 *g* to 5.5 *g* (*f* = 20–55 Hz, *A* = 2-mm, VV) [44]. Additionally, some researchers have placed accelerometers on body landmarks to determine the acceleration transmission of the vibration that passes through the various joints [2, 37] and found that greater accelerations were observed proximal to the vibration platform compared to distal locations. According to Lorenzen *et al.* [73] all studies should document maximum acceleration (m/s^2 or g) and provide an explanation of how peak or mean acceleration was determined.

Duration

Duration refers to the exposure time to vibration. Most VbX studies have either been performed acutely for single or multiple sessions, either intermittently (30–60 s exposure) or continuously (3–5 min) [13, 14]. It appears that Bosco's [120] acute intermittent protocol of 10 repeated exposures of 1 min interspersed with 1 min rest has been a common duration used in subsequent vibration studies, but with little justification. Currently, there is little scientific evidence on what the optimal duration is for intermittent and continuous sessions. Nevertheless, Adams *et al.* [3] found no significant differences in vertical jump peak power when untrained participants were exposed to acute vibration durations of 30 s, 45 s, or 60 s (*f* = 30–50 Hz *A* = 2–4, 4–6 mm). Moreover Stewart *et al.* [120] reported that standing (5° knee flexion) on a SV, isometric peak torque increased by 3.8 % after 2 min of continuous vibration, compared to decrements in peak torque at 4 and 6 min (*f* = 26 Hz, *A* = 4 mm). In long-term vibration training studies, various exposure times have been reported for studies conducted over 6–12 weeks and 3–8 months [1, 2, 14, 15, 18, 24, 25, 40, 45, 48, 57]. There seems to be a knowledge deficit regarding the ability of continuous VbX to potentiate performance measures. As with resistance training, there may be a point of diminishing returns with respect to the duration of VbX. Durations of greater than 1 min are likely to either involve lower levels of acceleration (and potential for adaptations in strength and power) or greater injury risk if high duration and accelerations are combined. Therefore, intermittent protocols may be preferred to continuous exposure because it stimulates muscle while limiting fatigue. However, more work is required to determine whether there is an optimal duration exposure time for VbX in acute and long-term studies.

Exercises and posture

Static and dynamic squats are common exercises performed on vibration platforms [13, 32, 77, 123]; however, a combination of lower and upper-body exercises have also been performed on various vibrating platforms [1].

The knee joint angle is a critical factor when performing a static or dynamic squat on a vibrating platform. Abercromby *et al.* [1] reported that a static squat at 18.5° provided greater muscle activation compared to dynamic squatting (10–35° knee angle). Additionally, these authors observed that during dynamic squatting, EMG_{rms} of vastus lateralis, gastrocnemius, and tibialis anterior activity were higher in smaller (10–15°) compared to larger flexion angles (31–35°) for acute exposures on both SV and VV platforms. Caution should be given to Abercromby *et al.*'s [1] findings, as a narrow range of knee angle (10–35°) was tested during the dynamic squat and only one fixed angle was assessed for the isometric squat position (18.5°). Further, it is unknown whether greater knee angles would continue to decrease muscle activity in dynamic squatting, and it is unknown what effect EMG activity has on high (120°) or low (90°) isometric squats. It remains equivocal whether a greater knee angle elicits a decrement in EMG activity for dynamic and static squatting, and if amplitude or frequency provides the greatest stimulus for muscle activity change and where the exposure duration influences this as well. Roelants *et al.* [107] reported that during VV (*f* = 35 Hz, *A* = 2.5 mm) EMG was significantly higher in single leg squat (knee angle 125°) compared to bilateral squat at 90° and 125° knee angle. Using 2 knee flexion angles of 10° and 70° (*f* = 20 Hz, *A* = 5–9 mm, SV, [Galileo 900]) Savelberg *et al.* [114] reported that after 4 weeks (3x/week) of VbX the 10° knee angle shifted to a more extended knee joint angle. In contrast, the larger knee angle (70°) shifted to a more flexed knee joint position, and the authors concluded that vibration caused a change in muscle length which shifted the knee angle. However, to confirm this finding a control condition should have been included. Therefore, future research needs to focus on different isometric knee angles in response to larger knee angles in dynamic squatting and its application to muscle performance.

Safety of vibration exercise

Occupational vibration can be detrimental to one's health, especially for workers who are constantly and continually exposed to vibrations from different types of machinery [82]. However, most exercise vibration studies are conducted acutely and intermittently with no incidences of ill-effects having being reported. Conversely, Crewther *et al.* [37] observed that untrained participants exposed to acute vibration frequencies (10, 20, 30 Hz), amplitudes (1.25, 3, 5.25 mm) and postures (standing, squat) suffered from side-effects, such as hot feet, itching of the lower limbs, vertigo and severe hip discomfort. Likewise, Cronin *et al.* [38] reported that untrained participants suffered from vibration pain of jaw, neck and lower limbs from an acute intermittent VbX protocol (*f* = 26 Hz; *A* = 6 mm), which subsided after 7–10 days of physiotherapy treatment. However, Crewther *et al.* [37] and Cronin *et al.* [38] did not fully disclose how the participants were familiarised on the vibration platform, or whether they screened the participants for vibration side-effects. Both studies required the participants to slightly flex their knees; this small knee angle may have increased the vibration transmission to areas such as the head or hip. Recent research has concluded that the smaller the knee angle, the greater the vibration transmission to the head [1, 91]. The findings of Crewther *et al.* [37] and Cronin *et al.* [38] are very uncommon, but highlight the need for researchers and exercise specialists to be fully trained on the use of vibration technology before participants take part in vibration led exercise, research and rehabilitation programmes.

Additionally, it has been reported by Rittweger *et al.* [101], Kerschan-Schandl *et al.* [67], Russo *et al.* [110], Roelants *et al.* [106], Hazell *et al.* [54], and Broadbent *et al.* [16] that acute VbX can elicit erythema of the lower limbs, with anecdotal reports from participants suggesting that VbX causes a hot sensation of the legs and acute itchiness, which normally subsides within minutes of VbX and has no deleterious effect on the body.

However, it is unknown what causes the itchiness; one proposal suggests that the increase in blood flow is the main contributor, while another thought is that vibration induces skin shear forces which promotes vasodilation and is mediated by release of histamine [100]. Broadbent *et al.* [16] has postulated that acute VbX may cause an excitatory response on mast cells to produce histamine, which causes vasodilation and promotes erythema itchiness. Results from their study, however, indicate that histamine levels were lower in the leg receiving vibration (*f*=40 Hz, *A*=5 mm, VV) after muscle damage was elicited from downhill running, compared to those with muscle damage who received no vibration. Further, they speculate that the increase in blood flow from the vibration could have increased the clearance rate of histamine. Therefore, the mechanism causing erythema remains unidentified, and warrants further investigation.

The effects of vibration exercise on reflex activity and Jendrassik manoeuvre

Tendon reflex (stretch reflex)

Rittweger *et al.* [103] reported an enhancement of the patellar tendon stretch reflex following acute VbX (*f*=26 Hz, *A*=6 mm, SV, [Galileo]) with dynamic squatting to exhaustion, and suggested that α-motoneurons were augmented by the vibration, which recruited high-threshold units and muscle fibres. However, no effect on patellar tendon reflex has been reported after acute intermittent (*f*=26 Hz, *A*=4 mm, SV, [Galileo]) [57] or continuous [33] (5 min) (*f*=26 Hz, *A*=6 mm, SV, [Galileo]) vibration exposure. Recently Melnyk *et al.* [81] elicited the stretch reflex in the hamstrings by inducing an anterior tibial translation during standing, and compared the reflex response between a control and acute intermittent vibration group (*f*=30 Hz, *A*=4 mm, VV, [Power Plate]). The researchers found post-vibration, anterior tibial translation displacement decreased with a corresponding increase in EMG of the hamstring short latency response. The authors concluded that the effect of increased knee stability was caused by reflex excitability. However, from this study it is not conclusive whether the stretch reflex was potentiated from acute VbX and it remains speculative whether spinal reflexes are the main mechanism.

Hoffmann reflex (H-reflex)

The Hoffmann reflex (H-reflex) is a measure of assessing monosynaptic activity of the spinal cord [93]. The H-reflex differs to the tendon reflex because it is activated by electrical rather than mechanical stimulation, which bypasses the muscle spindle by acting directly on the afferent fibre. The electrical stimulus causes a corresponding H-reflex, which is the result of increased excitability of the Ia afferent and α-motoneurons. As the strength of the electrical stimulus increases, the efferent fibres become excited and induce a direct muscle contraction, known as the M-response. Further increase in the stimulus strength results in suppression of the H-reflex but M-response becomes augmented.

Thompson and Belanger [121] reported that self-paced inline skating for 35 min elicited a mean vibration frequency of 141 Hz from the skate chassis and 34 Hz from the middle portion of the tibia, which resulted in the H-reflex being suppressed by 35% compared to resting conditions. The authors concluded that presynaptic inhibition was the main factor for suppressing the reflex response. Similarly, Armstrong *et al.* [5] found the H-reflex was suppressed in the first minute post-vibration after a single minute bout of VV (*f*=40 Hz, *A*=2–4 mm). But earlier work from Nishihira and associates [88] found that post-vibration the H-reflex and H max/M max ratio was enhanced, suggesting that motoneuron excitability was heightened. The dissonance between Nishihira and associates [88] and Armstrong *et al.*'s [5] findings is probably due to the different protocols. Nishihira *et al.* [88] used a 3 min exposure performed on SV platform (*f*=25 Hz) where the H-reflex was elicited from a seated position, which differs to Armstrong *et al.*'s [5] 1 min duration performed on VV (*f*=40 Hz) with the H-reflex elicited from a supine position.

Jendrassik manoeuvre

The Jendrassik manoeuvre involves contracting remote muscles, normally of the upper-body (particularly the forearm and jaw muscles) to induce a reflex response. A common method for eliciting a reflex is to grasp the hands and pull them apart – this potentiates the stretch reflex and H-reflex. In the clinical setting, the Jendrassik manoeuvre has been used to induce a full-sized reflex in neurologically impaired patients. In young (25 yrs) and older (75 yrs) healthy people directly applied vibration to the quadriceps (*f*=100 Hz, *A*=2 mm) produced a post-vibration decrease in patella tendon reflex force, but the younger group showed a greater reflex inhibition [50]. Moreover, the effect of the Jendrassik manoeuvre facilitated the patella tendon reflex more in young people than in the older group (97% vs. 64%). The authors concluded that the age-related changes were due to changes in pre-synaptic inhibition pathways and motoneuron input resistance, confirming that the integrity of the spinal interneuronal pathways deteriorate with ageing [19]. The reduction in muscle vibration inhibitory effect of older adults suggests that the pre-synaptic inhibition of Ia afferents may deteriorate with an increase in age, or the aged muscle spindle may reduce the number of Ia afferents activated by the vibratory stimulus. Recently, Cochrane *et al.* [31] reported that superimposing the Jendrassik manoeuvre upon acute VBX enhanced metabolic rate in old and young people but there were no significant differences in the elevated metabolic rate between the groups.

To date, there is a lack of research on how VbX may influence spinal reflexes but there remains a positive belief that spinal reflexes are responsible for VbX potentiating effects. However, in light of recent research it remains equivocal whether the spinal reflexes are the major contributor because blood flow, muscle temperature, and other neural aspects increase as a result of VbX. Additionally, it has been difficult to ascertain if spinal reflexes are potentiated from VbX due to different vibration methods, parameters (amplitude, exposure duration, rest interval), prescription (number of repetitions, sets, exercises) and participant characteristics (body/muscle mass, training status, age, gender). In the future, this needs to be standardised to determine if VbX influences spinal reflexes.

The effects of vibration exercise on muscle activity

Lower body

It is possible to measure electromyography (EMG) activity without any artefacts in response to vibrating muscle. Seroussi *et al.* [118] evoked acute vertical sinusoidal vibrations (*f*=3–10 Hz; *A*=0.4–13 mm) from a servohydraulic shaker, and were successful in removing motion artefacts by passing the raw EMG through a phaseless digital 6 pole Butterworth high pass filter with a cutoff frequency of 30 Hz. They found that when EMG of the erector spinae was adjusted for torque, a significant increase (19%) in mean torque was observed. Likewise, Bongiovanni and Hagbarth

[11] reported that tibialis anterior EMG activity and single motor unit discharge were augmented from a pneumatic vibratory unit (f=150 Hz, A=1.5 mm).

Using a small actuator (f=50 Hz, A=5 mm) applied acutely to the quadriceps, Warman *et al.* [132] reported an increase in EMG_{rms} of the rectus femoris during isometric (30%), isokinetic (43%), and concentric (107%) contractions. In a subsequent study, Humphries *et al.* [58] used the same vibrating actuator and reported no significant differences in peak normalised EMG_{rms} between acute vibration and resting conditions. Additionally, there were no corresponding changes in the rate of force development or peak force. However, the vibration exposure duration was not documented, therefore it may have been too short or too long to elicit the desired responses. Similarly, Torvinen, *et al.* [126] found no significant changes in soleus mean power frequency and EMG_{rms} from 4 min of VbX (f=25–40 Hz, A=2 mm, VV) (▶ **Table 2**), but reported a decrease in mean power frequency and EMG_{rms} for the vastus lateralis and gluteus medius muscles, which was accompanied by no changes in muscle function.

In a subsequent study, Torvinen *et al.* [123] used the same exercise routine and time constructs as the previous study, but in the latter study the participants performed the exercise routine on a SV platform and the vibration frequency was incrementally increased from 15–30 Hz (A=10 mm). During VbX EMG_{rms} was significantly augmented in the soleus and gastrocnemius but there was no change in vastus lateralis EMG_{rms}. However, an increase in isometric leg force and VJ height was reported. The authors provided no discussion on the dissonance between the 2 studies, consequently the reader can only surmise, that either the type of vibration platform (VV vs. SV) or vibration parameters (f=15–30 vs. 25–45 Hz, A=2 mm vs. 10 mm) may explain the variation in results. However, it is feasible that the action of the side alternating platform with a larger amplitude may have contributed to the increase in muscle performance. Recent evidence has reported that using a fixed frequency (30 Hz) and amplitude (4 mm), a SV platform generates greater muscle activation of lower limb muscles compared to a VV platform [1].

Upper body

The effect of acute upper-body VbX on EMG activity has produced similar results to that of acute lower-body vibration. Using a vibrating dumbbell, Bosco *et al.* [12] observed that during acute intermittent vibration (f=30 Hz) biceps brachii EMG_{rms} increased 2-fold compared to baseline measurements, and during post-vibration bicep power was augmented but no corresponding increase in EMG activity was found. Further evidence of increased EMG_{rms} has been observed from vibrating isometric elbow pull and push actions, with increases in co-contraction at loads of 20% and 40% of maximum force [84]. The authors speculate that the mechanism for increased EMG_{rms} cannot be entirely accounted for by spinal reflexes but by increased motor unit synchronisation and firing frequency. Although Mischi and Cardinale's [84] study provides some new insights to the response of superimposing acute vibration on agonist, antagonist and co-contraction of muscles, caution is required because only one vibration frequency (28 Hz) was tested with brief exposures of vibration and the recorded absence of amplitude restricts the findings of the study. Conversely, Moran *et al.* [85] reported that when a custom built vibrating unit was directly placed on the bicep brachii tendon (f=65 Hz, A=1.2 mm) it did not elicit an increase in EMG_{rms} during the lifting phase of bicep curls at 70% 1RM. Similarly, post-vibration showed no enhancement in EMG_{mpf} (mean power frequency) and peak force or power.

Finally, a novel study was conducted to investigate acute muscle activity on a VV platform on both the lower (vastus lateralis, and biceps femoris) and upper limb muscles (biceps brachii and triceps brachii) [54]. The investigators used a range of frequencies (f=25, 30, 35, 40, 45 Hz), amplitudes (A=2 and 4 mm), and body positions of static squat, dynamic squat, static bicep curl and dynamic bicep curl. They reported that a static squat EMG_{rms} of vastus lateralis and biceps femoris was augmented when vibration frequency and amplitude were increased, but no increase in muscle activity was evident in static and dynamic bicep curls, probably because the transmission of vibration was damped by the lower extremity. It is important to note that the raw EMG signal was passed through a sixth order Butterworth filter between 100 Hz and 450 Hz, which may have removed important muscle activity signals.

Posture

Roelants *et al.* [107] has recently determined whether posture affects muscle activation by investigating 3 different isometric squat positions of a two-leg, high squat (knee angle 125°, hip angle 140°); two-leg, low squat (knee and hip angle 90°); and one-leg, high squat (knee angle 125°, hip angle 140°). The investigators reported that acute VbX increased EMG_{rms} activity more in a one-leg high squat, compared to two-leg high and low squats. However, further testing is required to determine if any EMG differences exist in squatting positions that occur between 90° and 125° knee flexion.

Abercromby *et al.* [1] acutely investigated muscle activity of different lower limb postures of static squat (18.5°) and dynamic squat (eccentric and concentric 10–35° knee angle) performed on both SV and VV platforms (f=30 Hz, A=4 mm). For isometric, eccentric and concentric muscle action, EMG_{rms} increased significantly in all 4 lower limb muscles for both SV and VV. In support of this, Delecluse *et al.* [43] reported that standing in a static half-squat position on a VV platform (f=35 Hz, A=5 mm, a=3.9 g) increased gastrocnemius and rectus femoris EMG_{rms} activity, compared to placebo (a=0.4 g) control (no vibration); however, the sampling period was only conducted over 20 s. Conversely, Cormie *et al.* [36] observed that in a half-squat position (knee angle 100°) there were no changes in average iEMG (integrated) activity of the vastus lateralis, vastus medialis, bicep femoris during acute vibration treatment (f=30 Hz, A=2.5 mm, VV [Power Plate]).

The effects of vibration exercise on cardiovascular indices

Blood flow

Hand-held tools are normally operated at high vibration (80–100 Hz), which has been shown to decrease blood flow to the digits of the hand, resulting in 'white finger vibration' [20]. However, Kerschan-Schindl *et al.* [67] were first to report that acute VbX (f=26 Hz, A=3 mm, SV [Galileo]) increased blood flow of the popliteal artery (100%) and caused erythema in the foot and calf. Furthermore, Lythgo *et al.* [76] found that when an acute intermittent vibration protocol was performed (f=10 Hz–30 Hz, SV [Galileo]), an increase in mean blood cell velocity of the femoral artery was evident, with 30 Hz providing the greatest increase in blood flow compared to resting levels. In contrast, Hazell *et al.* [55] found that an acute intermittent vibration protocol (f=45 Hz, A=2 mm, VV [Wave]) reported no increases in femoral artery blood flow after 3 min. Likewise, Button *et al.* [20] reported no significant differences in leg blood flow of a vibrating cushion (f=60 Hz, A=not given, VV [ATL]) placed under the gluteal muscles, and a hand unit placed under the right foot while in the seated position. In this particular study, no rationale was given for using a hand-held device applied to the foot, or why the vibrating cushions were acutely applied to the gluteals rather than directly to the legs. Additionally, the participants were seated with knees and ankles at 90°, which suggests that vibration transmission may have been damped, attenuating blood flow.

Vibration massage has also been shown to increase skin blood flow. 3 min of acute continuous vibration (f=30 Hz, A=5–6 mm, VV [Power Plate]) increased gastrocnemius skin blood flow by 250% compared to baseline, but there were no treatment differences between with and without vibration [72]. Moreover, Maloney-Hinds *et al.* [78] found that when the forearm was passively vibrated on a VV platform [Power Plate] at 30 & 50 Hz (A=5–6 mm) for 10 min it significantly increased skin blood flow within 5 min and remained elevated for 9 min post-vibration.

Heart rate, blood pressure and arterial stiffness

Acute VbX has been reported to have little effect on heart rate (HR) and blood pressure [20, 55, 90]. Kerschan-Schindl *et al.* [67] observed no change in HR, systolic and diastolic blood pressure values after acute VbX (f=26 Hz, A=3 mm, SV [Galileo]). However, exhaustive VbX did increase HR and systolic pressures by 30% and 15% [101]. To date, only one study has investigated the effects of vibration on arterial stiffness by measuring brachial-ankle pulse velocity [90]. Following acute intermittent vibration (f=26 Hz, A=2–4 mm, VV [Power Plate]) arterial stiffness was significantly reduced (3%) at 20 and 40 min post-vibration compared to the same time series of no vibration.

The effects of vibration exercise on muscle function

Power

Acute vibration – lower body power

A summary of the studies that examined the acute effects of VbX on lower and upper body power can be found in ▶ **Table 2, 3**. Vertical countermovement jump (CMJ) has been used by many investigators to assess muscle power and its acute effects on VbX. The enhancement in VJ height has varied across the different research protocols. For instance, using a SV (Galileo) platform, Cochrane and Stannard [32] reported an 8.2% increase in CMJ height from 5 continuous minutes of acute vibration (f=26 Hz, A=6 mm) (▶ **Table 2**), and Torvinen *et al.* [123] observed a 2.5% enhancement following 4 continuous minutes of vibration (f=15–30 Hz, A=10 mm). Likewise, 5 min of continuous VbX has been shown to raise muscle temperature by 1.5°C, which significantly increased CMJ height (9.3%) and power (4.4%) but when the muscle temperature was elevated by the same amount in stationary cycling and hot water bath the increases in CMJ were similar between the 3 conditions [34].

Studies that have used VV platforms (Power Plate, Nemes) have shown similar findings. Bosco *et al.* [15] has reported an increase in VJ height of 4% from 10 min of intermittent vibration (f=26 Hz, A=4 mm, VV [Nemes]). Brief, single vibration (f=30 & 40 Hz, A=2–4 mm) exposures of 30 s and 45 s performed on a VV platform have respectively recorded a 0.6% and 9% improvement in VJ height [8, 36]. Conversely, Torvinen *et al.* [126] found no significant increases in VJ height when dynamic exercise was combined with 4 min of VbX (f=25–40 Hz, A=2 mm, VV [Kuntatory]). It is difficult to explain why Torvinen *et al.*'s [123] earlier study reported a 4.4% increase, as both studies used similar protocols and participants. However, a VV platform was used in the latter study where the amplitude was smaller (2 mm) than the previous study (10 mm), which could have negated the desired responses. The use of VbX to cause acute changes in power would appear similar to using contrast-complex training, a modality also believed to utilise the theory of post-activation potentiation PAP), which is referred to as an increase in muscle performance preceded by a muscle contractile activity [111] that involves myogenic and neurogenic factors [56]. To date, it is equivocal whether acute VbX causes PAP by enhancing muscle twitch and reflex properties [33, 35, 40, 64, 79, 92].

Measuring muscle power has not only been confined to vertical jump. Leg press, weighted squats, and knee extension have also been used to assess muscle power from an acute bout of VbX. Bosco *et al.* [14] found a 6–8% increase in single leg press power across loads of 70, 90, 100, 139 kg in elite volleyball players (n=6) from intermittent VbX (f=26 Hz, A=10 mm, SV [Galileo 2000]). Similarly, Rhea and Kenn [98] observed a 5.2% increase in squat power (3 reps, 75% 1RM) of male college athletes that received vibration (f=35 Hz, A=4 mm, VV) while dynamic squatting their body weight. However, when ballistic knee extensions were performed with direct vibration (f=65 Hz, A=1.2 mm) that was applied to distal tendon of quadriceps no significant changes in power variables were found [75].

Acute vibration – Upper body power

The effects of acute vibration on upper-body power have been explored less so, and with varying results. Bosco *et al.* [12] found a post-vibration 8% increase in average power of bicep brachii from 12 international boxers that isometrically gripped a hand-held vibrating device (f=30 Hz, A=6 mm). In a similar study, Issurin and Tenenbaum [60] used an isotonic vibrating cable (f=44 Hz, A=3 mm) where non-elite and elite athlete performed 3 sets of 3 reps (65–70% 1RM) at a tempo of 2 s per rep. They reported that both non-elite and elite athlete groups produced a 10.2% and 10.7% increase in mean power and 10.4% and 7.9% increase in peak power during vibration compared to no vibration.

Further support of vibration enhancing upper-body power has been reported by Poston *et al.* [94], where an Olympic barbell was fitted with a vibrating electric motor and experienced weight lifters performed an isometric vibration bench press hold (f=30 Hz, A=1.1 mm) for 30 s between the second and third sets of bench pressing (3 reps, 70% 1RM). Although, the average power of the bench press was higher with vibration than without, there were discrepancies in baseline power outputs, suggesting that either the athletes should have been blinded before receiving vibration or a greater familiarisation period with the vibration apparatus should have been included.

Some researchers have shown little or no effect of vibration on upper-body power. Moran *et al.* [85] observed no significant pre-post changes in power, moment, and angular velocity when a custom built vibratory unit (f=65 Hz, A=1.2 mm) was directly applied to the tendon of bicep brachii while resistance trained males performed 3 sets x 5 reps of bicep curls (70% 1RM). The same group of researchers [74] repeated a similar experiment and used the same vibratory unit (f=65 Hz, A=1.2 mm), and participants but with the addition of 40% and 70% 1RM loading with vibration did not produce any significant changes in power

Table 2 Acute Effects of VbX on Lower Body Power.

Author	Type of Study	Partici-pants	Condition	Exercise Type	Frequency (Hz)	Amplitude (mm)	Duration	Load	Results
Bazett-Jones *et al*. [8]	randomised	44 UT (33♂, 11♀)	VV	SS (90°)	0,30,35, 40	2–4; 4–6	9×5 s	BW	In women, VbX significantly increased CMJ height (9%) at 40 Hz, 2–4 mm and 8.3% at 50 Hz 4–6 mm. In men, VbX had no effect on CMJ height.
Bosco *et al*. [14]	randomised	6 EL♀	SV	SS (100°)	26	10	10×60 s	BW	Single leg press at 70, 90, 110, 130 kg significantly increased average force, velocity, and power increased (≈6%) from VbX.
			control	SS (100°)	0	0	10×60 s	BW	
Bosco *et al*. [15]	controlled	14 RA ♂	VV	SS (100°)	26	4	10×60 s	BW	VbX increased leg press power (160% of body mass) by 7% and enhanced CMJ height by 4%.
Cochrane *et al*. [34]	cross-over	8 RA (6♂, 2♀)	SV	DS	26	6 p-p	1×5 min	BW	CMJ height increased significantly (VbX 9.3%; cycle 7.5%; hot bath 7.1%) as did CMJ power (VbX 4.4%; cycle 4.4%; hot bath 6.5%) but no significant differences existed between the conditions
			control	cycle	NA	NA	70 W, 10 min	BW	
			control	hot bath	NA	NA	41°C, 17 min	BW	
Cochrane & Stannard [32]	randomised cross-over	16 EL ♀	SV	DS, SS, lunge	26	6	5×1 min	BW	VbX significantly increased CMJ height (8.1%) compared to no change in cycle and no VbX.
			control	DS, SS	0	0	5×1 min	BW	
			control	cycle	NA	NA	50 W, 5 min	BW	
Cormie *et al*. [36]	randomised	9 PA ♂	VV	SS (100°)	30	2.5	30 s	BW	VbX significantly increased height during the CMJ immediately following VbX compared to control. No significant differences were observed in CMJ peak power and peak force during isometric squat (100°).
			control	SS (100°)	0	0	0	BW	
Luo *et al*. [75]	randomised	14 H ♂	DV	knee extension	65	1.2	time taken to do reps and sets	3 sets 5 reps 60–70% 1 RM	During and after VbX no changes in peak angular velocity, time to peak angular velocity, peak moment, time to peak moment, peak power, time to peak power, of the rectus femoris and vastus lateralis were detected.
			control	knee extension	0	0		3 sets 5 reps 60–70% 1 RM	
Rhea & Kenn [98]	randomised	8 RA ♂	VV	DS	35	4	30 s	3 reps 75%1RM	VbX significantly increased squat power (5.2%)
		8 RA ♂	control	DS	0	0	30 s	3 reps 75%1RM	
Torvinen *et al*. [123]	randomised cross-over	16 H (8♂, 8♀)	SV	DS, jumping, standing on heels, standing erect	15–30	10	4 min	BW	VbX significantly increased CMJ (2.5%) compared to control.
			control	DS, jumping, standing on heels, standing erect	0	0	4 min	BW	
Torvinen *et al*. [126]	randomised cross-over	16 H (8♂, 8♀)	VV	DS, jumping, standing on heels, standing erect	25–40	2	4 min	BW	There was no significant changes in CMJ.
			control	DS, jumping, standing on heels, standing erect	0	0	4 min	BW	

UT = Untrained; **EL** = Elite; **RA** = Recreationally active; **BW** = body weight; **SV** = Side alternating vibration; **VV** = Vertical vibration; **DS** = Dynamic squat; **SS** = Static squat; **CMJ** = Countermovement jump; H = Healthy; DV = Direct vibration

Table 3 Acute Effects of VbX on Upper Body Power.

Author	Type of Study	Participants	Condition/Group	Exercise Type	Frequency (Hz)	Amplitude (mm)	Duration	Load	Results
Bosco *et al.* [12]	randomised	12 ♂ national boxers	DB	elbow flexion (2.5 rad)	26	6	5×60 s	2.8 kg	VbX increased elbow flexion average power (14 %).
Cochrane & Hawke [29]	randomised cross-over	12 climbers (5♀, 7♂)	DB	unilateral upper body exercises	26	3	5×60 s	3 kg	VbX produced no significant changes in medicine ball throw.
			arm crank	arm crank	NA	NA	5 mins	25 W	
			control	unilateral upper body exercises	0	0	5×60 s	3 kg	
Issurin & Tenenbaum [60]	randomised	14 EL ♂	elite athlete	cable dynamic elbow flexion (pronated grip)	44	3	3 sets 3 reps	67–70 % 1RM	Mean elbow flexion power increased 10.2 % and 10.7 % in recreation and elite athlete groups; while peak power increased 10.4 % and 7.9 % respectively during VbX.
		14 RA ♂	recreation athlete	cable dynamic elbow flexion (pronated grip)	44	3	3 sets 3 reps	67–70 % 1RM	
Luo *et al.* [74]	randomised cross-over	11 RT ♂	DV +BC(40 %) sham +BC (40 %)	dynamic elbow flexion	65	1.2	3 sets 5 reps	40 % 1RM	VbX did not increase mean and peak angular velocities, moment and power, time to peak power, and initial power at 100 milliseconds for either resistance loads.
			DV +BC (70 %) sham +BC (70 %)	dynamic elbow flexion	65	1.2	3 sets 5 reps	70 % 1RM	
Moran *et al.* [85]	randomised cross-over	14 RT ♂	DV+BC sham +BC	dynamic elbow flexion	65	1.2	3 sets 10 reps	70 % 1 RM	VbX did not enhance mean power peak power.
			DV-BC sham –BC	dynamic elbow flexion	65	1.2	3 sets 10 reps	70 % 1 RM	
Poston *et al.* [94]	randomised cross-over	10 RT ♂	vibration	isometric bench press	30	1.1	30 s	60 kg	VbX increased average bench press power (5.2 %).
			control	isometric bench press	0	0	30 s	60 kg	

EL = Elite; **RA** = Recreationally active; **RT** = Resistance trained; **SV** = Side alternating vibration; **VV** = Vertical vibration; **DS** = Dynamic squat; **SS** = Static squat; **DB** = Dumbbell; **DV** = Direct vibration; **+BC** = with bicep curls; **−BC** without bicep curls; **RM** = repetition maximum measures. From these results the researchers proposed that when performing dynamic exercise, such as bicep curls, it relies on the stretch-shortening cycle where smaller vibration amplitude may be required to activate and optimise muscle spindle sensitivity. However, Bosco *et al.*'s [12] findings contradict this because they reported an 8% increase in bicep brachii peak power from 5 min of intermittent dumbbell vibration (f=30 Hz, A=6 mm). Therefore, the direct application of the vibratory unit and its frequency (65 Hz) may have caused the insignificant findings from Moran *et al.* [85] and Luo *et al.* [74]. Moreover, Cochrane and Hawke [29] have also reported no significant increases in upper-body power of climbers that were exposed to an electric powered vibrating dumbbell (3 kg) (f=26 Hz, A=3 mm, [TOP Galileo]). At present the research has focussed on short- and long-term lower body power but there is lack of conclusive research on longer exposures of VbX on upper body power.

Short-term vibration (≤2 months) – Lower body power
Repeated single bouts of vibration performed over days or weeks have been investigated and the findings of the short-term VbX on lower body and upper body power can be found in ▶ **Table 4, 5**. Bosco *et al.* [13] reported a 11.9%. increase in VJ height (5 s continuous jumping protocol) in handball and waterpolo players after receiving 10 days of intermittent VbX (f=26 Hz, A=10 mm, SV, [Galileo]). Further support for short-term vibration potentiating CMJ has been reported by Fagnani *et al.* [49] where competitive female athletes increased their CMJ by 8.7% from 8 weeks of vibration training (f=35 Hz, A=4 mm, VV [Nemes]). Well-trained strength males (21–40 yrs) that underwent 5 weeks (3x/week) of vibration (f=40 Hz, A=not given, VV [Nemes]) combined with 6RM squats reported an increase in VJ by 8.8% [108]. Annino *et al.* [4] observed an increase in VJ height (6.3%) in well-trained ballerinas after performing 2 months (3x/week) of VbX (f=30 Hz, A=5 mm, VV [Nemes]) additionally, the average power, force and velocity of leg press increased significantly at loads of 50, 70, and 100 kg . In a recent study [44] where vibration frequency was set individually for each participant, the authors reported that after 8 weeks (3x/week) of vibration training, squat jump height increased by 11%, continuous rebound jump height was enhanced by 22% and mean power significantly increased by 18% respectively compared to a fixed (30 Hz), or no vibration . But no significant increases in CMJ height were found after 8 weeks in all 3 groups. Likewise, other vibration training protocols conducted over different time periods such as, 9 days [30], and 5 weeks, (3x/week) [42] have reported no significant increases in VJ.

Long-term vibration (>2 months) – Lower body power
Several studies have investigated the long-term effects of vibration on muscle power using VJ performance. The majority of these studies have found increases in VJ jump performance. Delecluse *et al.* [43] randomised 67 untrained females (21 yrs) into VbX (f=35–40 Hz, A=2.5–5 mm, VV [Power Plate]), resistance training (8–20RM of knee extension and leg press), placebo and control groups and found that after 12 weeks (3x/week) of training, VJ height increased by 7.6% from VbX. Likewise, healthy non-athletic males and females increased VJ height by 9.0% and 7.7% following 4 and 8 months of VbX (f=25–40 Hz, A=2 mm, VV [Kuntotary]) [124–125]. In addition, post-menopausal women have shown increases in VJ height of 19.4% and 4.7% from 24 weeks (3x/week) [106] and 6 months (2x/week) of VbX training [110]. However, no significant improvements in VJ height have been reported from 11 weeks (3x/week) [41] of VbX.

In summary, there is strong evidence that acute VbX can enhance upper and lower-body muscle power, and there is some indication that VbX can enhance lower and upper-body muscle power over a longer-term, although this is less convincing. Future studies need to be conducted to determine the optimal duration of the rest between repetitions, the optimal frequency and duration necessary to maximise power in both short and long term studies.

Force

Acute vibration – Upper body force. There are many methods of applying vibration to the upper-body; some researchers have used custom-built vibratory units applied directly to the muscle or attached to resistant training cables, while in recent times commercially manufactured vibrating dumbbells have also become available. A summary of the studies that investigated the acute effects of vibration on upper and lower body force can be found in ▶ **Table 6, 7**. In a study conducted by Kin-Isler and colleagues [68], an electromotor was used to transmit vibrations through a cable attached to a leather belt that was placed over the belly of the biceps brachii. Using a range of vibration frequencies (f=6, 12, 24 Hz, A=4 mm) and joint angles (90°, 120°, 150°) the researchers reported that during a 10 s vibration exposure, a 6.4% increase in MVC elbow flexors was observed. However, the length of muscle (conducted at various angles) did not affect isometric MVC. Finally, vibration has no effect on grip force when using an electric powered vibrating dumbbell [29] or when arms are exposed less proportionally to the legs on a vibrating platform [32, 123, 126].

Acute vibration – Lower body force
There is little consensus on whether acute vibration increases lower-body force of isometric, isokinetic and isoinertial muscle actions. De Ruiter *et al.* [58] reported that when the knee extensors were electrically stimulated, the maximum force-generating capacity and isometric contraction significantly declined after an intermittent acute bout of vibration (f=30 Hz, A=8 mm, SV, [Galileo 2000]). However, no changes in maximal isometric leg extensor strength were found following 4 min of vibration (f=25–40 Hz, A=2 mm, VV [Kuntotary]; [126]. Conversely, in a follow-up experiment using the same design and experimental protocol, the researchers [123] reported an increase of 3.2% in leg extensor strength. The use of different vibration machines and protocols could explain the discrepancy in results. It is possible that the SV elicited a greater response in leg extensor strength compared to the VV machine; this has recently been confirmed by Abercromby *et al.* [2]. However, other studies from Humphries *et al.* [58], Kemertzis *et al.* [66], and Erskine *et al.* [48] have indicated that acute vibration does not enhance isometric or isokinetic force and claim that inhibition rather than facilitation occurs. On the contrary, there have been reports that vibration does increase force attributes with Warman *et al.* [132] reporting that direct vibration increased isotonic knee extensor force, but no changes were seen in isometric or isokinetic force (▶ **Table 7**). However, using a vibration platform of 2 and 6 min exposure (f=26 Hz), Stewart *et al.* [120], and Jacobs and Burns [63] have reported increases in knee isokinetic peak torque of 3.8% and 7.7% respectively and Mileva *et al.* [83] reported an increase in isoinertial peak torque by 25% and 12% using loads of 30% and 70% 1RM knee extension with a vibrating system (f=10 Hz, A=not given).

Table 4 Short-Term Effects (≤ 2months) of VbX on Lower Body Power.

Author	Type of Study	Participants	Group	Exercise Type	Frequency (Hz)	Amplitude (mm)	Duration	Results
Annino *et al*. [4]	randomised controlled	22 ♀ ballerinas	VV + ballet practice	SS (100°)	30	5	5 × 40 s, 3/wk, 8 wks	VbX increased CMJ height (6.3 %), it also enhanced leg-press power (8–18 %), and velocity (8–26 %) at loads of 50, 70, 100 kg.
			control	ballet practice only	NA	NA	3/wk, 8 wks	
Bosco *et al.* [13]	randomised	14 RA	SV	standing, SS, lunge	26	10	5 × 90 s, 10 days	VbX increased continuous (5 s) mean jump height by 12 %.
Cochrane *et al.* [30]	randomised controlled	12 RA (8♂, 4 ♀)	SV	standing, SS, DS	26	11 p-p	5 × 2 min, 9 days	No significant differences were noted in CMJ performance following VbX.
		12 RA (8♂, 4 ♀)	control	standing, SS, DS	0	0	5 × 2 min, 9 days	
Delecluse *et al.* [42]	randomised controlled	13 ST (9♂, 4♀)	VV	sprint training + VbX (DS, SS, lunge)	35–40	1.7–2.5	6 × 30–60 s, 3/wk 5 wks	No significant changes in vertical jump height between VbX and control groups.
		12 ST (9♂, 3♀)	control	sprint training	NA	NA	3/wk, 5 wks	
Di Giminian *et al*. [44]	randomised	RA						Individualised vibration frequency increased vertical jump height (11 %), rebound jump height (22 %) and mean power (18 %) compared to fixed vibration frequency and control.
		9 (4♂, 5♀)	VV – individualised	SS (90°)	30	2	10 × 1 min, 3 × /wk, 8 wks	
		10 (5♂, 5♀)	VV – fixed	SS (90°)	20–50	2	10 × 1 min, 3 × /wk, 8 wks	
		11 (5♂, 6♀)	VV – control	SS (90°)	0	0	10 × 1 min, 3 × /wk, 8 wks	
Fagnani *et al*. [49]	randomised controlled	13 Ath ♀	VV	lunge (90°)	35	4	3–4 × 20–60 s 3–4 × 15–25 s 3/wk, 8 wks	VbX significantly increased CMJ height (8.7 %) compared to control.
		11 Ath ♀	control	sports activity	NA	NA	NA	
Ronnestad [108]	randomised controlled	7 ♂RT	VV	DS	40	NR	3 × 10RM 4 × 8RM 4 × 6RM	Squatting with and without VbX increased 1RM strength (32.4 % vs. 24 %) and CMJ height (8.8 % vs. 4 %) but no significant differences were evident between groups.
		7 ♂RT	control	DS	0	NR	2–3 × /wk, 5 wks	

Ath = Athlete; **RT** = Resisted trained; **ST** = Sprint trained; **RA** = Recreationally active; **SV** = Side alternating vibration; **VV** = Vertical vibration; **DS** = Dynamic squat; **SS** = Static squat; **NR** = Not reported; **NA** = Not applicable; **CMJ** = Countermovement jump

Table 5 Long-Term Effects (> 2 months) of VbX on Lower Body Power.

Author	Type of Study	Participants	Groups	Exercise Type	Frequency (Hz) or Load	Amplitude (mm)	Duration	Results
de Ruiter *et al.* [41]	randomised controlled	10 RA (6 ♂, 4 ♀)	SV	SS (110°)	30	8	3/wk, 11 wks	VbX failed to significantly increase vertical jump height.
		10 RA (6 ♂, 4 ♀)	control	SS (110°)	0	0	3/wk, 11 wks	
Delecluse *et al.* [43]	randomised controlled	18 UT ♀ 19 UT ♀ 18 UT ♀	VV placebo resistance	DS, SS, lunge DS, SS, lunge cardio + knee & leg extensor strength	35–40 low cardio (20 mins), 20RM (2wks), 15RM (3wks), 12RM (3wks), 10RM (4wks)	2.5–5 low	1–3 × 2–6 × 30–60 s (3 × /wk, 12 wks)	VbX significantly increased vertical jump height (7.6 %) but no other changes were seen in the other conditions.
		19 UT ♀	control	no training			3 × /wk, 12 wks	
Roelants *et al.* [106]	randomised controlled	24 PM ♀	VV	SS, lunge	35–40	2.5–5	1–3 (series) × 2–9 (type) × 30–60 s (3 × /wk, 24 wks)	There was no difference in the increase in isometric and dynamic knee extensor strength between VbX (15.0 % and 16.1 %) and resistance (18.4 % and 13.9 %) respectively).
		20 PM ♀	resistance	cardio + knee & leg extensor strength	cardio (20 mins), 2 × 20RM (2wks) 2 × 10,12,15RM (12wks) 3 × 12RM;1 × 8RM (10wks)		3 × /wk, 24 wks	
		25 PM ♀	control	no training				
Russo *et al.* [110]	randomised controlled	14 PM ♀	SV	SS	12–28 (1 mth) 28 (5 mths) + vitamin D & $CaC0_3$ supplements 3 mths prior to study	NR	3 × 1 min (1 mth) 3 × 2 min (5 mths) (2 × /wk, 6 mths, ave number of sessions attended = 34)	VbX significantly increased vertical jump velocity and power (5 %) compared to control group.
		15 PM ♀	control	no training				
Torvinen *et al.* [124]	randomised controlled	26 H (9♂, 17 ♀)	VV	DS, jumping, standing on heels, standing erect	1st 2 wks = 25–30 (2 min) 1.5 mths = 25–35 (3 min) 2 mths = 25–35 (4 min)	2	3–5 × /wk, 4 mth	At 2 and 4 months VbX significantly increased CMJ height (10.2 %, 8.5 %) compared to control.
		26 H (10♂, 16 ♀)	control	NR	NA	NA	4 mth	
Torvinen *et al.* [125]	randomised controlled	27 H (9♂, 18 ♀)	VV	DS, jumping, standing on heels, standing erect current physical activity	1st 2 wks = 25–30 (2 min) 1.5 mths = 25–35 (3 min) 2 mths = 25–40 (4 min) 4 mths = 30–45 (4 min)	2	3–5 × /wk, 8 mth	VbX increased CMJ height (7.8 %) compared to control.
		26 H (10♂, 16 ♀)	control		NA	NA	8 mth	

H = Healthy; **UT** = Untrained; **RA** = Recreationally active; **PM** = Postmenopausal; **SV** = Side alternating vibration; **VV** = Vertical vibration; **DS** = Dynamic squat; **SS** = Static squat; **CMJ** = Countermovement jump

Table 6 Acute Effects of VbX on Upper Body Force.

Author	Type of Study	Participants	Groups	Exercise Type	Frequency (Hz)	Amplitude (mm)	Duration	Results
Cochrane & Hawke [29]	randomised cross-over	12 Climbers (5 ♀, 7 ♂)	DB	unilateral upper body exercises	26	3	5×60 s	VbX produced no significant changes in hand grip strength, and specific climbing strength.
			control	unilateral upper body exercises	0	0	5×60 s	
			arm crank	arm crank	NA	NA	5 mins, 25 W	
Cochrane & Stannard [32]	randomised cross-over	16 EL ♀	SV	DS, SS, lunge, press up	26	6	5×1 min	VbX showed no significant increased in grip strength.
			control	DS, SS	0	0	5×1 min	
			control	cycle	NA	NA	5 mins, 50 W	
Kin Isler *et al*. [68]	randomised	10 ♂RA	DV -6 Hz	90, 120, 150° elbow flexion	6	4	5×60 s	VbX at 6, 12 and 24 Hz of vibration resulted in increased isometric MVC, 48 Hz VbX resulted in decreased isometric MVC. In addition, the length of the contracting muscle did not affect the vibration load that was applied with different frequencies.
		10 ♂RA	DV -12 Hz	90, 120, 150° elbow flexion	12	4	5×60 s	
		10 ♂RA	DV -24 Hz	90, 120, 150° elbow flexion	24	4	5×60 s	
		10 ♂RA	DV -48 Hz	90, 120, 150° elbow flexion	48	4	5×60 s	
Torvinen *et al*. [123]	randomised cross-over	16 H (8♂, 8♀)	SV	DS, jumping, standing on heels, standing erect	15–30	10	4 min	There was no significant changes in grip strength.
			control	DS, jumping, standing on heels, standing erect	0	0	4 min	
Torvinen *et al*. [126]	randomised cross-over	16 H (8♂, 8♀)	VV	DS, jumping, standing on heels, standing erect	25–40	2	4 min	There was no significant changes in grip strength.
			control	DS, jumping, standing on heels, standing erect	0	0	4 min	

H = Healthy; **EL** = Elite; **RA** = Recreationally active; **DV** Direct vibration; **SV** = Side alternating vibration; **VV** = Vertical vibration; **DS** = Dynamic squat; **SS** = Static squat

Table 7 Acute Effects of Lower Body Force.

Author	Type of Study	Participants	Conditions	Exercise Type	Frequency (Hz)	Amplitude (mm)	Duration	Results
de Ruiter *et al.* [40]	randomised controlled	10 RA (6 ♂, 4 ♀)	SV	SS (110°)	30	8	5×60 s	Maximum force-generating capacity and isometric contraction significantly declined after VbX.
			control	SS (110°)	0	0	5×60 s	
Erskine *et al*. [48]	randomised cross-over	7 H♂	VV	SS (half-squat)	30	4	10×60 s	VbX significantly reduced maximal isometric knee extensor force immediately (9.2 %), 1h (8.3 %), 2h (7.7 %) post VbX. No change in rate of torque development.
			control	SS (half-squat)	0	0	10×60 s	
Humphries *et al*. [58]	controlled	16 H (19 ♂, 9 ♀)	DV	isometric (120°)	50	5	30 s	Isometric force, peak rate of force development, rate of force development of peak force were not significantly different.
Jacobs & Burns [63]	randomised cross-over	20 UT (10♂, 10♀)	SV	SS	26	NR	6 mins	VbX significantly increased peak (7.7 %) and average (9.6 %), isokinetic torque of knee extension compared to cycling.
			control	cycle	NA	NA	6 mins, 50 W	
Kemertzis *et al.* [66]	randomised cross-over	12 H ♂	SV	static ankle plantar-flexion	26	4–4.5	5×1 min	A significant (41 %) decrease in the angle of peak plantar-flexor torque occurred after VbX compared to no VbX. No significant changes in plantarflexor ROM or peak torque were found after VbX.
			control	static ankle plantar-flexion	0	0	5×1 min	
Mileva *et al*. [83]	randomised	12 H ♂	35 % 1RM + VbX	knee extension	10	NR	4 sets×8 reps	During 1RM tests, muscle dynamic strength was significantly higher during VbX than nonvibrated trials, and strength was significantly higher post- than pre-exercise except during 35 % 1RM-VbX.
			35 % 1RM − VbX	knee extension	10	NR	4 sets×8 reps	
			70 % 1RM + VbX	knee extension	10	NR	4 sets×8 reps	
			70 % 1RM − VbX	knee extension	10	NR	4 sets×8 reps	
Stewart *et al*. [120]	randomised Balanced	12 RA♂	SV	SS (5°)	26	4	2,4,6 min	2 min of VbX significantly increased isometric knee extension torque (3.6 %) compared to 4 and 6 min, which produced torque decreases.
			control	SS (5°)	0	0	2,4,6 min	
Torvinen *et al*. [123]	randomised cross-over	16 H (8♂, 8♀)	SV	DS, jumping, calf raise, standing	15–30	10	4 min	VbX significantly increased isometric leg extension force (3.2 %) compared to control.
			control	DS, jumping, calf raise, standing	0	0	4 min	
Torvinen *et al*. [126]	randomised cross-over	16 H (8♂, 8♀)	VV	DS, jumping, calf raise, standing	25–40	2	4 min	There was no significant changes in isometric leg extension force following VbX.
			control	DS, jumping, calf raise, standing	0	0	4 min	
Warman *et al*. [132]	controlled	28 H (19 ♂, 9 ♀)	DV	knee isometric (120°)	50	5	30 s	No significant improvements in isometric and isokinetic force were evident.
				knee isokinetic (60°/s)				

H = Healthy; **UT** = Untrained; **RA** = Recreationally active; **DV** = Direct vibration; **NA** = Not applicable; **NR** = Not reported; **DV** = Direct vibration; **SV** = Side alternating vibration; **VV** = Vertical vibration; **DS** = Dynamic squat; **SS** = Static squat

The discrepancy of the above findings could be due to the various protocols used for testing vibration. These include different methods of vibration, types and parameters of muscle contraction, and duration and frequency of vibration, as well as the muscle contraction velocities and variables.

Short-term vibration (<2 months) – Upper body force

A summary of the studies that examined the short- and long-term effects of vibration on upper and lower body force can be found in ▶ **Table 8, 9**. Using an electric motor to transmit eccentric oscillations (*f*=44 Hz, *A*=3 mm) to a cable system a series of seated bench-pull repetitions were performed by male physical education students at 80–100% 1RM for 3 weeks (3x/week) while control groups performed the same resistance routine without vibration or performed calisthenics [59]. The researchers found that by combining vibration with force the 1RM bench-pull significantly increased by 50% compared to a 16% improvement by the conventional resistance group, with no change being reported in the calisthenics group.

In a recent upper-body study by Silva *et al.* [119], untrained participants (24 yrs) were either assigned to isometric bicep training (12 MVCs, 6 s in duration) without or with vibration (*f*=8 Hz, *A*=6 mm). The participants were seated with elbow flexed at 90°, and vibrations were produced by an amplifier connected to a steel cable with a hand grip that was applied in the opposite direction of muscle shortening. After 4 weeks of training (3 days/week) there was a significant increase of 26% bicep MVC from the group that received isometric and vibration compared to isometric alone (10% increase bicep MVC).

Short-term vibration (<2 months) – Lower body force

Short-term vibration on lower-body force has produced mixed results with de Ruiter *et al.* [40, 41] and Delecluse *et al.* [42] reporting no increase in muscle force from short-term vibration training. De Ruiter *et al.* [40] reported that MVC and maximal force-generating capacity with and without muscle stimulation of knee extensors were not enhanced after 11 weeks (3x/week) of intermittent vibration (*f*=30 Hz, *A*=8 mm, SV [Galileo]). Delecluse *et al.* [42] found that 5 weeks of vibration (*f*=35–40 Hz, *A*=1.7–2.5 mm, VV [Power Plate]) failed to potentiate isometric and dynamic knee extensor and flexor strength in well-trained sprinters.

Increases in force from VbX have been reported from Mahieu *et al.* [77] and Fagnani *et al.* [49]; both studies observed an increase in torque post-vibration. Mahieu *et al.* [77] noted an increase in isokinetic torque of ankle plantar flexors of young skiers after 6 weeks (3x/week) of vibration training (*f*=24–28 Hz, *A*=2–4 mm, VV [FitVibe]). Fagnani *et al.* [49] reported a 11.2% in isokinetic knee extensor in trained female athletes after 8 weeks (3x/week) intermittent vibration protocol (*f*=35 Hz, *A*=4 mm, VV [Nemes]). Both studies failed to compare vibration with the appropriate controls of performing the same activity with and without vibration. However, Ronnestad *et al.* [108] compared 5 weeks (2–3x/week) of weighted squats (6–10RM) with vibration (*f*=40 Hz, *A*=not given) and without vibration. They reported a 32% increase in 1RM squat from vibration, but it was not significantly different from the 24% increase in 1RM squat without vibration. The differences in vibration duration, amplitude, frequency, muscle groups, and vibration machines used in the aforementioned studies, may account for the discrepancy in results.

Long-term vibration (>2 months) – Lower body force

Torvinen *et al.* [124, 125] conducted 2 separate studies on the long-term effects of vibration (*f*=25–35 Hz, *A*=2 mm, VV [Kuntotary]) performed over 4 and 8 months in healthy young participants (19–38 yrs). In the 4 month study [124] the authors found that isometric knee extensor strength improved by 3.7%. at 2 months compared to the control condition, but no further improvements were evident at 4 months. Likewise, after 8 months [125] vibration had produced no significant differences in isometric knee extensor strength. Therefore, the vibration stimulus of frequency, amplitude, and duration may have not been effective in eliciting the desired neuromuscular responses. Ideally, the additional load should have been included in the latter stages of an 8 months' programme, which could have been achieved by progressively increasing body mass with external loads of a weighted vest or belt. Additionally, all of Torvenien's studies [123–126] have included an exercise routine of light squatting, light jumping and standing performed in addition to the vibration stimulus; however, this routine has never been quantified in terms of load or cadence. Similarly, the dynamic nature of the protocol could have inhibited the vibratory stimulus to realise its full potential.

To overcome the shortcomings of Torvinen's studies [123–126] Delecluse *et al.* [43] devised a 12 week (3x/week) periodised training plan, where vibration frequency, amplitude, exercise duration, load, sets and reps were progressively and systemically overloaded. 74 untrained females were randomly allocated to: 1) vibration (*f*=35–40 Hz, *A*=2.5–5 mm, *a*=2.3*g*–5.1 *g* VV [Power Plate]); 2) cardio-resistance training; 3) placebo (very small amount of vibration *a*=0.4 *g* VV, [Power Plate]); and 4) control. A 16% and 9% increase of isometric and dynamic knee force were observed in the vibration group, which was similar to the resistance training group (14% and 7% respectively), but significantly different to placebo and control groups.

Roelants *et al.* [106] reported similar findings, that in older post-menopausal women (64 yrs) isometric knee extensor strength increased by 15% and isokinetic strength by 16% from 24 weeks of vibration training (*f*=35–40 Hz, *A*=2.5–5 mm, VV [Power Plate]), however there was no significant difference in the respective increase found in the resistance training group. In a follow-up study using untrained females, this research group [69] confirmed their earlier findings of isometric and isokinetic knee extensor force, but they also noted that the increases were not significantly different from those who did a combined cardio and leg-strength programme.

The same research group [9] conducted a year-long study on older men (67 yrs) and repeated the same protocol, and observed that vibration increased muscle mass and isometric force but it was not significantly different from performing a combined cardio, strength, balance, and flexibility programme. Finally, Kvoring *et al.* [69] reported that after 9 weeks (2–3x/week) of weighted squats with vibration (*f*=20–25 Hz, *A*=4 mm, SV [Galileo 2000]) isometric leg press strength produced an increase of 9.3% which was comparable to the 12% increase in leg strength from weighted squats without vibration. Therefore, combining vibration with squats was no more beneficial than weighted squatting alone.

In summary, it is not conclusive whether acute vibration increases force attributes. This has been fraught by the type and parameters used for various muscle contractions, and the different sample populations that have varied in chronological age, experience and training status. Furthermore, the debate sur-

Table 8 Short-Term (≤ 2months) Effects of VbX on Upper & Lower Body Force.

Author	Type of Study	Participants	Groups	Exercise Type	Upper Body Frequency (Hz)	Amplitude (mm)	Duration	Results
Issurin *et al*. [59]	randomised controlled	10 RA ♂	conventional strength +	bench pull	NA	NA	bench: 6×80–100% 1RM	conventional strength + VbX significantly increased bench pull force (50%) compared to conventional training (16%) and control (no change).
		8 RA ♂	VbX (cable) flexibility	leg ring flexibility	44	3	flex: 6×40–90s (3wks; 3/wk)	
			VbX (cable) strength +	bench pull	44	3	bench: 6×80–100% 1RM	
			conventional flexibility	leg ring flexibility	NA	NA	flex: 6×40–90s (3wks; 3/wk)	
		10 RA ♂	control	calisthenics, jogging and/or & basketball	NA	NA	55 min (3wks; 3/wk)	
Silva *et al*. [119]	randomised controlled	9 UT ♂	VbX (cable)	elbow isometric MVC (45°)	8	6	12 MVC, 6s 3/wk, 4 wks	VbX + elbow isometric increased MVC force significantly (26%) compared to conventional isometric elbow training (10%).
		10 UT ♂	control	elbow isometric MVC (45°)	0	0	12 MVC, 6s 3/wk, 4 wks	
Author	**Type of Study**	**Participants**	**Groups**	**Exercise Type**	**Lower Body Frequency (Hz)**	**Amplitude (mm)**	**Duration**	**Results**
Delecluse *et al.* [42]	randomised controlled	13 ST (9♂, 4♀)	VV	ST + VV (DS, SS, lunge)	35–40	1.7–2.5	6×30–60s; 5 wks (3/wk)	VbX did not significantly increase isometric or dynamic knee extensor and flexor force.
		12 ST (9♂, 3♀)	control	ST	NA	NA	5 wks (3/wk)	
Fagnani *et al*. [49]	randomised controlled	13 RA ♀	VV	lunge (90°)	35	4	3–4×20–60s 3–4×15–25s 3/wk, 8 wks	VbX significantly increased isokinetic leg press peak force (9.3%) and total work (11.2%) compared to control.
		11 RA ♀	control	sports activity	NA	NA	NA	
Mahieu *et al*. [77]	randomised controlled	17 skiers	VV	DS, calf raises, jumping, ski movements	24–28	4–6	3/wk, 6 wks	Both VbX and resistance increased isokinetic concentric knee flexor & extensor (60°/s, 180°/s), and concentric ankle plantar- & dorsi-flexion (30°/s, 120°/s). However, only ankle plantar-flexion (30°/s) was significantly higher in VbX compared to resistance.
		16 skiers	resistance	DS, calf raises, jumping, ski movements	0	0	3/wk, 6 wks	
Ronnestad [108]	randomised controlled	7 ♂RT	VV	DS	40	NR	3×10RM 4×8RM 4×6RM	Squatting with and without VbX increased 1RM squat strength.
		7 ♂RT	control	DS	0	NR	2–3×/wk, 5 wks	

ST = Sprint trained; **UT** = Untrained; **RA** = Recreationally active; **SV** = Side alternating vibration; **VV** = Vertical vibration; **DS** = Dynamic squat; **SS** = Static squat; **MVC** = Maximal voluntary contraction; **RT** = Resisted trained; **NR** = Not reported; **NA** = Not applicable

Table 9 Long-Term (≥ 2months) Effects of VbX on Lower Body Force.

Author	Type of Study	Partici-pants	Groups	Exercise Type	Frequency (Hz) or Load	Amplitude (mm)	Duration	Results
Bogaerts *et al*. [10]	randomised controlled	31 O ♂ 30 O ♂ 36 O ♂	VV	DS, lunge, calf raise	35–40	2.5–5	4–15 exercises 3×/wk 12 mths	Both VbX and fitness groups significantly increased isometric knee (9.8% & 13.1%) torque, but there were no differences between the groups.
			fitness	cardio + knee & leg extensor strength	walking/running, cycling, or stepping 1–2 sets 8–15RM	NA	3×/wk 12 mths	
			control	no training	NA	NA	NA	
Delecluse *et al.* [43]	randomised controlled	18 UT ♀ 19 UT ♀ 18 UT ♀	VV placebo resistance	DS, SS, lunge DS, SS, lunge cardio + knee & leg extensor strength	35–40 low cardio (20 mins),20RM (2wks), 15RM (3wks), 12RM (3wks), 10RM (4wks)	2.5–5 low	1–3×2–6×30–60 s (3×/wk, 12 wks)	VbX significantly increased.
		19 UT ♀	control	no training			3×/wk, 12 wks	
Kvoring *et al*. [69]	randomised controlled	9 RA ♂	SV	DS	20–25, 6 sets×8 reps	4	2–3/wk, 9 wk	Squat and VbX + squat increased isometric leg press force 12.1% & 9.3% respectively but no differences were evident between control groups.
		10 RA ♂	SV + squat	DS	20–25, 6 sets×8 reps, 8,10RM	4	2–3/wk, 9 wk	
		9 RA ♂	squat	DS	0, 6 sets×8 reps, 8,10RM	0	2–3/wk, 9 wk	
						de		
Roelants *et al*. [106]	randomised controlled	24 PM ♀	VV	SS, lunge	35–40	2.5–5	1–3 (series)×2–9 (type)×30–60 s (3×/wk, 24 wks)	There was no difference in the increase in isometric knee extensor force between VbX (15.0%) and resistance (18.4%) group.
		20 PM ♀	resistance	cardio + knee & leg extensor strength	cardio (20 mins), 2×20RM (2wks) 2×10, 12, 15RM (12 wks) 3×12RM;1×8RM (10wks)		3×/wk, 24 wks	
		25 PM ♀	control	no training				
Torvinen *et al*. [124]	randomised controlled	26 H (9♂, 17 ♀)	VV	DS, jumping, standing on heels, standing erect	1st 2 wks = 25–30 (2 min) 1.5 mths = 25–35 (3 min) 2 mths = 25–35 (4 min)	2	3–5×/wk, 4 mth	At 2 months VbX significantly increased isometric leg extensor force (3.7%) compared to control, but no differences were seen at 4 mths.
		26 H (10♂, 16 ♀)	control	NR	NA	NA	4 mth	
Torvinen *et al*. [125]	randomised controlled	27 H (9♂, 18 ♀)	VV	DS, jumping, standing on heels, standing erect	1st 2 wks = 25–30 (2 min) 1.5 mths = 25–35 (3 min) 2 mths = 25–40 (4 min) 4 mths = 30–45 (4 min)	2	3–5×/wk, 8 mth	VbX increased evident in isometric leg extensor force but it was no different to the control.
		26 H (10♂, 16 ♀)	control	current physical activity	NA	NA	8 mth	

O = Older; **PM** = Postmenopausal; **UT** = Untrained; **A** = Recreationally Active; **SV** = Side alternating vibration; **VV** = Vertical vibration; **DS** = Dynamic squat; **SS** = Static squat; **H** = Healthy rounding the length-tension proposal that muscle must be lengthened in order to benefit from vibration has caused confusion. However, recent evidence suggests that when vibration was applied at 120° knee flexion, which maximises the limb's greatest mechanical advantage, no increases in force were evident. Moreover, vibration applied to concentrically active muscle has shown to improve muscle force, which cannot explain the length-tension relationship. There may also be an optimal contraction velocity where vibration is most effective, and testing the effect of vibration on self-selected isokinetic contraction velocities warrants further investigation. Overall, acute VbX has a greater beneficial effect on power and force than short- and long-term studies, this could be due to the lack of knowledge surrounding the optimal method of periodising, loading, and progressing VbX variables in way that will sufficiently stimulate the musculoskeletal system. Currently there is a lack of scientific-based, short- and long-term VbX-training programmes. Secondly the acute exposure of VbX may provide a myogenic and neurogenic potentiation that reaches a threshold, which diminishes rapidly over an extended period of time, suggesting that VbX acts similar to a warm-up effect that may be promoted by post-activation potentiation.

The effects of vibration exercise on compromised health

Multiple Sclerosis

Multiple Sclerosis (MS) is a demyelinating disease of the central nervous system where decreases in power and strength can impair functional performance along with sensory losses, and visual disturbances. Shuhfried *et al.* [115] reported that MS patients undertaking acute intermittent VbX (f=2–4.4 Hz, A=3 mm, [Zeptor-Med]) improved timed get up and go test compared to the placebo group that performed transcutaneous electrical nerve stimulation of the forearm, however no improvement in functional reach test was found. In a randomised cross over study where MS patients received 30 s of low frequency (f=2 Hz, A=6 mm) and high frequency (f=26, A=6 mm, SV [FitVib]) there was a trend for higher torque in the quadriceps and hamstrings after 26 Hz, compared to 2 Hz, but they were not significantly different [61]. Using a counter-balance research design [116], MS patients were randomly allocated into 2 groups (n=8) that received 3x/week for 4 weeks of strengthening and stretching exercises with or without vibration. Results found that VbX and exercise alone had a positive effect on isometric muscle force and well-being but there were no significance differences between the interventions. Likewise, the addition of vibration failed to enhance the functional measures of 10 m walk time and mobility (timed up and go) compared to conventional exercises. There are positive signs that VbX may have an effect on MS, however a long-term training study with appropriate controls is required to validate whether VbX is a viable exercise training option.

Stroke

Stroke can impact on motor function and impair balance, gait and reduce voluntary strength [122]. To date, 2 studies have reported favourable findings of using VbX for stroke patients. Using a force platform to measure the centre of pressure, postural control, Stroke patients improved their function from an intermittent exposure (4×45 s) of VbX (f=30 Hz, A=3 mm, SSV [Galileo 900]) [129]. Tihanyi *et al.* [122] found that an intermittent exposure (6×60 s) of VbX (f=20 Hz, A=5 mm, VV [Nemes]) improved isometric and eccentric knee extension torque, along with corresponding increase in EMG amplitude of the vastus lateralis compared to a control (no vibration). Conversely, a 6 week vibration study performed 5x/week of 4×45 s (f=30 Hz, A=3 mm, SSV [Galileo 900]) reported no significant differences in balance and functional activities between vibration group and those who performed exercise therapy to music [129].

Parkinson's Disease

Favourable results have been reported from patients suffering from Parkinson's disease (PD). Turbanski *et al.* [128] found that intermittent vibration (5×60 s) exercise (f=6 Hz, A=3 mm, [Zeptor-Med]) improved postural stability of tandem standing as measured by Coordex platform system compared to control. Haas *et al.* [53], reported that PD patients exposed to intermittent (5×60 s) VbX (f=6 Hz, A=1 mm, Zeptor-Med system) significantly improved their motor score by 17% from a rating scale (Unified Parkinson's Disease Rating Scale). However, the same investigator [52] found no improvement in proprioception from intermittent VbX (f=6 Hz, A=not given, SRT-medical system) compared to control. Conversely, Ebersbach *et al.* [47] reported a significant improvement in balance score (Tinetti Balance) from PD patients performing VbX (f=not given, irregular low frequency administered A=not given, SV [Galileo 2000]) 2x/week for 3 weeks, however conventional balance training improved by the same margin.

Age-related aspects of the elderly

There have been positive effects of using VbX to improve balance in older people [7,10,28,130]. Recently Rees *et al.* [96] have reported benefits for older people (73 yrs) completing 2 months (3x/week) of VbX (f=26 Hz, A=5–8 mm, SSV [Galileo]) with improvements in chair-rising time, timed-up-and-go test and faster walking speed, but, these increases were comparable to the exercise group that performed the same exercises without vibration. However, VbX did significantly increase ankle plantar flexion compared to the conventional exercise group but this did not correspond to enhancing physical performance. Kawanabe *et al.* [65] found that continuous (4 min) VbX (f=12–20 Hz, A=not given, SSV [Galileo]) performed 1x/week for 2 months significantly improved 10 m walk time, step length and the maximum standing time on one leg (right and left) in older participants (72 yrs) compared to an exercise routine performed without vibration. However, this experiment was not a randomised controlled study as the choice to have VbX was determined by the participants. Moreover the study lacked documentation on how the vibration frequency was progressed and the number of reps and sets that were performed by the participants. Bogaerts *et al.* [9] reported that in older males (60–80 yrs) isometric knee extensor strength, VJ height and muscle mass increased significantly by 9.8%, 10.9%, and 3.4% after 12 months (3x/week) of VbX (f=35–40 Hz, A=2.5–5 mm, VV, [Power Plate]). However, these increases were not significantly different from performing a combined cardiovascular, strength, balance, and flexibility programme conducted over the same duration.

Postmenopausal women

Long-term VbX studies (≥6 months) have shown that balance, postural sway and muscle power is significantly enhanced in postmenopausal women [51,110,130]. Additionally, isometric (knee joint=130°), isokinetic strength (100°/s) and VJ height have been reported to increase after 6 months of VbX

(f=35–40 Hz, VV, [Power Plate]), in postmenopausal women [106,130]. Raimundo *et al.* [95] conducted an 8 month study where 27 postmenopausal women (66 yrs) were randomly assigned to VbX (f=12.6 Hz, A=6 mm, Galileo [SSV]) or a walk programme (60 min, 70–75 %MHR) performed 3x/week. The researchers reported that the walk programme significantly improved 4 m walk time, and chair rise test more than VbX, however VbX had a significant effect of increasing VJ, but neither intervention improved knee isokinetic strength. This finding is not surprising given that only a low frequency dose was used during the 8 months and the vibration frequency was not progressively increased over the course of the study.

Other

VbX (f=20–25 Hz, A=3 mm, SSV [Galileo 2000]) performed 5x/week for 3 months has been shown to improve muscular performance in Cystic Fibrosis (CF) of chair rising time, peak jump force and velocity, but no changes were found in forced expiratory volume and forced vital capacity [99]. In women with Fibromyalgia a significant improvement in pain and fatigue was recorded from receiving intermittent VbX (f=30 Hz, A=2 mm, VV [Power Plate]) 2x/week for 6 weeks compared to exercise (salsa dancing, stretching and relaxation techniques) and control groups.

In a recent study conducted by Lauper *et al.* [71] they investigated pelvic floor stimulation using 2 different types of vibration platforms, SV (Galileo 900) and stochastic resonance vibration (SRV) (Zeptor-Med) which has 2 separate footplates which vibrate vertically and independently. Using an intravaginal surface EMG electrode the researchers reported that the SRV (f=2, 4, 6, 8, 10, 12 Hz, A=3 mm) activated the pelvic floor muscles significantly more than SV (f=5,15,25 Hz, A=2 & 4 mm) and initiated a higher pelvic floor activation than maximum contraction alone in post-partum compared to healthy controls. However, it is unknown whether this increase in muscle activation can lead to an increase in functional performance and whether symptoms of poor pelvic floor activation can be alleviated.

It is unclear if VbX is beneficial for those with osteoarthritis as there has been limited research conducted in this area. Trans *et al.* [127] randomly allocated patients suffering from knee osteoarthritis to VbX, conventional balance and control groups. The results showed a non-significant (p=0.051) improvement in proprioception from intermittent (6–9 × 30–70 s) VbX (f=25–30 Hz, A=not given, [VibM]) with an increase in knee extensor strength. But those performing balance board with an implanted vibratory device showed a significant increase in proprioception, with no knee strength increases.

There is some evidence to suggest that cardiovascular or aerobic exercise may be able to enhance glycemic control in type II diabetics [89,117], and that resistance training may be a possible treatment to fight metabolic diseases [17,27,46]. Di Loreto *et al.* [45] found that intermittent VbX (f=30 Hz, A=±4 mm, VV, [Nemes]) decreased plasma glucose levels which may indicate that glucose is transported into the muscle by VbX, which may be of benefit to diabetics. In a study that randomised type 2 diabetics into resistance, vibration, and flexibility groups, the researchers reported that intermittent VbX (f=30–35 Hz, A=2 mm, VV [VibroGym]) performed 3x/week for 12 weeks had no effect on isometric knee extension, while fasting glucose levels, plasma glucose concentration from an oral ingestion of 75 g of glucose drink and haemoglobin showed reductions but were not significant from baseline measures [6].

In conclusion,VbX is a safe modality to increase reflex and muscle activity, and muscle performance in athletes, the aged and compromised health. However, there seems little benefit of using VbX to enhance cardiovascular indices, where VbX cannot increase heart rate to the same extent as conventional aerobic exercise. Despite its wide use there remain gaps of knowledge on aspects such as mechanism of action, clinical effects, and even details of regimens for particular therapeutic use. There is some dissonance that exists between various studies which can be explained by the different types of vibration platforms (SV, VV), the participant characteristics (body/muscle mass, training status, muscle strength and stiffness, age, gender), the different permutations of vibration parameters (amplitude, exposure duration, rest interval) and the prescription (number of repetitions, sets, exercises). In summary, vibration is a harmless exercise modality that has the potential to benefit sport, exercise and health; likewise it can be used to compliment other modalities to enhance muscle activity and function and compromised health.

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