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The Use of Vibration Training to Enhance Muscle Strength and Power

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Contents

Abstract

Vibration has been combined with conventional resistance training in an attempt to attain greater gains in neuromuscular performance than from conventional resistance training alone. Although there is a lack of strictly controlled studies on the vibration training effect, current findings in this area suggest that vibration may have a beneficiary acute and/or chronic training effect on strength and power enhancement. However, the effect of vibration on strength and power development appears dependent upon the vibration characteristics (method of application, amplitude and frequency) and exercise protocols (training type, intensity and volume) employed. Vibration amplitude and frequency determine the load that vibration imposes on the neuromuscular system. This vibration load should be in an optimal range to elicit strength and power enhancement. To activate the muscle most effectively, vibration frequency should be in the range of 30–50Hz. It is less clear to what the optimal amplitude should be, but smaller amplitudes may be insufficient to elicit an enhancement. It should also be noted that the method of vibration application (i.e. vibration applied directly or indirectly to a targeted muscle) may have an influence on the magnitude of amplitude and frequency that are delivered to the muscle and, therefore, may have an influence on vibration training effect.

The employment of a greater exercise intensity and volume within a vibration training programme may facilitate a larger enhancement in strength and power. In addition, benefits from vibration training may be greater in elite athletes than non-elite athletes.

Further studies are required to examine these inter-dependencies, especially in relation to chronic adaptation to dynamic exercises, which are the most relevant response to practitioners, but where the least amount of research has been undertaken.

Neuromuscular performance, as determined through measures of muscle strength and power, is important for successful performance of athletic activities as well as for the preservation and improvement in functional aspects of daily life. Resistance training is presently the most popular way to improve muscle strength and power.[1] In a search of techniques to enhance resistance training, Russian scientists have combined vibration stimulation with resistance training.[2] This has been termed vibration training[3] or vibration exercise.[4] During the last 5 years, this method of strength training has gained in popularity with a number of systems now commercially available (e.g. Nemes®, Nemesis, The Netherlands; Galileo 2000®, Novotech, Germany; Power-Plate®, The Netherlands).**1**

In the only review on vibration training that could be found, Cardinale and Bosco[5] suggest that “vibration can effectively enhance neuromuscular performance”. However, their review on neuromuscular performance enhancement has a number of notable limitations. Firstly, only six studies were reviewed and half of these failed to include an appropriate control group (see inclusion/exclusion criteria in section 1). Secondly, the review failed to include any studies where vibration training had either no effect on[6,7] or a reduction in neuromuscular performance.[8,9] Finally, the authors did not address the effect of different vibration characteristics (method of application, frequency and amplitude) or the time-effect (acute, acute-residual and chronic) of vibration training.

The purpose of this review is to critically examine the effect of vibration training on neuromuscular performance, with a focus on muscle strength and power, and to investigate the influence of the vibration characteristics (method of application, frequency and amplitude) and exercise protocol on this effect. Consideration is given to the different time-effects of vibration: (i) during the application of vibration (‘acute effect’); (ii) immediately after the application of vibration (‘acute residual effect’); and (iii) following a series of bouts of vibration training over an extended period (‘chronic training effect’). In each of these categories, the effect on force, power and electromyography (EMG) during isometric and dynamic force production will be examined. Purported mechanism of vibration training will also be briefly presented. This review will provide sufficient detail to guide practitioners in their

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1 The use of trade names is for product identification purposes only and does not imply endorsement.

use of vibration training and clearly direct researchers towards those areas that need addressing in order to further understand vibration training.

1. Inclusion/Exclusion Criteria

Studies that fulfilled the following criteria were included in this review:

- *A control group element was employed and subjects were randomly allocated to the treatment and control groups*. In those studies examining the acute and acute residual effects of vibration, the control group consisted of the same subjects being tested under repeated measures. However, these studies were only included provided the order of testing (vibration versus non-vibration) was randomised. Moreover, studies were included provided subjects in the control group performed the same exercise as those in the treatment group. This is essential as otherwise it is not possible to determine if the outcome is due to the exercise or the vibration.
- *Healthy subjects were examined*. This, therefore, negates those studies that examined the facilitatory effect of vibration on patients with neuromuscular disease and those that investigated the potential for neuromuscular disorder associated with long-term (years) exposure to vibration in the occupational environment.
- *The outcome measures were related to muscle force, power or EMG and a statistical analysis was undertaken*.
- *The study was published in the form of full-text and in English*.

2. Literature Search

A literature search was performed on Medline database (1966–2003), the Cochrane Central Register of Controlled Trails (CENTRAL) and Sports Discus. The keywords used were: ‘vibration’ and (‘muscle’ or ‘tendon’ or ‘exercise’ or ‘training’). The identified papers were used to locate other appropriate research papers.

A total of 14 articles met our inclusion criteria, eight of them studied the acute effect of vibration treatment, five of them studied the acute residual effect of vibration treatment and three of them studied the chronic effect of vibration treatment. Details of these studies are listed in tables I–VI.

3. Methodology of Vibration Training

Vibration is a mechanical oscillation that can be defined by frequency and amplitude. Frequency is defined as the cycles per unit time and is generally measured in the unit of hertz (Hz) [cycles per second].[10] Amplitude is defined as the half difference between the maximum and the minimum value of the periodic oscillation.[11]

The methodology of vibration training includes the vibration characteristics and exercise protocol. Vibration characteristics include the method of vibration application, vibration amplitude and vibration frequency. The intensity of the vibration load on the neuromuscular system is determined by the vibration amplitude and frequency.[12] The exercise protocol includes the type of exercise, training intensity, training volume, number and duration of rest period and frequency of training.

There are two methods of applying vibration to the human body during exercises. In the first method, vibration is applied directly to the muscle belly[9,13,14] or the tendon[8] of the muscle being trained, by a vibration unit that may either be held by hand[8,13] or be fixed to an exterior support.[9,14] In the second method, vibration is applied indirectly to the muscle being trained, i.e. the vibration is transmitted from a vibrating source away from the target muscle, through part of the body to the target muscle.[3,15] For example, during the training of the quadriceps, the subject may stand on a vibrating platform that oscillates up and down in the vertical direction and perform various exercises (such as squatting). The vibration is transmitted from the platform through the lower extremities to the quadriceps.[3,7,16] This method has been termed ‘whole-body vibration training’.[3] As another example, during the training of the biceps brachii, the subject may grasp a vibrating handle while performing a bicep curl exercise.[15]

In examining the effects of vibration training, both indirectly and directly applied vibration are reviewed together, as they both produce vibration to stimulate the muscle. The key difference in these methods is the magnitude of amplitude and frequency of the original vibration that reaches the target muscle. With direct vibration, the amplitude and frequency does not differ notably from the reported values measured at the vibration source.[8,9,13] In contrast, with indirectly applied vibration,[3,7,15-17] the amplitude and frequency may be attenuated in a non-linear manner by soft tissues during transmission of the vibration to the target muscle.[12,18] The effect of this will be addressed within the relevant sections.

Duration of vibration is also a factor that should be considered in examining the effect of vibration training. Its influence should be analysed in conjunction with the point of time when the neuromuscular performance was evaluated. As shown in figure 1, if vibration stimulation is short in duration, resulting in the measurement of neuromuscular capacity without fatigue, any enhancement is indicative of an increase in neuromuscular performance by vibration stimulation (M_a [unfatigued] and M_{ar} [unfatigued] in figure 1a). This will be discussed as a facilitatory (positive) effect of vibration on neuromuscular performance later in this review. With increases in the duration of vibration, fatigue will become more predominant. Therefore, an increase in neuromuscular performance, above a no vibration condition, measured in the unfatigued state (M_a [unfatigued] in figure 1b), will still indicate a facilitatory effect of vibration. However, a decrease in neuromuscular performance measured when fatigued (M_a [fatigued] and M_{ar} [fatigued] in figure 1b) may be due to either: (i) an increase in neuromuscular performance earlier in the exercise, resulting in greater fatigue, which can be viewed positively; or (ii) an inhibition effect of vibration on neuromuscular capacity. These two effects are discussed in sections 4.1 and 4.2. These factors are pertinent in both acute and acute residual effects, as shown in figure 1. However, these factors have no relevance in interpreting the long-term studies, as the retest is not undertaken during or immediately following vibration stimulation.

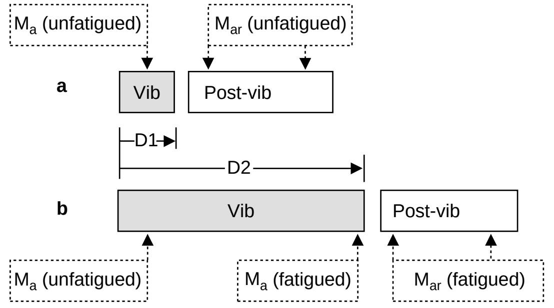

Fig. 1. Vibration duration and the measurement of neuromuscular performance during unfatigued (**a**) and fatigued (**b**) training. **D1** = short duration; **D2** = long duration; **M_a** = measurement of the acute effect of vibration stimulation on neuromuscular performance; **M_{ar}** = measurement of the acute residual effect of vibration on neuromuscular performance; **vib** = vibration.

Both isometric[8,13,14,19,20] and dynamic[15,17,21] exercises have been employed during vibration training. The intensity of these exercises ranged from submaximal contractions[3,4,6,7,16,19] to maximal contractions.[8,13,15,17,20,21] The duration of exercise with applied vibration also varied among studies, ranging from only 5 seconds[13,14,17] to 30 minutes[9] in each set, and with different numbers of sets employed, ranging from one set[4,7,8,14,16,20] to several sets in a training session.[3,6,15,17] The protocol appears indicative of whether or not the aim was to investigate the effect of fatigue.[8,9,13,14,17,20]

4. Acute Effect of Vibration on Neuromuscular Performance

4.1 Acute Effect of Vibration on Strength and Electromyography (EMG) Activity During Isometric Actions

4.1.1 Maximal Isometric Contraction

As shown in table I, four of the five studies have investigated the short-term effect of vibration on maximal isometric contraction.[8,13,14,20] The duration of vibration and contraction was short in two of these studies (5 seconds[13,14]) and prolonged in the two other studies (1 minute[8] and until exhaustion[20]). In the latter two studies, measurement of neuromuscular performance was made both in an unfatigued and fatigued state (figure 1b).[8,20]

Table I. Acute effect of vibration on isometric muscle performance

Study	Subjects	Vibration characteristics			Neuromuscular performance change		
		method (location)	amp (mm)	freq (Hz)	contraction performed	force	EMG
Bongiovanni et al.[8]	25 UT	D (ankle dorsiflexor tendon)	1.5	150	1 min dorsiflexion (100% MVC)	Fm (5%↓ NSC) Fd (13%↓+)	NR
		Control	NA	NA	1 min dorsiflexion (100% MVC)	Fm Fd	NR
Curry and Clelland[13]	30 UT (15 M, 15 F)	D (wrist extensor muscle)	1.5	120	5 sec wrist extension (100% MVC)	Fm: 3.7%↑*	NM
	30 UT (20 M, 10 F)	Control	NA	NA	5 sec wrist extension (100% MVC)	Fm: 3.9%↓*	NM
Humphries et al.[14]	16 UT	D (upper thigh)	0.13	50	5 sec knee extension (100% MVC)	Fm: 581N (17.8%↑ NSC) $RFD_{0.01}$: 983 N/sec (NSC) $RFD_{0.05}$: 1349 N/sec (NSC) $RFD_{0.1}$: 1525 N/sec (NSC) $RFD_{0.5}$: 913 N/sec (NSC)	EMGrms: RF: 84.74% (NSC)
		Control	NA	NA	5 sec knee extension (100% MVC)	Fm: 493N $RFD_{0.01}$: 658 N/sec $RFD_{0.05}$: 1240 N/sec $RFD_{0.1}$: 1620 N/sec $RFD_{0.5}$: 786 N/sec	EMGrms: RF: 88.1%
Kihlberg et al.[19]	15 UT	I (hand)	8 m/sec^{2}[a]	50	Hand grip and arm push (30N)	NM	IEMG: forearm flexor (83.3%↑+) Forearm extensor (45.5%↑+) Triceps brachii (100%↑+)
		Control	NA	NA	Hand grip and arm push (30N)	NM	IEMG: forearm flexor Forearm extensor Triceps brachii
		I (hand)	8 m/sec^{2}[a]	137	Hand grip and arm push (30N)	NM	IEMG: forearm flexor (40%↑+) Forearm extensor (27.3%↑+) Triceps brachii (30%↑ NSC)
Samuelson et al.[20]	14 UT M	I (applied to one leg)	1.8	20	Sustained knee extension until exhausted (100% MVC)	Fm: 594N (6%↑ NSC) Td: 15.8 sec (30%↓+)	NM
		Control (the other leg of the subject)	NA	NA	Sustained knee extension until exhausted (100% MVC)	Fm: 561N Td: 22.5 sec	NM

a Amplitude reported in the form of weighted acceleration.

amp = vibration amplitude; **D** = directly applied vibration; **EMG** = electromyography; **EMGrms** = root-mean-squared value of EMG; **F** = females; **Fd** = decline of maximal voluntary contraction force; **Fm** = maximal voluntary contraction force; **freq** = vibration frequency; **I** = indirectly applied vibration; **IEMG** = integrated EMG; **M** = males; **MVC** = maximal voluntary contraction force; **NA** = not applicable; **NM** = no measurement; **NR** = not reported; **NSC** = not statistically significant compared with control; **RF** = rectus femoris; **RFD** = rate of force development; **Td** = time to exhaustion; **UT** = untrained; ↓ indicates decrease; ↑ indicates increase; * indicates statistically significant compared with pre-treatment; + indicates statistically significant compared with control.

When the neuromuscular system was unfatigued, only one of the four studies found that vibration had a significant facilitatory effect on maximal force.[13] The authors[13] in this study found that vibration induced a 3.7% significant increase ($p < 0.05$) in maximal isometric contraction force of the wrist extensors and the contraction force tested without vibration had a 3.9% significant decrease ($p < 0.05$) from their baseline force levels. Thus, the net increase was approximately 7.8%. Samuelson et al.[20] and Humphries et al.[14] also found net increases in maximal knee extensor force with vibration (6% and 17.8%), but these increases were not significant ($p > 0.05$) due to the variability in response. Bongiovanni et al.[8] found that vibration induced a non-significant net decrease of maximal ankle dorsiflexion force of about 5% ($p > 0.05$).

Only one study[14] reported the EMG activity of maximal isometric contraction during vibration. The authors[14] found that vibration did not have a significant effect ($p > 0.05$) on the root-mean-squared value of EMG (EMGrms), measured on the rectus femoris muscle during maximal knee extension.

Humphries et al.[14] also examined the rate of force development (RFD) at times 0.05, 0.01, 0.1 and 0.5 seconds during a 5-second maximal isometric knee extension. The authors[14] found that vibration did not enhance the RFD at any of these time points ($p > 0.05$).

Neuromuscular performance was also measured in a fatigued state in two of the studies.[8,20] In the study of Samuelson et al.,[20] subjects performed sustained maximal knee extension until exhausted. The time to exhaustion decreased significantly ($p < 0.05$) by 30% in the vibration condition compared with a control group. In a study by Bongiovanni et al.,[8] subjects were asked to maintain their maximal contraction for 1 minute. The results showed that the decline of the maximal isometric force measured at the end of the 1-minute contraction was significantly greater (13%; $p < 0.05$) when vibration was applied. These findings indicate that vibration could accentuate the muscle fatigue of sustained maximal contractions. However, as discussed above, the maximal isometric contraction force measured in both studies[8,20] at the unfatigued state did not have any significant enhancement by vibration. Thus, it is unlikely that prolonged vibration accentuate the fatigue by recruitment of more motor units during the early stage of contraction. Bongiovanni et al.[8] suggested that vibration had a suppression effect that increased gradually with the sustained vibration on motor output of maximal voluntary contractions. This suppression effect mainly decreased the subject's ability to generate high firing rates in high-threshold motor units.[8] Thus, it appears that prolonged vibration decreases the neuromuscular performance of maximal voluntary contraction by inhibiting motor units from recruitment, rather than by fatiguing the motor units by recruitment.

4.1.2 Submaximal Isometric Contraction

Only one study in table I investigated the acute effect of vibration on submaximal isometric contraction.[19] The study could not directly determine if vibration enhances submaximal isometric force because the subjects were asked to maintain contraction force at a constant level during vibration treatment (e.g. 30N[19]). However, the muscle activity measured by EMG showed that the integrated EMG value (IEMG) was enhanced significantly ($p < 0.05$) by vibration,[19] indicating that applied vibration is likely to enhance the submaximal contraction force.[22]

4.2 Acute Effect of Vibration on Strength and Power During Dynamic Actions

4.2.1 Maximal Dynamic Contraction

Only two studies have examined this effect, both employing indirect vibration of the biceps through a grasped vibrating handle.[17,21] Maximal force[21] and power[17] during concentric elbow flexion were enhanced significantly ($p < 0.05$) by vibration (table II). This facilitatory effect may be greater in elite athletes. Issurin and Tenenbaum[17] found that the vibration induced a significantly larger ($p < 0.05$) increase in maximal power for elite athletes (10.4% increase), than for amateurs (7.9% increase) consisting of participants in club or college sports. Liebermann et al.[21] examined the one repetition

Table II. Acute effect of vibration on dynamic muscle performance

Study	Subjects	Vibration characteristics			Neuromuscular performance change		
		method (location)	amp (mm)	freq (Hz)	contraction performed	performance measure	EMG
Issurin and Tenenbaum[17]	28 T M (14 = elite, 14 = amateur)	I (hand)	0.3–0.4	44	Concentric bicep curl (MVC)	P_{max}: elite: 10.4%↑*§+; amateur: 7.9%↑*+ P_{mean}: elite: 10.2%↑*+; amateur: 10.7%↑*+	NM
		Control	NA	NA	Concentric bicep curl (MVC)	P_{max}: elite: 0.3%↑ NS; amateur: 0.9%↑ NS P_{mean}: elite: 2.9%↓ NS; amateur: 3%↓ NS	NM
Liebermann and Issurin[21]	41 T M (8 Olympic, 11 national, 11 amateur, 11 junior)	I (hand)	0.3–0.4	44	Concentric bicep curl (MVC)	1RM strength: Olympic (8.3%↑+#), national (4.8%↑+), junior (6.2%↑+), amateur (4.9%↑+)	NM
		Control	NA	NA	Concentric bicep curl (MVC)	1RM strength: Olympic, national, junior, amateur	NM
Rittweger et al.[4]	19 UT (10 F, 9 M)	I (WBV)	6	26	Squatting on platform with load till exhaustion	Endurance time: 5.8 min +	NM
		Control	NA	NA	Squatting on platform with load till exhaustion	Endurance time: 8.6 min	NM

1RM = one repetition maximum; **amp** = vibration amplitude; **EMG** = electromyography; **F** = females; **freq** = vibration frequency; **I** = indirectly applied vibration; **M** = males; **MVC** = maximal voluntary contraction; **NA** = not applicable; **NM** = no measurement; **NS** = not statistically significant; **P_{max}** = maximal power; **P_{mean}** = mean power; **T** = trained; **UT** = untrained; **WBV** = whole-body vibration; ↓ indicates decrease; ↑ indicates increase; ***** indicates statistically significant compared with pre-treatment; + indicates statistically significant compared with control; § indicates statistically significant compared between elite and amateur; # indicates statistically significant compared with national, junior and amateur.

maximum (1RM) strength in four groups of athletes with different expertise levels. They found that all groups could lift significantly ($p < 0.05$) heavier loads with vibration and that the enhancement was significantly larger ($p < 0.05$) for Olympic athletes (8.3%) than the other groups (4.8% for national senior level, 6.2% for national junior level and 4.9% for amateurs).

4.2.2 Submaximal Dynamic Contraction

In a study by Rittweger et al.,[4] subjects performed exhaustive squatting with an additional load of 40% of the body mass, both with and without whole-body vibration. It was found that the time to exhaustion was significantly ($p < 0.05$) shorter with vibration than that without vibration. Oxygen consumption during the squatting exercise was also enhanced significantly ($p < 0.05$) by whole-body vibration, leading the authors[4] to suggest that the shorter time to fatigue was due to greater muscle activity during squatting.

From the discussion of sections 4.1 and 4.2, it appears that the muscle activity in submaximal dynamic and isometric contractions may be enhanced by vibration. During maximal effort dynamic contractions, vibration appears to be able to facilitate force and power output. This facilitatory effect has been shown to be greater in elite athletes. It is unclear whether the maximal isometric contraction force can be enhanced by vibration. However, prolonged vibration induces more muscular fatigue in both the maximal and submaximal isometric and dynamic muscle contractions. This exacerbated muscle fatigue by vibration may be due to: (i) a facilitatory effect of vibration on muscle contraction force and activity during the early part of exercise; and/or (ii) a suppression effect of vibration on neuromuscular performance.

4.3 Acute Residual Effect of Vibration on Force and EMG During Isometric Actions

The strength of maximal voluntary contraction (MVC), EMG of MVC and RFD have been assessed by four studies at different timepoints, from immediately after vibration[4,17] to 60 minutes after vibration[7,16] (table III). Among them, two studies measured the neuromuscular performance of muscle in an unfatigued state.[7,16] Both studies were by Torvinen et al.[7,16] and examined maximal knee extension strength 2 minutes and 60 minutes after 4 minutes of whole-body vibration. The studies differed only by the amplitude of vibration (4mm[16] vs 1mm[7]). Neither study found a significant effect of vibration training 60 minutes post-training. However, a small but significant enhancement in strength was found 2 minutes post-vibration training compared with the sham vibration group (1% vs –2%; $p < 0.05$) when the larger amplitude of vibration was employed (4mm[16]). No difference was evident with a 1mm amplitude of vibration. This indicates that with sufficient amplitude, vibration has a small transient residual effect that could improve maximal isometric strength output.

Two studies measured neuromuscular performance in a fatigued state.[4,9] One of them assessed the maximal voluntary isometric contraction force[9] and one assessed submaximal contraction muscle activity.[4] Jackson and Turner[9] found that both the MVC strength and the RFD were significantly reduced ($p < 0.05$) following 30 minutes of vibration treatment (30Hz), compared with a control group. This finding suggests that vibration can elicit greater neuromuscular fatigue.

One study by Rittweger et al.[4] measured the EMG activity of a submaximal isometric contraction (70% MVC), performed in a fatigued state, immediately and 10 minutes after vibration. Spectrum analysis on these EMG signals found that the median frequency (EMGmf) was significantly higher than that performed by a control group.[4] Similar to the force evaluation, this effect on EMG was only observed immediately after vibration.[4] The authors,[4] therefore, suggested that the facilitatory effect of vibration observed in an unfatigued state may be due to an enhanced central motor excitability, which appears to recruit predominantly large motor units as shown by the shift of EMGmf to a higher frequency.[4,23,24] It is also noted that the vibration amplitude and duration in this study are 6mm and 5.6 minutes, respectively, which is similar to those in the study by Torvinen et al.[16] (4mm and

Table III. Acute residual effect of vibration on isometric muscle performance

Study	Subject	Vibration and exercise characteristics					Neuromuscular performance change				
		method (location)	amp (mm)	freq (Hz)	exercise	duration (min)	contraction performed	tp (min)	force or torque	RFD	EMG
Jackson and Turner[9]	10 UT M	D (RF)	1.5–2.0	30	None	30	Knee extension (100% MVC)	0.5	7%↓*+#	70%↓*+#	IEMG: RF: 15 mV.sec ↓* VL: 8 mV.sec ↓ NS
		D (RF)	1.5–2.0	120	None	30	Knee extension (100% MVC)	0.5	4.2%↓* (NSC)	30%↓* (NSC)	IEMG: RF: 7 mV.sec ↓ NS VL: 7 mV.sec ↓ NS
		Control	NA	NA	None	30	Knee extension (100% MVC)	0.5	2%↓*	18%↓ NS	IEMG: RF: 2.5 mV.sec ↓ NS VL: 0 mV.sec ↓ NS
Rittweger et al.[4]	19 UT (10 F, 9 M)	I (WBV)	6	26	Squatting on platform with load	5.8	Knee extension (70% MVC)	0 10	NM NM	NM NM	EMG$_{mf}$: VL: 55.2Hz EMG$_{mf}$: VL: 50Hz (NSC)
		Control	NA	NA	Squatting on platform with load	8.6	Knee extension (70% MVC)	0 10	NM NM	NM NM	EMG$_{mf}$: VL: 42.4Hz EMG$_{mf}$: VL: 40Hz
Torvinen et al.[16]	16 UT (8 M, 8 F)	I (WBV)	4	15–30	Standing on platform with light exercise	4	Knee extension (100% MVC)	2 60	1.0%↑+ 0.8%↓ (NSC)	NM NM	NM NM
		Sham vibration	NA	NA	Standing on platform with light exercise	4	Knee extension (100% MVC)	2 60	2.0%↓ 3.2%↓	NM NM	NM
Torvinen et al.[7]	16 UT (8 M, 8 F)	I (WBV)	1	25–40	Standing on platform with light exercise	4	Knee extension (100% MVC)	2 60	1.3%↑ (NSC) 1.5%↓ (NSC)	NM NM	NM NM
		Sham vibration	NA	NA	Standing on platform with light exercise	4	Knee extension (100% MVC)	2 60	0.1%↑ 0.9%↓	NM NM	NM NM

amp = vibration amplitude; **freq** = vibration frequency; **D** = directly applied vibration; **EMG** = electromyography; **EMG$_{mf}$** = EMG median frequency; **F** = females; **I** = indirectly applied vibration; **IEMG** = integrated EMG; **M** = males; **MVC** = maximal voluntary contraction; **NA** = not applicable; **NM** = no measurement; **NS** = not statistically significant; **NSC** = not statistically significant compared with control; **RF** = rectus femoris; **RFD** = rate of force development; **tp** = test time from the end of vibration; **UT** = untrained; **VL** = vastus lateralis; **WBV** = whole-body vibration; ↓ indicates decrease; ↑ indicates increase; ***** indicates statistically significant compared with pre-treatment; + indicates statistically significant compared with control; # indicates statistically significant compared with 120Hz.

4 minutes) that found the facilitatory effect on maximal isometric strength 2 minutes post-vibration. This suggests that sufficient vibration amplitude is also necessary for the enhancement of central motor excitability.

4.4 Acute Residual Effect of Vibration on Strength and Power During Dynamic Actions

Three studies have examined the residual effect of vibration on power during dynamic actions in an unfatigued state,[7,16,17] although none of them have examined the effect on strength (table IV). Only one of these studies found that vibration treatment had a facilitatory effect. Torvinen et al.[16] found that a 4-minute whole-body vibration training session could induce a small but significantly larger increase in counter-movement jump height than the sham-vibration group, 2 minutes after vibration treatment (2% vs 0%; $p < 0.05$). Two other studies found no significant effect on dynamic muscle performance after vibration[7,17] (table IV). The first of these two studies[7] was identical to the study by Torvinen et al.[16] that found the positive residual enhancement in vertical jump performance, except the vibration amplitude was smaller (1mm[7] vs 4mm[16]). In the second study, the amplitude of vibration on the muscle was also small (<0.3–0.4mm) and the duration of vibration was fairly short (6–7 seconds[17]). It is possible that with small amplitudes and short durations of stimulation no residual effect is produced.

The facilitatory effect of vibration on dynamic muscle performance also appears transient.[16] The significantly larger increase in counter-movement jump height at 2 minutes after vibration treatment was not present at 60 minutes after vibration.[7,16]

Only one study examined dynamic muscle performance following a fatiguing vibration exercise. Rittweger et al.[4] examined the jump height and the ground contact time of a series of continuous jumps, immediately and 10 minutes after whole-body vibration. The results showed that vibration treatment did not have any significant effect on these parameters ($p > 0.05$).[4]

From the discussions in sections 4.3 and 4.4, it is suggested that a bout of vibration treatment may have a small transient facilitatory residual effect on isometric and dynamic muscle performance. This facilitatory effect on muscle strength and power performance could be observed in an unfatigued state and may be due to an enhanced central motor excitability to recruit predominantly large motor units during isometric and dynamic contractions.[4] It appears that the vibration amplitude and duration of vibration may need to be of sufficient magnitude to elicit this facilitatory effect. In addition, a bout of prolonged vibration training may exacerbate muscle fatigue, which can decrease subsequent muscle performance.

5. Chronic Effect of Vibration on Neuromuscular Performance

5.1 Isometric Strength

Only two studies[3,6] have appropriately examined the chronic effect of vibration on isometric strength (table V). Their results are contradictory. Delecluse et al.[3] found that 12 weeks of whole-body vibration training could induce a significant increase ($p < 0.05$) in knee extensor MVC strength (16.6%), while the placebo group only produced a non-significant increase (5%). In contrast, however, de Ruiter et al.[6] reported no significant difference in knee extensor isometric strength between the vibration group and the control group after 11 weeks of training. The vibration frequency was similar in these two studies (35–40Hz[3] vs 30Hz[6]), but the vibration amplitude was slightly smaller in the study that found the significant increase of MVC strength (1.25–2.5mm[3] vs 4mm[6]). Thus, it appears that vibration amplitudes and frequencies in both studies are sufficient to activate the muscle, and the difference in results may be due to the different exercise intensity and volume undertaken in these two studies.[6] Firstly, Delecluse et al.[3] included both dynamic and isometric exercises, such as the squat, deep squat, wide-stance squat, one-legged squat and lunge. In contrast, de Ruiter et al.[6] only asked subjects to stand on the vibrating platform with their

Table IV. Acute residual effect of vibration on dynamic muscle performance

Study	Subject	Vibration and exercise characteristics					Neuromuscular performance change			
		method (location)	amp (mm)	freq (Hz)	exercise	duration (min)	contraction performed	tp (min)	performance measure	EMG
Issurin and Tenenbaum[17]	28 T M (14 = elite, 14 = amateur)	I (hand)	0.3–0.4	44	Bicep curl	0.1	Bicep curl (MVC)	0	Elite: power 5%↑ NS; amateurs: power 2%↑ NS	NM
		Control	NA	NA	Bicep curl	0.1	Bicep curl (MVC)	0	Elite: power 1%↓ NS; amateurs: power 3%↓ NS	NM
Rittweger et al.[4]	19 UT (10 F, 9 M)	I (WBV)	6	26	Squatting on platform with load	5.8	Serial jump	0 10	Height (NSC) Tg (NSC) Height (NSC) Tg (NSC)	NM NM
		Control	NA	NA	Squatting on platform with load	8.6	Serial jump	0 10	Height; Tg Height; Tg	NM NM
Torvinen et al.[16]	16 UT (8 M, 8 F)	I (WBV)	4	15–30	Standing on platform with light exercise	4	CMJ	2 60	Height: 2.2%↑+ Height: 1.9%↓ (NSC)	NM
		Sham vibration	NA	NA	Standing on platform with light exercise	4	CMJ	2 60	Height: 0%↑ Height: 2.2%↓	NM
Torvinen et al.[7]	16 UT (8 M, 8 F)	I (WBV)	1	25–40	Standing on platform with light exercise	4	CMJ CMJ	2 60	Height: 2.2%↑ (NSC) Height: 4.0%↓ (NSC)	NM
		Sham vibration	NA	NA	Standing on platform with light exercise	4	CMJ CMJ	2 60	Height: 0%↑ Height: 3.5%↓	NM

amp = vibration amplitude; **CMJ** = counter-movement jump; **EMG** = electromyography; **F** = females; **freq** = vibration frequency; **I** = indirectly applied vibration; **M** = males; **MVC** = maximal voluntary contraction; **NA** = not applicable; **NM** = no measurement; **NS** = not statistically significant; **NSC** = indicates not statistically significant compared with control; **T** = trained; **Tg** = ground contact time; **tp** = test time from the end of vibration; **UT** = untrained; **WBV** = whole-body vibration; ↓ indicates decrease; ↑ indicates increase; + indicates statistically significant compared with control.

Table V. Chronic effect of vibration training on isometric muscle performance

Study	Subjects	Vibration and exercise characteristics					Neuromuscular performance change	
		method (location)	amp (mm)	freq (Hz)	exercise	timing	performance test	test results
Delecluse et al.[3]	20 UT F	I (WBV)	1.25–2.5	35–40	Standing on platform, static and dynamic knee extensor exercise	3–20 min/session 3 ×/wk; 12wk	Knee extension (100% MVC)	16.6%↑*
	21 UT F	Placebo	Neg	35–40	Standing on platform, static and dynamic knee extensor exercise	3–20 min/session 3 ×/wk; 12wk	Knee extension (100% MVC)	5%↑ NS
de Ruiter et al.[6]	10 UT (6 M, 4 F)	I (WBV)	4	30	Standing on platform, isometric squatting (knee angle 110)	60 sec × 5 sets – 60 sec × 8 sets 3 sessions/wk, 11wk	Knee extension (100% MVC)	MVC: 0% NS RFD: 3.3%↑ NS
	10 UT (6 M, 4 F)	Control	NA	NA	Standing on platform, isometric squatting (knee angle 110)	60 sec × 5 sets – 60 sec × 8 sets 3 sessions/wk, 11wk	Knee extension (100% MVC)	MVC: 5.4%↑ NS RFD: 4.6%↓ NS

amp = vibration amplitude; **F** = females; **freq** = vibration frequency; **I** = indirectly applied vibration; **M** = males; **MVC** = maximal voluntary contraction force; **NA** = not applicable; **Neg** = negligible; **NS** = not statistically significant; **RFD** = rate of force development; **UT** = untrained; **WBV** = whole-body vibration; ↓ indicates decrease; ↑ indicates increase; ***** indicates statistically significant compared with pre-treatment.

knee angle flexed at 110 . Thus, the exercise intensity in the study of Delecluse et al.[3] appears to be significantly higher. Secondly, in the training programme of Delecluse et al.,[3] the total duration of vibration training of the study increased with time, initially lasting 3 minutes, but reaching 20 minutes by the end. However, in the study of de Ruiter et al.,[6] the total duration of vibration training increased from 5 minutes initially, to only 8 minutes by the end of the study. Thus it seems that the exercise intensity and volume was greater in the study of Delecluse et al.[3] and may indicate that these parameters must be of significant magnitude to induce benefits associated with vibration training.

de Ruiter et al.[6] found no chronic effect on RFD following vibration training, but again this may be due to insufficient training volume and intensity employed in that study.

5.2 Dynamic Strength and Power

Three studies[3,6,15] examined the chronic effect of vibration on dynamic strength and power (table VI). Two studies[3,15] found that vibration enhanced the gain of dynamic muscle performance. Three weeks of heavy strength training by untrained males, employing a seated bicep curl with vibration, could induce a significantly larger increase of concentric elbow flexion strength, than that in a control group where only the heavy strength training was performed (49.8% vs 16%; $p < 0.05$).[15] Isokinetic knee extension strength and counter-movement jump height were also enhanced significantly (9%; $p < 0.05$ and 7.6%; $p < 0.05$) after 12 weeks of training with superimposed whole-body vibration, while the same training without vibration (control group) did not show any significant increase.[3] However, the authors[3] did not find any significant increase in the maximal speed of ballistic knee extension with resistances of 0%, 20%, 40% and 60% of maximal isometric strength, in either the whole-body vibration-trained group or the control group. In contrast to the reported enhancement in counter-movement jump height,[3] de Ruiter et al.[6] found no significant difference between a vibration-trained group and a control group, after 11 weeks of training. This lack

Table VI. Chronic effect of vibration training on dynamic muscle performance

Study	Subjects	Vibration and exercise characteristics					Neuromuscular performance change	
		method (location)	amp (mm)	freq (Hz)	exercise	timing	performance test	test results
de Ruiter et al.[6]	10 UT (6 M, 4 F)	I (WBV)	4	30	Standing on platform, isometric squatting (knee angle 110)	60 sec × 5 sets – 60 sec × 8 sets 3 sessions/wk, 11wk	CMJ	Jump height: 3.0%↑ NS
	10 UT (6 M, 4 F)	Control	NA	NA	Standing on platform, isometric squatting (knee angle 110)	60 sec × 5 sets – 60 sec × 8 sets	CMJ	Jump height: 3.7%↑ NS
						3 sessions/wk, 11wk		
Delecluse et al. [3]	20 UT F	I (WBV)	1.25–2.5	35–40	Standing on platform, static and dynamic knee extensor exercise	3–20 min/session 3 ×/wk; 12wk	Isokinetic knee extension (100 /sec)	Maximal strength: 9%↑*
							CMJ	Jump height: 7.6%↑*
							Ballistic knee extension (resistance: 0%, 20%, 40%, 60% of maximal isometic strength)	Maximal speed: 0% NS
	21 UT F	Placebo	Neg	35–40	Standing on platform, static and dynamic knee extensor exercise	3–20 min/session 3 ×/wk; 12wk	Isokinetic knee extension (100 /sec)	Maximal strength: 3%↑ NS
							CMJ	Jump height: 0% NS
							Ballistic knee extension (resistance: 0%, 20%, 40%, 60% of maximal isometric strength)	Maximal speed: 0% NS
Issurin et al.[15]	10 UT M	I (hand)	0.3–0.4	44	Sitting bicep curl with (80–100% 1RM)	6 sets, 3 ×/wk 3wk	Sitting bicep curl	Maximal strength: 49.8%↑*+
	8 UT M	Control	NA	NA	Sitting bicep curl with (80–100% 1RM)	6 sets, 3 ×/wk 3wk	Sitting bicep curl	Maximal strength: 16%↑*+

1RM = one repetition maximum; **amp** = vibration amplitude; **CMJ** = counter-movement jump; **F** = females; **freq** = vibration frequency; **I** = indirectly applied vibration; **M** = males; **NA** = not applicable; **Neg** = negligible; **NS** = not statistically significant; **UT** = untrained; **WBV** = whole-body vibration; ↑ indicates increase; ***** indicates statistically significant compared with pre-treatment; + indicates statistically significant compared with control.

of effect following vibration training may be due to the low level of exercise intensity and volume employed, as outlined in section 5.1.

Issurin et al.[15] employed a heavy resistance training programme in which subjects were asked to complete seated bicep curls, with a load of 80–100% 1RM. This exercise intensity was the largest among the three studies.[3,6,15] It was also noted that the gains in maximal strength in this study were also the largest, both with and without vibration (49.8% vs 16%; $p < 0.05$[15]), although the length of this study was the shortest (3 weeks[15] vs 11 weeks[6] and 12 weeks[3]).

These findings indicate that vibration training can induce chronic adaptations, provided the exercise intensity and volume is sufficient and that the higher the exercise intensity and volume, the greater the strength and power gain that may be achieved. However, it is also clear that there is a lack of research into chronic vibration training with a strict control group design. This area in particular requires addressing as chronic adaptation is the main aim of resistance training.

6. Effect of Vibration Characteristics and Exercise Protocols on the Enhancement in Neuromuscular Performance

The short- and long-term effects of vibration on neuromuscular performance seem to be affected by the vibration training methodology, which includes vibration characteristics (vibration amplitude, vibration frequency and the method of vibration application) and exercise protocols (type of exercise, intensity and volume of exercise). As shown in tables I–VI, there is diversity in the vibration training methodology employed among the studies to date. While it is difficult to identify the optimal vibration characteristics and exercise protocols for vibration training, some useful information about the effect of vibration methodology can still be obtained from these studies.

6.1 Vibration Amplitude

Two studies by Torvinen et al.[7,16] were identical except for the vibration amplitude (4mm;[16] 1mm[7]) employed. Therefore, comparison of their findings provides insights into the influence of vibration amplitude on vibration training effect. In both studies,[7,16] subjects undertook a 4-minute whole-body vibration training session in which light exercises (e.g. light squatting, standing in erect position, standing with knee flexed, light jumping, standing on heels) were performed on the vibrating platform. EMG activity was measured on calf muscles and thigh muscles during the vibration training process, but was not measured in the sham-vibration condition. Therefore, while it is not possible to determine the absolute effect of vibration training on EMG activity, it is possible to examine the relative effect of vibration amplitude on muscle EMG response by comparing these studies.

Both of the above studies measured the change of EMG activity on the soleus and vastus lateralis muscles during the 4-minute vibration training process.[7,16] The larger vibration amplitude (4mm) induced a significant decrease ($p < 0.05$) of mean power frequency of EMG (EMGmpf) on both muscles (soleus: 18.8%; vastus lateralis: 8.6%) and a significant increase ($p < 0.05$) of EMGrms in the soleus muscle (21.6%), from the first minute to the fourth minute of the training process. The latter finding was suggested to be indicative of more pronounced muscle fatigue on soleus muscle.[16] In contrast to this study, there was no significant change ($p > 0.05$) of these EMG parameters on either muscle in the study with the smaller vibration amplitude (1mm) during the 4-minute training process.[7] These results suggest that the larger vibration amplitude was more able to activate both muscles during training and thus induced more pronounced muscle fatigue.

In addition, analysis of the acute residual effects in these two studies (table III and table IV) showed that only the vibration with the larger amplitude (4mm) induced a significantly larger increase ($p < 0.05$) in MVC strength and jump height than the sham-vibration group.[7,16] These results support our above analysis that the whole-body vibration with larger amplitude may activate the leg muscles more effectively, inducing a facilitatory residual effect on

MVC strength and jump height. It may also be suggested that the vibration amplitude may have to be of a sufficient threshold level in order to effectively activate the muscle being trained. The study by Rittweger et al.[4] also indicated that the enhancement of central motor excitability was elicited by whole-body vibration with sufficient amplitude (6mm). This summary finding is likely to be equally applicable to chronic-based adaptations, as chronic adaptations are reflective of acute responses. However, no studies to date have directly examined this.

6.2 Vibration Frequency

A variety of frequencies, ranging from 15 to 137Hz, have been used in indirect vibration studies (tables I–VI). In these studies, there are also differences in vibration amplitude and exercise protocol. For indirectly applied vibration, only one study has specifically investigated the effect of vibration frequency (table I).[19] Subjects gripped a vibrating handle and pushed isometrically away from their body while standing. EMG activity of the forearm flexor, forearm extensor and triceps brachii muscles were examined under two vibration frequencies (50 and 137Hz[19]). At both vibration frequencies, the IEMG of the forearm flexors and forearm extensors increased significantly more than in the control group ($p < 0.05$). However, the amount of increase appears to be larger with the 50Hz vibration than 137Hz (flexor: 83.3% vs 40%; extensor: 45.5% vs 27.3%). For the triceps brachii muscle, only 50Hz vibration induced a significant increase of IEMG ($p < 0.05$).[19] This result suggests that low frequency (50Hz) may be more effective in activating the muscle in indirectly applied vibration than high frequency (137Hz). However, care should be taken in employing frequencies that are much lower. Mester et al.[12] suggest that in whole-body vibration training, frequency in the range <20Hz should be avoided because of the resonance of human body, which may induce injury effect.

For directly applied vibration, only Jackson and Turner[9] have specifically examined the effect of vibration frequency. In this study, vibration was applied to the muscle belly of the rectus femoris[9] and the acute residual effect on knee extension strength, following 30 minutes of vibration training with two different vibration frequencies (30 and 120Hz), was investigated. The investigators[9] found that the reductions of knee extension MVC strength and RFD were significantly greater in the 30Hz vibration group, than in the 120Hz vibration group and the control group ($p < 0.05$). The IEMG was also attenuated significantly ($p < 0.05$) by 30Hz vibration only. The results of this study suggest that low-frequency vibration (30Hz) may induce more muscle fatigue, possibly by activating muscle more effectively.

The results of the above two studies suggest that low-frequency (30–50Hz) vibration may have a greater acute effect in vibration training. As in the discussion of vibration amplitude, it is likely that the observation of greater enhancements from low frequency is applicable to chronic-based adaptations, although no studies have directly investigated this.

6.3 Method of Vibration Application

Two methods of vibration application have been used in vibration training studies: indirectly applied vibration[3,15] and directly applied vibration.[8,9,13,14] The method of vibration application may influence the magnitude of vibration amplitude and frequency, i.e. the intensity of vibration load on the muscle being trained.

Two studies on whole-body vibration training by Torvinen et al.,[7,16] will be examined here to demonstrate the influence of vibration application method. As introduced in section 6.1, the design of these two studies was identical, except for the vibration amplitude employed. In order to exclude the influence of exercise alone on measured EMG activity during vibration treatment, the muscles (soleus and vastus lateralis) on which EMG activity was measured in both studies will be selected in this analysis. In the study with the smaller amplitude (1mm[7]), EMGrms and EMGmpf on both the soleus and the vastus lateralis did not change significantly ($p > 0.05$) during the 4 minutes vibration training process. As discussed in section 6.1, this may be due to the fact that vibration amplitudes on both of these muscles was not sufficient to elicit any effect. However, in the second study with the larger amplitude (4mm[16]), 4 minutes of vibration training did significantly decrease EMGmpf on both the soleus and the vastus lateralis ($p < 0.05$). Importantly, the amount of decrease was larger on soleus (18.8%) than on vastus lateralis (8.6%). It was also found in this second study[16] that EMGrms increased significantly ($p < 0.05$) only on the soleus. The authors[16] suggested that fatigue of the soleus was more pronounced because the increase in EMGrms indicated that more motor units were recruited to compensate for fatigue during training. This finding clearly demonstrated that the muscle group that was nearer to the vibration platform (soleus) may have been more activated than the muscle group that was further away from the platform (vastus lateralis).

Kihlberg et al.[19] found that when employing a vibrating handle, 50Hz vibration could induce a significant increase ($p < 0.05$) in IEMG on forearm flexor, forearm extensor and triceps brachii muscles. However, when vibration frequency was increased to 137Hz, only the IEMG on the forearm flexors and forearm extensors was enhanced significantly ($p < 0.05$). The IEMG of the triceps brachii did not change significantly ($p > 0.05$). The investigators[19] also found that 50Hz vibration could transmit to the elbow without attenuation, while 137Hz vibration was attenuated by about 20dB at the wrist and, therefore, would have less influence on the muscle activity of the triceps brachii.

The above-mentioned studies all employed the method of indirectly applied vibration. These findings suggest that with indirectly applied vibration there may be a greater vibration training effect on the muscles closer to the vibration source because of the attenuation of the vibration by the body structures during transmission. This attenuation may also result in the vibration amplitude on the muscle groups further from the vibration source being less than the threshold level necessary for muscle activation, which has been discussed in section 6.1. Moreover, the attenuation of vibration appears to be larger with the increase of vibration frequency.[18,19] This may be the reason that almost all vibration studies that have employed the indirect method of vibration application, have used a frequency of <50Hz (tables I–VI).

There are two ways to apply vibration directly to a muscle. One is by applying vibration on the muscle belly,[9,13,14] the other is by applying vibration on the muscle tendon.[8] Compared with indirectly applied vibration, there are few studies employing the direct vibration method (four studies with direct vibration vs 11 studies with indirect vibration, as shown in tables I–VI). There have been no chronic vibration training studies to date employing direct vibration. Although it has been suggested that indirectly applied vibration may be able to stimulate more muscle groups at the same time,[15] the method of direct vibration may have its advantage in stimulating the target muscle without signal attenuation. Thus, given the same amplitude of vibration source, direct vibration may facilitate more effective utilisation of this amplitude. In addition, vibration with a higher frequency may be employed in direct vibration. Some studies[25] have suggested that the most effective location to stimulate the muscle by vibration is the muscle tendon.

6.4 Exercise Protocol

Short-term studies have shown that it is unclear whether the maximal isometric contraction force can be enhanced by vibration,[8,13,14,20] but vibration may increase the submaximal isometric contraction force, as evident by increased EMG activity during vibration.[19] For dynamic contractions, vibration can increase the maximal voluntary contraction force[21] and power.[17] The exercise protocols used in chronic vibration training studies appear to be consistent with the above findings on exercise type and intensity (see sections 5.1 and 5.2). To date, however, maximal isometric contractions have not been employed in chronic vibration training studies. In whole-body vibration training studies, submaximal isometric and dynamic contractions were always used, such as standing on the platform with knee flexed,[6] squatting[3] and light jumping.[7,16] Maximal effort has only been used with dynamic exercises in chronic vibration training studies[15] and the results showed that this kind of exercise protocol, with applied vibration, could achieve significantly more strength gain ($p < 0.05$).[15]

As discussed in section 5.1 and 5.2, the increase in exercise intensity and volume tends to induce greater muscle performance improvement in chronic vibration training.[3,6] However, because of the lack of chronic vibration training studies and the diversity of the training programmes employed, the optimal vibration training programme remains unclear.

7. Summary of Vibration Treatment on Neuromuscular Performance

Although there is a lack of strictly controlled studies, the available studies on vibration training to date still allow us to make some conclusions about this new training method. It appears that vibration training can induce enhancements in strength and power, both acute and chronic.[3,13,15-17,19,21] However, vibration training may also have some limits, e.g. it is still unclear whether the maximal isometric contraction force can be enhanced by vibration. Moreover, the inhibition effect of vibration on motor unit recruitment should be taken into consideration. It also seems that the methodology of vibration training, both the vibration characteristics and exercise protocols, plays an important role in eliciting this enhancement.

Vibration amplitude and frequency are very important in vibration training because they determine the load that vibration imposes on the neuromuscular system during training.[12] Present studies indicate that vibration amplitude needs to be of a sufficient magnitude if it is to elicit an enhancement of strength and power.[7,16] Due to the lack of studies directly comparing different amplitudes, it is not currently possible to stipulate the specific optimal magnitude of this minimum amplitude for either direct or indirect vibration methods. There is also a frequency range (e.g. 30–50Hz) that has been shown to be able to activate the muscle most effectively.[9,19]

The amplitude and frequency that are delivered to a muscle being trained are influenced by the method of vibration application. With indirectly applied vibration, a situation may exist that the vibration amplitude and frequency on a muscle close to the vibration source may be sufficient to activate the muscle effectively, but those on a muscle further away from vibration source may not be sufficient.[16,19] This is because vibration amplitude and frequency may be attenuated during its transmission through soft tissues.[12,18] Moreover, this attenuation is increased with the increases in vibration frequency.[18] In contrast, direct vibration may stimulate specific muscle group more effectively because the distance of transmission is shorter and the amount of attenuation is less. However, the effect of direct vibration is more localised and indirect vibration may be able to activate more muscle groups during its transmission.[15]

It appears that the greater the exercise intensity and volume employed in vibration training, the larger the enhancement in strength and power that may be achieved by vibration.[3,15]

Vibration appears to induce greater strength and power gain in elite athletes than non-elite athletes. Although this vibration training effect was only examined in two studies that investigated the acute responses,[17,21] it suggests that vibration training may have a great potential for elite athletes as it is harder to produce enhancement in neuromuscular performance in elite athletes than non-elite athletes when conventional strength training methods are used.

Currently, there is no clear consensus on the mechanism by which vibration may enhance neuromuscular performance; in fact, there is a lack of research in this area. However, a number of mechanisms have been postulated upon, including: tonic vibration reflex,[5,13] perceptual change by vibration,[21] enhanced motor neuron excitability,[3-5,26] increased muscle temperature and blood flow,[17,27] increased hormone secretion[5,28] and muscle hypertrophy.[3,29,30] Elaboration of these underlying causative mechanisms is beyond the scope of this review. Interested readers are referred to the above papers and the review by Cardinale and Bosco.[5]

8. Conclusions and Direction for Future Studies

In recent years, the use of vibration stimulation during resistance training (vibration training) has gained in popularity. Current findings suggest that vibration training may have positive acute and chronic effects on neuromuscular performance and training. However, this facilitatory effect of vibration training is influenced by training protocols in terms of both vibration characteristics (method of application, frequency and amplitude) and exercise protocol (training type, intensity and volume). In addition, a dearth in research in chronic-based dynamic studies is evident. This is unfortunate as chronic adaptation is the most important area of interest, given the aim of resistance training. The lack of research is probably due to the more time consuming and challenging nature of long-term compared with short-term studies.

In light of the present review, the following areas in particular need addressing with appropriate control studies if the potential for vibration training is to be understood:

- To identify optimum vibration amplitudes and frequencies for training based on the method of vibration application (direct or indirect), and the type, intensity and duration of exercise.
- In light of the general acceptance that dynamic training is more beneficial to neuromuscular development in athletes than isometric training, more studies should employ dynamic exercise.
- Examination of acute effects have shown that elite athletes may benefit more from vibration training.[17,21] However, chronic vibration training studies to date have only employed untrained subjects (tables V and VI). Chronic studies with trained athletes are needed to demonstrate the effectiveness of vibration training on performance enhancement in elite athletes.

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