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Review Article

The effects of whole-body vibration on muscle strength and power: a meta-analysis

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Abstract

Exercise with whole-body vibration (WBV) is becoming popular as an alternative to conventional training or as supplementary training. However, despite increasing research efforts in this field, additive effects of WBV on muscle performance remain unclarified. In this review, we investigated the additive effects of long-term WBV on muscle strength and power. This meta-analysis was restricted to randomized controlled trials lasting for at least 5 weeks comparing exercise with and without WBV, or comparing only WBV exposure and control. Data from a total of 314 participants in 10 studies on knee extension muscle strength, and 249 participants in 7 studies on countermovement jump height were pooled using random-effect models. Meta-analysis showed significant additional effects of WBV on muscle strength (standardized mean difference [SMD]=0.76, 95% confidence interval [CI]=0.21-1.32; p=0.007) and countermovement jump (SMD=0.87, 95% CI=0.29-1.46; p=0.003). Based on these findings, we concluded that the use of WBV would lead to greater improvements in both knee extension muscle strength and countermovement jump than under identical conditions without WBV.

Keywords: Vibration, Muscle Strength, Muscle Power, Review

Introduction

Whole-body vibration (WBV) has recently been introduced in fitness clubs, beauty clinics and professional sports teams as an alternative or supplementary to conventional training. Physically, the force generated by a vibration platform becomes workload in an exercise program with WBV[1]. In addition, application of vibration to skeletal muscles causes in muscle spindles a response harmonized to frequencies of vibration, termed a 'tonic vibration reflex'[2,3]. Although a number of studies have reported the effects of intervention using WBV, the extent to which muscle strength and power can be improved as compared with non-WBV conditions remains unclear.

Previous studies have investigated the effects of intervention exercise programs combined with WBV, and have shown increases in muscle strength[4,5], muscle power[4,5], flexibility[6], muscle cross sectional area[7-9], bone mineral density[10], and decreases in abdominal fat[11]. However, no standard prescription, including the determinations of vibration frequency and peak-to-peak displacement, has so far been established for optimizing the effects of WBV, due mainly to inconsistent effects of WBV across studies. Also, there may be some controversy about the presence of additive effects of WBV on muscle performance when compared with identical exercise regimens without WBV.

In recent two systematic reviews, Marin & Rhea concluded that the effects of exercise with WBV on muscle power and muscle strength depend on the type of vibration platform, frequency, displacement, and training duration (acute vs. long-term)[12,13]. However, because these reviews performed pre vs. post comparisons, there is a possibility that the great variety of exercise programs affect the results. Therefore, it is still controversy whether using WBV would be meaningful for muscle power and strength gains compared with the identical program without WBV.

Here, to clarify the effects of WBV on muscle strength and power gains compared with those of identical conditions without WBV, we systematically reviewed recently published reports on the additive chronic effects of WBV on knee extensor muscle strength and countermovement jump height.

The authors have no conflict of interest.

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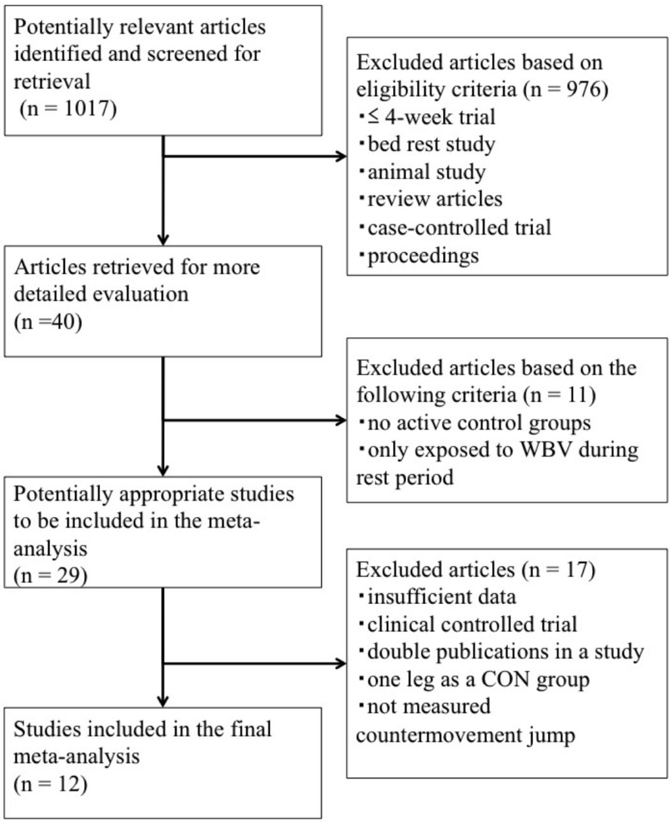

Figure 1. Flow of the study.

Methods

Literature search strategy

Electrical databases of MEDLINE (PubMed), EBSCO (SPORTDiscus™), and Web of Science^{SM} were accessed online in March 2012 and searched using the following key words: 'vibration', 'exercise', 'training', 'performance', 'strength', 'power', and 'fitness'. References lists of potentially useful articles were also scanned for additional articles. If the study title was related to vibration exercise, the article was selected as the first selection round. In the second selection round, we read the abstract and then selected the article if muscle strength or muscle power was evaluated before and after intervention longer than 4 weeks. In the third selection round, we read the full articles.

Selection criteria

Eligibility criteria

The eligibility criteria for the meta-analysis were: (a) human study, (b) intervention period >4 weeks, (c) included outcome measurements for knee extension muscle strength or countermovement jump height, and (d) studies that had an exercise combined with WBV group and another group performing exercise only (active control, CON), or studies that performed a structured WBV exposure intervention without any exercise (i.e. participants remained standing upright or in slightly flexed knee positions during WBV exposure) and no intervention (passive CON).

Exclusion criteria

The exclusion criteria for this meta-analysis were: (a) studies with a single repeated measure design with no CON groups, (b) studies that had only CON group performed different exercise programs from the WBV group, (c) WBV was applied only during the rest periods between exercises, (d) bedrest studies, (e) clinical controlled trials, (f) case-control studies, (g) proceedings, and (h) when double (or triple) publications of single trial were identified.

Assessment of methodological quality

Methodological quality was assessed based on the guidelines for systematic reviews established by the Method Guidelines Cochrane Back Review Group[14]. Briefly, risk of bias was evaluated based on responses to 12 questions inquiring about the randomization, treatment allocation, incomplete outcome data (e.g. drop-out rate), and potential bias. These 12 criteria were scored with 'yes', 'no', or 'unsure'.

In addition, we also evaluated the quality of each study based on the recommendation of the International Society of

Author, year	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Quality Score
Bautmans et al. 2005	y	u	y	y	y	n	y	y	y	u	y	y	9
Delecluse, Roelants 2003	y	u	y	u	u	y	n	y	y	u	y	y	7
Kvorning et al. 2006	y	u	u	u	u	y	y	y	u	u	y	y	6
Mahieu, 2006	y	u	u	u	u	u	u	y	n	y	y	y	5
Mikhael et al. 2010	y	y	y	n	y	n	n	y	y	u	y	n	7
Osawa & Oguma 2011	y	u	u	u	u	y	n	y	y	y	y	y	7
Osawa et al. 2011	y	n	n	n	y	y	y	y	y	u	y	y	8
Petit, Pensini 2010	y	u	u	u	u	n	u	u	y	u	u	y	3
Rees et al. 2007	y	u	u	u	u	u	n	y	y	u	y	y	5
Russo et al. 2003	y	u	u	u	u	y	n	y	y	y	n	y	6
von Stengel et al. 2010	y	u	y	u	y	y	y	y	y	n	y	y	9
Wyon et al. 2010	y	u	u	u	u	y	u	u	y	u	u	y	4

Q1, Random allocation; Q2, Concealed allocation; Q3, Blinded participants; Q4, Blinded care provider; Q5, Blinded assessor; Q6, Dropped out; Q7 Intension-to-tread analysis; Q8, Selective outcome reporting; Q9, Groups similarity at baseline; Q10, Co-intervention avoided; Q11, Compliance; Q12, Similarity of assessment timing.

Table 1a. Methodological quality assessment by the Methodological Guidelines Cochrane Back Review group.

Author, year	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Quality Score
Bautmans et al. 2005	y	y	y	u	u	u	u	y	u	u	y	u	y	6
Delecluse, Roelants 2003	y	y	y	u	y	y	u	u	n	u	y	u	y	7
Kvorning et al. 2006	y	y	y	u	u	u	u	y	y	y	y	y	y	9
Mahieu, 2006	y	u	y	u	u	u	u	y	u	u	y	u	y	5
Mikhael et al. 2010	y	y	y	y	u	u	u	y	u	y	y	y	y	9
Osawa & Oguma 2011	y	y	y	u	u	y	u	y	y	y	y	y	y	10
Osawa et al. 2011	y	y	y	u	u	y	u	y	u	y	y	y	y	9
Petit, Pensini 2010	y	y	y	u	u	u	u	y	y	y	y	y	y	9
Rees et al. 2007	y	y	y	u	u	u	u	y	y	y	u	y	y	8
Russo et al. 2003	y	y	y	u	u	u	u	y	u	u	u	u	y	5
von Stengel et al. 2010	y	u	y	u	u	u	u	y	u	u	u	u	y	4
Wyon et al. 2010	u	u	y	u	u	u	u	y	u	u	u	u	y	3

Q1, Brand name of vibration platform; Q2, Type of vibration; Q3, Vibration frequency; Q4, Vibration amplitude; Q5, Peak acceleration; Q6, Accuracy of vibration parameter; Q7, Evaluation of skidding of the feet; Q8, Changes of vibration parameters; Q9, Rationale for choosing vibration parameters; Q10, Support devices during vibration exposure; Q11, Type of footwear; Q12, Body position; Q13, Description of exercise.

Table 1b. Methodological assessment by the recommendations of the ISMNI.

Musculoskeletal and Neuronal Interactions (ISMNI) for reporting WBV intervention studies, consisting of 13 factors[15]. Briefly, we evaluated whether each article adequately described the WBV-related factors based on responses to 13 questions inquiring about the WBV parameters (e.g. frequency, peak-to-peak displacement, and acceleration) and participants' position (e.g. holding bar, exercise position, and foot wear condition). Whether the article adequately described each of the above was scored with 'yes', 'no', or 'unsure'. 'Vibration amplitude' was scored as 'unsure' if it was unclear whether the described displacement was peak-to-peak. If we knew bar holding and foot-wear condition by figures, we scored these with 'yes'.

Data extraction

Participant characteristics (age, gender, and training level), WBV parameters (frequency, peak-to-peak displacement, and if applicable, accelerations), exercise program, and outcomes were extracted.

Data synthesis

The standardized mean difference was calculated using the Review Manager version 5.1.6 (Copenhagen, Nordic Cochrane Center, The Cochrane Collaboration, 2011). Intervention effects were calculated as 'post-trial mean minus pre-trial mean' for each intervention group. The standard deviation of the dif-

Study details						Outcomes	
Author, year	*Design*	*Duration*	*Frequency (times/s)*	*Volume (set/exercise)*	*Period (s, per set)*	*Muscle strength*	*Muscle power*
Young							
Delecluse, Roelants 2003	RCT(B)	12W	3	BW, squat exercises, and lunge	30-60/60-5	ISOM ISOK	CMJ
Kvorning et al. 2006	RCT (B)	9W	2, 3	Squat (free weight)	30/120	ISOM	CMJ
Mahieu et al. 2006	RCT (B)	6W	3	BW; squat exercises, calf raise Skiing movement, jump	30-100/60	ISOK	NM
Osawa et al. 2011	RCT (A)	12W	2	BW; squat exercises, lunge Trunk muscle exercises	30/60	ISOK	NM
Osawa & Oguma 2011	RCT (A)	13W	2	Weight-loading exercise and body weight exercise; squat, Bulgarian squat	80/60	ISOM ISOK	CMJ
Petit, Pensini 2010	RCT(B)	6W	3	BW; static squat	30/30	NM	Vertical jump, CMJ
Wyon et al. 2010	RCT(B)	6W	2	BW; static	30/NR	NM	Vertical jump
Old							
Bautmans et al. 2005	RCT (A)	6W	3	BW; 6 static exercises	30, 45, 60 /30-60	LE	NM
Mikhael et al. 2010	RCT (A)	3M	3	BW; flexed knees (20 deg flexion) or locked knees	60/60	1RM (LP)	NM
Rees et al. 2007	RCT (A)	2M	3	BW; 1-4W, knee-flexed position (static), 5-8W, (dynamic)	45-80/ 45-80	ISOK	NM
Russo et al. 2003	RCT (B)	6M	2	Standing upright	60-120/NR	NM	Ground reaction force
von Stengel et al. 2010	RCT (A)	18M	2	Heel rise, one-legged deep squat, leg abduction	60/60	LP CMJ	

BW, body weight; CMJ, countermovement jump height; ISOK, isokinetic muscle strength; ISOM, isometric muscle strength; M, month; NM, not measured; NR, not reported; LE, leg extension; RCT, randomized controlled trial; RCT (A), randomized controlled trial reported the randomization method and it is adequate; RCT (B), randomized controlled trial not reported the randomization method; W, week.

Table 2. Study characteristics.

ference scores from the standard deviation of each intervention group was calculated using the following equation:

$$SD_{diff} = \sqrt{SD_{pre}^2 + SD_{post}^2 - 2 x r x SD_{pre} x SD_{post}}$$

where r is the correlation coefficient between pre and post trials. It has been shown that the correlation coefficient can be estimated from related studies[16], so that we estimated a correlation coefficient as r=0.95 from a related systematic review[17]. We then calculated the standardized mean differences (SMD= the Hedges' correction g). If a study consisted of two or more exercise groups using WBV (e.g. different amplitude and frequency), the values of mean and standard deviation in a group exhibiting the greatest improvement were used for analyses as an intervention group.

Sub-group analysis

We divided subjects into two sub-groups for each parameter: for age, a young to middle-aged group ("YOUNG group") and older group ("OLD group"); for WBV frequency, a lower frequency group (≤30 Hz) and higher frequency group (>30 Hz); and for WBV peak-to-peak displacement, a lower displacement group (<2-4 mm) and higher displacement group (>4-6 mm). In case of progressive overload due to changing frequency or displacement throughout the training period, studies were grouped based on WBV variables used in more than half of the training sessions.

Test for heterogeneity

Heterogeneity among included studies was assessed using the Cochrane Q statistic. P values were obtained by comparing the Q statistic with a χ^2 distribution and $\varkappa - 1$ degrees of freedom, where $\varkappa$ represents the number of studies included. Because heterogeneity is, to a certain degree, inevitable in meta-analysis, particularly for exercise trials, we reported the I^2 statistic using the following equation:

$$I^2 = \frac{(Q - df)}{Q} x 100\%$$

Study details	Subjects	WBV conditions			
Author, year	*Group*	*FREQ (Hz)*	*DIS (mm)*	*ACC (g)*	*Progressive overload*
Young					
Delecluse, Roelants 2003	Ex-WBV	35,40	2.5-5.0	2.28-5.09	Exercise time, rest period, and WBV conditions
	Active CON	NA	NA	NA	
Kvorning et al. 2006	Ex-WBV	20, 25	4	NR	Increased the number of training days/ week, FREQ, and training intensity (8 reps × 10 RM → 8 reps × 8 RM)
	Active CON	NA	NA	NA	
Mahieu et al. 2006	Ex-WBV	24-28	2-4	NR	Duration of exercise, number of repetitions, number of different exercises, and WBV conditions
	Active CON	NA	NA	NA	
Osawa et al. 2011	Ex-WBV	30-40	2	1.4-3.4	FREQ
	Active CON	NA	NA	NA	
Osawa & Oguma 2011	EX-WBV	35	2	2.1	Progressively overloaded by increasing the number of sets and weight-loading
	Active CON	NA	N	NA	
Petit, Pensini 2010	Ex-WBV_A	50	4	NR	Knee flexed position changed from 70° to 80° to 90° every 2 weeks
	Ex-WBV_B	30	2	NR	
	Active CON	NA	NA	NA	
Wyon et al. 2010	Ex-WBV	35	4	NR	Fixed
	Active CON	NA	NA	NA	
Old					
Bautmans et al. 2005	Ex-WBV	30, 40	2-4	NR	Exercise menu and duration, WBV conditions (FREQ, and DIS)
	Active CON	NA	NA	NA	
Mikhael et al. 2010	WBV_A	12	1	0.3	Fixed
	WBV_B				
	Passive CON	NA	NA	NA	
Rees et al. 2007	Ex-WBV	26	2-5	NR	Increased DIS (5-8 mm) and introduced dynamic movement
	Active CON	NA	NA	NA	
Russo et al. 2003	WBV	12-28	NR	NR	Increased FREQ (12-28 Hz) and prolonged exercise time per set
	Passive CON	NA	NA	NA	
von Stengel et al. 2010	Ex-WBV	25-35	1.7-2.0	NR	Increased FREQ (25, 30, to 35 Hz)
	Active CON	NA	NA	NA	

ACC, acceleration; CON, control; DIS, peak-to-peak displacement; Ex-WBV, exercise with whole-body vibration; FREQ, frequency; NA, not applicable; NR, not reported; RM, repetition maximum; WBV, whole-body vibration.

Table 3. Whole-body vibration characteristics.

where Q and df are Cochran's heterogeneity statistic and the degrees of freedom, respectively. I^2=0-40% indicates the absence heterogeneity, and I^2=30-60%, I^2=50-90%, and I^2=75-100% indicate the presence of moderate, large and extremely large heterogeneity, respectively[18]. In this meta-analysis, I^2 of >50% was used as the indication of significant heterogeneity. If significant heterogeneity was observed, a random effect meta-analysis model was applied.

Statistical analysis

Normality and equal variance assumptions were examined using the Kolmogorov-Smirnov and Levene tests, respectively. If the normality and equal variance assumptions were satisfied, group differences were examined using an unpaired t-test; if not, a Mann-Whitney U test was used. Statistical analysis was performed using PASW software version 21.0 for Macintosh (SPSS, Inc., Tokyo, Japan). The level of significance was set at p<0.05, and all values are presented as mean ± standard deviation.

Results

Study selection

Of the 1,017 references screened, 40 articles reported the effects of >4-week exercise programs using WBV or short-term WBV exposure without any exercise on either or both muscle strength and power (Figure 1). Of these initial 40, 8 were excluded for lack of an active CON group. Although Lamont et al. did investigate the effects of a 6-week exercise program using WBV on muscle strength and power compared with an active CON group, WBV was not applied during exercise but during the rest period between exercises[19-21], we excluded these studies because all other remaining articles involved WBV use during exercise. Further, due to multiple publications of a trial, three articles were excluded from sensitivity analyses[22-24]. Two of the 40 articles which allocated one leg to an intervention group and the other leg to active CON group were excluded from this review process[25,26]. Two of the

Study details		Subjects			
Author, year	*Group*	*Mean age (years)*	*Sample size (N)*	*Gender*	*Characteristics*
Young					
Delecluse, Roelants 2003	Ex-WBV	21.5	18	F	Untrained
	Active CON		18		
Kvorning et al. 2006	Ex-WBV	23	10	M	Recreationally active
	Active CON		9		
Mahieu et al. 2006	Ex-WBV	12.9	17	C	Skiers
	Active CON	11.8	16		
Osawa et al. 2011	Ex-WBV	26.8	10	C	Untrained adults
	Active CON	28.1	8		
Osawa & Oguma 2011	EX-WBV	36.8	16	C	Untrained adults
	Active CON	37.7	16		
Petit, Pensini 2010	Ex-WBV_A	21	12	M	Physically active men
	Ex-WBV_B		10		
	Active CON		10		
Wyon et al. 2010	Ex-WBV	19	9	F	Students majoring in dance
	Active CON	21.1	9		
Old					
Bautmans et al. 2005	Ex-WBV	77.5	10	C	Institutionalized older individuals
	Active CON		11		
Mikhael et al. 2010	WBV_A	64.4	5	C	Non-institutionalized individuals aged > 50 years
	WBV_B		4		
	Passive CON		7		
Rees et al. 2007	Ex-WBV	74.3	15	C	Healthy older individuals
	Active CON		13		
Russo et al. 2003	WBV	60.7	14	F	Postmenopausal women
	Passive CON		15		
von Stengel et al. 2010	Ex-WBV	68.8	46	F	Postmenopausal women
	Active CON		47		

C, combined male and female; CON, control; Ex-WBV, exercise coupled with whole-body vibration; F, female; M, male; WBV, whole-body vibration.

Table 4. Participant characteristics.

articles were excluded because they only evaluated chair rising test as muscle power[27,28]. Ten of the remaining articles were non-randomized controlled trial (RCT) studies and were therefore excluded. After the above exclusion, 12 of the remaining studies were RCTs which satisfied the eligible criteria, and all were included in this meta-analysis[4,5,9,29-37].

Methodological characteristics

The methodological quality scores of included trials are shown in Table 1a. The overall mean score was 6.3±1.9 (range: 3 to 9) of 12 points. For sub-groups by age, the mean score of the YOUNG studies was found to be 5.7±1.8 points, whereas that of the OLD studies was 7.2±1.8 points (p=0.19, unpaired t-test).

The quality score of each study followed by the ISMNI recommendation is shown in Table 1b. The overall mean score were 7.0±2.3 (range: 3 to 10) of 13 points. For sub-groups, the mean score of the YOUNG studies was 7.4±2.6 points, whereas that of the OLD studies was 6.4±2.1 points. No significant differences were identified between the study groups stratified by age (p=0.48, unpaired t-test).

Study characteristics

Of these 12 articles, only 5 adequately described the randomization methods[9,29,32,33,35], while the other 7 did not state the randomization procedure at all[4,5,30,32,34,36,37]. Tables 2 and 3 show the study design and WBV parameters in these included studies, respectively.

Subject characteristics

A total of 358 participants were included in the analysis. The mean age in each study ranged from 11.8 to 77.5 years (Table 4).

Treatment characteristics

Mean duration of training period in all included trials was 16.0±17.8 weeks (range: 6 weeks to 18 months). For subgroups based on age, respective mean duration and number of total training sessions of the YOUNG studies were 9.1±3.2 weeks and 22.4±27.6 sessions (p=0.34; Mann-Whitney U test), whereas those of the OLD studies were 24.4±27.5 weeks and

Study	WBV			CON			Weight[#]	Standardized Mean Difference
Author, year [unit]	*Mean*	*SD*	*N*	*Mean*	*SD*	*N*		*Random, 95%CI*
Young								
Kvorning et al. 2006 [N]	199	214.6	10	259	115.4	9	9.7%	-0.33 [-1.24, 0.58]
Petit, Pensini 2010 [Nm]	13.18	10.4	12	11.24	13.8	10	10.1%	0.15 [-0.69, 1.00]
Osawa et al. 2011 [Nm/kg]	0.2	0.2	10	0.1	0.3	8	9.6%	0.38 [-0.56, 1.32]
Mahieu et al. 2006 [Nm]	22.6	14.5	17	15.6	15.1	16	10.9%	0.46 [-0.23, 1.15]
Delecluse, Roelants 2003 [Nm]	32.52	11.9	18	7.27	11.6	18	10.2%	2.10 [1.27, 2.93]
Osawa & Oguma 2011 [N/kg]	3.1	0.5	16	1.3	0.5	16	8.4%	3.51 [2.36, 4.66]
Subtotal (95% CI)			**83**			**77**	**58.9%**	**1.01 [-0.00, 2.03]**
Heterogeneity: τ^2=1.40; χ^2=40.46, df=5 (P<0.00001); I^2=88%								
Test for overall effect: Z=1.95 (P=0.05)								
Old								
Bautmans et al. 2005 [N]	57.6	56.5	10	42.9	43	11	10.0%	0.28 [-0.58, 1.14]
Rees et al. 2007 [Nm]	11.2	12.8	15	7	11.4	13	10.6%	0.33 [-0.41, 1.08]
von Stengel et al. 2010 [N]	119.6	61.6	46	84.1	70.5	47	12.3%	0.53 [0.12, 0.95]
Mikhael et al. 2010 [N]	145.3	190.3	5	34.4	125.6	7	8.2%	0.66 [-0.53, 1.85]
Subtotal (95% CI)			**76**			**78**	**41.1%**	**0.47 [0.15, 0.79]**
Heterogeneity: τ^2=0.00; χ^2=0.49, df=3 (P=0.92); I^2=0%								
Test for overall effect: Z=2.87 (P=0.004)								
Total (95% CI)			**15 9**			**15 5**	**100.0%**	**0.76 [0.21, 1.32]**
Heterogeneity: τ^2=0.61; χ^2=43.50, df=9 (P<0.00001); I^2=79%								
Test for overall effect: Z=2.70 (P=0.007)								
Test for subgroup differences: Chi²=1.00, df=1 (P=0.32), I^2=0%								
CI, confidence interval; CON, control; SD, standard deviation; WBV, whole-body vibration								
[#], percent weights given to each study								

Table 5a. Meta-analysis for muscle strength.

54.0±51.6 sessions (p=0.15; Mann-Whitney U test). Type of footwear in the included trials was as follows: shoes in 2 trials[4,31], socks in 4 trials[5,9,32,33], and barefoot[30] or sandals[29] in 1 trial each.

Main effects

Maximal knee extensor strength

Pooled data from 10 studies (n=314) showed that WBV significantly increased knee extensor muscle strength when compared with CON (SMD [WBV vs. CON]=0.76, 95% CI=0.21-1.32, p=0.007; Table 5a).

For the YOUNG studies, pooled data from 6 studies (n=160) showed that WBV no significant increases were seen in knee extensor muscle strength when compared with CON (SMD [WBV vs. CON]=1.01, 95% CI=-0.00-2.03, p=0.05; Table 5a), whereas significant increases were obtained from pooled data from 4 OLD studies (n=154; SMD [WBV vs. CON]=0.47, 95% CI=0.15-0.79, p<0.001; Table 5a).

For the lower frequency studies, pooled data from 5 studies showed that the WBV group had significantly greater increases in muscle strength than the CON group (n=185; τ^2=0.00, χ^2=3.09, df=4 [p=0.54]; I^2=0%, Z=2.72, p=0.007; SMD [WBV vs. CON]=0.41, 95% CI=0.11-70), and significant increases in muscle strength were also found based on findings of 6 higher frequency studies (n=172; τ^2=1.10, χ^2=34.97, df=5 [p<0.001]; I^2=86%, Z=2.41, p=0.02; SMD [WBV vs. CON]=1.12, 95% CI=0.21-2.04).

For the lower displacement studies, pooled data from 7 studies showed a significant additive effect in muscle strength in the WBV group compared with the CON group (n=245; τ^2=0.77, χ^2=35.40, df=6 [p<0.001]; I^2=83%, Z=2.90, p=0.004; SMD [WBV vs. CON]=1.08, 95% CI=0.35-1.81), whereas no significant increases were found in 4 higher displacement studies (n=102; τ^2=0.00, χ^2=2.71, df=3 [p=0.44]; I^2=0%, Z=1.44, p=0.15; SMD [WBV vs. CON]=0.28, 95% CI=-0.10-0.65).

Muscle power

Pooled data from 7 studies (n=249) showed that WBV significantly increased countermovement jump height when compared with CON (SMD [WBV vs. CON]=0.87, 95% CI=0.29-1.46, p<0.001; Table 5b).

For the YOUNG studies, pooled data from 5 studies (n=127) showed that WBV significantly increased countermovement jump height when compared with CON (SMD [WBV vs. CON]=1.00, 95% CI=0.04-1.95, p<0.001; Table

Study	WBV			CON			Weight#	Standardized Mean Difference
Author, year [unit]	*Mean*	*SD*	*N*	*Mean*	*SD*	*N*		*Random, 95%CI*
Young								
Kvorning et al. 2006 [cm]	1.4	1.2	10	2.3	1.4	9	13.3%	-0.66 [-1.59, 0.27]
Osawa & Oguma 2011[cm]	3.4	2.9	16	2.4	2.2	16	15.5%	0.38 [-0.32, 1.08]
Petit, Pensini 2010 [cm]	1.9	1.4	12	-0.2	1.2	10	12.9%	1.52 [0.54, 2.49]
Delecluse, Roelants 2003 [cm]	19.5	12	18	0.2	11	18	14.9%	1.64 [0.87, 2.41]
Wyon et al. 2010 [cm]	2.3	0.7	9	-1.5	2.1	9	10.4%	2.31 [1.05, 3.57]
Subtotal (95% CI)			**65**			**62**	**67.0%**	**1.00 [0.04, 1.95]**
Heterogeneity: τ^2=0.97; χ^2=22.90, df=4 (P=0.0001); I^2=83%								
Test for overall effect: Z=2.04 (P=0.04)								
Old								
von Stengel et al. 2010 [W/kg]	1.5	1.4	46	0.8	1.1	47	18.2%	0.53 [0.11, 0.94]
Russo et al. 2003 [N]	8.4	11.3	14	-0.8	9.4	15	14.9%	0.86 [0.10, 1.63]
Subtotal (95% CI)			**60**			**62**	**33.0%**	**0.60 [0.24, 0.97]**
Heterogeneity: τ^2=0.00; χ^2=0.57, df=1 (P=0.45); I^2=0%								
Test for overall effect: Z=3.25 (P=0.001)								
Total (95% CI)			**125**			**124**	**100.0%**	**0.87 [0.29, 1.46]**
Heterogeneity: τ^2=0.45; χ^2=24.57, df=6 (P = 0.0004); I^2=76%								
Test for overall effect: Z=2.93 (P=0.003)								
Test for subgroup differences: Chi^2=0.56, df=1 (P=0.45), I^2=0%								
CI, confidence interval; CON, control; SD, standard deviation; WBV, whole-body vibration								
#, percent weights given to each study								

Table 5b. Meta-analysis for muscle power.

5b), and similar results from pooled data from 2 OLD studies (n=122; SMD [WBV vs. CON]=0.60, 95% CI=0.24-0.97, p=0.45; Table 5b).

For the lower frequency studies, pooled data from 3 studies showed that the WBV group had no significantly greater increases in countermovement jump height than the CON group (τ^2=0.29, χ^2=6.73, df=2 [p=0.03]; I^2=70%, Z=0.84, p=0.40; SMD [WBV vs. CON]=0.31, 95% CI=-0.42-1.04), whereas significant increases were found based on findings of 4 higher frequency studies (τ^2=0.47, χ^2=9.95, df=3 [p=0.02]; I^2=70%, Z=3.32, p<0.001; SMD [WBV vs. CON]=1.38, 95% CI=0.56-2.19).

For the lower displacement studies, pooled data from 2 studies showed a significant additive effect in countermovement jump height in the WBV group compared with the CON group (τ^2=0.15, χ^2=1.97, df=1 [p=0.16]; I^2=49%, Z=3.22, p=0.001; SMD [WBV vs. CON]=1.25, 95% CI=0.49-2.01), whereas no significant increases were found in 5 higher displacement studies (τ^2=0.53, χ^2=18.04, df=4 [p=0.001]; I^2=78%, Z=1.91, p=0.06; SMD [WBV vs. CON]=0.72, 95% CI=-0.02-1.47).

Discussion

Of the 12 included studies, 7 would be regarded as "low risk of bias" because they fulfilled with at least 6 criteria with no serious flaws[14]. Our evaluation showed that half of the studies performed adequate random sequence generation, and one third blinded outcome assessment (Table 3a). In vibration-based intervention studies, blinding of participants and personnel would not be realistic. Increasing the number of evidence-based WBV training programs will require configuring a study with intention to treat analysis, blinding assessors, and reporting the risk of co-interventions in future research.

When we evaluated the quality of each study according to the ISMNI recommendations[15], some factors related to the acceleration were not sufficiently documented in the included studies. First, few studies measured the actual acceleration of the WBV platform[4,9,33]. Second, no study described the method used to ensure consistent targeting amplitude of WBV in side-to-side alternating platform-type WBV, such as with a Galileo platform. Because the acceleration generated by the WBV platform is one of the most salient factors in WBV studies[1], future studies should strictly adhere to these guidelines.

Previous meta-analysis showed that the type of WBV platform, frequency, and displacement would mediate the extent to which muscle strength and muscle power gains by exercise with WBV by means of pre vs. post comparisons[12,13]. In the present meta-analysis, when we examined the additive effects of WBV on muscle strength and power by restricting our analysis to RCTs for longer than 4 weeks in duration, that directly compared exercises with and without WBV, or compared structured WBV exposure without any exercise program and maintenance of daily lifestyles, the results of the present review suggest that the use of WBV would lead to greater muscle strength and countermovement jump height compared with the identical conditions without WBV. We observed significant heterogeneity in both muscle strength and countermovement jump and therefore conducted random effects modeling. We also noted significant heterogeneity even in a sub-group analysis stratified by age and WBV parameters (frequency and displacement) likely due to the inconsistencies in how progressive overloading was mixed with WBV parameters, exercise protocols, exercise duration per set, and training period.

The additive effect of WBV on countermovement jump performance was classified as 'large' based on the criteria proposed by Cohen[16]. Countermovement jump is characterized as a stretch-shortening cycle movement. A stretch reflex may play a role in a rapid increase in muscle stiffness, which is considered to be important in successfully transferring elastic energy from an eccentrically stretched muscle-tendon complex to a subsequent concentric contraction in the stretch-shortening cycle[38]. Both mono- and poly-synaptic stretch reflex pathways including Ia afferent neurons from muscle spindles are thought to be activated on application of vibration[39]. Although exact mechanisms remain unclear, lasting application of WBV may enhance the activity of stretch reflex, thereby leading to a considerable improvement in countermovement jump performance.

After stratification by age, 'large effects' of adding WBV to intervention programs on countermovement jump height were identified in the YOUNG studies[16]. In these studies, participants took part in exercise programs for the lower extremities, such as squat exercises[4,5,9,30,32-34,37], whereas participants kept upright or in a slightly knee-flexed position on a vibration platform in two of the five OLD studies[32 29,34-36] (Table 1). It has been shown that the sensitivity of muscle spindle is enhanced by voluntary contraction through coactivation of gamma-motoneurons[39,40], the effects of WBV is expected to be stronger when it is applied during contracting state than during relaxing state. Further, improving muscle performance requires a longer training period in the elderly than in the young, as older individuals have a lower trainability due to age-related morphological musculoskeletal and nervous system changes (e.g. muscle spindles and excitability of motor neurons), accumulation of chronic disease, disuse atrophy, malnutrition, and reductions in hormonal secretions[41,42]. However, no significant differences were found in training volume (training period and total training sessions) between the YOUNG and OLD studies. As such, while few studies have assessed muscle power in older individuals, we presume that a more marked improvement in countermovement jump performance occurred in YOUNG studies.

The additive effect of WBV on knee extensor muscle strength was found to be significant in OLD studies but only close to significant in YOUNG ones (p=0.05). A longer exposure to vibration may be necessary to elicit WBV effects on muscle strength, as a decrease in muscle activation was reported after 30 sec of muscle contractions with locally applied vibration[43]. Further support for this concept was provided by Rittweger et al., who reported that the time to exhaustion was shorter for static squat exercises with WBV than for identical exercise without WBV (349 vs. 515 sec, respectively)[44]. The duration of exercise time was also shorter in the YOUNG studies than in OLD studies. When we further compared the included studies for knee extensor muscle strength with those for countermovement jump height, studies with relatively short exercise duration were weighted more heavily in the meta-analysis than those for countermovement jump height, resulting in no statistical difference in knee extensor muscle strength across the YOUNG studies.

The present meta-analysis found significant heterogeneity, likely due to inconsistencies in progressive overloading combined with WBV and exercise protocols, exercise duration per set, and training periods among the included studies. Although we were unable to strictly investigate the influence of the WBV parameters on heterogeneity due to the great diversity in progressive overloading, these parameters would likely not differ substantially between the YOUNG and the OLD studies even on more invasive investigation, suggesting that the parameter differences might not cause the heterogeneity. Significant heterogeneity was found in some sub-groups based on age and WBV parameters (Table 5), suggesting that heterogeneity may be attributable to factors other than WBV frequency or displacement, such as participant characteristics, particularly body mass and weight loading. Pel et al. found that the WBV platform generates greater acceleration by adding weight loading to the platform[45]. We neglected to conduct sub-group analysis stratified by body mass because the magnitude of acceleration affected by body mass should be varied in combination with WBV platform type and WBV parameters[45]. In addition, the degree of muscle contraction enhanced by WBV depended on the footwear condition[46]. As such, the observed significant heterogeneity may be partly attributable to the diversity of footwear worn by participants in the included studies.

Several limitations to the present study are to be mentioned. First, our meta-analysis included participants with varying characteristics (e.g. gender, age, and fitness level) and involved comparison of aggregate outcomes in muscle strength. Second, the present study did not conduct funnel plotting or perform testing for funnel plot asymmetry, as the power of test is too low to distinguish chance from real asymmetry if less than 10 studies are included[16]. Therefore, the risk of publication bias could not be excluded. Third, the present study did not suggest the optimal vibration parameters or exercise prescription due to the lack of consistency in methodologies. In addition, although we attempted to investigate the effect of WBV parameters on muscle strength and muscle power, most included articles progressively overloaded by changing frequency and displacement, resulting in not performing strict sub-group analyses based on these methods of overloading. Last, method of muscle strength assessment (e.g. based on type of muscle contraction [isometric or isokinetic], range of movement, or velocity) varied among the studies for meta-analysis of knee extensor muscle strength, and only countermovement jump height was assessed in the meta-analysis for muscle power.

In conclusion, the present meta-analysis showed that adding WBV to an exercise program or even simple daily living cause greater improvements in knee extensor muscle strength and countermovement jump performance than identical conditions without WBV.

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