

Review Article

Effects of vibration on flexibility: a meta-analysis

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Abstract

Exogenous stimulation of skeletal muscle or tendon is often used to improve range of motion. Despite substantial research efforts, however, the effects of vibration on flexibility have not been clarified. In this review, we investigated the effects of acute and chronic intervention programs which used vibration to improve flexibility in young healthy individuals. Effect size was calculated using data from a total of 600 participants in 19 studies before and after the introduction of vibration-based intervention, and a total of 324 participants in 13 studies on the additive effects of vibration compared with the identical conditions without vibration. Sub-group analyses were performed based on intervention period, type of exercise, and type of vibration. Meta-analysis showed that vibration interventions had significant effects on flexibility (standardized mean difference [SMD]=−0.79, 95% confidence interval [CI]=−1.14–−0.43; $p<0.001$), albeit with the possibility of heterogeneity ($I^2=75\%$). Another meta-analysis revealed a significant additive effect of vibration on flexibility compared with the identical condition without vibration (SMD=0.25, 95%CI=0.03–0.48; $P=0.03$), with small heterogeneity ($I^2=0\%$). The risk of publication bias was low judged from Kendall's τ statistic. We concluded that the use of vibration might lead to additive improvements in flexibility.

Keywords: Whole-body Vibration, Localized Vibration, Flexibility, Review

Introduction

Joint mobility is restricted and flexibility is decreased by age-related changes in tendons and ligaments and inactive lifestyles, and at least one authority advises that flexibility exercises such as stretching and yoga exercises should be performed on a regular basis¹. Exogenous stimulation to skeletal muscle or tendon consisting of vibration, transcutaneous electrical nerve stimulation, and hot packs are often employed to improve range of motion (ROM)².

Application of vibration to a muscle belly or tendon causes a response in muscle spindles which is harmonized to the frequency of vibration, termed a 'tonic vibration reflex'^{3,4}. This use of vibration is sometimes called localized vibration (LV). Further, whole-body vibration (WBV) has recently been introduced into fitness clubs, beauty clinics and professional sports

teams as an alternative or supplement to conventional exercise. While the effects of intervention programs using either LV or WBV have been investigated, the extent to which flexibility is improved by the intervention programs themselves remains unclear. In addition, if vibration does enhance flexibility, it is unclear what kind of program would be most beneficial in enhancing flexibility in combination with vibration.

Previous studies of the effects of intervention exercise programs combined with vibration have shown increases in muscle strength^{5,6}, muscle power^{5,6}, flexibility⁷, muscle cross sectional area⁸⁻¹⁰, bone mineral density¹¹, and decreases in abdominal fat¹². However, conclusive findings based on which the effects of vibration can be optimized have yet to be established, including those for vibration frequency and amplitude, mainly due to the inconsistent effects of vibration across studies. Further, controversy has arisen over the potential additive effects of vibration on flexibility compared with identical intervention programs without vibration.

Here, to clarify the effects of intervention programs using vibration on flexibility, we systematically reviewed recently published reports on the acute and chronic effects of LV or WBV on flexibility. Our primary aim was to investigate the effects of intervention programs which compared pre- and post vibration intervention data. We also compared data from programs with vibration with those from programs having the

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same intervention but without vibration. Our secondary aim was to investigate the effects of the following differences in programs on flexibility: (1) acute and long-term effects, (2) WBV and LV, and (3) type of exercise, i.e., stretching vs. body weight exercises.

Methods

Literature search strategy

The online MEDLINE (PubMed), EBSCO (SPORTDiscus™), and Web of ScienceSM databases were accessed in the beginning of March 2013 and searched using the following key words: ‘vibration’, ‘flexibility’, ‘extensibility’, ‘muscle length’, ‘stiffness’, and ‘range of motion’. References lists of potentially useful articles were searched to identify additional articles.

Selection criteria

Eligibility criteria

Eligibility criteria for the meta-analyses were: (a) human study in healthy young individuals (mean age less than 30 years); (b) outcome measurements included flexibility, and detected the effects of single-session and long-term intervention using vibration on flexibility; and (c) the experimental group received an intervention in combination with WBV or LV, and a second group received the same intervention under identical conditions but without WBV or LV. With regard to eligibility criterion (a), we included studies of children because muscle-tendon structures and properties do not largely differ between children and adults in their 20s, but excluded studies of older adults due to the possibility of age-related changes in these variables^{13–15}.

Exclusion criteria

Exclusion criteria for this meta-analysis were: (a) animal studies, (b) case-control studies, (c) studies reported in proceedings, and (d) studies with missing data which prevented meta-analysis, despite attempts to impute them.

Assessment of methodological quality

Risk of bias was assessed based on the guidelines for systematic reviews established by the Cochrane Handbook for Systematic Reviews of Interventions¹⁶. Briefly, risk of bias was evaluated based on responses to seven questions inquiring about the randomization, treatment allocation, blinding, incomplete outcome data (e.g. drop-out rate), and other potential bias. These seven criteria were scored as ‘yes’, ‘no’, or ‘unsure’ based on the criteria in the Cochrane Handbook¹⁶. To assess the risk of bias in cross-over trials, we also checked whether trial reports carried information about the evaluation of carry-over effect. If the possibility of carry-over was found, we scored ‘no’ for other potential bias.

Additionally, we also evaluated the quality of each study based on recommendations of the International Society of Musculoskeletal and Neuronal Interactions (ISMNI) for reporting WBV intervention studies, consisting of 13 factors¹⁷. Briefly, we evaluated whether each article adequately de-

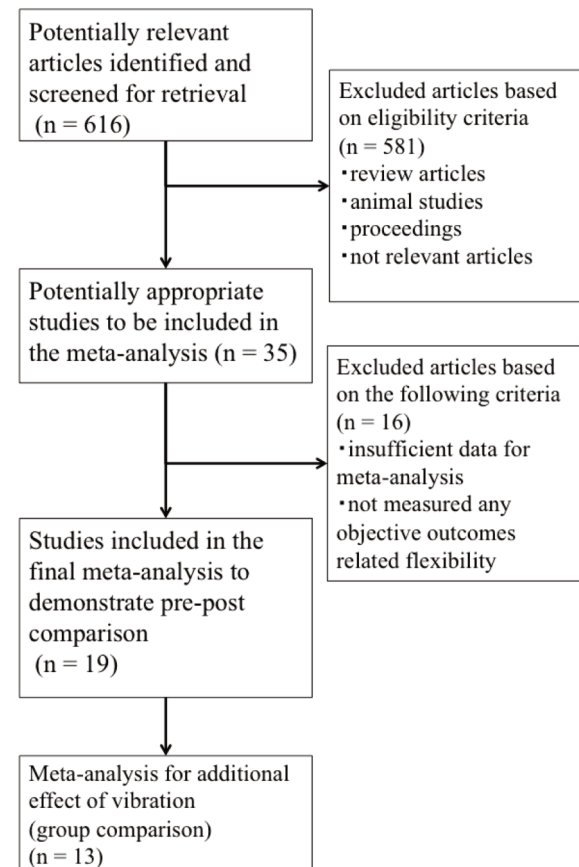


Figure 1. Flow of the meta-analysis.

scribed WBV-related factors based on responses to 13 questions about WBV parameters (e.g. frequency, amplitude, and acceleration) and participant position (e.g. holding bar, exercise position, and footwear condition). Articles were scored for the adequacy of their description of these factors with ‘yes’, ‘no’, or ‘unsure’. If bar holding and footwear conditions could be discerned in figures, we scored these as ‘yes’. We also applied this recommendation to studies of LV.

Data extraction

Participant characteristics (age, gender, and physical activity), vibration parameters (vibration type, frequency, amplitude, and if applicable, accelerations), exercise program, and outcomes were extracted.

Missing data

If included articles lacked particular information that was necessary for meta-analysis, we used previously described imputation techniques to assume unknown statistics¹⁶.

Data synthesis

Standardized mean differences were calculated using Review Manager version 5.1.6 (Copenhagen, Nordic Cochrane

Study design							Outcomes
Author, year	Design	Duration	Frequency (times/w)	Exercise	Volume (set/exercise)	Exercise/ rest period (per set)	
Acute							
Apple et al. 2010	RCT (B)	NA	NA	Static SQ	1	3 m	PROM (DF)
Atha et al. 1976	RCO (B)	NA	NA	NR	1	15 m	AROM (SR)
Cochrane et al. 2005	RCO (B)	NA	NA	static Ex × 6	1	30 or 60 s	AROM (SR)
Cronin et al. 2008	RCO (B)	NA	NA	SS	3	30 s/ 30 s	AROM (KE)
George et al. 2012	CCT (A)	NA	NA	SS	4 × 2	10 s/ 5 s	AROM (bridge)
Herda et al. 2009	RCO (B)	NA	NA	NA	1	20 m	PROM (PF)
Jacobs et al. 2009	RCO (B)	NA	NA	Upright position	1	6 m	AROM (SR)
Kemertzis et al. 2008	RCO (B)	NA	NA	SS	5	60 s/ 60 s	PROM (instrumental PF)
Kinser et al. 2008	CCT (B)	NA	NA	SS × 2	4	10 s/5 s	PROM (split forward)
Sands et al. 2008	RCO (B)	NA	NA	SS × 2	1	45 s	PROM (split forward)
Siu et al. 2010	RCO (B)	NA	NA	Static SQ	10	60 s/60 s	Muscle stiffness
Short-term chronic							
Bakhtiary et al. 2011	RCT (A)	8W	3	SS	3	20-45 s/60 s	PROM (manual KE)
Bosco et al. 2001	RM (B)	30D	7	Semi-SQ	5	60 s / 60 s	AROM (SR)
Fagnani et al. 2006	RCT (B)	8W	3	static SQ ×2	3-4	15-60 s/60-30s	AROM (SR)
Feland et al. 2010	RCT (B)	4W	5	SS	5	30 s/30 s	PROM (manual KE)
Issurin et al. 1994	RCT (B)	3W	3	SS × 2, BS × 1	2-4	6-7 s/3-4 s	AROM (SR, split)
Lapole et al. 2011	RM (B)	2W	7	NA	1	1 h	PROM (instrumental PF)
Marshall et al. 2012	RCT (B)	4W	2	Ex × 9	2	30-40 s/NR	AROM (developpes)
van den Tillaar et al. 2006	RCT (B)	4W	3	SS, SQ	1	30 s	PROM (manual SLR)
AROM, active range of motion; BS, ballistic stretching; CCT, crinical controlled trial; D, day; DF, dorsiflexion; Ex, body-weight exercise; KE, knee extension test; NA, not applicable; NR, not reported; PF, plantar flexion; PROM, passive range of motion; RCO, randomized cross-over trial; RCT, randomized controlled trial;RM, repeated measure design; SLR, straight leg raise test; SR, sit and reach test; SS, static stretching; SQ, squat; W, week.							

AROM, active range of motion; BS, ballistic stretching; CCT, crinical controlled trial; D, day; DF, dorsiflexion; Ex, body-weight exercise; KE, knee extension test; NA, not applicable; NR, not reported; PF, plantar flexion; PROM, passive range of motion; RCO, randomized cross-over trial; RCT, randomized controlled trial; RM, repeated measure design; SLR, straight leg raise test; SR, sit and reach test; SS, static stretching; SQ, squat; W, week.

Table 1. Study characteristics.

Center, The Cochrane Collaboration, 2011). Intervention effects were calculated as ‘post-trial mean minus pre-trial mean’ for each intervention group. When a lower score on a test indicated improvement, the pre-experiment mean value was subtracted from the post-experiment mean¹⁸. Standard deviation (SD) of the difference scores from the SD of each intervention group was calculated using the following equation:

$$SD_{pooled} = \sqrt{\frac{(N_{post} - 1)SD_{post}^2 + (N_{pre} - 1)SD_{pre}^2}{N_{post} + N_{pre} - 2}}$$

where N represents the number of participants. We then calculated standardized mean differences (SMD= the Hedges’ correction g). In addition, to clarify the effects of vibration on flexibility gains in comparison with those of identical conditions without vibration, meta-analysis was performed using

studies that had an experimental group using vibration and another group performing the identical condition but without vibration. Data for multi-arm studies with more than two intervention groups were combined as follows¹⁶:

$$N_{combined\ group} = N_1 + N_2$$

$$Mean_{combined\ group} = \frac{N_1M_1 + N_2M_2}{N_1 + N_2}$$

$$SD_{combined\ group} = \sqrt{\frac{(N_1 - 1)SD_1^2 + (N_2 - 1)SD_2^2 + \frac{N_1N_2}{N_1 + N_2}(M_1^2 + M_2^2 - 2M_1M_2)}{N_1 + N_2 - 1}}$$

where the sample size of group 1 was N_1 ; sample size of group 2 was N_2 ; mean of group 1 was M_1 ; mean of group 2 was M_2 ; SD of group 1 was SD_1 ; and SD of group 2 was SD_2 .

Study details	Subjects	Vibration			
Author, year	Group	Device	F (Hz)	D (mm)	A (g or m/s ²)
Acute					
Apple et al. 2010	SS+WBV	Pneumex Vibration Plate®	40	2-4	NR
	SS	NA	NA	NA	NA
Atha et al. 1976	LV	NR (provided by Niagara Therapy)	44	0.1	NR
	CON	NA	NA	NA	NA
Cochrane et al. 2005	Ex+WBV	Galileo Sport	26	6	NR
	Ex	NA	NA	NA	NA
Cronin et al. 2008	SS/LV	NR	34	3	42.2 m/s ²
	SS	NA	NA	NA	NA
George et al. 2012	SS+WBV	Power-Plate Pro 5 Airdaptive	30	2	3.62 g
	SS	NA	NA	NA	NA
Herda et al. 2009	LV	Foredom Percussion Hammer	70	NR	NR
	CON	NA	NA	NA	NA
Jacobs et al. 2009	WBV	Galileo 2000	0-26	*1	NR
Kemertzis et al. 2008	SS+WBV	Galileo 900	26	4-4.5	NR
	SS	NA	NA	NA	NA
Kinser et al. 2008	SS+LV	NR(33.6 cm×22.8 cm×22.8 cm)	30	2	NR
	SS	NA	NA	NA	NA
Sands et al. 2008	SS+LV	Power-Plate Pro 5 Airdaptive	30	2	3.62
	SS	NA	NA	NA	NA
Siu et al. 2010	Ex+WBV	Galileo Sport	40	4	106.75 m/s ²
	Ex+WBV		26	8	
	Ex	NA	NA	NA	NA
Short-term chronic					
Bakhtiary et al. 2011	LV+SS	Model VR-7N	50	NR	NR
	CON	NA	NA	NA	NA
Bosco et al. 2001	Ex+WBV	Nemes L-C	30	5	3.6 g
Fagnani et al. 2006	WBV	Nemes LCB-040	35	4	17 g
		NA	NA	NA	NA
Feland et al. 2010	SS+WBV	Gallileo 2000	26	4	NR
	SS	NA	NA	NA	NA
Issurin et al. 1994	SS&BS+LV	Specially desinged device	44	0.6-0.8	22 m/s ²
	SS&BS	NA	NA	NA	NA
Lapole et al. 2011	LV	Techno-Concept, VB 115	50	0.2	NR
Marshall et al. 2012	Ex+WBV	NR	35-40	8	NR
	Ex	NA	NA	NA	NA
van den Tillaar et al. 2006	SS/Ex+WBV	Nemes Bosco system	28	10	NR
	SS	NA	NA	NA	NA

A, acceleration; CON, control; BS, ballistic stretching; D, displacement; Ex, exercise; F, frequency; LV, local vibration; NA, not applicable; NR, not reported; SS, static stretching; WBV, whole-body vibration.

*1, 16 cm to the rotation axis.

Table 2. Vibration characteristics.

Assessment of 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 $\kappa - 1$ degrees of freedom, where κ represents the number of studies included. Because some heterogeneity is inevitable in meta-analysis, particularly for exercise trials, we reported the *I*² statistic using the following equation:

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

where Q and df are Cochrane's heterogeneity statistic and degrees of freedom, respectively. *I*²=0-40% indicates the absence of 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, respectively¹⁶. In this meta-analysis, *I*² of >50% was used as to indicate significant heterogeneity. A fixed effects meta-analysis model was used if no significant heterogeneity was found. However, if significant heterogeneity was observed, a random effects meta-analysis model was applied.

Author, year	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Quality Score
Acute								
Apple et al. 2010	u	u	u	u	y	u	y	2
Atha et al. 1976	u	u	u	u	y	u	y	2
Cochrane et al. 2005	u	u	u	u	y	u	y	2
Cronin et al. 2008	u	u	u	u	y	u	y	2
George et al. 2012	n	u	u	u	y	u	y	2
Herda et al. 2009	u	u	u	u	y	u	y	2
Jacobs et al. 2009	u	u	u	u	y	u	y	2
Kemertzis et al. 2008	u	u	u	y	y	u	y	3
Kinser et al. 2008	n	n	u	u	y	u	y	2
Sands et al. 2008	u	u	u	u	y	u	y	2
Siu et al. 2010	u	u	u	u	y	u	y	2
Short-term chronic								
Bakhtiary et al. 2011	y	n	n	y	y	u	y	4
Bosco et al. 2001	n	n	n	u	y	u	n	1
Fagnani et al. 2006	u	u	u	u	y	u	n	1
Feland et al. 2010	u	u	u	u	y	u	y	2
Issurin et al. 1994	u	u	u	u	y	u	y	2
Lapole et al. 2011	n	n	u	u	y	u	n	1
Marshall et al. 2012	u	u	u	u	y	u	n	1
van den Tillaar et al. 2006	u	u	u	y	y	u	y	3

Q1, Random sequence generation; Q2, Allocation concealment; Q3, Blinding of participants and personnel; Q4, Blinding of outcome assessment; Q5, Incomplete outcome data; Q6, Selective reporting; Q7, Other bias.

Table 3a. Risk assessment by the Methodological Guidelines Cochrane Review.

Sub-group analysis

Studies were divided into sub-groups based on study characteristics (intervention period, acute and short-term chronic; vibration type, WBV and LV; and type of exercise, stretching or body weight exercise).

Publication bias

Publication bias was examined by using Kendall's τ statistic¹⁹.

Statistical analysis

Statistical analysis was performed using PASW software version 21.0 for Macintosh (SPSS, Inc., Tokyo, Japan). The level of significance was set at $p < 0.05$.

Results

Study characteristics

Of the 616 references screened, 19 articles satisfied the eligibility criteria and all were included in the meta-analysis. Of these, 13 were also included in the meta-analysis for the additive effect of vibration effect on flexibility compared with the identical intervention program without vibration²⁰⁻³² (Figure 1).

Of these 19 articles, 7 were randomized controlled trials (RCTs)^{7,20,21,24,27,32,33}, 2 were clinical-controlled trials^{25,29}, 8 were randomized cross-over trials (RCOs)^{22,23,26,28,30,31,34,35}, and 2 were conducted under a single repeated measures design^{36,37}. Eight articles investigated the short-term (range 2 to 8 weeks)

chronic effects of vibration on flexibility^{7,20,24,27,32,33,36,37}, while the other 11 investigated the acute effects of this intervention^{21-23,25,26,28-31,35}. Of the RCTs or RCOs, only one study adequately described randomization methods³³, while the others made no mention of randomization procedures^{7,20-24,26-28,30-32,34,35}. Tables 1 and 2 show the study design and vibration parameters in these included studies, respectively.

Methodological characteristics

The methodological quality scores of the included trials are shown in Table 3a. Overall mean score was $2.0 \pm 0.7/7$ (range: 1 to 4) points. For sub-groups, the mean score of acute studies was 2.1 ± 0.3 points, whereas that of the short-term chronic studies was 1.9 ± 1.1 points.

The quality score of each study according to the ISMNI recommendation is shown in Table 3b. Overall mean score was $8.8 \pm 2.4/13$ (range: 4 to 12) points. For sub-groups, the mean score of acute studies was 9.1 ± 2.5 points, whereas that of the short-term chronic studies was 8.4 ± 2.4 points.

Subject characteristics

A total of 600 participants in 19 articles were included in analysis for the effect of intervention on flexibility, and 324 participants in 13 articles were included in that for the additional effects of vibration on flexibility. Mean age in the studies ranged from 10.6 to 28.6 years old. Participants in the 19 studies consisted of elite sports players, gymnasts, recreationally

Author, year	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Quality Score
Acute														
Apple et al. 2010	y	u	y	y	n	n	n	y	y	y	y	y	y	9
Atha et al. 1976	u	u	y	y	n	n	n	y	n	n	u	u	y	4
Cochrane et al. 2005	y	y	y	u	n	n	n	y	u	y	y	y	y	8
Cronin et al. 2008	y	y	y	y	y	u	n	y	u	y	y	y	y	10
George et al. 2012	y	y	y	y	y	y	n	y	y	y	y	y	y	12
Herda et al. 2009	y	y	y	n	n	n	n	y	y	u	y	u	u	6
Jacobs et al. 2009	y	y	y	u	n	n	u	y	u	y	y	y	y	8
Kemertzis et al. 2008	y	y	y	y	n	y	n	y	y	y	y	y	y	11
Kinser et al. 2008	u	y	y	y	n	n	n	y	y	y	y	y	y	9
Sands et al. 2008	y	y	y	y	y	y	n	y	y	y	y	y	y	12
Siu et al. 2010	y	y	y	y	y	n	n	y	y	y	y	y	y	11
Short-term chronic														
Bakhtiary et al. 2011	y	y	y	n	n	n	n	y	y	y	y	u	y	8
Bosco et al. 2001	y	y	y	y	y	n	n	y	u	u	u	y	y	8
Fagnani et al. 2006	y	y	y	y	y	n	n	y	u	y	y	y	y	10
Feland et al. 2010	y	y	y	u	n	n	n	y	y	y	y	y	y	9
Issurin et al. 1994	y	y	y	y	y	y	n	y	y	y	y	y	y	12
Lapole et al. 2011	y	y	y	y	n	n	n	y	y	y	u	u	u	7
Marshall et al. 2012	n	n	y	y	n	n	n	y	u	u	u	u	y	4
van den Tillaar et al. 2006	y	y	y	y	n	n	n	y	y	y	y	y	y	10

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 3b. Methodological assessment by the recommendations of the ISMNI.

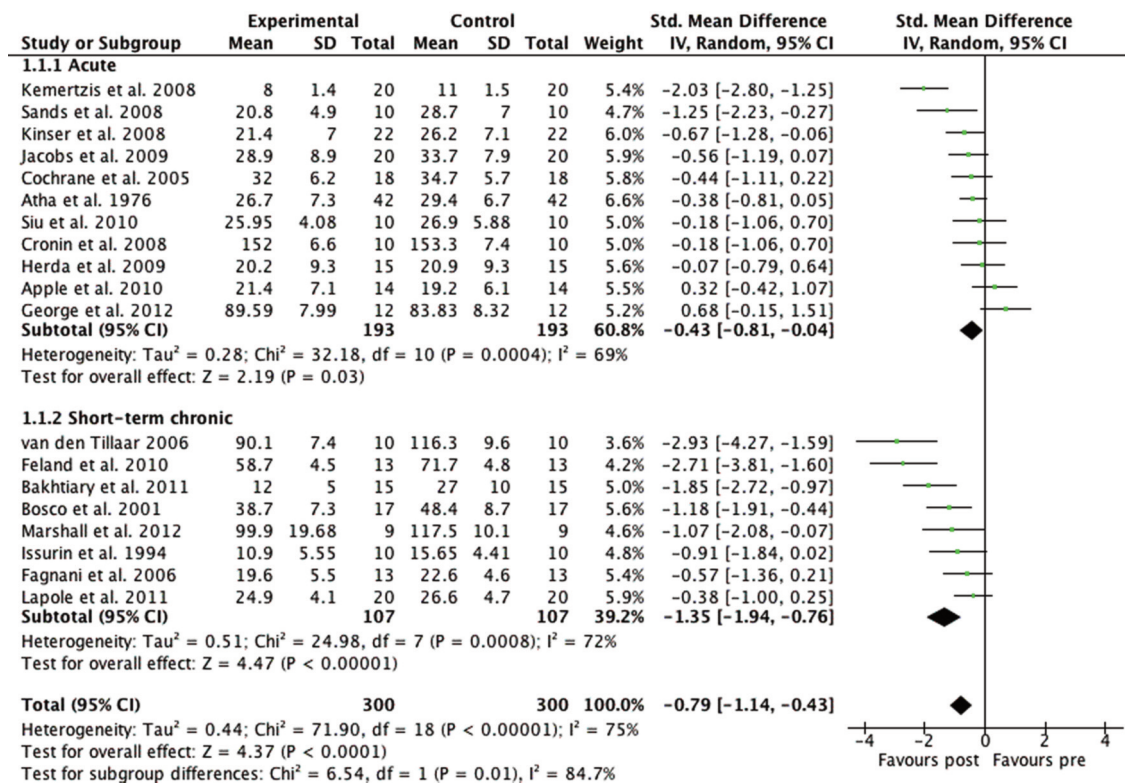


Figure 2. Effect of intervention using vibration on flexibility.

Study details				Subjects	
Author, year	Group	Mean age (years)	Sample size (N)	Gender	Characteristics
Acute					
Apple et al. 2010	Ex+WBV	25.9	14	FM	Healthy adults (> 21 year-old)
	Ex	23.9	13		
Atha et al. 1976	LV	23.1	42	M	Undergraduate and post-graduate students
	CON				
Cochrane et al. 2005	Ex+WBV	21.8	18	F	Elite field hockey players
	Ex				
Cronin et al. 2008	SS/LV	22.7	10	M	No musculoskeletal problems
	SS				
George et al. 2012	SS+WBV	23	12	F	Artistic gymnasts
	SS	20.3	12		Physical education students
Herda et al. 2009	LV	24	15	M	Healthy adults
	CON				
Jacobs et al. 2009	WBV	28.6	20	FM	Recreationally active
Kemertzis et al. 2008	SS+WBV	21.2	20	M	Healthy young adults
	SS				
Kinser et al. 2008	SS+LV	11.3	22	F	Competitive gymnasts
	SS	10.6	7		
Sands et al. 2008	SS+LV	10.7	10	M	Gymnasts
	SS				
Siu et al. 2010	Ex+WBV(40)	21.9	10	M	Recreationally active
	Ex+WBV(26)				
	Ex				
Short-term chronic					
Bakhtiary et al. 2011	LV	20	15	F	Non-athletic females with limited hamstring extensibility
	CON	20	15		
Bosco et al. 2001	WBV	21-34	17	M	Professional soccer players
	WBV	24	13	FM	
Fagnani et al. 2006	CON	23.63	11		Athletes (volleyball, basketball, track and field, gymnastics)
Feland et al. 2010	SS+WBV	23	13	FM	College-age with tight hamstrings
	SS	24	12	FM	
Issurin et al. 1994	SS&BS+LV	19-25	10	M	Physical education students
	SS&BS		8		
Lapole et al. 2011	LV	21.7	19	NR	Healthy and active students
Marshall et al. 2012	Ex+WBV	22	9*	F	Students at a conservatoire modern dance school
	Ex	25	8*		
van den Tillaar et al. 2006	SS/Ex+WBV	21.5	10	FM	Undergraduate students
	SS		8		

BS, ballistic stretching; Ex, exercise; F, female only; FM, female and male; LV, local vibration; M, male only; NR, not reported; SS, static stretching; WBV, whole-body vibration * Imputed the missing data.

Table 4. Participant characteristics.

active individuals, and college-aged individuals were included in the participants (Table 4).

Treatment characteristics

Mean duration of training period in studies of short-term chronic effects was 4.3 ± 2.5 weeks (range: 2 to 8 weeks).

Type of vibration in the included trials was WBV in 11 (6 acute, 5 short-term chronic) and LV in 8 (5 acute, 3 short-term chronic) (Table 2). Type of footwear in the trials using WBV was shoes in 3 trials^{7,22,32}, socks in 4^{21,24,31,35}, and barefoot²⁸ and

hands²⁹ in 1 each. In trials using LV, the vibration source was applied to the anterior or posterior thigh muscles^{23,33,34} and Achilles tendon or heels^{26,27,29,30,37}.

Main effects

Intervention effect on flexibility

Acute and chronic effects

Pooled data from 19 studies (n=600) showed that post-intervention flexibility following vibration was significantly higher than pre-intervention flexibility ($p < 0.001$) (Figure 2).

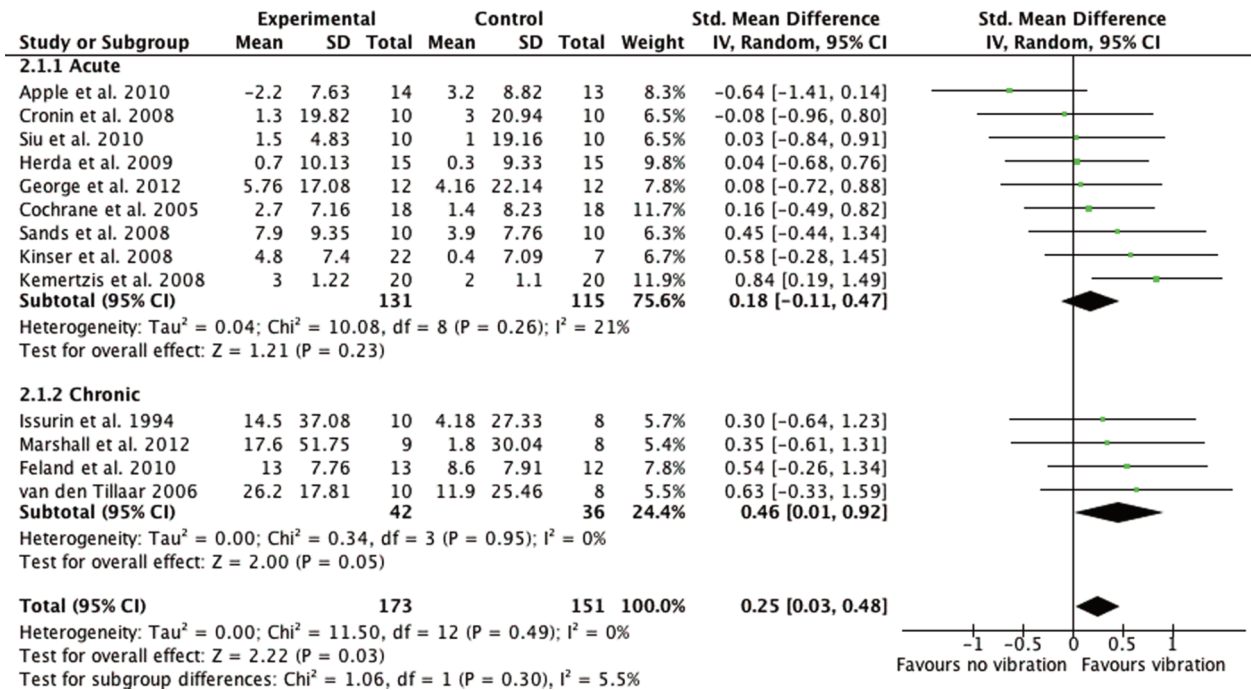


Figure 3. Additional effect of vibration on flexibility compared with the identical intervention without vibration.

For the acute studies, pooled data from 11 studies showed a significant difference between pre- and post-intervention flexibility ($p=0.03$). Similarly, a significant difference was observed between pre- and post-intervention flexibility in pooled data from 8 short-term chronic intervention studies ($p<0.001$).

Vibration difference

On stratification by vibration characteristics, a significant difference was observed between pre- and post-intervention flexibility using WBV (SMD=-0.90, 95%CI=-1.40-0.31, $p=0.003$), albeit with significant heterogeneity ($\tau^2=0.81$; $\chi^2=56.62$; $df=10$; $I^2=82\%$, $p<0.001$). Sub-group analysis stratified by training period showed no significant difference between pre- and post-single session of intervention (SMD=-0.37, 95%CI=-1.09-0.34, $p=0.30$; Heterogeneity: $\tau^2=0.65$; $\chi^2=27.53$; $df=5$; $I^2=82\%$), whereas a significant difference was observed between pre- and post-short-term intervention (SMD=-1.59, 95%CI=-2.43-0.75, $p<0.001$; Heterogeneity: $\tau^2=0.66$; $\chi^2=15.31$; $df=4$; $I^2=74\%$).

A significant difference was also observed between pre- and post-intervention flexibility using LV (SMD=-0.64, 95%CI=-1.00-0.28, $p<0.001$; Heterogeneity: $\tau^2=0.13$; $\chi^2=14.38$; $I^2=51\%$, $p=0.04$). Sub-group analysis stratified by training period showed a significant difference between pre- and post-single session of intervention (SMD=-0.45, 95%CI=-0.77-0.14, $p<0.001$; Heterogeneity: $\tau^2=0.02$; $\chi^2=4.61$; $df=4$; $I^2=13\%$, $p=0.33$), and a significant difference was similarly observed between pre- and post-short-term intervention using LV (SMD=-1.01, 95%CI=-1.89-0.13, $p=0.03$; Heterogeneity: $\tau^2=0.43$; $\chi^2=7.17$; $df=2$; $I^2=72\%$).

Type of exercise

On stratification by type of exercise, a significant difference was observed between pre- and post-stretching flexibility on exercise with vibration (SMD=-0.94, 95%CI=-1.61-0.27, $p=0.006$; Heterogeneity: $\tau^2=0.87$; $\chi^2=50.26$; $df=8$; $I^2=84\%$, $p<0.001$). Sub-group analysis stratified by training period showed no significant difference between pre- and post-single session stretching exercise with vibration (SMD=-0.58, 95%CI=-1.52-0.36, $p=0.23$; Heterogeneity: $\tau^2=0.99$; $\chi^2=29.78$; $df=4$; $I^2=87\%$), whereas a significant difference was observed between pre- and post-short-term intervention using vibration (SMD=-1.40, 95%CI=-2.40-0.40, $p=0.006$; Heterogeneity: $\tau^2=0.84$; $\chi^2=16.11$; $df=3$; $I^2=81\%$).

A significant difference was observed between pre- and post-intervention using body-weight exercise (SMD=-0.76, 95%CI=-1.36-0.15, $p=0.01$; Heterogeneity: $\tau^2=0.47$; $\chi^2=21.78$; $df=6$; $I^2=72\%$, $p=0.001$). Sub-group analysis stratified by training period showed no significant difference between pre- and post-single session body-weight exercise with vibration (SMD=-0.12, 95%CI=-0.58-0.34, $p=0.61$; Heterogeneity: $\tau^2=0.02$; $\chi^2=2.28$; $df=2$; $I^2=12\%$, $p=0.61$). Meanwhile, a significant difference was observed between pre- and post-short-term body-weight exercise with vibration (SMD=-1.31, 95%CI=-2.11-0.51, $p=0.001$; Heterogeneity: $\tau^2=0.43$; $\chi^2=8.86$; $df=3$; $I^2=66\%$).

Additional effects of vibration on flexibility

Pooled data from 13 studies ($n=324$) showed a significantly greater improvement in flexibility in the experimental groups

which used vibration than in those with the identical interventions but without a source of vibration ($p=0.03$) (Figure 3).

For the acute studies, pooled data from nine studies showed no significant difference in flexibility between interventions with or without vibration ($p=0.23$), whereas those from the three short-term chronic studies showed a significant difference ($p=0.05$).

After stratification by vibration characteristics, pooled data from eight WBV studies showed no significant difference in flexibility between interventions with or without WBV (SMD=0.26, 95%CI=-0.01–0.54, $p=0.06$; Heterogeneity: $\chi^2=9.85$; $df=7$; $I^2=29\%$, $p=0.20$). Further, no significant improvement was seen in interventions with and without LV (SMD=0.24, 95%CI=-0.14–0.61, $p=0.22$; Heterogeneity: $\chi^2=1.63$; $df=4$; $I^2=0\%$).

Additionally, significant difference was seen in flexibility in stretching exercises using vibration (SMD=0.33, 95%CI=0.03–0.63, $p=0.03$; Heterogeneity: $\chi^2=9.40$; $df=6$; $I^2=36\%$), whereas no significant difference was found in groups performing body-weight exercises with and without vibration (SMD=0.17, 95%CI=-0.29–0.63, $p=0.47$; Heterogeneity: $\chi^2=0.22$; $df=2$; $I^2=0\%$).

Publication bias

Kendall's τ statistic showed that there was no possibility of publication bias in either the meta-analysis of pre-post comparisons ($r_t=-0.31$; $p=0.07$), or in that of the additive effects of vibration on flexibility ($r_t=0.08$; $p=0.71$).

Discussion

Our evaluation of the risk of bias showed that few articles performed adequate random sequence generation³³ and blinding of outcome assessment^{32,33}. In vibration-based intervention studies, blinding of participants and personnel would not be realistic. However, although most studies included in our meta-analysis showed high reliability, most of the outcome measurements used, such as sit and reach testing, would likely be influenced by a lack of blinding, and it is accordingly necessary to minimize detection bias by measuring flexibility using more objective parameters, such as musculoskeletal stiffness or torque-controlled joint ROM tests. In addition, it is necessary to ensure the absence of a carry-over effect for cross-over trials entered into meta-analysis. Although the effects of a single session of stretching on flexibility would be relatively short and no additional long-term effects were found using diathermy^{38–41}, experiments in most articles in our meta-analysis were performed at an interval of at least 2–3 days. Thus, the carry-over of treatment effect across periods was unlikely, warranting the inclusion of these studies in our meta-analysis.

Evaluation of the quality of our included studies according to the ISMNI recommendations¹⁷ revealed that several factors related to acceleration were not sufficiently documented. First, few studies have measured the actual acceleration of the WBV platform^{25,27,36}. Second, no study has described a method 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 studies⁴², future studies should strictly adhere to these guidelines.

In this meta-analysis, we examined the effects of interventions using vibration on flexibility and the additive effects of vibration on flexibility, which directly compared experimental groups with and without vibration. Taken together, our findings suggest that flexibility increases after interventions using vibration, but that the additive effects of vibration might be small when compared with the same experimental condition without vibration. In sub-group analyses based on intervention period, type of vibration, and type of exercise, no significant effects were observed by type of vibration or exercise, whereas a significant effect was seen in short-term chronic studies. To our knowledge, this is the first systematic review of the effects of vibration-based intervention programs on flexibility.

We observed a significant effect of interventions using vibration on flexibility in pre-post comparison. Although the mechanisms of this effect are not precisely known, previous studies suggest that the improvement in ROM by vibration is associated with the following mechanisms, either alone or combination: suppression of the central nervous system owing to a decrease in motor neuron pool excitability⁴³; decrease in pain sensation^{44,45}; increase in blood flow^{38,46}; relaxation of stretched muscles⁴⁷; inhibition of muscular antagonist mediated by the Golgi tendon organ-Ib afferent neuron pathway⁴⁸; and a decrease in musculoskeletal stiffness^{34,49–51}. The effect size of the combination of stretching exercise and vibration was higher than that of the combination of body-weight exercise in pre-post comparison. Additionally, sub-group analysis by type of exercise revealed a significant difference in stretching exercise studies, but no significant difference in body-weight exercise studies. However, there appears little doubt that that stretching exercise would enhance ROM more effectively than body-weight exercise. Our meta-analysis also suggests that the optimal exercise type of vibration-induced enhancement of flexibility would be stretching exercise rather than body-weight exercise.

A significant additive effect of vibration on flexibility was also found on comparison of interventions which used vibration with the identical intervention without vibration. In their recent meta-analysis comparing heat (ultrasound, diathermy, and hot pack) and stretching with stretching alone, Nakano et al. showed a significantly higher improvement in ROM after stretching with heat compared with stretching alone (acute effect, SMD=1.34, 95% CI=0.13–2.55; long-term effect, SMD=1.74, 95%CI=1.12–2.37)². Because their analysis was limited to studies using stretching exercise², the effect size for the degree of flexibility enhancement would likely be larger than in the present review study. However, comparison by effect size might show that vibration is not superior to other types of exogenous stimulation in augmenting the effect of stretching exercises on flexibility.

Although the great diversity in vibration settings prevented any strict investigation of the influence of vibration parameters on flexibility improvement, we speculate that several vibration

parameters might likely affect this improvement. Based on the descriptive data shown in Table 1, Figure 2 and Figure 3, the time of exposure to vibration would not affect the flexibility improvement. In studies with the WBV device, the use of higher displacement might provide better improvement in flexibility than lower displacement. In contrast, no such trend might be seen in studies with the LV device (Table 2; Figure 3). Although acceleration may be more attenuated through body in WBV than LV, and the difference of rigidity of the vibration plate may also affect the displacement and acceleration generation¹⁷, few studies evaluated the vibration parameters (Table 2). Because the acceleration generated by the vibration device is one of the most salient factors in vibration exercise¹⁷, future studies should evaluate the vibration parameters in a given situation. In addition, the degree of enhancement of muscle contraction by WBV depended on footwear conditions⁵². In the LV studies, in contrast, the vibration source was directly applied to the anterior or posterior thigh muscles^{23,33,34} and Achilles tendon or heels^{26,27,29,30,37}, which meant that vibration displacement was less likely affected by footwear condition. Taken together, although vibration parameters might possibly influence flexibility improvements, the degree of influence might differ by the type of vibration device, i.e. WBV or LV.

Several limitations of the present study warrant mention. First, our meta-analysis included various vibration settings (e.g. vibration device, vibration frequency, vibration amplitude), and included comparisons of aggregate outcomes in flexibility (e.g. mixture of active and passive ROM, examination of different body regions). In addition, participant characteristics differed (e.g. gender, physical fitness level). Second, due to the lack of consistency in methodologies, we were unable to strictly suggest optimal vibration parameters or exercise prescription.

Conclusions

In conclusion, interventions using vibration provide additive effects on flexibility in young healthy individuals. The combination of stretching exercise with vibration enhances enhancement of vibration-induced flexibility compared with the identical exercise without vibration. Future studies should ensure the inclusion of more objective outcomes for detecting mechanisms and minimize potential detection bias. In addition, current understanding of the chronic effects of vibration-based intervention on flexibility is poor, indicating the need for long-term evaluation, particularly by randomized controlled trials.

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