REVIEW ARTICLE

A systematic review of studies investigating the effects of controlled whole-body vibration intervention on peripheral circulation

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Summary

The findings of the published studies investigating the changes in peripheral circulation induced by exposure to whole-body vibration (WBV) are not consensual or conclusive. Also, those studies did not consider the role of vibration magnitude on the peripheral circulatory responses making the interpretation of the observed findings difficult. We aimed to review the published literature investigating the effects of controlled WBV intervention on peripheral circulation by characterizing the relevant exposure conditions including vibration magnitudes, and ascertain the specific patterns of responses in peripheral circulation of the lower extremity from such exposure. A computerized search was performed in PubMed and Scopus using selected key search terms, and the relevant data were extracted. The vibration magnitude in the included studies frequently exceeded the limit specified in the International Standard ISO 2631-1 (1997) for such exposure. As observed, exposure to WBV with frequencies ≤30 Hz caused an improvement in peripheral blood flow (BF) and/or skin temperature (ST) of the lower extremity. In contrast, the responses in BF and ST from exposure to WBV of higher frequencies (31 Hz–50 Hz) produced conflicting results. The findings of this review indicate that WBV exposure with relatively lower frequency and magnitude can be safely and effectively used to induce improvements in peripheral circulation. For this purpose, the limits recommended by the ISO 2631-1 (1997) should be considered till safe and effective vibration-related parameters are established.

Introduction

Over the last decades, the training or treatment intervention using whole-body vibration (WBV) device has become increasingly popular in sports clinics, physiotherapy, rehabilitation centres and orthopaedic clinics (Hiroshige *et al.*, 2014). Intervention with WBV is considered to be a relatively safe and easy-to-conduct training modality (Rogan *et al.*, 2017). As reported in the literature, the training or treatment intervention using controlled exposure to WBV device induced various beneficial effects in human body. Exposure of both healthy subjects and patients (with Parkinson's disease, multiple sclerosis, cerebral palsy, stroke, type II diabetes, etc.) to such intervention showed improvements in proprioception, joint position sense, leg balance and gait, increase in bone mineral density, functional mobility and muscle strength, enhancement in muscle oxygenation and peripheral circulation (Ko *et al.*, 2017; Orr, 2015; Robinson *et al.*, 2016). Reduced peripheral circulation caused by peripheral vascular diseases or various clinical disorders as diabetes and rheumatologic diseases poses increased risk for mortality or morbidity, especially, among the elderly with declined ability to control skin blood flow and greater susceptibility and severity in macrovascular and microvascular impairments of the extremities (Mayfield *et al.*, 2001; Tew *et al.*, 2012). Therefore, as a non-invasive therapeutic modality with the potential to improve or restore blood flow, intervention with WBV would be of utmost importance for the subjects with impaired peripheral circulation. Furthermore, such interventions may help in accelerated healing of chronic wounds like pressure injuries or diabetic ulcers, etc (Arashi et al. 2010; Weinheimer-Haus et al. 2014).

Although the positive effects of WBV on human peripheral circulation have been described in the literature, however, the results are not consensual or conclusive yet. From exposure to WBV, a number of studies demonstrated significant improvements in peripheral circulation (Herrero *et al.*, 2011a, 2011b; Johnson *et al.*, 2014; Sañudo *et al.*, 2013), whereas others could not reveal any such beneficial effects (Mitchell et al., 2016; Sonza *et al.*, 2015). The situation has been further complicated by the fact that the useful vibration parameters such as frequency, amplitude and acceleration, etc., relevant to improvements in peripheral circulation have not yet been established making the application of WBV into practices difficult. Furthermore, a number of the published studies reporting beneficial effects of acute and long-term exposures to WBV on peripheral circulation exposed subjects to relatively high intensities or magnitudes of vibration (Lohman *et al.*, 2012; Manimmanakorn *et al.*, 2017; Menéndez *et al.*, 2015). According to the International Standard, ISO 2631-1 (1997), the use of vibration with such high magnitudes may be potentially harmful to the human body. On the other hand, the upper boundary of health risks for a short duration of exposure (<10 min) has been estimated to be at the frequency-weighted acceleration of $6{\cdot}0\ \mathrm{m\ s^{-2}}$ r.m.s. (Griffin, 2004; ISO 2631-1, 1997). Therefore, the use of high magnitudes of vibration exceeding the recommended limit raises concern regarding the safe application of WBV for the desired health benefits (Muir *et al.*, 2013). However, this issue has not been clearly focused or adequately discussed in the literature. Furthermore, there is a severe lack of review studies that focused on the specific patterns of alterations in peripheral circulation induced by exposure to WBV of different frequencies with consideration of the exposure limit specified in ISO 2631-1 (1997) or EU Directive 2002/44/EU (2002). In a relevant systematic review including meta-analysis, Games *et al.* (2015) reported positive and greater influence of WBV on peripheral blood flow at lower frequencies, but the authors did not consider the influence of vibration intensity or magnitude on peripheral circulation making the interpretation of their observed positive effects of WBV on peripheral circulation difficult. A clear understanding of useful vibration-related parameters, especially frequency and magnitude, should help the clinicians and researchers in ensuring safe and effective applications of WBV interventions to human subjects for the mentioned purpose.

Therefore, the purposes of this review study were to characterize the experimental conditions and vibration parameters used in the published studies investigating the effects of controlled WBV intervention on peripheral circulation and ascertain the specific patterns of responses in peripheral circulation of the lower extremity induced by acute and long-term exposure to WBV of different frequencies and magnitudes in light of the recommended limit for such exposure.

Methods

Data sources and search strategy

To identify all relevant papers, a computerized search was performed by two of the reviewers (MHM and KH) independently in 2 online databases: PubMed and Scopus. The latest search was carried out on 8 January 2019. Due to the possibility of limited number of studies published on this topic, no restrictions were applied regarding the study design or intervention period, matching of participants or blinding of participants and researchers. Also, study populations were not restricted based on age, gender, race, level of physical activity and health status. Two groups of key search terms were used in this review: 1. 'whole body vibration' OR 'whole-body vibration'; 2. 'blood flow' OR 'temperature' OR 'peripheral circulation' OR 'circulation' OR 'circulatory' OR 'haemodynamic change'. These terms were searched in PubMed using 'Title/Abstract' and in Scopus using 'Article Title, Abstract, Key words', in combination with the Boolean operator 'AND'.

Selection of studies

The titles and/or abstracts of all articles retrieved from the initial search were extracted and screened for appropriateness by the previous two reviewers independently. Then, the full text of all potentially eligible articles was read and assessed for inclusion in this review. To identify additional relevant studies, the reference list of the retrieved potential studies and other review articles was cross-searched manually. Any disagreements among the two reviewers in the process of study identification and selection were resolved by discussion.

Criteria for study selection

In this review, a study was considered for inclusion regardless of the study design if it met the following eligibility criteria: (i) full-text original article published in a peer-reviewed journal in English; (ii) investigation of the effects of WBV on peripheral blood flow (BF) and/or peripheral skin temperature (ST); (iii) exposure of subjects to vertical WBV from a platform generating sinusoidal vibration; (iv) enrolment of at least one group of subjects with exposure to WBV not combined with other form of exercise or interventions like localized or passive vibration, massage or electric stimulation; (v) comparison of results from the vibration exposure condition with a condition without exposure to it; and (vi) reporting of the quantitative changes in parameter/s related to peripheral BF and/or ST induced by exposure to WBV. The exclusion criteria adopted in this review were as follows: (i) exposure to vibration not transmitted vertically to the body and not fulfilling the above-mentioned criteria for active WBV; (ii) duplicate publication; (iii) ongoing/unpublished study; and (iv) review article.

Data extraction

All data used in this review were extracted from the information provided in each of the published articles selected finally for this review. A data extraction form was created and finalized by all the study authors. It included necessary information related to the study and subject characteristics, characteristics of vibration intervention and measurement conditions, and observed changes in peripheral circulation reported in a study. Relevant data were extracted independently by the same two reviewers (MHM and KH) using this form. Any disagreements among the reviewers were resolved by consensus.

Data synthesis and results

We synthesized data from all of the selected studies regardless of their methodological quality. However, there was considerable heterogeneity between the studies in terms of populations studied (healthy or patient), vibration exposure parameters (exposure method, type of vibration, vibration frequency and magnitude) and measured parameters for responses in peripheral circulation, etc. Therefore, the pooled estimates for the effects of WBV exposure on peripheral circulation could not be calculated, and hence, descriptive statistics of the extracted data have been presented in this systematic review. The knee flexion angle during exposure to WBV was calculated from the anatomical neutral (considering the fully extended knee as 0°). In this review, we used the term peak-to-peak displacement (PPD) as the displacement from the lowest to the highest point and amplitude as the maximum displacement from the equilibrium, that is amplitude = 1/2 PPD (Rauch *et al.*, 2010). For each study, we reported the PPD value using the relevant available information in the respective studies. Due to the ambiguity in reporting of PPD and/or amplitude values among studies, we considered the reported relevant values as PPD, if the following terms or words were included while describing those values for characterizing WBV in the original paper: (i) PPD, (ii) peak-to-peak amplitude, (iii) peak-to-peak, (iv) peak-peak or (v) relatively high values of amplitude or displacement that included a value ≥5 mm. All other values reported as the amplitude or displacement (<5 mm) for the generated WBV were considered as amplitudes (half of PPD). We converted the reported acceleration values by the study authors expressed as 'g' into m s^{-2} (1 g = 9·81 m s^{-2}). Furthermore, the magnitude of WBV was represented by the vibration acceleration values. The unweighted peak acceleration was estimated using the following formula: peak acceleration (in m s^{-2}) = $2 \times \pi^2 \times f^2 \times D$, where f is the frequency in Hz and D is the PPD expressed in meters (Rauch et al. 2010). The root-mean-squared acceleration was obtained by dividing the unweighted peak acceleration value by $\sqrt{2}$. We then calculated the frequency-weighted acceleration in accordance with the table for 'Principal frequency weightings in one third octaves' (ISO 2631-1, 1997). Also, as suggested in the international standard ISO 2631-1 (1997), we calculated the daily vibration exposure normalized to a reference period of 8 h, termed as A(8), as follows: $A(8) = a_{wz}\sqrt{\frac{T_{exp}}{T_0}}$, where a_{wz} is the frequency-weighted r.m.s. acceleration in vertical direction, T_{exp} is the exposure time (h), and T_0 is the reference duration of 8 h.

Results

Search summary

Initial electronic search resulted in a total of 73 articles from PubMed and 148 articles from Scopus. After removing the duplicates (n = 67), the titles and/or abstracts of a total of 154 articles were screened, and among those, 22 potentially relevant articles could be identified as potentially eligible for further consideration. The studies were excluded because quantitative measurement of peripheral circulation of the lower extremity was not performed by the study authors or the studies did not expose participants to WBV as defined in our study, or the studies were not human experiments or original/peer-reviewed articles. Review of the full text of those 22 studies yielded 17 articles that met the selection criteria and were included in the final review: Games & Sefton (2013), Hazell *et al.* (2008), Herrero *et al.* (2011a, 2011b), Johnson *et al.* (2014), Kerschan-Schindl *et al.* (2001), Lohman *et al.* (2012), Lohman *et al.* (2011), Lohman *et al.* (2007), Lythgo *et al.* (2009), Manimmanakorn *et al.* (2017), Menéndez *et al.* (2015), Mitchell *et al.* (2016), Robbins *et al.* (2014), Sañudo *et al.* (2013), Seixas *et al.* (2012) and Sonza *et al.* (2015). Further examination of bibliographies and relevant review articles did not yield any more articles. Figure 1 shows the PRISMA flow diagram of studies considered for the current review.

Description of included studies

Among the included studies (n = 17), the majority (n = 13) were quasi-experimental and the rest 4 (Lohman *et al.*, 2007; Manimmanakorn *et al.*, 2017; Sañudo *et al.*, 2013; Seixas *et al.*, 2012) were randomized controlled trials (RCTs). The studies were published between 2001 and 2017 (Table 1). In those studies, 8 to 45 subjects were evaluated. The mean age of the participants ranged between 20·8 ± 1·1 and 72·0 ± 8·0 years. There was a predominance of male subjects in the studies.

Characteristics of vibration intervention methods

The methods for vibration intervention are depicted in Table 1. Two types of sinusoidal vibration were used in the studies: vertical vibration in nine studies (Games & Sefton,

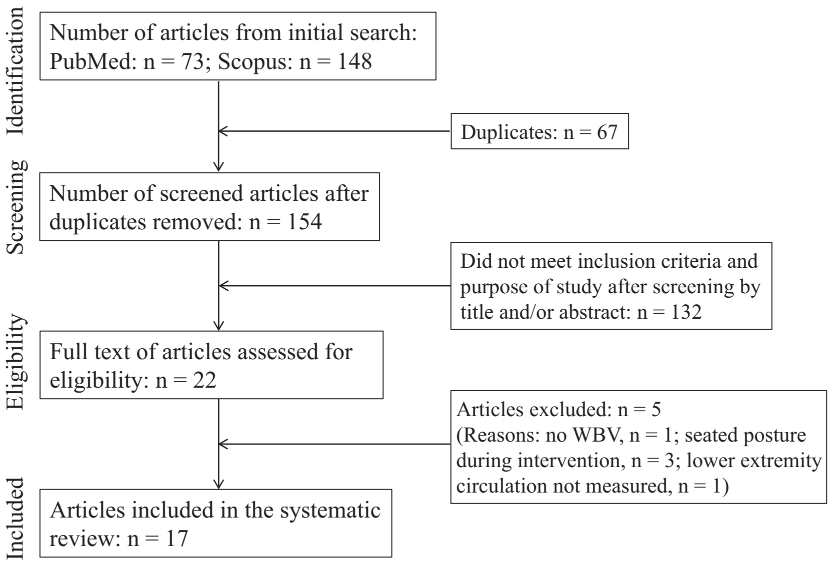

Figure 1 Search and selection of eligible studies (adapted from PRISMA 2009 flow diagram).

2013; Hazell *et al.*, 2008; Lohman *et al.*, 2012; Lohman *et al.*, 2011; Lohman *et al.*, 2007; Manimmanakorn *et al.*, 2017; Robbins *et al.*, 2014; Seixas *et al.*, 2012; Sonza *et al.*, 2015) and side-alternating vibration in seven studies (Herrero *et al.*, 2011a, 2011b; Johnson *et al.*, 2014; Kerschan-Schindl *et al.*, 2001; Lythgo *et al.*, 2009; Menéndez *et al.*, 2015; Sañudo *et al.*, 2013). This information was not reported in the study by Mitchell et al. (2016). During interventions, the subjects stood on the vibrating platform in all studies except the studies by Herrero et al. (2011a, 2011b) where the subjects laid down and were fixed on a tilt (45°) table to receive the vibration in the vertical direction from a leaned device.

No study reported the precise feet position (e.g. distance from the centre) in relation to the platform. Nine studies did not report the distance between the feet on the vibrating platform (Hazell *et al.*, 2008; Johnson *et al.*, 2014; Kerschan-Schindl *et al.*, 2001; Lohman *et al.*, 2012; Lohman *et al.*, 2011; Manimmanakorn *et al.*, 2017; Mitchell *et al.*, 2016; Robbins *et al.*, 2014; Sañudo *et al.*, 2013). Four studies did not report the information on the use of footwear (Hazell *et al.*, 2008; Lohman *et al.*, 2007; Mitchell *et al.*, 2016; Sañudo *et al.*, 2013). Other studies performed the intervention barefoot (Kerschan-Schindl *et al.*, 2001; Lohman *et al.*, 2012; Lohman *et al.*, 2011; Lythgo *et al.*, 2009; Robbins *et al.*, 2014; Seixas *et al.* 2012; Sonza *et al.*, 2015), or wearing shoes (Herrero *et al.*, 2011a, 2011b; Johnson *et al.*, 2014; Manimmanakorn *et al.*, 2017; Menéndez *et al.*, 2015) or socks (Games & Sefton, 2013).

In majority of the studies, the participants were positioned on the vibration platform with knees bent (considering fully extended knees as 0°) to various degrees that differed widely between studies; the knees were flexed slightly or at an angle ranging between 10 and 125° (Table 1). Two studies exposed subjects to vertical WBV while lying supine and fixed on a tilt (45°) table with a knee flexion angle of 60° (Herrero *et al.*, 2011a, 2011b). On the other hand, 3 studies exposed subjects to WBV while standing with straight legs only on the platform (Lohman *et al.*, 2012; Lohman *et al.*, 2011; Robbins *et al.*, 2014).

WBV intervention protocols

A summary of the vibration intervention protocols is shown in Table 2. Among the studies, there was a wide variation in the number of exposure sessions and duration. The total number of intervention sessions ranged from 1 to 36 sessions with a single session comprising a single or multiple (up to 15) bouts of exposure. For a single-bout only session, the exposure time ranged between 3 min (Herrero *et al.*, 2011a) and 15 min (Sonza *et al.*, 2015), and for a session with multiple (up to 15) WBV bouts, between 30 s (Johnson *et al.*, 2014) and 3 min (Kerschan-Schindl *et al.*, 2001) with a rest period of 2 s (Lohman *et al.*, 2012) to 2 min (Lythgo *et al.*, 2009) between the intermittent bouts. The overall duration of intervention varied between 1 to 4 days for acute exposure and the latter reflect different types of interventions on different days. The duration for long-term intervention ranged from 2 weeks (Mitchell *et al.*, 2016) to 12 weeks (Manimmanakorn *et al.*, 2017; Sañudo *et al.*, 2013) with an intervention frequency of three times per week in those studies.

The vibration stimulus frequency across the included studies varied between 5 Hz and 50 Hz among which exposure to the frequencies ≤30 Hz was used in nine studies (Herrero *et al.*, 2011a, 2011b; Johnson *et al.*, 2014; Kerschan-Schindl *et al.*, 2001; Lohman *et al.*, 2007; Lythgo *et al.*, 2009; Menéndez *et al.*, 2015; Mitchell *et al.*, 2016; Sañudo *et al.*, 2013), and between 31 and 50 Hz, in eight studies (Games & Sefton, 2013; Hazell *et al.*, 2008; Lohman *et al.*, 2012; Lohman *et al.*, 2011; Manimmanakorn *et al.*, 2017; Robbins *et al.*, 2014; Seixas *et al.*, 2012; Sonza *et al.*, 2015) except that the study by

Table 1 Characteristics of subjects and methods for vibration intervention.

		Subject characteristics			Methods for vibration intervention			
Author/s and reference year	Type of study	Patient or healthy	Number	Age in years (Mean ± SD)	Type of sinusoidal vibration	Feet location/ position on platform	Used footwear	Knee flexion angle (°)
Games & Sefton (2013)	Quasi-experimental	Healthy	14 (M, 5; F, 9)	M, 20·8 ± 1·1; F, 21·7 ± 2·4	Vertical	Feet shoulder width apart	Socks	10–15
Hazell *et al.* (2008)	Quasi-experimental	Healthy	8 (all males)	25·0 ± 2·6	Vertical	NR	NR	60 ± 5
Herrero *et al.* (2011a)	Quasi-experimental	Patient (FA)	10 (M, 7; F, 3)	38·1 ± 10·5	Side-alternating	Parallel, 38 cm apart from each other	Shoes	60
Herrero *et al.* (2011b)	Quasi-experimental	Patient (SCI)	8 (M, 6; F, 2)	36·1 ± 5·0	Side-alternating	Parallel, 38 cm apart from each other	Shoes	60
Johnson *et al.* (2014)	Quasi-experimental	Patient (DM)	10 (M, 3; F, 7)	71·0 ± 8·3	Side-alternating	NR	Shoes	30–40
Kerschan-Schindl *et al.* (2001)	Quasi-experimental	Healthy	20 (M, 12; F, 8)	M, 32·7 ± 3·3; F, 28·5 ± 2·2	Side-alternating	NR	Barefoot	0 and 60–70
Lohman *et al.* (2012)	Quasi-experimental	Healthy	10 (M, 7; F, 3)	M, 64·5 ± 7·0; F, 67·0 ± 2·0	Vertical	NR	Barefoot	0
Lohman *et al.* (2011)	Quasi-experimental	Healthy	10 (M, 5; F, 5)	M, 25·6 ± 1·5; F, 25·8 ± 4·1	Vertical	NR	Barefoot	0
Lohman *et al.* (2007)	RCT	Healthy	45 (M, 23; F, 22)	23·9; range, 18–43[a]	Vertical	Middle of the plate (15–20 cm apart)	NR	25, 80, 100
Lythgo *et al.* (2009)	Quasi-experimental	Healthy	9 (all males)	21·8 ± 4·4	Side-alternating	Parallel, 28 or 50 cm apart from each other	Barefoot	50
Manimmanakorn *et al.* (2017)	RCT	Patient (DM)	WBV, 17 (M, 7; F, 10); con, 19 (M, 6; F, 13)	WBV, 60·9 ± 11·2; con, 63·9 ± 4·9	Vertical	NR	Shoes	Slight, 90, 125
Menéndez *et al.* (2015)	Quasi-experimental	Healthy	13 (all males)	21·2 ± 1·5	Side-alternating	Parallel, 38 cm apart from each other	Shoes	30
Mitchell *et al.* (2016)	Quasi-experimental	Patient (RLS)	WBV, 11 (M, 7; F, 4); Con, 11 (M, 7; F, 4)	WBV, 54·7 ± 12·4; con, 53·6 ± 10·4	NR	NR	NR	40
Robbins *et al.* (2014)	Quasi-experimental	Healthy	20 (17 in analysis) (M, 12; F, 8)	24·0 ± 3·0	Vertical	NR	Barefoot	0
Sañudo *et al.* (2013)	RCT	Patient (DM)	WBV, 20 (M, 11; F, 9); con, 20 (M, 10; F, 10)	WBV, 72·0 ± 8·0; con, 67·0 ± 11·0	Side-alternating	NR	NR	80
Seixas *et al.* (2012)	RCT	Healthy	WBV, 12 (all males); Con, 12 (all males)	WBV, 26·3 ± 1·1; con, 23·4 ± 4·2	Vertical	Feet shoulder width apart	Barefoot	45
Sonza *et al.* (2015)	Quasi-experimental	Healthy	24 (M, 11; F, 13)	26·4 ± 4·1	Vertical	Feet shoulder width apart	Barefoot	20

Con, control group; DM, diabetes mellitus; F, females; FA, Friedreich's ataxia; M, males; NR, not reported; RCT, randomized controlled trial; RLS, restless leg syndrome/Willis-Ekbom disease; SCI, spinal cord injury; WBV, whole-body vibration group.
[a]SD (standard deviation) not reported.

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Table 2 Characteristics of WBV intervention sessions and vibration-related parameters.

	Characteristics of WBV intervention					Characteristics of vibration parameters						
	Single session on a day			Total session/s					Peak acceleration			
										Calculated		
Author/s and reference year	Number of bouts	Duration of each bout	Rest between bouts (s)	Number	Frequency	Frequency (Hz)	Reported term for displacement	Considered PPD (mm)	Reported ($m\ s^{-2}$)	Unweighted ($m\ s^{2}$)	Weighted ($m\ s^{-2}$ r.m.s.)	Peak A(8) ($m\ s^{-2}$ r.m.s.)
Games & efton (2013)	5	1 min	10 s	2	1/day	50	PPD2 mm	2	NR	98·60	17·15	1·75
Hazell et al. (2008)	15	1 min	1 min	2 (1 for each of 2 interventions)	1/day	45	Amplitude 2 mm	4	NR	159·73	27·79	4·91
Herrero et al. (2011a)	a) 1 b) 3	a) 3 min b) 1 min	– 1 min	6 (1 for each of 6 interventions)	1/day	10, 20, 30	Peak to peak 5 mm	5	NR	9·86, 39·44, 88·74	6·89, 17·74, 25·42	0·54, 1·40, 2·01
Herrero et al. (2011b)	a) 1 b) 3	a) 3 min b) 1 min	– 1 min	6 (1 for each of 6 interventions)	1/day	10, 20, 30	Peak–peak 5 mm	5	NR	9·86, 39·44, 88·74	6·89, 17·74, 25·42	0·54, 1·40, 2·01
Johnson et al. (2014)	10	30 s	1 min	2 (1 for each of 2 interventions)	1/day	26	Amplitude 2 mm	4	NR	53·32	19·34	1·97
Kerschan-Schindl et al. (2001)	3	3	No	1	–	26	Amplitude 3 mm	6	78·0	79·98	29·02	3·97
Lohman et al. (2012)	10	1 min	2 s	6	2/day	50	Displacement 5–6 mm	5–6	NR	246·49–295·79	42·88–51·46	6·19–7·43
Lohman et al. (2011)	10	1 min	NR	6	2/day	50	Amplitude 5–6 mm	5–6	62·4	246·49–295·79	42·88–51·46	6·19–7·43
Lohman et al. (2007)	3	1 min	No or 10 s	3 (1 for each of 3 interventions)	1 for each intervention	30	Amplitude 5–6 mm	5–6	68·67[b]	88·74–106·48	25·42–30·50	2·01–2·41
Lythgo et al. (2009)	14 (12 vib and 2 no-vib)	1 min	2 min	1	–	5–30[a]	Amplitude 2·5 and 4·5 mm	5, 9	9·91, 10·50[b]	2·46-159·73	1·81–45·75	0·29–7·23
Manimmanakorn et al. (2017)	6 (2 sets)	1 min	20 s	36	3/week for 12 weeks	30–40	Amplitude 2–4 mm	4–8	14·03 –72·01[b]	70·99–252·41	20·33–56·05	3·21–8·86
Menéndez et al. (2015)	10	1 min	1 min	4 (1 for each of 4 interventions)	1/day	26	PPA 5 mm	5	66·7	66·65	24·18	3·49
Mitchell et al. (2016)	10	30 s	1 min	6	3/week for 2 weeks	26	Amplitude 2 mm	4	NR	53·32	19·34	1·97
Robbins et al. (2014)	5	1 min	1 min	2 (1 for each of 2 interventions)	1/day	40	Displacement 1·9 mm	3·8	NR	119·89	26·62	2·72
Sañudo et al. (2013)	(Total 12–20 min)	30–60 s	30 s	36	3/week for 12 weeks	12–16	PPD 4 mm	4	NR	11·36–20·19	7·25–10·97	1·15–2·24

(continued)

Table 2 (continued)

Author/s and reference year	Characteristics of WBV intervention: Single session on a day: Number of bouts	Duration of each bout	Rest between bouts (s)	Total session/s: Number	Frequency	Characteristics of vibration parameters: Frequency (Hz)	Reported term for displacement	Considered PPD (mm)	Peak acceleration: Reported ($m s^{-2}$)	Calculated: Unweighted ($m s^2$)	Weighted ($m s^{-2}$ r.m.s.)	Peak A(8) ($m s^{-2}$ r.m.s.)
Seixas *et al.* (2012)	1	5 min	–	2 (1 for each of 2 interventions)	2/day	35	Amplitude 5–6 mm	5–6	NR	120·78–144·94	34·59–41·51	3·53–4·24
Sonza *et al.* (2015)	1	15 min	–	4 (1 for each of 4 interventions)	1/day	31, 35, 40, 44	PPA 1 mm	1	NR	18·95, 24·16, 31·55, 38·18	5·43, 6·92, 7·01, 8·48	0·96, 1·22, 1·24, 1·50

NR, not reported; PBD, peak-to-base displacement; PPA, peak-to-peak amplitude; PPD, peak-to-peak displacement.
[a]Results analyzed for each 1-min bout of vibration at different frequency separately.
[b]Reported acceleration in 'g' was converted into $m s^{-2}$ (1 g = 9·81 $m s^{-2}$).

Manimmanakorn *et al.* (2017) also used the vibration frequency of 30 Hz (Table 2). The reported and/or calculated PPD in those studies varied from 1 to 6 mm. However, ambiguous and inconsistent terms have been used by the researchers to describe the PPD or amplitude of the WBV device used in the respective studies. For example, diversified terms such as 'displacement' (Lohman *et al.*, 2012; Robbins *et al.*, 2014), 'peak-to-peak' (Herrero *et al.*, 2011a) or 'peak-peak' (Herrero *et al.*, 2011b), 'amplitude'/'peak-to-base displacement' (Lythgo *et al.*, 2009), 'peak-to-peak amplitude' (Sonza *et al.*, 2015), etc., have been reported by the authors. For the included studies, we calculated the unweighted vibration acceleration level widely ranging between 2·46 $m s^{-2}$ r.m.s. (Lythgo *et al.*, 2009) and 295·79 (Lohman *et al.*, 2012; Lohman *et al.*, 2011) $m s^{-2}$ r.m.s. Among these studies, only 6 studies reported own-calculated peak acceleration level for the applied vibration (Kerschan-Schindl *et al.*, 2001; Lohman *et al.*, 2011; Lohman *et al.*, 2007; Lythgo *et al.*, 2009; Manimmanakorn *et al.*, 2017; Menéndez et al., 2015); we observed a large discrepancy between the levels of the reported vibration acceleration and our calculated vibration acceleration for those studies except the studies by Kerschan-Schindl *et al.* (2001) and Menéndez et al. (2015). Furthermore, no study except the one by Lythgo *et al.* (2009) reported the locations for the measurement of vibration acceleration which were between the teeth, and at the right upper thigh.

The calculated frequency-weighted acceleration in the included studies ranged between 1·81 (Lythgo *et al.* 2009) and 56·05 (Manimmanakorn *et al.*, 2017) $m s^{-2}$ r.m.s., and the corresponding calculated A(8) values ranged between 0·29 and 8·86 $m s^{-2}$ r.m.s. (Table 2). As observed, majority of the studies with exposure of subjects to a short duration of WBV in a single session on any day used a frequency-weighted acceleration far exceeding the value of 6·0 $m s^{-2}$ r.m.s. (Griffin, 2004; ISO 2631-1, 1997). The higher frequencies of vibration used in the included studies were generally accompanied by higher values of A(8).

Experimental room temperature and measurement of peripheral circulation

Only 7 studies reported the experiment room temperature which ranged between 21 and 25°C (Hazell *et al.*, 2008; Lohman *et al.*, 2012; Lohman *et al.*, 2011; Lohman *et al.*, 2007; Manimmanakorn *et al.*, 2017; Seixas *et al.*, 2012; Sonza *et al.*, 2015). An adaptation period of 5 (Lythgo *et al.* 2009) to 35 (Hazell *et al.*, 2008) min was reported before the baseline measurements of peripheral circulation (Table 3).

Among the studies included in the review, majority (n = 14) measured the parameters related to peripheral BF without or with peripheral ST, and three studies (Games & Sefton, 2013; Seixas *et al.*, 2012; Sonza *et al.*, 2015) assessed ST only as the peripheral circulatory outcome. While BF was measured both after acute (n = 11) and long-term exposure (n = 3) to WBV, ST was investigated in the studies

Table 3 Characteristics of peripheral BF and ST measurement conditions and methods in the included studies.

	Measurement room temperature		Characteristics of measurements for peripheral circulation			
			Blood flow (BF)		Skin temperature (ST)	
Author/s and reference year	(°C)	Adaptation period (min)	Method	Location	Method	Location
Games & Sefton (2013)	NR	20	–	–	DIRT	Gastrocnemius (medial head)
Hazell *et al.* (2008)	21·2 ± 0·5	25–35	DUS	Common femoral artery	Temperature probe	Above left lateral malleolus
Herrero *et al.* (2011a)	NR	10	DUS	Upper thigh (right)	–	–
Herrero *et al.* (2011b)	NR	10	DUS	Upper thigh (right)	–	–
Johnson *et al.* (2014)	NR	10 to 15	LDI	Dorsum of foot (right)	–	–
Kerschan-Schindl *et al.* (2001)	NR	NR	DUS	Popliteal artery	–	–
Lohman *et al.* (2012)	22–24	NR	LDF	Posterior calf	Thermistor	Medial Calf
Lohman *et al.* (2011)	22·2–23·9	10	LDF	Middle of gastrocnemius muscle	Thermistor	Within 2 cm of Doppler probe
Lohman *et al.* (2007)	22–24	10	LDI	Distal lower leg (right)	–	–
Lythgo *et al.* (2009)	NR	5	DUS	Common femoral artery (right)	–	–
Manimmanakorn *et al.* (2017)	25	15	DUS	Mid-popliteal fossa (right)	–	–
Menéndez *et al.* (2015)	NR	10	DUS	Popliteal fossa (right)	IT	Gastrocnemius (left)
Mitchell *et al.* (2016)	NR	NR	LDI	Dorsum of foot (right)	–	–
Robbins *et al.* (2014)	NR	10	LDF	Dorsum of foot	Thermocouple probes	Upper leg and foot
Sañudo *et al.* (2013)	NR	5	DUS	Common femoral artery (right)	–	–
Seixas *et al.* (2012)	22·0	15	–	–	Thermography	Thighs, knees, legs, ankles
Sonza *et al.* (2015)	21·0 ± 2·0	20	–	–	IT	Thighs, knees, lower legs, feet (dorsal)

DIRT, dynamic infrared thermography; DUS, Doppler ultrasound; IT, infrared thermography; LDF, laser Doppler flowmetry; LDI, laser Doppler Imaging; NR, not reported.

investigating the effects of acute exposure to the latter. In the selected studies, Doppler ultrasound (DUS) or laser Doppler Imaging (LDI) was commonly used for the assessment of BF, and infrared thermography (IT) or thermistor probe was the commonly used modality for the measurement of ST (Table 3).

Responses in lower extremity peripheral circulation from exposure to WBV

Table 4 shows the observed responses in peripheral circulation induced by WBV intervention in different studies. Out of a total of 17 studies, 11 studies demonstrated an improvement in peripheral circulation as indicated by a clear increase in BF and/or ST induced by acute (Games and Sefton, 2013; Hazell *et al.*, 2008; Herrero *et al.*, 2011a, 2011b; Johnson *et al.*, 2014; Kerschan-Schindl *et al.*, 2001; Lohman *et al.*, 2007; Lythgo *et al.*, 2009; Menéndez *et al.*, 2015; Robbins *et al.*, 2014; Sañudo *et al.*, 2013) and long-term exposure (Sañudo *et al.*, 2013) to WBV. Seven out of those 11 studies exposed subjects to WBV from a side-alternating vibration platform producing vertical vibration (Herrero *et al.*, 2011a, 2011b; Johnson et al., 2014; Kerschan-Schindl *et al.*, 2001; Lythgo *et al.*, 2009; Menéndez *et al.*, 2015; Sañudo *et al.*, 2013) while the rest 4 studies, to vertical synchronous vibration. On the other hand, the studies that showed no clear change or a decrease in BF and/or ST exposed subjects to vertical synchronous vibration (Lohman *et al.*, 2012; Lohman *et al.*, 2011; Manimmanakorn *et al.*, 2017; Seixas *et al.*, 2012; Sonza *et al.*, 2015; excluding the study by Mitchell *et al.*, 2016 that did not report the type of vibration).

In general, compared with corresponding control or baseline conditions, an improvement in BF was observed after acute exposure to WBV when the exposure frequency was ≤30 Hz (Herrero *et al.*, 2011a, 2011b; Johnson *et al.*, 2014; Kerschan-Schindl *et al.*, 2001; Lohman *et al.*, 2007; Lythgo *et al.*, 2009; Menéndez *et al.*, 2015). Overall, the studies with acute exposure of subjects to vibration frequencies between 20 Hz and 30 Hz produced more increase in peripheral circulation compared with other lower exposure frequencies (Herrero *et al.*, 2011a, 2011b; Lythgo *et al.*, 2009; Menéndez *et al.*, 2015). These studies showing a significant positive effect of acute exposure to WBV in increasing peripheral circulation, used a frequency-weighted acceleration of vibration ranging between 1·81 and 45·75 m s^{-2} r.m.s. and an A(8) value, ranging between 0·29 and 7·23 m s^{-2} r.m.s. Also, among these studies, three studies exposed subjects to WBV with a relatively lower values of A(8) near to lower than 2·0 m s^{-2} r.m.s. (Herrero *et al.*, 2011a, 2011b; Johnson *et al.*, 2014). On the other hand, acute exposure to WBV of >30 Hz produced mixed results in peripheral circulation: three studies observed a significant increase in BF or ST when the exposure frequency ranged between 40 and 50 Hz, frequency-weighted acceleration between 17·15 and 27·79 m s^{-2} r.m.s. and the A (8) values, between 1·75 and 4·91 m s^{-2} r.m.s (Games & Sefton, 2013; Hazell *et al.*, 2008; Robbins *et al.*, 2014). In contrast, the studies by Seixas *et al.* (2012) and Sonza *et al.* (2015) observed a significant decrease in ST. In these two studies, the exposure frequency ranged between 31 and 44 Hz, frequency-weighted acceleration between 5·43 and 41·51 m s^{-2} r.m.s. and the A(8) values, between 0·96 and 4·24 m s^{-2} r.m.s. Furthermore, with an exposure frequency of 50 Hz, frequency-weighted accelerations between 42·88 and 51·46 m s^{-2} r.m.s. and A(8) values between 6·19 and 7·43 m s^{-2} r.m.s., two studies by Lohman *et al.* (2011, 2012) could not reveal any significant change either in BF or in ST.

Among the three studies evaluating the effects of long-term exposure (2 weeks to 12 weeks) to WBV displayed mixed results in BF: a significant increase in BF was observed in only 1 study (Sañudo *et al.*, 2013) while the rest two studies (Manimmanakorn *et al.*, 2017; Mitchell *et al.*, 2016) did not observe any significant improvement in it. The study by Sañudo *et al.* (2013) exposed subjects to comparatively low frequencies of vibration (12-16 Hz) with relatively low values of A(8) (ranging between 1·15 and 2·24 m s^{-2} r.m.s.). It is noteworthy here that none of these 3 studies evaluating the effects of long-term exposure of WBV on peripheral circulation reported the exact time points of after-intervention measurements for the latter.

Discussion

Intervention with WBV is considered to be a safe, easy to perform and well-tolerated training modality which involves minimal active movement by the participant, and may be especially useful as a rehabilitation modality for the elderly and immobile patients who are unable to perform conventional exercise or high impact physical exercise (Brooke-Wavell & Mansfield, 2009; Sonza, 2010). Till now, a large body of literature has been published showing the effects of WBV intervention on human body. Unfortunately, the current literature does not provide an adequate description of the vibration-related parameters and the rationale for those parameters adopted in the published studies making the application of WBV into practices difficult. Our increased understanding on vibration exposure characteristics and corresponding response patterns in peripheral circulation might help to resolve the apparent conflicts present in the existing literature and guide the researchers and clinicians to select the appropriate WBV intervention parameters in inducing improvements in peripheral circulation.

Our findings show that all the studies selected for this review had various methodological limitations which have been summarized in Table 5. As observed in this review, vertical or side-alternating vibration platforms were used for generation of sinusoidal vibration. For the side-alternating vibration platform, variation in the foot position and/or the distance between feet on it can change the intensity of transmitted WBV largely. However, as observed, the precise feet position on the platform has not been reported by the researchers. Furthermore, non-reporting of the use of footwear makes the replication of study results difficult.

A number of included studies used straight knees while exposing subjects to WBV. It has been mentioned that straight posture of subjects on the vibration platform causes enhanced transmission of vibration to the upper body (Kiiski *et al.*, 2008). Such augmentation of vibration transmitted to the head and the spine may be associated with adverse health effects. Brooke-Wavell & Mansfield (2009) suggested that vibration transmitted to the head should be minimized while exposing subjects to WBV. This is partially achieved by slightly bending (semiflexed) knees during exposure (Cardinale & Wakeling, 2005). Future studies should not expose subjects to WBV while standing in upright posture due to potential transmission of high-magnitude vibration to the head.

As observed, the characteristics of WBV intervention including information on vibration exposure frequencies and PPD, number of sessions and duration of each session and overall duration of intervention, etc., used in the studies included in this review varied markedly. To determine the intensity or magnitude of vibration, information on PPD or amplitude and frequency of generated vibration is important. The International Society of Musculoskeletal and Neuronal Interactions (ISMNI) recommended mentioning parameters such as frequency, PPD/amplitude and acceleration level while describing the vibration involving exposure of subjects to WBV (Rauch *et al.*, 2010). However, the terms used to describe PPD or amplitude of vibration differed markedly between the included studies which sometimes appeared to be confusing. Therefore, it is not possible to calculate the peak vibration acceleration level accurately with such vague descriptions of reported vibration amplitude or PPD. Furthermore, as recommended by the ISO 2631-1 (1997), transducers for the measurement of WBV should be located between the feet and the surface of vibration. However, majority of the reviewed studies did not mention the location of measurement of vibration. This situation has been further complicated by the fact that most of the reviewed studies did not mention the peak vibration acceleration level. All these led to the observation of a large discrepancy between the levels of the 'reported vibration acceleration' and our 'calculated vibration acceleration' in some studies. The observed discrepancy, deficiency or inaccuracy in a number of studies in the reported vibration-related parameters would make it difficult or even impossible to replicate the research works.

Table 4 Characteristics of measurements and the specific patterns of responses in peripheral BF and ST induced by exposure to WBV.

Author/s and reference year	Time points for measurements of BF and/or ST	Included parameters for measured BF	Responses in lower extremity circulation induced by WBV intervention	
			BF	ST
Games & Sefton (2013)	At baseline and 0, 5, 10, 15 and 20 min postintervention	–	–	Significant increase at each time point
Hazell *et al.* (2008)	At baseline, during intervention and 10 min following intervention	BF (ml min^{-1})	Significant increase in BF during vibration	Significant increase at several time points during and after vibration
Herrero *et al.* (2011a)	At baseline, at the end of each min during intervention and at each min for 2 min following it	MBV (cm s^{-1}), PBV (cm s^{-1})	Significant increases in MBV and PBV during intervention; greater responses for 30 Hz and continuous vibration conditions	–
Herrero *et al.* (2011b)	At baseline, at the end of each min during intervention and at each min for 2 min following it	MBV (cm s^{-1}), PBV (cm s^{-1})	Significant increases in MBV and PBV during and following (1st min) intervention, particularly at 20 and 30 Hz frequencies	–
Johnson *et al.* (2014)	At baseline, immediately after intervention and after 5 min of recovery	SBF (Flux)	Significant increase immediately after intervention; gradually returned to baseline following intervention	–
Kerschan-Schindl *et al.* (2001)	Before and after exposure	MSV (cm s^{-1}), MDV (cm s^{-1}), MBV (cm s^{-1}), RI	Significant increase in MBV; significant decrease in RI	–
Lohman *et al.* (2012)	Baseline, immediately after intervention and at 10th min following cessation of exposure	SBF (flux)	No significant change under active vibration	No significant change under active vibration
Lohman *et al.* 2011	Baseline, immediately after intervention and at 9th min following cessation of exposure	SBF (flux)	No significant change under active vibration	No significant change under active vibration
Lohman *et al.* (2007)	Baseline, immediately after intervention and at 10th min following cessation of exposure	SBF (flux)	Significant increase at both measurement time points	–
Lythgo *et al.* (2009)	At baseline, during intervention and for 2 min following intervention	MBV (cm s^{-1}), PBV (cm s^{-1})	Significant increases in MBV (10–30 Hz) & PBV (20–30 Hz) during and immediately after intervention	–
Manimmanakorn *et al.* (2017)	At baseline and after 12 weeks	PSV (cm s^{-1}), EDV (cm s^{-1})	Non-significant trend in reduction of PSV; significant reduction in EDV (compared to baseline values)	–
Menéndez *et al.* (2015)	At baseline, at rests during intervention and at each min for 5 min following intervention	MBV (cm s^{-1}), PBV (cm s^{-1})	Significant increase in MBV and PBV during intervention	No significant change

(continued)

Table 4 (continued)

Author/s and reference year	Time points for measurements of BF and/or ST	Included parameters for measured BF	Responses in lower extremity circulation induced by WBV intervention	
			BF	ST
Mitchell *et al.* (2016)	At baseline and 2 weeks (after completion) of intervention	SBF (flux)	No increase in resting SBF after completion of intervention	–
Robbins *et al.* (2014)	At baseline, at rests during interventions and at each min for 5 min following intervention	BFV (cm s^{-1})	Significant increase in MBV during first 3 min of intervention	No significant change
Sañudo *et al.* (2013)	At baseline and after 12 weeks	BF (ml min^{-1}), MSV (cm s^{-1}), MDV (cm s^{-1}), PI, RI	Significant increases in BF and MDV	–
Seixas *et al.* (2012)	Before and immediately after exposure	–	–	Significant decrease at thighs and knees
Sonza *et al.* (2015)	At each min during 15 min of intervention and 10 min following intervention	–	–	Significant decrease during and after vibration

BF, blood flow; BFV, blood flow velocity; DV, maximum diastolic velocity; EDV, end-diastolic velocity; MBV, mean blood velocity; MDV, maximum diastolic velocity; MSV, maximum systolic velocity; PBV, peak blood velocity; PI, pulsatility index; PSV, peak systolic velocity; RI, resistance/resistive index; SBF, skin blood flow; ST, skin temperature.

It has been mentioned that regular long-term exposure to WBV is considered to be a health risk and can cause low back pain, sciatic pain and degenerative changes in the spine (Kiiski *et al.*, 2008). Even exposure to WBV for short durations should be treated with extreme cautions (ISO 2631-1, 1997/Amd.1:2010). Also, the International Standard ISO 2631-1 (1997) suggests that subjects should not be exposed to high levels of vibration during experiments involving human exposure to vibration and shock. In this context, ISO 2631-1 (1997) suggested a health guidance caution zone with values of its upper and lower boundaries for exposure to WBV. As mentioned in the standard, health risks are likely above this caution zone. For exposures between 1 min and 10 min (the exposure period commonly being used for exposure to devices producing WBV), the upper boundary of the caution zone is assumed to be at the frequency-weighted acceleration of 6·0 m s^{-2} r.m.s. and the lower boundary at 3·0 m s^{-2} r.m.s. (Griffin, 2004). As observed in this review, most of the studies exposed subjects to WBV with frequency-weighted accelerations far exceeding the value of 6·0 m s^{-2} r.m.s. In this regard, the European Union, 2002/44/EU (2002) has set the norms for exposure to WBV. According to this EU Directive, people regularly exposed to WBV at workplaces should not be exposed to a vibration exceeding an A(8) value of 1·15 m s^{-2} r.m.s. It can be argued that ISO health guidelines or the EU Directive on exposure with WBV were developed to assess the effects of chronic exposure of healthy individuals to WBV regularly and may not be applicable for assessment of adverse health effects from infrequent WBV training (Abercromby *et al.*, 2007). However, exposure to WBV in exercise and rehabilitation therapy would need long-term chronic exposure to it. It has been mentioned that with some commercially available WBV training platforms, while using the highest magnitude settings, above-mentioned A(8) limit can be exceeded in a period of less than 5 min (Brooke-Wavell & Mansfield, 2009). Considering all these and the fact that even brief exposure to high levels of WBV may be extremely dangerous to various physiologic systems (Muir *et al.*, 2013), the researchers should design a WBV training protocol considering the potential health risks and benefits from such exposure. Furthermore, the available research works involving human exposure to WBV did not consider or discuss the recommendations of the international standard or the European standard for such exposure. Rather, a good number of studies exposed the experimental subjects to higher level of WBV far exceeding the recommended limit of A(8) 1·15 m s^{-2} r.m.s. For example, the calculated A(8) values in the study of Lohman et al. (2012) were 6·19–7·43 m s^{-2} r.m.s. Manimmanakorn et al. (2017) was 3·21–8·86 m s^{-2} r.m.s. and Hazell et al. (2008) was 4·91 m s^{-2} r.m.s. In this context, Kiiski *et al.* (2008) suggested that the studies involving WBV intervention should adopt the safety limits mentioned in ISO 2631-1 (1997) as a guideline in determining vibration frequency, amplitude and the duration applicable for a single session in any intervention involving vibration.

Table 5 Summary of limitations of the reviewed studies.

Author/s and reference year	Limitations
Games & Sefton (2013)	No information on measurement method or value of peak acceleration; calculated peak acceleration exceeded recommended limit; and information on measurement of room temperature not provided.
Hazell *et al.* (2008)	Distance between feet on vibration platform not reported; no information on footwear; no information on measurement method or value of peak acceleration; and calculated peak acceleration largely exceeded recommended limit.
Herrero *et al.* (2011a)	Precise feet position on side-alternating vibration platform not reported; lacking accurate description of PPD; no information on measurement method or value of peak acceleration; WBV exposure included peak acceleration exceeding recommended limit; and information on measurement room temperature not provided.
Herrero *et al.* (2011b)	No clear statement for ethical approval; precise feet position on side-alternating vibration platform not reported; lacking accurate description of PPD; no information on measurement method or value of peak acceleration; WBV exposure included peak acceleration exceeding recommended limit; and information on measurement room temperature not provided.
Johnson *et al.* (2014)	Precise feet position on side-alternating vibration platform not reported; no information on measurement method or value of peak acceleration; calculated peak acceleration exceeded recommended limit; and information on measurement room temperature not provided.
Kerschan-Schindl *et al.* (2001)	No statement for ethical approval; precise feet position on side-alternating vibration platform not reported; exposure included straight knee condition; no information on location of vibration acceleration measurement; calculated peak acceleration largely exceeded recommended limit; information on measurement room temperature not provided; and no information on adaptation period.
Lohman *et al.* (2012)	Distance between feet on vibration platform not reported; exposure with straight knees; lacking accurate description of PPD; no information on measurement method or value of peak acceleration; calculated peak acceleration largely exceeded recommended limit; and no information on adaptation period.
Lohman *et al.* (2011)	Distance between feet on vibration platform not reported; exposure with straight knees; no information on location of vibration acceleration measurement; and calculated peak acceleration largely exceeded recommended limit.
Lohman *et al.* (2007)	No information on footwear; no information on location of vibration acceleration measurement; and calculated peak acceleration exceeded recommended limit.
Lythgo *et al.* (2009)	Precise feet position on side-alternating vibration platform not reported; WBV exposure included peak acceleration largely exceeding recommended limit; and information on measurement room temperature not provided.
Manimmanakorn *et al.* (2017)	Distance between feet on vibration platform not reported; no information on location of vibration acceleration measurement; calculated peak acceleration largely exceeded recommended limit; and exact time points of after-intervention measurements not stated.
Menéndez *et al.* (2015)	Precise feet position on side-alternating vibration platform not reported; lacking accurate description of PPD; no information on location of vibration acceleration measurement; calculated peak acceleration largely exceeded recommended limit; and information on measurement room temperature not provided.
Mitchell *et al.* (2016)	Type of vibration platform and precise feet position on it not reported; no information on footwear; no information on measurement method or value of peak acceleration; calculated peak acceleration exceeded recommended limit; information on measurement room temperature not provided; no information on adaptation period; and exact time points of after-intervention measurements not stated.
Robbins *et al.* (2014)	No clear statement for ethical approval: distance between feet on vibration platform not reported; exposure with straight knees; lacking accurate description of PPD; no information on measurement method or value of peak acceleration; calculated peak acceleration exceeded recommended limit; and information on measurement room temperature not provided.
Sañudo *et al.* (2013)	Precise feet position on side-alternating vibration platform not reported; no information on footwear; no information on measurement method or value of peak acceleration; calculated peak acceleration exceeded recommended limit; information on measurement room temperature not provided; and exact time points of after-intervention measurements not stated.
Seixas *et al.* (2012)	No statement for ethical approval; no information on measurement method or value of peak acceleration; and calculated peak acceleration largely exceeded recommended limit.
Sonza *et al.* (2015)	Lacking accurate description of PPD; no information on measurement method or value of peak acceleration; and WBV exposure included peak acceleration exceeding recommended limit.

PPD, peak-to-peak displacement; WBV, whole-body vibration.

A number of studies included in this review did not report the environmental room temperature. Blood flow in the human skin is highly variable. Also, vibration-induced changes in peripheral circulation are influenced by different conditions of room temperature (Mahbub *et al.*, 2006). Therefore, it has been suggested that environmental conditions should be carefully controlled during studies of the vascular responses to vibration (Ye and Griffin, 2011). In future, the studies investigating changes in peripheral circulation induced by exposure to WBV should control and report the environmental conditions for such measurements.

The reviewed studies showed the effects of acute or long-term exposure to WBV on peripheral circulation. In general, an improvement of the BF was observed in the studies from intervention with WBV when the vibration frequency was relatively lower (≤30 Hz) compared with the vibration frequencies exceeding 30 Hz. For example, a group of researchers could not reveal any significant improvement in BF when they used a comparatively high vibration frequency (50 Hz) with a high vibration magnitude (Lohman *et al.*, 2012; Lohman *et al.*, 2011). On the other hand, the same group of researchers found a significant increase in BF while using lower vibration frequency (30 Hz) with a lower magnitude of WBV (Lohman *et al.*, 2007). In a recent meta-analysis of relevant studies, Games et al. (2015) also suggested that exposure to WBV of lower frequencies resulted in a greater response in peripheral BF than did higher frequencies. It has been postulated that exposure to WBV causes activation of muscle spindle receptors with subsequent generation of vibration tonic reflexes causing an increase in muscle metabolic demand and oxygen consumption (Cardinale & Wakeling, 2005; Coupé *et al.*, 2011; Kasai *et al.*, 1992; Kerschan-Schindl *et al.*, 2001; Rothmuller & Cafarelli, 1995). This causes rhythmic contraction and relaxation of the precapillary sphincter with subsequent vasodilation (Figueroa *et al.*, 2015; Hazell *et al.*, 2008). Also, exposure to WBV results in a pulsatile blood flow and shear stress of endothelial cells which in turn leads to an increase in the endothelial nitric oxide (NO) synthase or eNOS and increased production of NO causing vasodilation and an increase in BF in the vibrated legs (Coupé *et al.*, 2011; Lohman *et al.*, 2007; Menéndez *et al.*, 2015; Sackner *et al.*, 2005; Ziegler *et al.*, 1998). On the other hand, occupational exposure to WBV of higher frequencies and intensities has been reported to cause impairments in peripheral circulation and associated symptoms among workers exposed to vibration with the dominant frequency range of 28 Hz and 40 Hz (Eger *et al.*, 2014). Exposure to vibration of higher frequencies and intensities may induce various functional, physiological and morphological changes including autonomic dysfunction with enhanced sympathetic activation and/or exaggerated vasoconstriction, increased responsiveness to α_2C adrenoreceptor-mediated vasoconstriction and/or a reduced responsiveness to acetylcholine (ACh)-mediated vasodilation, thickening of the vascular smooth muscle wall, etc (Eger *et al.*, 2014; Murata *et al.*, 1997; Thompson *et al.*, 2010). All these may lead to a high frequency vibration-induced decrease in peripheral circulation.

All these observations suggest that exposure to WBV at higher frequencies or intensities should not be recommended. In contrast, as significant increase in BF was observed for lower frequencies with relatively lower A(8) values, use of safe and lower frequencies of vibration seems to be appropriate. Considering the frequencies and magnitudes of exposure (Table 2), and the observed increases in peripheral circulation (Table 3), it appears that a frequency between 20 Hz and 30 Hz with a relatively low value of A(8) may be used for the purpose. As we observed, compared to vertical WBV, exposure to side-alternating WBV induced better positive responses in peripheral circulation which corresponds to the findings by Games et al. (2015) on such responses. However, in the future, the studies should clarify the clear response patterns in peripheral circulation from exposure of subjects to both vertical and side-alternating type of WBV. Also, the studies should clearly report the timing for measurements of peripheral circulation from long-term exposure to WBV, that is on the same day immediately after the last intervention or later, or on a different day than the day of last intervention.

The findings of the current review need to be interpreted with caution in light of several possible limitations that may have resulted from any inappropriate study design or other methodological flaws of the included studies. Firstly, we did not assess the methodological quality of the studies included in this review as we focused here on the characteristics of WBV intervention and associated changes in peripheral circulation. Secondly, for each study, we reported the PPD value that we considered reasonable from the available information in the relevant studies with the possibility of using a lower value than the actual value leading to a probable underestimation of vibration magnitude values used in the original studies. Thirdly, exposure to WBV was commonly accompanied by flexed knees on the platform and the magnitudes measured at the feet were probably overestimates of the vibration magnitude values transmitted to the body as such a posture is believed to cause dampening of the mechanical energy from exposure to WBV. Therefore, WBV exposure limits mentioned in the current standard may not be entirely applicable to such interventions with WBV as a modality for exercise, treatment or rehabilitation. Lastly, although hand searches by checking the reference lists of different studies did not yield any additional study, selection of studies from only two electronic databases (PubMed and Scopus) could be a potential limitation to the findings of this systematic review.

Conclusions

Overall, acute exposure to WBV of relatively lower frequency (especially between 20 Hz and 30 Hz) resulted in a consistent improvement in peripheral circulation. However, long-term effects from chronic exposure to WBV in enhancing peripheral circulation should be investigated further. For this purpose, relatively lower magnitudes of WBV should be selected considering the human exposure limits recommended by the ISO 2631-1 (1997) till safe and effective vibration-related parameters with standardized protocols are established. In future studies, the investigators should report the vibration-related parameters using standard terminologies and measurement methods following the recommendations of relevant international standards.

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Conflict of interest

The authors declare no conflict of interest.

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