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ARTICLE

Impact of low-intensity resistance and whole-body vibration training on aortic hemodynamics and vascular function in postmenopausal women

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Abstract

To examine the effects of low-intensity resistance exercise training (LIRET) and whole-body vibration training (WBVT) with an external weighted vest on arterial stiffness, wave reflection, brachial flow-mediated dilation (FMD), and physical performance in postmenopausal women. Thirty-three postmenopausal women were stratified by age, body mass index (BMI), and maximal voluntary contraction (MVC) (age, 65 ± 4 years; BMI, 23.3 ± 2.6 kg/m^2; MVC, 17.4 ± 2.6 kg) and randomized into LIRET, WBVT, or a nonexercising control group for 12 weeks. Arterial stiffness, augmentation index (AIx), augmented pressure (AP), brachial FMD, gait speed and leg strength were measured at baseline and 12 weeks. WBVT induced improvements in pulse pressure amplification (PPA) (0.04 ± 0.02) compared to control ($P = 0.048$) and in wave reflection indices [AIx (−4.3 ± 1.4%) and AP (−2.9 ± 1.3 mmHg)] compared to LIRET ($P = 0.039$ and 0.048, respectively). WBVT (3.8 ± 1.4%) and LIRET (5.0 ± 1.5%) induced similar improvements in FMD compared to control ($P = 0.029$ and 0.008, respectively). WBVT and LIRET elicited similar increases in leg strength ($P = 0.001$ and 0.019, respectively), compared to no improvement in the control group. LIRET significantly increased gait speed compared to WBVT ($P = 0.043$). Although both WBVT and LIRET increased brachial artery FMD (systemic effect), WBVT seemed to be more efficacious in improving wave reflection and cardiac pulsatile load. Interestingly, LIRET elicited a significant improvement in gait speed. Both modalities seem effective in improving systemic endothelial function and muscle strength in postmenopausal women.

Keywords Whole-body vibration · Resistance training · Postmenopausal women · Endothelial function · Wave reflection

Introduction

Women are more affected by the adverse impact of increased aortic pulsatile hemodynamic load on the left ventricle due to greater pressure wave reflection than men despite lower arterial stiffness (pulse wave velocity, PWV) [1]. Augmentation pressure (AP), the proposed main wave reflection index [2], is a primary contributor to increased aortic pulse pressure (PP) in older women [3], independent of aortic PWV, which consequently induces a greater left ventricular afterload. Increased afterload may further contribute to the rising prevalence of hypertension and heart failure in postmenopausal women [4, 5]. In addition, impaired endothelial vasodilatory function after menopause [6] is an underlying mechanism for the increase in aortic PP and AP [3]. In nonobese older women, endothelial dysfunction has been associated with lower muscle strength [7], the main characteristic of sarcopenia over low muscle mass and physical performance [8]. Endothelial dysfunction has been associated with sarcopenia, as reduced blood flow impairs anabolic processes necessary to maintain muscle properties [9], in postmenopausal women. Brachial artery endothelial function (i.e., flow-mediated dilation, FMD) is an accepted biomarker of cardiovascular risk prediction and vascular health.

Reduced walking capacity, muscle mass, and muscle strength are associated with increased risk for cardiovascular and all-cause mortality in older adults [10, 11].

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Evidence suggests that loss of muscle strength exceeds the loss of muscle mass, a phenomenon more prominent in the legs [12]. Grip strength has a strong association with cardiovascular mortality not explained by reduced muscle mass [13]. Furthermore, normalized grip strength (NGS) to body mass is robustly associated with cardiometabolic disease risk [14] and physical disability [15]. Therefore, interventions that target both skeletal muscle and vascular maladaptations are paramount.

High-intensity resistance exercise training (RET) has shown effectiveness in increasing muscle strength and walking speed [16]. However, concerns about high-intensity RET are potential adverse effects on PWV [17, 18]. These effects appear to be related to intensity and to upper-body, but not lower-body, exercises [17]. Low-intensity RET (LIRET) with slow-contractile speed has been shown to improve muscle strength comparable to high-intensity RET in untrained young adults [19]. Furthermore, LIRET has improved muscle strength, blood pressure (BP), and indices of wave reflection in postmenopausal women [20, 21] and brachial FMD in young, healthy, untrained adults [22]. There are no data regarding the effects of LIRET on FMD in postmenopausal women.

An alternative low-intensity strength exercise modality is whole-body vibration training (WBVT), which utilizes a controlled vibration stimulus while performing leg exercises [23]. Previous findings suggest WBVT ameliorates elevated BP, indices of wave reflection, and arterial stiffness in obese women [24–26]. As shear stress levels play a large role in resistance artery remodeling and endothelial nitric oxide (NO) expression [27], WBVT is proposed to improve vascular function (e.g., arterial stiffness, wave reflection, and endothelial function) via increased NO production [24, 28, 29]. Both LIRET and WBVT are effective in increasing muscle strength; however, the ability of either to improve vasodilatory capacity (FMD) and exercise performance in postmenopausal women at risk for sarcopenia is not known.

The purpose of this study was to examine the effects of WBVT and LIRET on wave reflection, arterial stiffness, endothelial function, and physical performance in apparently healthy postmenopausal women. We hypothesize that although WBVT will have a greater effect on aortic hemodynamics, WBVT and LIRET will have equivalent effects on brachial FMD and leg exercise performance, and both interventions will be superior to nonexercise control.

Methods

Participants

Thirty-three nonobese (BMI < 30 kg/m^2) women aged 55–75 years volunteered to participate in this study. Participants were postmenopausal for at least 1 year. Exclusion criteria included BMI > 30 kg/m^2, history of cardiovascular diseases, renal/pulmonary/metabolic diseases, systolic BP > 160 mmHg, current smokers (or cessation less than 1 year earlier), metal implants, inability to complete the 6-min walk test (6MWT) without stopping, and hormone replacement therapy prescribed within the last 6 months. Participants were also excluded if they were taking beta-blockers or anti-inflammatory drugs and if they were participating in regular resistance or aerobic training. Due to the negative relationship between heart rate and augmentation index (AIx) [30] as well as the disparity of effects on aortic BP and FMD between different generations of beta-blockers [31], participants on beta-blockers were excluded to ensure that our results were accurate. Usage of anti-inflammatory medications, specifically cyclooxygenase-2 inhibitors, is associated with elevated cardiovascular risk and foam cell formation, although these data are controversial and have been for a few decades [32]. To maintain homogeneity within our sample, it was essential that participants taking anti-inflammatory medications be excluded due to the potential differences in duration of use. The study protocol was approved by the Institutional Human Subject Committee.

Protocol and experimental procedures

We used a parallel experimental design. Following an initial screening and familiarization session, eligible women were randomly assigned to WBVT, LIRET, or control for 12 weeks. Randomization was stratified and balanced by age and grip strength. Laboratory personnel were blinded to group assignment. Participants reported to the laboratory in the morning following an overnight fast before and after the 12 weeks (±1 h to avoid diurnal variations), at least 48 h after the last training session to avoid any acute effects of the exercise on the vascular measures (i.e., BP). Participants were asked to abstain from alcohol, vitamins, and dietary supplements for 24 h and from vasoactive medication 8 h prior to testing. Vascular measurements were taken in a dark, quiet, temperature-controlled room (23 °C). Prior to vascular assessments, height, weight, waist circumference (midpoint between lowest rib and iliac crest), and grip maximal voluntary contraction (MVC) were measured. Waist circumference was taken as the average of duplicate measurements that had less than a 5 mm difference. MVC was taken three times, with the highest score recorded from each hand. NGS was calculated as MVC/BMI [15].

Arterial stiffness and wave reflection

Following 10 min of supine rest, PWV was recorded by a semiautomatic device (VP-2000; Omron Healthcare,

Vernon Hills, IL), which uses BP cuffs around both arms (brachial artery) and ankles (posterior-tibial artery) and tonometers over the right carotid and femoral arteries to obtain brachial-ankle PWV (baPWV), carotid-femoral PWV (cfPWV), and femoral-ankle PWV (faPWV). The feet of the pulse waves are related to the ECG's R-wave to calculate transit time. The distance between sampling points for cfPWV was measured with a segmometer, whereas for baPWV and faPWV, this value was calculated automatically according to the subject's height. PWV was calculated as distance/transit time, while heart rate (HR) was obtained from the ECG. PWV measurements were taken in duplicate with less than 5% difference between measures. A third measurement was recorded when the difference was greater than 5%.

Radial applanation tonometry assessed wave reflection through pulse wave analysis. Brachial BP, measured in duplicate with an automated device (Omron HEM-907XL Pro Healthcare, Vernon Hills, IL) following ~20 min of quiet rest, was used to calibrate radial waveforms obtained from a 10-s epoch using a high-fidelity tonometer (SPT-301B; Millar Instruments, Houston, TX). Aortic pressure waveforms were derived using a generalized validated transfer function (SphygmoCor, AtCor Medical, Sydney, Australia). PP was calculated as the difference between systolic (SBP) and diastolic BP (DBP). Pulse pressure amplification (PPA) was depicted as the ratio of brachial to aortic PP [33]. AP was calculated as the difference between the first and second systolic peaks. AIx was calculated as the ratio of AP–PP and was standardized at 75 bpm (AIx@75) given the inverse relationship between HR and AIx [30]. Measurements were taken in duplicate with less than 5% difference and an operator index >80.

Endothelial function

Brachial artery diameter and mean blood velocity (MBV) were measured using Doppler ultrasound (Philips HD11XE; Philips Ultrasound, Bothell, WA, USA). A 12–2 MHz linear-array probe was held in place 1–5 cm proximal to the antecubital fossa at an insonation angle <60°. Following baseline measurements, a cuff on the upper forearm was inflated to at least 50 mmHg above SBP for 5 min. Measurements were recorded continuously from 30 s prior to the release of the occlusion pressure to 3 min after cuff deflation. FMD was calculated as the maximal postocclusion diameter relative to the averaged preocclusion diameter.

Brachial artery diameter was analyzed in late diastole using ECG-gated automated edge-detection and wall-tracking software (Medial Imaging Applications; Coralville, IA, USA). All videos and images were recorded and saved to an offline computer for future analysis. Each sequence of images was visually reviewed to ensure that diameters were continually tracked from the intima-lumen interface at the distal and proximal vessel wall. MBV was measured by a full-width pulsed-wave gate, positioning the cursor mid vessel, and detecting the peak of the waveform. Brachial artery blood flow (ml/min) [34] and vascular conductance [35] were calculated as follows:

$$\text{Blood flow} = \pi \times (\text{diameter}/2)^2 \times \text{MBV} \times 60$$

$$\text{Vascular conductance} = \text{blood flow}/\text{mean arterial pressure}$$

Strength and physical performance

During the familiarization session, participants performed three leg exercise 1RM tests and a 6MWT. Briefly, the 1RM was obtained by finding the maximum load the participants could move through the full range of motion in the leg press, flexion, and extension (MedX, Ocala, FL, USA) as previously described [36]. For the 6MWT, participants were instructed to walk as fast as possible around a 45-m course. Verbal feedback was given after the completion of every lap, and every minute that passed was announced. The 1RM and 6MWT were repeated after at least 48 h of rest, and the highest value was reported. Both tests were supervised and recorded by the same researcher before and after the 12 weeks.

Exercise training protocol

Participants in the WBVT group performed dynamic exercises for the legs (full squats, high squats, wide squats, and calf raises) on a vibration platform (pro6 AIRdaptive; Health Performance International, Northbrook, IL, USA). Exercises were performed starting from an upright position to 90° and 120° knee flexions (squat) and maximal heel elevation (toe stand). The training volume was increased progressively by increasing the intensity of vibration (24–40 Hz), the number of sets per exercise (2–3), and the total duration of the training session (20–35 min) and by increasing the external load using a weight vest. The vest (1 lb) was worn during the first 2 weeks without external weight.

The LIRET sessions consisted of leg press, leg extension, leg flexion, and calf raise exercises initially prescribed at 40% of the 1RM, with the maximum goal of 15 repetitions. Exercises in both WBVT and LIRET were performed with slow contractions (2-second concentric and 3-s eccentric contractions) controlled with a metronome. Both groups began with 2 weeks of 20-min sessions, while the rest of the training intervention had sessions of 30–35 min. Weight was progressively increased 5–10% if the participant could complete 15 repetitions with a rating of perceived exertion below 7 (Borg CR-10) across 2 consecutive sessions.

Statistical analyses

An estimation of an appropriate sample size was conducted using previous research investigating the effects of LIRET on FMD in young adults [37]. With an effect size of 0.48, an a priori estimated sample size of 21 would enable us to observe a significant difference (2–3%) between treatments (WBVT and/or LIRET vs. control) with a power of 95%. Normality of distributions was tested using the Shapiro–Wilk test for all variables. One-way analysis of variance (ANOVA) was used to detect possible differences between the groups at baseline. Between- and within-group comparisons were performed with a two-way ANOVA with repeated measures (groups (WBVT *vs.* LIRET *vs.* control) × time (0 *vs.* 12 weeks)) with Bonferroni adjustments. When there was a significant group-by-time interaction, one-way ANOVA across change scores was used to detect between-group differences in the responses. Pearson's partial correlations were used to analyze the relationship between changes in leg strength and walking speed. All statistical analyses were performed using SPSS, version 21.0 (SPSS, Chicago, IL, USA). Statistical significance was considered at $P < 0.05$. Data are presented as mean ± SEM.

Results

One hundred sixty-seven postmenopausal women were assessed for eligibility, 126 were excluded, and 41 were enrolled in the study. Participants were randomized to the three groups, with two dropping from each training group and four from the control group. Thirty-three participants were analyzed. A Consolidated Standards of Reporting Trials (CONSORT) study design flowchart is shown in Fig. 1. Compliance with supervised WBVT and LIRET training sessions was 94% and 95.7%, respectively. Participant characteristics at baseline are shown in Table 1. There were no significant differences between groups in any baseline characteristic. Following 12 weeks, the WBVT group significantly increased MVC (8.3%) and NGS (7.9%)

Table 1 Participant characteristics before whole-body vibration training (WBVT), low-intensity resistance training (LIRET), or nonexercise control

Variable	WBVT ($n = 13$)	LIRET ($n = 12$)	Control ($n = 8$)	*P*-value
Age (years)	64 ± 1	64 ± 1	67 ± 1	0.249
Height (m)	1.61 ± 0.02	1.58 ± 0.01	1.62 ± 0.02	0.296
Weight (kg)	59.8 ± 2.3	60.3 ± 2.3	58.6 ± 2.1	0.883
BMI (kg/m^2)	23.2 ± 0.8	24.0 ± 0.6	22.5 ± 0.9	0.441
MVC (kg)	18.2 ± 0.6	17.0 ± 0.9	16.6 ± 0.9	0.360
NGS (kg/m^2)	0.80 ± 0.05	0.71 ± 0.03	0.74 ± 0.05	0.252
WC (cm)	75.7 ± 2.1	78.5 ± 2.7	73.5 ± 2.2	0.389
SBP (mmHg)	121 ± 4	123 ± 5	130 ± 5	0.443
DBP (mmHg)	68 ± 2	67 ± 3	68 ± 2	0.879
MAP (mmHg)	90 ± 3	88 ± 3	92 ± 3	0.680

Data are mean ± SEM

BMI body mass index, *MVC* maximal voluntary contraction, *NGS* normalized grip strength, *WC* waist circumference, *SBP*, systolic blood pressure, *DBP* diastolic blood pressure, *MAP* mean arterial pressure

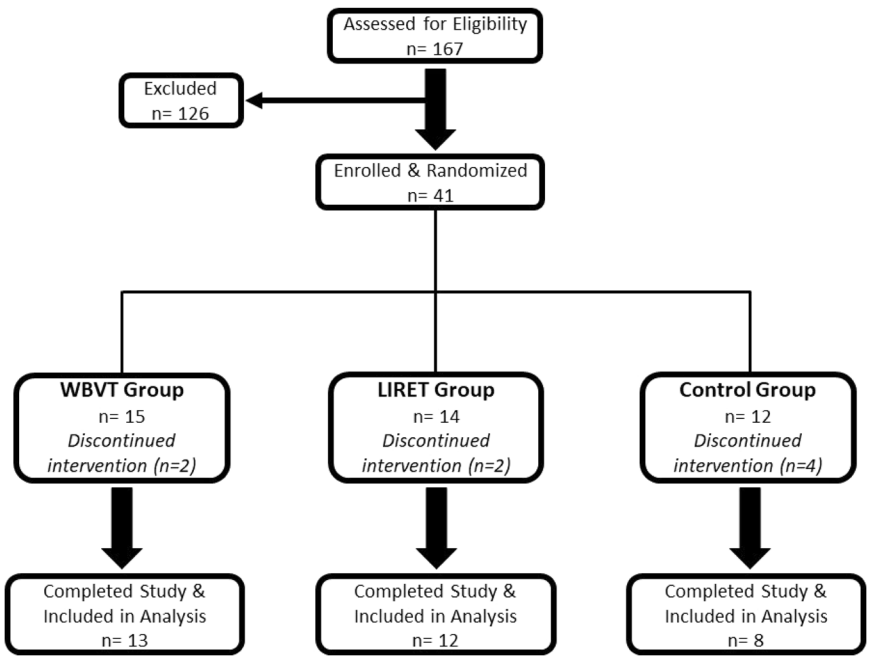

Fig. 1 Consolidated Standards of Reporting Trials (CONSORT) diagram of the study design

($P = 0.011$), but it was not different compared with the LIRET and control groups. There were no significant changes in BP or anthropometric variables in any of the groups.

Resting and vasodilatory hemodynamic and arterial characteristics

Peripheral BP, central hemodynamics, wave reflection, and arterial stiffness values before and after 12 weeks of the assigned interventions are presented in Table 2. All vascular measures were similar at baseline across all groups. PPA increased ($P = 0.026$) and AP, AIx (Fig. 2), and AIx@75 significantly decreased in the WBVT over time ($P = 0.043$, 0.008, and 0.025, respectively). The magnitude of change in PPA ($P = 0.048$) was significantly greater in the WBVT compared to the control group, and AP ($P = 0.048$) and AIx ($P = 0.039$) were significantly greater in WBVT compared to LIRET (Fig. 2). There were no significant differences in brachial BP, aortic BP, cfPWV, faPWV, baPWV, or HR over time in any of the groups.

Brachial artery characteristics at rest and responses to FMD before and after 12 weeks are presented in Table 3. There were no between-group differences in brachial artery measurements at baseline. Following 12 weeks, both the WBVT and LIRET groups showed significant increases in FMD compared to the control group ($P = 0.029$ and 0.008, respectively; Fig. 2d).

Physical performance

Leg strength and walking speed before and after 12 weeks of the assigned interventions are presented in Table 4. Leg press, flexion, and extension 1RM were similar in all groups before training and increased similarly in the WBVT ($P =$ 0.0001, 0.0012, and 0.0001, respectively) and LIRET groups ($P = 0.0005$, 0.006, and 0.028, respectively) compared to the control group. Walking distance and speed significantly increased in the LIRET group, and the magnitude of increase was significantly greater compared to the WBVT and control groups ($P = 0.045$ and 0.037); however, these changes were not correlated with the changes in leg strength ($r = .131$, $P = 0.48$).

Table 2 Participant peripheral and central hemodynamics, wave reflection, and arterial stiffness before and after 12 weeks of whole-body vibration training (WBVT), low-intensity resistance training (LIRET), or nonexercise control

Variable	WBVT ($n = 13$)		LIRET ($n = 12$)		Control ($n = 8$)	
	Before	After	Before	After	Before	After
Brachial (mmHg)						
SBP	121 ± 4	119 ± 4	123 ± 5	121 ± 5	130 ± 5	122 ± 5
DBP	68 ± 2	68 ± 2	67 ± 3	66 ± 3	68 ± 2	67 ± 2
PP	53 ± 3	52 ± 2	56 ± 4	55 ± 3	62 ± 4	55 ± 5
Aortic (mmHg)						
SBP	116 ± 4	112 ± 4	115 ± 5	114 ± 5	121 ± 4	114 ± 5
DBP	69 ± 2	68 ± 2	67 ± 3	67 ± 3	69 ± 2	68 ± 2
MAP	90 ± 3	86 ± 2	88 ± 3	87 ± 4	92 ± 3	88 ± 3
PP	48 ± 3	45 ± 2	47 ± 3	48 ± 3	52 ± 3	46 ± 4
PPA	1.13 ± 0.02	1.17 ± 0.02[*,a]	1.18 ± 0.03	1.18 ± 0.02	1.20 ± 0.03	1.18 ± 0.02
AP (mmHg)	18 ± 2	15 ± 1[*,a]	15 ± 2	17 ± 2	18 ± 1	17 ± 2
AIx (%)	36.9 ± 1.4	32.6 ± 1.6[†,a]	31.4 ± 2.5	34.8 ± 2.4	35.1 ± 2.8	36.3 ± 3.2
AIx@75 (%)	28.8 ± 1.9	24.8 ± 1.6[*]	25.4 ± 2.3	28.2 ± 2.2	30.6 ± 2.5	30.5 ± 3.3
cfPWV (m/s)	9.1 ± 0.3	8.5 ± 0.2	9.9 ± 0.7	9.3 ± 0.7	10.1 ± 0.9	10.3 ± 1.0
faPWV (m/s)	8.3 ± 0.2	8.1 ± 0.3	8.5 ± 0.3	8.3 ± 0.3	8.5 ± 0.4	8.3 ± 0.4
baPWV (m/s)	11.0 ± 0.4	10.6 ± 0.4	11.7 ± 0.7	11.6 ± 0.7	12.6 ± 0.9	12.6 ± 1.1
HR (bpm)	58 ± 2	59 ± 3	63 ± 2	61 ± 3	63 ± 1	60 ± 1

Data are mean ± SEM

SBP systolic blood pressure, *DBP* diastolic blood pressure, *MAP* mean arterial pressure, *PP* pulse pressure, *PPA* PP amplification, *AP* augmented pressure, *AIx* augmentation index, *AIx@75* AIx standardized at 75 bpm, *cfPWV* carotid-femoral pulse wave velocity, *faPWV* femoral-ankle PWV, *baPWV* brachial-ankle PWV, *HR* heart rate

[*] $P < 0.05$; [†] $P < 0.01$ different from baseline (time effect)

[a] $P < 0.05$ magnitude of change from baseline different from LIRET (group × time interaction).

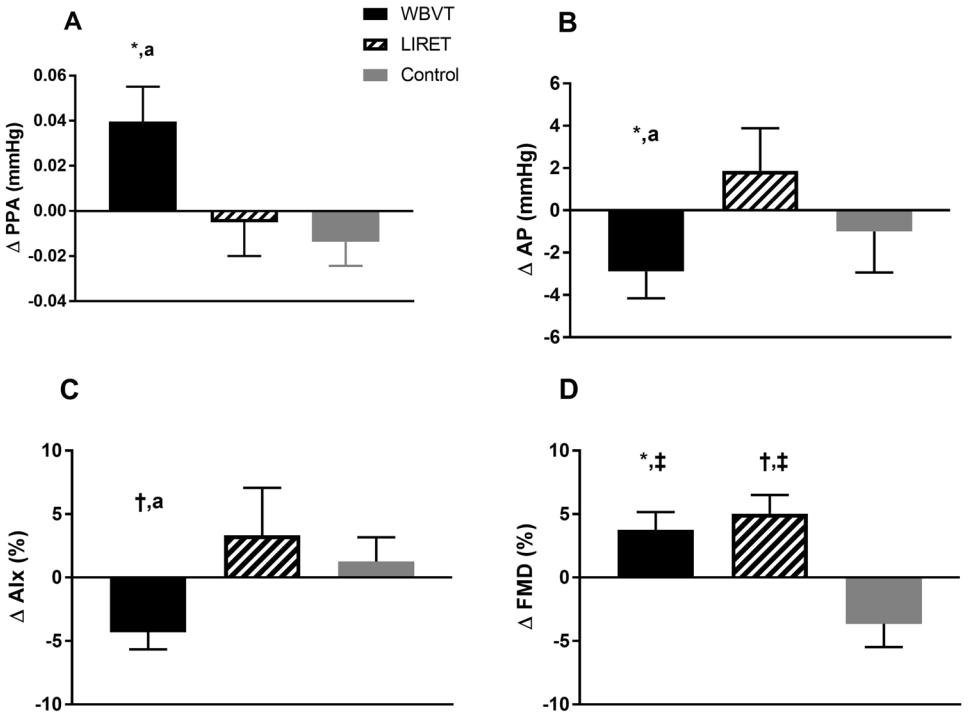

Fig. 2 Changes in **a** pulse pressure amplification (PPA), **b** augmented pressure (AP), **c** augmentation index (AIx), and **d** brachial artery flow-mediated dilation (FMD) following 12 weeks of the assigned intervention. Values are mean and SEM. $^{*}P < 0.05$, $^{\dagger}P < 0.01$ different from baseline (time effect). $^{\ddagger}P < 0.01$ different from control (group × time interaction). $^{a}P < 0.05$ different from LIRET (group × time interaction)

Table 3 Participant brachial artery characteristics at rest and in response to vasodilatory stimuli before and after 12 weeks of whole-body vibration training (WBVT), low-intensity resistance training (LIRET), or nonexercise control

Variable	WBVT ($n = 13$)		LIRET ($n = 12$)		Control ($n = 8$)	
	Before	After	Before	After	Before	After
Diameter (cm)	0.35 ± 0.02	0.36 ± 0.01	0.33 ± 0.01	0.35 ± 0.01	0.33 ± 0.02	0.35 ± 0.03
MBV (cm/s)	14.7 ± 2.3	16.7 ± 2.6	13.3 ± 1.7	14.2 ± 2.4	12.2 ± 2.3	14.2 ± 3.6
BF (ml/min)	96.6 ± 13.9	101.9 ± 15.5	71.1 ± 16.2	82.8 ± 18.0	58.0 ± 7.5	72.4 ± 15.0
VC (ml/min·mmHg)	1.14 ± 0.17	1.21 ± 0.19	0.84 ± 0.21	0.97 ± 0.22	0.67 ± 0.09	0.86 ± 0.18
FMD (%)	8.0 ± 0.9	11.7 ± 1.3^{*,a}	9.2 ± 1.3	14.2 ± 1.4^{†,a}	8.9 ± 0.9	6.9 ± 1.2

Data are mean ± SEM

MBV mean blood velocity, *BF* blood flow, *VC* vascular conductance, *FMD* flow-mediated vasodilation (relative change in diameter)

$^{*}P < 0.05$; $^{\dagger}P < 0.01$ different from baseline (time effect)

$^{a}P < 0.01$ magnitude of change from baseline different than control (group × time interaction).

Discussion

The primary purpose of this study was to determine the effectiveness of WBVT and LIRET in improving wave reflection, endothelial function, and physical performance. The key findings and strengths of the present study are as follows: (1) only WBVT improved PPA, AP, AIx, and AIx@75, (2) both WBVT and LIRET increased brachial artery FMD, and (3) LIRET significantly increased walking speed. Taken together, these results suggest that WBVT and LIRET are equally efficacious strength modalities to improve brachial artery vasodilatory capacity, suggesting a systemic effect. Although WBVT reduced indices of wave reflection, it did not affect walking speed.

In the present study, neither training intervention significantly changed resting brachial or aortic BP in predominantly normotensive postmenopausal women. In contrast to these findings, our previous work has shown significant reductions in central and peripheral SBP in young, overweight/obese, normotensive women [38] and in obese postmenopausal women [24, 25, 39] after 6–12 weeks of WBVT. Previous research evaluated pre-hypertensive or hypertensive subjects. In contrast, our population of interest was nonobese postmenopausal women who were 42.4% normotensive, 21.2% elevated BP, and 18.2% hypertensive. The lack of change in BP under dynamic WBVT can likely be attributed to the relatively normal resting BP.

Table 4 Participant leg strength and physical performance before and after 12 weeks of whole-body vibration training (WBVT), low-intensity resistance training (LIRET), or nonexercise control

Variable	WBVT ($n = 13$)		LIRET ($n = 12$)		Control ($n = 8$)	
	Before	After	Before	After	Before	After
Leg press (kg)	107 ± 6	125 ± 7^{‡,c}	100 ± 6	114 ± 7^{†,b}	111 ± 8	112 ± 10
Leg flexion (kg)	66 ± 3	71 ± 3^{†,a}	59 ± 3	67 ± 3^{†,b}	67 ± 5	65 ± 5
Leg extension (kg)	70 ± 3	84 ± 4^{‡,b}	69 ± 5	77 ± 4^{*,a}	71 ± 6	68 ± 6
6MWT (m)	702 ± 17$^{\#}$	698 ± 20	639 ± 12	661 ± 13^{*,d}	656 ± 23	655 ± 24
Walking speed (m/s)	1.95 ± 0.05	1.94 ± 0.05	1.77 ± 0.03	1.84 ± 0.04^{*,d}	1.82 ± 0.18	1.82 ± 0.07

Data are mean ± SEM

6MWT six-minute walk test

$^{\#}P < 0.01$ different from LIRET at baseline

$^{*}P < 0.05$; $^{\dagger}P < 0.01$, $^{\ddagger}P < 0.001$ different than baseline (time effect).

$^{a}P < 0.05$, $^{b}P < 0.01$, $^{c}P < 0.001$ magnitude of change from baseline different than control (group × time interaction).

$^{d}P < 0.05$ magnitude of change from baseline different than WBVT and control (group × time interaction).

In a healthy arterial system, wave reflection is an integral component of coronary perfusion, as the reflected wave returns to the aorta during diastole in healthy young adults [40]. The widening of central PP associated with aging in women is largely caused by increased AP, independent of cfPWV [1, 3, 41], resulting in reduced PPA and a consequential increase in end-systolic stress and cardiac hypertrophy [33]. Therefore, while decreases in peripheral and central BP are important, targeting the underlying factors contributing to the increased aortic wave reflection (AP and AIx) and reduced PPA are essential to attenuate the increased risk of heart failure with preserved ejection fraction [1] in older women with hypertension. The WBVT reduced wave reflection indices compared to LIRET. In agreement with the present findings, Wong et al. [24] observed significant decreases in AP, AIx, and AIx@75 in obese postmenopausal women with high BP after 8 weeks of WBVT. Previously, we have shown similar decreases in AP and AIx (−5 mmHg and −10%, respectively) as well as a negative association between changes in leg strength and AP over a 6-week WBVT protocol [25].

Conversely, there were no changes in wave reflection characteristics in the LIRET group of the present study, which is consistent with previous research in obese postmenopausal women [21]. Casey et al. [42] and Taaffe et al. [43] found no reductions in wave reflection indices after moderate-intensity resistance training for 18 and 20 weeks in older adults. With sedentary aging, the reflected wave returns during late systole, resulting in an augmented afterload (AP and AIx) and reduced coronary perfusion and stroke volume [44]. Augmented central pressures induced by increases in AP and AIx are strongly associated with end-organ damage (heart, brain, and kidneys) [45] and cardiovascular events [46]. Although aortic PP was not a significant predictor, elevation of AIx by 10% has resulted in a 31.8% increase in cardiovascular events independent of peripheral BP [47]. Therefore, the reductions in AP and AIx evoked by WBVT, even without an impact on aortic PP, may reduce the prevalence of cardiovascular events in postmenopausal women.

A novel finding of our study is that both WBVT and LIRET increased FMD, which is consistent with findings in other studies using whole-body LIRET or high-intensity RET in young, healthy or prehypertensive adults [22, 37, 48]. This is clinically relevant, as previous literature has reported that for every 1% increase in brachial FMD, cardiovascular risk is reduced by 17% [49]. LIRET, but not WBVT [50] or moderate-intensity RET [42], has improved brachial FMD in healthy young men [22]. This is the first study demonstrating increases in brachial FMD in response to either WBVT or LIRET in this population (of whom 15% of the entire sample were on estrogen therapy). Because these interventions exercised only the leg muscles at low intensity, we hypothesize that the improved brachial artery reactivity was induced by a systemic effect caused primarily by the effect of regular exercise–upregulated NO production/bioavailability [28].

It is important to note that the mean value of FMD was relatively high when compared to that reported for a similar population in the literature. We did not measure any biomarkers, so we are unable to report values that may suggest potential lipidemia or glycemia dysregulation in our sample. Our participants were nonobese, as defined by waist circumference and BMI, and relatively healthy postmenopausal women. Miyazaki et al. [51] displayed a strong, negative correlation between FMD and waist circumference in older adults. Although Moreau et al. [6] found the mean FMD in early- and late-postmenopausal women to be 5–6%, waist circumference in those cohorts was higher than in our cohort, which may explain the uncharacteristically high FMD values in our study. Furthermore, there is a nonsignificant decrease in FMD following the control period. Boyle et al. [52] reported that endothelial function may be significantly reduced by as little as 5 days of physical inactivity in recreationally active men. This may explain the nonsignificant ($P = 0.122$) reduction in brachial FMD in the control group following 12 weeks of inactivity.

WBVT and LIRET have been shown to significantly increase muscle strength compared to high-intensity RET in untrained sedentary adults [19, 53]. Roelants et al. [54] reported similar increases in leg extension (16.1%) in postmenopausal women following 24 weeks of WBVT and moderate- to high-intensity RET (8–15 RM), suggesting that RET required greater intensity for comparable strength improvements. Conversely, we have previously reported a 24.4% increase in leg strength following 12 weeks of LIRET in obese postmenopausal women [20, 21]. This is the first study comparing these two low-intensity strength modalities. The similarity in strength gains between modalities may exemplify the need to add an external weight to WBVT in postmenopausal women who are normal-weight or slightly overweight to match the relative intensity of LIRET applied in the present study.

Although the participants in the WBVT group had no change, LIRET increased walking speed to a small (~0.06 m/s) but meaningful level [55]. Nunes et al. [56] reported a similar meaningful change (~0.1 m/s) in response to 16 weeks of high-volume (six sets) moderate-intensity (70% of 1RM) RET in postmenopausal women. Vincent et al. [57] reported similar increases in stair climbing speed following 24 weeks of low- (50% 1RM) or high-intensity (80% 1RM) RET in older adults. Given the augmented risk of cardiovascular events and physical disability in older adults, the prospect of having similar benefits from LIRET compared to high-intensity RET is of clinical significance. A potential explanation for the apparent inefficacy of WBVT on walking capacity is a higher baseline value and, consequently, less room for improvement. It is important to note that previous cross-sectional studies have associated lower limb muscular strength with a faster walking speed (Fragala et al. 2016; Inoue et al. [58]). Furthermore, Santos et al. [59] reported that the improvement in walking speed following 8 weeks of whole-body moderate-intensity resistance training was associated with increases in knee extensor strength ($r = -0.45$) but not associated with favorable changes in body composition. Although our participants significantly increased knee extensor strength, this was not associated with increases in walking speed. This may be due to the different methods used to measure walking speed. Santos et al. [59] utilized a 10-m protocol, whereas ours was longer. Therefore, leg strength has been associated with maximal walking speed; however, this correlation may not be sensitive enough to detect walking speed during longer protocols. Lastly, it is important to note that our population was highly functional (gait speed of 1.85 ± 0.03 m/s) compared to those at high disability risk (<1.22 m/s) in previous studies [55, 56], so these results may not be generalizable to sarcopenic or frail adults.

We attempted to design exercise programs that would be comparable in intensity. For this reason, we are unable to compare absolute loads between the two modalities (WBVT was based on body weight and external weight, while LIRET used conventional weight machines). However, we were able to progressively increase the relative intensity on an individual basis using 15RM and an RPE scale. Notably, our greatest limitation was the lack of detailed physical activity information, whose presence might have shed more light on the matter. In the health history questionnaire, we simply asked for an approximate level of physical activity per week. All the participants were either sedentary or self-reported sparse participation in group exercise classes such as Zumba and Pilates, prior to beginning our interventions. It is important to note that those classes were immediately halted at least 2 weeks prior to their participation in the study (i.e., before baseline measures). However, none of the participants reported regular aerobic or resistance training, the latter of which was our primary concern. Given the relatively high mean FMD values highlighted in the first major comment, our participants may have had higher-than-average physical activity levels at baseline compared to the general population, though we cannot confirm this. Unfortunately, those data were neither recorded nor reported. This study has several strengths, including vascular and muscular benefits following two unconventional strength training modalities for the legs in nonobese postmenopausal women. Our study adds to the current literature that has found that WBVT may be a viable alternative to ameliorate endothelial dysfunction, aortic pressure load, and muscular weakness in nonobese postmenopausal women. To our knowledge, this study is the first to report increases in brachial FMD and muscle fitness (muscle strength and walking speed) in response to LIRET in this population.

In conclusion, WBVT and LIRET are effective modalities to improve brachial artery endothelial function. Although both WBVT and LIRET benefit leg muscle strength, only LIRET improves walking capacity, while WBVT may have a greater benefit on prevention of cardiovascular events via reduction of indices of wave reflection and cardiac pulsatile load in apparently healthy nonobese postmenopausal women. These results suggest that WBVT has a greater benefit on the attenuation of left ventricular afterload, while LIRET may be more appropriate to increase physical performance in postmenopausal women.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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