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Impact of L-citrulline supplementation and whole-body vibration training on arterial stiffness and leg muscle function in obese postmenopausal women with high blood pressure

Arturo Figueroa [a,*], Stacey Alvarez-Alvarado [a], Michael J. Ormsbee [a], Takudzwa A. Madzima [a], Jeremiah C. Campbell [a], Alexei Wong [a,b]

[a] *Department of Nutrition, Food and Exercise Sciences, Florida State University, 120 Convocation Way, Tallahassee, FL 32306-1493, USA*
[b] *Department of Physical Education, University of Puerto Rico at Mayagüez, 259 Blvd. Alfonso Valdez Cabian, Mayagüez 00680, Puerto Rico*

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ABSTRACT

Aging is associated with increased arterial stiffness (pulse wave velocity, PWV) and muscle strength/mass loss. Exercise training alone is not always effective to improve PWV and lean mass (LM) in older women. To investigate the independent and combined effects of whole-body vibration training (WBVT) and L-citrulline supplementation on PWV and muscle function in women, forty-one postmenopausal women aged 58 ± 3 years and body mass index (34 ± 2 kg/m^2) were randomly assigned to the following groups: WBVT, L-citrulline, and WBVT + L-citrulline for 8 weeks. WBVT consisted of four leg exercises three times weekly. Aortic (cfPWV) and leg (faPWV) PWV, leg LM index, leg strength, and body fat percentage (BF%) were measured before and after the interventions. WBVT + L-citrulline decreased cfPWV (−0.91 ± 0.21 m/s, $P < 0.01$) compared to both groups. All interventions decreased faPWV ($P < 0.05$) similarly. Leg LM index increased (2.7 ± 0.5%, $P < 0.001$) after WBVT + L-citrulline compared with L-citrulline. Both WBVT interventions increased leg strength (~37%, $P < 0.001$) compared to L-citrulline while decreased BF% (~2.0%, $P < 0.01$). Reductions in cfPWV were correlated with increases in leg LM index ($r = -0.63$, $P < 0.05$). Our findings suggest that leg muscle strength and arterial stiffness can be improved after WBVT, but its combination with L-citrulline supplementation enhanced benefits on aortic stiffness and leg LM. Therefore, WBVT + L-citrulline could be an intervention for improving arterial stiffness and leg muscle function in obese postmenopausal women with prehypertension or hypertension, thereby reducing their cardiovascular and disability risk.

1. Introduction

Increased aortic stiffness may contribute to the higher prevalence of systolic hypertension (Berry et al., 2004) and heart failure in older women (Coutinho et al., 2013). Carotid–femoral pulse wave velocity (PWV) is considered the gold standard measure of arterial stiffness (O'Rourke et al., 2002). Alternatively, brachial-ankle PWV (baPWV), which mainly includes carotid–femoral PWV (cfPWV) and femoral-ankle PWV (faPWV), has been proposed as an index of central arterial stiffness (Sugawara et al., 2005). Thus, both cfPWV and baPWV are similarly associated with age and systolic blood pressure (BP) (Choo et al., 2014; Tanaka et al., 2009) and are predictors of cardiovascular events and mortality (Vlachopoulos et al., 2010, 2012). Although faPWV is less affected by aging, accumulating evidence suggests that leg arterial stiffness (femoral and faPWV) is clinically relevant as positively associates with systolic BP (SBP) (Choo et al., 2014; Park et al., 2010), central adiposity (Park et al., 2010; Snijder et al., 2004), and cardiovascular events and mortality (van Sloten et al., 2014).

Increased PWV may be involved in the age-related loss of muscle mass known as sarcopenia, which preferentially affects the legs in women (Abbatecola et al., 2012; Kohara et al., 2012; Ochi et al., 2010; Snijder et al., 2004). Several studies have shown that sarcopenia is inversely associated with cfPWV (Abbatecola et al., 2012) and baPWV (Kohara et al., 2012; Ochi et al., 2010; Sanada et al., 2010). This relationship appears to be more important for women than men (Sanada et al., 2010). Moreover, the increased mortality risk in postmenopausal women with sarcopenia (Batsis et al., 2014) may be related to the increased cardiovascular mortality associated with high PWV (van Sloten et al., 2014; Vlachopoulos et al., 2010, 2012). Since high leg lean mass is the strongest determinant of reduced aortic and leg arterial stiffness in older adults (Snijder et al., 2004), improvements in leg lean mass may result in cardiovascular benefits in postmenopausal women.

High-intensity resistance training (RT) is an effective exercise mode for improving mass muscle and strength in postmenopausal women (Casey et al., 2007; Figueroa et al., 2003). However, RT may increase

* Corresponding author.
E-mail addresses: afiguero@fsu.edu (A. Figueroa), sa12d@my.fsu.edu (S. Alvarez-Alvarado), mormsbee@fsu.edu (M.J. Ormsbee), tam07g@my.fsu.edu (T.A. Madzima), jcc12d@my.fsu.edu (J.C. Campbell), alexei.wong@upr.edu (A. Wong).

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cfPWV and faPWV in middle-aged adults with high SBP (Collier et al., 2008). Alternatively, there is increased evidence to support that whole-body vibration exercise training (WBVT), which is generally performed as a type of RT, is as effective as RT for improving muscle strength and mass in postmenopausal women (Machado et al., 2010; Verschueren et al., 2004). Although it has been shown that WBVT can decrease baPWV and faPWV in older adults (Figueroa et al., 2014b; Lai et al., 2014), a reduction in cfPWV has not been observed. A recent meta-analysis suggested that RT is not an effective intervention for reducing PWV (Ashor et al., 2014). Thus, addition of a nutritional intervention to exercise training may be essential to positively affect PWV.

L-Citrulline, a non-protein amino acid naturally found in watermelon, is efficiently converted to L-arginine, the substrate for endothelial production of nitric oxide (NO), a potent vasodilator (Schwedhelm et al., 2008). L-Citrulline, either synthetic or from watermelon extract, has shown to reduce baPWV and faPWV in middle-aged adults (Figueroa et al., 2013b; Ochiai et al., 2012). Interestingly, improved leg muscle blood flow has been proposed as a mechanism for the increased muscle mass in older adults (Dillon et al., 2011). Therefore, it is possible that the addition of L-citrulline to WBVT may reduce PWV and increase leg lean mass (LM) in postmenopausal women.

The purpose of this study was to investigate the independent and additive effects of L-citrulline supplementation and WBVT on PWV and muscle function in obese postmenopausal women. It was hypothesized that WBVT with L-citrulline supplementation would have greater improvements in PWV and leg muscle strength/mass than either intervention alone. Moreover, WBVT and L-citrulline alone would reduce PWV; however, L-citrulline supplementation would not alter muscle strength.

2. Methods

2.1. Participants

Forty-one women volunteered for a randomized, parallel-design study to evaluate the independent and combined effects of L-citrulline supplementation and WBVT on PWV, BP, and muscle function. Participants were postmenopausal (≥1 year without menstruation), overweight or obese (BMI ≥ 30 kg/m^2) with prehypertension or stage-1 hypertension, nonsmokers, and sedentary (<60 min of aerobic exercise/week and no RT during the past 6 months). Medical-history questionnaires were used to screen for chronic diseases. Participants were excluded if they had diabetes and/or cardiovascular diseases other than stage-1 systolic hypertension (140–159 mm Hg). Participants were also excluded if they were on a weight loss program, hormone replacement therapy, dietary supplements (amino acids [L-citrulline, L-arginine, and L-glutamine], vitamins [C and E]) and β blockers or had wounds in the legs, joint prosthetic devices, or recent thrombosis. Participants undergoing antihypertensive treatment used ACE inhibitors (WBVT [n = 1], L-citrulline [n = 2], and WBVT + L-citrulline [n = 2]). These participants did not modify the treatment during the study. The study protocol was approved by Florida State University Human Subject Committee (2012.9674) and registered in Clinicaltrial.gov (NCT02143817). All the participants gave written informed consent to participate in the study before being included.

2.2. Study design

Participants were randomly assigned to one of three interventions for 8 weeks: WBVT with placebo (WBVT, n = 14), L-citrulline (n = 14), or WBVT + L-citrulline (n = 13). Prior to baseline measurements, allocation was stratified for BMI (≤30.0 or ≥30.1 kg/m^2) and SBP (≤139 or ≥140 mm Hg). PWV, body composition, and muscle strength were assessed in all participants before and after the interventions. Before each visit, participants were asked to abstain from caffeine and alcohol consumption for 24 h. Participants were also asked to discontinue medication the night and morning before testing. Cardiovascular measurements were collected during the same time of day (±1 h) in the morning following an overnight fast and between 48 and 72 h following the last exercise session. Participants rested in the supine position for at least 10 min before data collection in a quiet temperature-controlled room (23 °C ± 1 °C). Women were asked not to make any changes in their regular lifestyle other than the assigned intervention (s).

2.3. Interventions

Participants in the WBVT and WBVT + L-citrulline groups completed supervised training 3 times a week separated by at least 48 h for 8 weeks. Participants performed four static and four dynamic leg exercises on a vibration platform (pro5 AIRdaptive; Performance Health Systems, Northbrook, IL). Considering 180° as full knee extension, exercises were squats at 90° and 120° knee angle with normal stance, squat at 120° knee angle with wide-stance, and calf raises with maximal heel elevation. Static exercises were performed maintaining the joint angles without movement (Machado et al., 2010). Dynamic exercises were performed with slow controlled movements starting from an upright position to the assigned knee angles (90° and 120°) described for the three types of squat and also moving the heels from maximal elevation to below the platform for the calf raises. The movement during dynamic exercises was controlled by the use of a metronome at a rate of 3 s eccentric/2 s concentric phases. The training volume was progressed by increasing the intensity of vibration (25 to 40 Hz of frequency and 1 mm to 2 mm of amplitude), duration of the exercise set (30–60 s), number of sets (1–5), total duration of the training session (11–60 min), and decreasing the duration of rest periods (60–30 s). The training protocol was adapted from others previously used in postmenopausal and obese women (Figueroa et al., 2012, 2014b; Machado et al., 2010).

Participants in the L-citrulline and WBVT + L-citrulline groups were supplemented with 6 g of L-citrulline/day. The L-citrulline was ingested in the form of 750 mg capsules corresponding to 4 capsules (3 g) before breakfast and 4 capsules before sleeping. Likewise, the WBVT group consumed 4 capsules of maltodextrin before breakfast and 4 capsules before sleeping to match the number of capsules ingested daily by the WBVT + L-citrulline group. The selected dose and times of ingestion were based on previous studies with L-citrulline or watermelon supplementation that showed decreases in BP, arterial stiffness, and wave reflection magnitude (Figueroa et al., 2013b; Ochiai et al., 2012; Schwedhelm et al., 2008). The last dose of L-citrulline and placebo was ingested 48 h prior to the last visit in order to avoid any possible acute vascular effects of L-citrulline. Participants self-recorded supplementation logs on a weekly basis. Participants were required to return the logs and unused capsules after 4 and 8 weeks to verify their adherence to the supplementation. Compliance was calculated by dividing the consumed capsules by the expected number of capsules.

2.4. Arterial stiffness

Following at least 10 min of supine rest, PWV, brachial SBP, and diastolic BP (DBP) were assessed using a PWV/ABI automatic device (VP-2000, Omron Healthcare Inc., Vernon Hills, IL). Three arterial segments, cfPWV (aortic), faPWV (leg), and baPWV (systemic), were obtained by wrapping BP cuffs around both arms (brachial arteries) and ankles (posterior tibial arteries) and two tonometers over the right carotid and femoral arteries. The time delay between the feet of the pulse waves was related to the R-wave of the ECG, which automatically determined the transit time. A non-elastic tape measure was used to measure the distance between the right common carotid and femoral arteries. The brachial-ankle and femoral-ankle distances were automatically calculated by the device, which were based on the subject's height (Yamashina et al., 2002). cfPWV, faPWV, and baPWV were calculated from the measurements of the transit time and the distance between 2 recording sites (Yamashina et al., 2002).

2.5. Body composition

Body weight and height were measured to the nearest 0.1 kg and 1 cm using a beam scale (Sunbeam Products Inc., Boca Raton, FL) and stadiometer, respectively. BMI was computed as weight in kg/height in m^2. Leg LM, arm LM, appendicular LM (ALM = arms LM + legs LM), leg LM index (LM / total mass), and body fat mass percentage (BF%) were evaluated using whole-body dual-energy X-ray absorptiometry (DXA) scans (GE Lunar DPX-IQ, Madison, WI). Appendicular LM index (ALMI) was calculated as ALM/height in m^2.

2.6. Muscle strength

The eight-repetition maximum test (8RM), defined as the maximum weight that can be moved in good form eight times through a full range of motion, was used the leg press to assess muscle strength (MedX Corp., Ocala, FL, USA). The 8RM has been shown to be safe and reliable in postmenopausal women (Figueroa et al., 2013a, 2014a; Phillips et al., 2010).

2.7. Statistical analysis

The Shapiro–Wilk test was used to examine data normal distribution. Based on previous data (Donley et al., 2014; Figueroa et al., 2014b), we calculated that 12 participants per group would provide 80% power (two-sided $\alpha = 0.05$) to detect a 9% and 7.5% reduction in cfPWV and faPWV. One-way analysis of variance (ANOVA) was used to examine group differences at baseline. Changes in dependent variables were evaluated by a 3 × 2 ANOVA with repeated measures (group [WBVT, L-citrulline, and WBVT + L-citrulline] × time [before × after 8 weeks]). When a significant group-by-time interaction and/or time effect was identified, between-groups and within-group comparisons were performed using Tukey's test and paired *t*-test, respectively. $P < 0.05$ was considered statistically significant. Pearson's correlation coefficients were used to examine associations between changes in cfPWV and indices of muscle function (leg LM index and strength). Data analysis was performed using SPSS version 21.0 (SPSS, Chicago, IL, USA). Data are presented as mean ± SE.

3. Results

3.1. Participants

The WBVT and WBVT + L-citrulline completed at least 99.7 ± 1.1% of the exercise session. Compliance to the supplementation was 95.8 ± 3.0%, 97.5 ± 2.7%, and 96.4 ± 3.6% for the WBVT, L-citrulline, and WBVT + L-citrulline groups. Participant characteristics are shown in Table 1. There were no significant differences in characteristics (Table 1) and arterial parameters (Table 2) at baseline.

3.2. Arterial parameters

PWV of the 3 arterial segments are shown in Table 2. There was a significant group-by-time interaction for cfPWV ($P < 0.01$). There was a decrease in cfPWV following WBVT + L-citrulline (−0.91 ± 0.21 m/s, $P < 0.01$) compared with no significant changes in aortic stiffness after WBVT (−0.15 ± 0.18 m/s) and L-citrulline (−0.26 ± 0.30 m/s). Moreover, faPWV was similarly decreased following WBVT (−0.75 ± 0.23 m/s, $P < 0.01$), L-citrulline (−0.41 ± 0.16 m/s, $P < 0.05$), and WBVT + L-citrulline (−0.55 ± 0.14 m/s, $P < 0.01$). Similarly, baPWV decreased with WBVT (−0.99 ± 0.35 m/s, $P < 0.05$), L-citrulline (−0.91 ± 0.27 m/s, $P < 0.01$), and WBVT + L-citrulline (−1.38 ± 0.10 m/s, $P < 0.001$) with no significant between-group differences.

Table 1
Participants' characteristics at baseline. Q2

Variable	WBVT	L-CIT	WBVT + L-CIT
Number	14	14	13
Age	58 ± 1	58 ± 1	58 ± 1
Weight (kg)	89. 5 ± 2.8	83.8 ± 2.3	88.3 ± 3.2
Height (m)	1.60 ± 0.01	1.60 ± 0.01	1.62 ± 0.01
BMI (kg/m^2)	35.0 ± 0.9	33.0 ± 0.8	33.8 ± 1.1
SBP (mm Hg)	141 ± 3	137 ± 4	140 ± 3
DBP (mm Hg)	80 ± 2	77 ± 2	78 ± 2
Arm LM (kg)	5.0 ± 0.2	4.6 ± 0.2	4.6 ± 0.3
Leg LM (kg)	16.0 ± 0.8	14.8 ± 0.5	15.1 ± 0.7
Leg strength (kg)	238 ± 19	227 ± 15	233 ± 14

Data are mean ± SEM.
WBVT, whole-body vibration training; L-Cit, L-citrulline supplementation; BMI, body mass index; SBP, systolic blood pressure; DBP, diastolic blood pressure; and LM, lean mass.

3.3. Body composition and muscle strength

Body weight, BMI, arm LM, and arm strength did not change following the three interventions. WBVT + L-citrulline increased leg LM (6.0 ± 2.2%, $P < 0.05$) and ALMI (4.8 ± 1.8%, $P < 0.05$), but WBVT and L-citrulline did not affect leg LM (0.7 ± 1.1% and 0.8 ± 2.6%) and ALMI (Table 2). There were group-by-time interactions for leg LM index ($P < 0.05$) and leg strength ($P < 0.001$). Leg LM index increased ($P < 0.001$) following 8 weeks of WBVT + L-citrulline (Table 2 and Fig. 1a) compared to no changes after the other 2 interventions. Leg muscle strength increased ($P < 0.001$ for both) after both WBVT interventions compared to a no significant change after L-citrulline (Fig. 1b). BF% decreased after WBVT (−2.0 ± 0.6%, $P < 0.05$) and WBVT + L-citrulline (−1.9 ± 0.7%, $P < 0.01$), but not after L-citrulline supplementation (Table 2).

There was a negative relationship between the changes in cfPWV and leg LM index (r = −0.63, $P < 0.05$). No significant relationship was found between changes in cfPWV and leg strength.

4. Discussion

The main findings of our study were that L-citrulline supplementation added to WBVT reduced cfPWV and increased leg LM index in obese postmenopausal women with prehypertension or stage-1 hypertension. Moreover, the three interventions decreased systemic and leg arterial stiffness as measured by baPWV and faPWV.

Increased cfPWV leads to systolic hypertension, preferentially in older women (Berry et al., 2004), and to higher risk for cardiovascular events and mortality (Vlachopoulos et al., 2010). The annual increase in cfPWV is ~1.47 m/s in treated hypertensive adults (Benetos et al., 2002). We observed that cfPWV was reduced by 0.91 m/s (7.6%) after 8 weeks of WBVT + L-citrulline supplementation, corresponding to ~62% of the annual increase observed in middle-aged hypertensive adults (Benetos et al., 2002). Because each 1 m/s increase in cfPWV corresponds to a 14% increase in cardiovascular events (Vlachopoulos et al., 2010), our finding is relevant for the reduction of cardiovascular risk in postmenopausal women with prehypertension and hypertension. The majority of the studies have shown that aerobic training (Montero et al., 2014b) and RT (Collier et al., 2008) do not reduce cfPWV in middle-aged and older adults with prehypertension or hypertension and in obese individuals (Montero et al., 2014a,b). In contrast, reduction of cfPWV (−1.0 m/s) has been reported following 8 weeks of aerobic training in middle-aged overweight/obese adults with high SBP (Donley et al., 2014), suggesting that cfPWV can be positively modified by short-term exercise training if the appropriate stimulus is provided to a population with high cardiovascular risk. Interestingly, some studies have shown that cfPWV was reduced (0.4–0.6 m/s) following 9–16 weeks of aerobic training in middle-aged and older adults treated with antihypertensive drugs including vasodilators (Guimaraes et al.,

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Table 2
Arterial stiffness and body composition at baseline and after 8 weeks of interventions.

Variable	WBVT (n = 14)		L-CIT (n = 14)		WBVT + L-CIT (n = 13)	
	Baseline	8 weeks	Baseline	8 weeks	Baseline	8 weeks
cfPWV (m/s)	11.4 ± 0.4	11.2 ± 0.4	11.5 ± 0.4	11.3 ± 0.5	11.7 ± 0.3	10.8 ± 0.3**,****
faPWV (m/s)	10.2 ± 0.2	9.5 ± 0.3**	10.0 ± 0.2	9.6 ± 0.2*	10.4 ± 0.3	9.8 ± 0.2**
baPWV (m/s)	14.5 ± 0.4	13.5 ± 0.6*	14.1 ± 0.5	13.2 ± 0.5**	14.7 ± 0.4	13.4 ± 0.4***
ALMI	8.1 ± 0.3	8.2 ± 0.3	7.4 ± 0.3	7.5 ± 0.3	7.6 ± 0.3	7.9 ± 0.3*
Leg LMI	0.53 ± 0.01	0.53 ± 0.01	0.53 ± 0.02	0.53 ± 0.02	0.52 ± 0.02	0.54 ± 0.02***,*****
BF%	46.9 ± 1.4	46.0 ± 1.3*	46.7 ± 1.3	46.7 ± 1.5	47.1 ± 1.3	46.2 ± 1.4**

Data are mean ± SEM.
WBVT, whole-body vibration training; L-Cit, L-citrulline supplementation; PWV, pulse wave velocity; cfPWV, carotid–femoral PWV; faPWV, femoral-ankle PWV; baPWV, brachial-ankle PWV; ALMI, appendicular lean mass index; Leg LMI, leg lean mass index; and BF%, body fat percentage.
* $P < 0.05$ different than baseline.
** $P < 0.01$ different than baseline.
*** $P < 0.001$ different than baseline.
**** $P < 0.05$ different than WBVT.
***** $P < 0.05$ different than L-citrulline.

2010; Vogel et al., 2013). These findings support an additive effect of vasodilatory drugs and exercise training on cfPWV. Our participants were overweight or obese women with prehypertension or hypertension. In this population, 6 weeks of L-citrulline-rich watermelon supplementation reduced baPWV and SBP (Figueroa et al., 2013b). Therefore, the combination of a vasodilatory amino acid (L-citrulline) and WBVT during 8 weeks had an additive effect, reducing cfPWV in postmenopausal women.

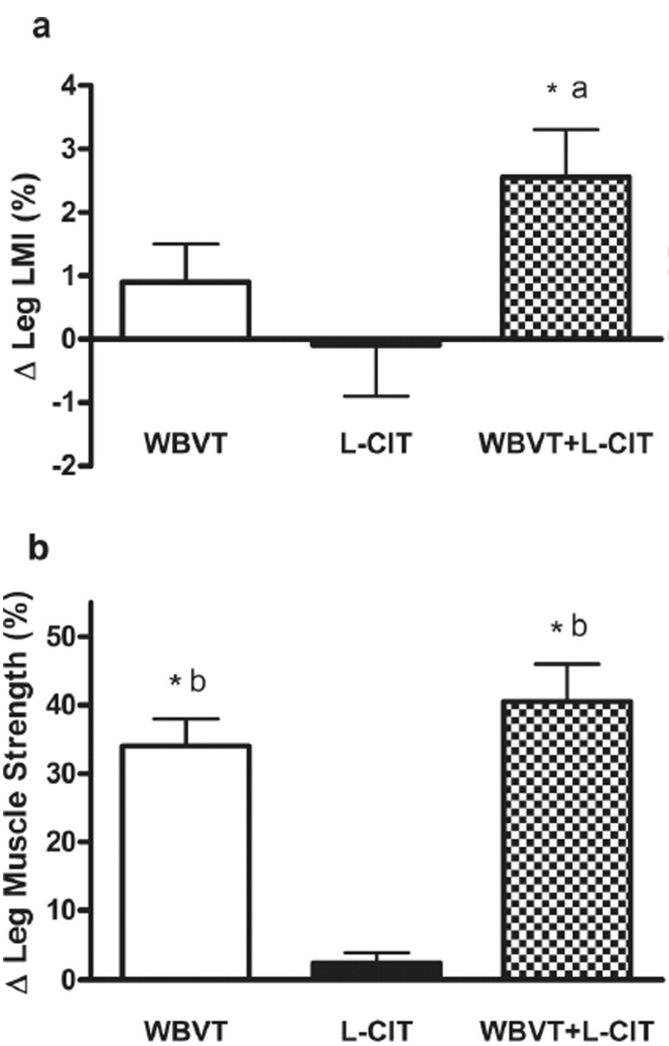

Fig. 1. Percent changes (Δ) in leg lean mass index (a) and muscle strength (b) after 8 weeks of intervention. Abbreviations: LMI, lean mass index; WBVT, whole body vibration training; and L-CIT, L-citrulline. Data are expressed as mean ± SEM. *$P < 0.001$ vs. before the intervention (within-group differences); $^{a}P < 0.05$ and $^{b}P < 0.001$ vs. L-citrulline (between-group differences).

In agreement with the result of our WBVT alone, 8 to 12 weeks of RT did not reduce cfPWV in postmenopausal women (Casey et al., 2007; Figueroa et al., 2013a; Rossow et al., 2014), although some variation may exist in this response. The inability of short-term exercise training to reduce cfPWV in older adults with hypertension might be explained by a difficulty to reverse age related structural changes in the aortic wall including altered collagen and elastic fibers content (Zieman et al., 2005). It appears that cfPWV is specifically resistant to decrease in older hypertensive adults (Vogel et al., 2013) due to accelerated arterial aging (Benetos et al., 2002).

Women experience a progressive increase in baPWV after the menopause (Zaydun et al., 2006). We found that our three interventions caused similar reductions in systemic (baPWV) and leg (faPWV) PWV. Consistent with our current findings, previous studies have reported that 6–12 weeks of WBVT reduced baPWV in obese young normotensive women (−0.9 m/s) (Figueroa et al., 2012), obese prehypertensive and hypertensive postmenopausal women (−1.3 m/s) (Figueroa et al., 2014b), and non-obese normotensive older adults (−0.7 m/s) (Lai et al., 2014). Moreover, previous studies have reported decreases in baPWV (−1.1 m/s) following L-citrulline or L-citrulline-rich watermelon supplementation (Figueroa et al., 2013b; Ochiai et al., 2012). Similarly, vasodilatory drugs can reduce baPWV (Takami and Shigemasa, 2003) without affecting cfPWV in older adults with hypertension (Mackenzie et al., 2009). Since baPWV is determined by cfPWV and faPWV (Yamashina et al., 2002), and only faPWV was decreased in the present study, our findings indicate that L-citrulline supplementation and WBVT exerted their systemic vascular effects through a reduction in faPWV.

We have previously reported a reduction in faPWV after 12 weeks of WBVT in obese older women with prehypertension or hypertension (Figueroa et al., 2014b). This positive effect of WBVT on faPWV might be clinical relevant as increased leg arterial stiffness is associated with systolic hypertension (Choo et al., 2014; Wohlfahrt et al., 2013), abdominal adiposity and insulin resistance (Park et al., 2010). Of clinical concern, RT has shown to be inefficient to reduce faPWV in overweight and obese older women (Casey et al., 2007; Figueroa et al., 2013a; Rossow et al., 2014), but more importantly, it has increased faPWV and cfPWV in middle-aged adults with prehypertension and untreated stage-1 hypertension (Collier et al., 2008).

Increased PWV is associated with sarcopenia in the legs (Abbatecola et al., 2012; Ochi et al., 2010). We used the leg LM index (lean mass / total mass) because our WBVT exclusively targeted leg muscles. In the present study, leg LM index increased with WBVT + L-citrulline by increasing LM without changing fat mass. Because adiposity is associated with an accelerated loss of leg LM (0.02 kg/year) in older women (Koster et al., 2011), our findings indicate that WBVT + L-citrulline

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may reduce sarcopenia-related physical disability in obese postmenopausal women. In contrast, WBVT alone had no apparent effect on leg LM index. Indeed, this is not surprising since no muscle hypertrophy has been reported in postmenopausal women after 10 to 24 weeks of RT (Figueroa et al., 2013a; Phillips et al., 2010; Verschueren et al., 2004), which is considered the most effective exercise modality for improvements in muscle function. It could be that 8 weeks of WBVT is too short and/or the intensity is low (20 repetitions/set) (Tapp and Signorile, 2014) for increasing leg LM in obese middle-aged women (Milanese et al., 2013).

A greater decrease in leg muscle strength than LM occurs in older women (Koster et al., 2011); thus, strength training may prevent muscle weakness and disability in older women. In the present study, leg muscle strength increased similarly following 8 weeks of WBVT (33.4%) and WBVT + L-citrulline (41.0%). Since leg muscle loss is 2.6% per year in older women (Koster et al., 2011), the 7.6% difference between both WBVT interventions in strength gain might correspond to the reversal of muscle strength loss that is experienced in 3 years. These findings confirm that WBVT is an effective strengthening alternative for postmenopausal women (Figueroa et al., 2014b; Machado et al., 2010; Tapp and Signorile, 2014; Verschueren et al., 2004). The lack of correlation between the changes in leg muscle strength and the three PWV parameters indicates that muscle strength gain is not a determinant for the improvements in PWV observed with WBVT. Nevertheless, because cardiovascular disease risk increases by 23% in obese adults with reduced muscle mass, but not in those with normal strength (Stephen and Janssen, 2009), improvements in leg muscle strength with WBVT may reduce cardiovascular risk in obese postmenopausal women by reducing physical disability. It is known that overweight and obese older adults with high strength levels have reduced all-cause mortality (Stenholm et al., 2014) emphasizing the importance of strength training. Our study demonstrated that improvements in leg muscle strength and leg PWV coexist in postmenopausal women after WBVT.

Aortic stiffening is determined by structural characteristics of the arterial wall (Zieman et al., 2005) and impaired endothelial NO-dependent vasodilation (Campbell et al., 2011). Both WBVT and L-citrulline supplementation have shown to increase circulating NO (Humphries et al., 2009; Ochiai et al., 2012) and reduce baPWV (Figueroa et al., 2012, 2014b; Ochiai et al., 2012). Although the exact underlying mechanism for the increase in leg LM index is unclear, it is possible that the increased leg muscle perfusion through NO-induced vasodilation may contribute to muscle mass gains (Dillon et al., 2011).

Our study is limited by a relatively small sample size, although our findings were both statistically and clinically significant. Moreover, our participants were overweight–obese postmenopausal women with prehypertension or stage-1 hypertension, and thus, the findings of this study may not apply to a population with different age, sex, and health condition. Because the increase in vascular reactivity appears to occur earlier than the reduction in cfPWV with strength training in some postmenopausal women (Rossow et al., 2014), interventions longer than 8 weeks are needed to clarify the effect of WBVT on PWV and lean mass.

5. Conclusion

In conclusion, 8 weeks of combined WBVT and L-citrulline supplementation improved aortic stiffness and muscle function in obese postmenopausal women. Although 8 weeks of L-citrulline and WBVT alone reduced leg arterial stiffness, L-citrulline had no effect on muscle function while WBVT increased muscle strength but not LM index. Therefore, WBVT + L-citrulline supplementation could be an alternative intervention for counteracting the effects of aging and obesity on arterial stiffness and leg sarcopenia in postmenopausal women.

Conflict of interest

The authors declare no conflict of interest.

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