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All-Extremity Exercise Training Improves Arterial Stiffness in Older Adults

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Abstract

Large elastic arteries stiffen with age which predisposes older adults to increased risk for cardiovascular disease. Aerobic exercise training is known to reduce the risk for cardiovascular disease, but the optimal exercise prescription for attenuating large elastic arterial stiffening in older adults is not known.

Purpose—The purpose of this randomized controlled trial was to compare the effect of all-extremity high-intensity interval training (HIIT) and moderate-intensity continuous training (MICT) on aortic pulse wave velocity (PWV) and carotid artery compliance in older adults.

Methods—Forty-nine sedentary older adults (age: 64±1 years), free of overt major clinical disease, were randomized to HIIT (n=17), MICT (n=18) or non-exercise controls (CONT; n=14). HIIT (4x4 minutes at 90% of peak heart rate interspersed with 3x3 minutes active recovery at 70% of peak heart rate) and isocaloric MICT (70% of peak heart rate) were performed on an all-extremity non-weight-bearing ergometer, 4 days/week, for 8 weeks under supervision. Aortic (carotid to femoral; cfPWV) and common carotid artery compliance were assessed at pre- and post-intervention.

Results—cfPWV improved by 0.5 m/sec in MICT (P=0.04), but did not significantly change in HIIT and CONT (P>0.05). Carotid artery compliance improved by 0.03 mm^2/mmHg in MICT (P=0.001), while it remained unchanged in HIIT and CONT (P>0.05). Improvements in arterial stiffness in response to MICT were not confounded by changes in aortic or brachial blood pressure, heart rate, body weight, total and abdominal adiposity, blood lipids or aerobic fitness.

Conclusion—All-extremity MICT, but not HIIT, improved central arterial stiffness in previously sedentary older adults free of major clinical disease. Our findings have important implications for aerobic exercise prescription in older adults.

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The authors declare no conflict of interest.

The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

The results of the present investigation do not constitute endorsement by the American College of Sports Medicine.

Keywords

AORTIC PULSE WAVE VELOCITY; CAROTID ARTERY COMPLIANCE; AEROBIC EXERCISE; MODERATE INTENSITY CONTINUOUS TRAINING HIGH-INTENSITY INTERVAL TRAINING; AGING

INTRODUCTION

Aging leads to vascular changes including thickening and stiffening of large elastic arteries (aorta and carotid), increases in systolic blood pressure, and widening of pulse pressure, which predispose older adults to cardiovascular disease (CVD) (reviewed in Fleg and Strait 2012 (5)). Arterial stiffness is a strong predictor of future CVD events and mortality (16, 35), therefore, it is an important therapeutic target for CVD prevention. Aerobic exercise training is often prescribed for reducing CVD risk, but exercise prescription for older adults remains generic and there is still controversy regarding the optimal exercise regimen for attenuating arterial stiffening in aging.

High-intensity interval training (HIIT) and isocaloric moderate-intensity continuous training (MICT) on the treadmill have been reported to improve CVD risk factors, including aerobic fitness, endothelial function, and cardiac function, in patients with cardiometabolic diseases (18, 24, 32, 38) while the effect of HIIT on these risk factors has been found to be greater compared with MICT. We are aware of only two studies that have compared the effect of HIIT and MICT on arterial stiffness (4, 6). These studies demonstrated that HIIT is more effective in improving arterial stiffness than MICT in young and middle-aged patients with hypertension (6) and young women at high familial risk for hypertension (4). However, the effect of HIIT vs. MICT on arterial stiffness in older adults has not been investigated.

In older adults, balance and musculoskeletal problems often limit weight-bearing exercise. Due to the aging of the world population, the number of musculoskeletal disorders is expected to increase by 70% worldwide in the next 15 years (23), therefore, alternative non-weight-bearing exercise modalities need to be established to allow implementation in a larger portion of the aged population. All-extremity non-weight-bearing exercise is an appealing modality because it allows compensation for fatigue due to unilateral or lower extremity musculoskeletal problems and also activates a large amount of muscle mass. We have recently established that all-extremity HIIT and MICT are feasible and safe in older adults (9), but whether these non-weight-bearing alternatives improve arterial stiffness in aging is unknown. Therefore, the purpose of this randomized controlled trial was to compare the effect of all-extremity non-weight-bearing HIIT and MICT on arterial stiffness in previously sedentary older adults free of cardiovascular and other major clinical disease.

METHODS

Subjects

Men and women 55 and 79 years of age were recruited in the study. More than 80% of those enrolled were 60 years or older. Subjects did not smoke or use tobacco products and were free of overt cardiovascular and other major clinical disease (e.g., diabetes, liver and renal

disease) as assessed by rigorous screening: medical history, physical examination, blood tests (i.e., comprehensive metabolic and lipid panels and complete blood count with differential) and 12-lead electrocardiogram during rest and diagnostic graded exercise test. Prior to study enrollment, subjects were not on hormone replacement therapy (i.e., estrogen, progesterone, testosterone) for at least 2 years and female subjects were postmenopausal (i.e., cessation of menses for ≥ 2 years). Subjects on stable use of medication for controlling lipids and blood pressure were included in the intervention, but were required not to alter their therapeutic regimen during study participation. Subjects were weight stable (i.e., <5% body weight change) for at least 6 months prior to enrollment and were asked to maintain their dietary habits constant during study participation. Subjects were sedentary for at least 12 months prior to enrollment, defined as no regular aerobic exercise training (i.e, they engaged in <30 min of aerobic exercise ≤2 times/week), based on self-reported habitual physical activity using the modifiable activity questionnaire. Subjects were instructed not to increase their leisure-time activity during study participation. Triaxial accelerometers (ActiGraph GT3X, software version 5.10.0) were used to monitor physical activity for 4 days (3 weekdays and 1 weekend day) prior to study enrollment. Activity monitoring was repeated at the end of the intervention to examine any potential changes in physical activity that could confound our results.

The study was approved by the Institutional Review Board of the University of Florida. The purpose, nature, and risks of the study were explained to the subjects and their written informed consent was obtained prior to participation.

Study Design

A total of 89 research volunteers provided written informed consent to participate in the study. Subjects who met the study inclusion criteria (n=49) were randomized to HIIT (n=17; 13 women), MICT (n=18; 10 women), or non-exercise controls (CONT; n=14; 10 women). Randomization was based on computer-generated random numbers and was stratified by initial peak oxygen consumption (L/min). Arterial stiffness measurements were performed in the morning, at the same time of day pre- and post-intervention, by the same researchers strictly following standard operating procedures. Data were coded to ensure blinding during analysis.

Exercise Intervention

HIIT and MICT were performed on an all-extremity non-weight-bearing air-braked ergometer (Airdyne AD4, Schwinn, Vancouver, WA) which incorporates pulling/pushing the handlebars with the upper extremities while cycling with lower extremities. Exercise sessions were carried out 4 days/week, for 8 weeks under supervision. MICT consisted of 47 minutes at 70% of peak heart rate (HR_{peak}) and included a 10-min warm-up and 5-minute cool-down at the same intensity. HIIT consisted of 40 minutes as follows: 4x4 minutes at 90% of HR_{peak} alternated by 3x3 minutes active recovery at 70% of HR_{peak} and a 10-min warm-up and 5-minute cool-down at 70% of HR_{peak}. The intensity and duration of HIIT and MICT were based on the protocols published by Tjonna et al (32) which were designed to result in isocaloric expenditure on the treadmill. In the current study, the caloric cost of the

all-extremity HIIT and MICT protocols was confirmed to be equal by measuring oxygen consumption during HIIT and MICT using computer-assisted open-circuit spirometry.

HR_{peak} was determined during the maximal exercise test at pre-intervention. A heart rate telemetry system (Polar Team 2 Pro, version 1.4.3) was used to monitor and record heart rate throughout each training session. Subjects were instructed to alter the speed of their arm and leg movement to achieve their target heart rate. The intervention was preceded by a period of familiarization/preconditioning because subjects were previously sedentary and unfamiliar with all-extremity exercise. The initial exercise duration/intensity was determined by the subject's motivation, fitness level, and capacity to perform all-extremity exercise. Initial intensity was based on a self-selected comfortable pace and in the majority of subjects ranged between 65 and 75% of HR_{peak}, while the initial duration was at least 15 min (average=24±2 min). The duration and intensity were gradually increased every session as tolerated until subjects were able to complete 40 continuous minutes of exercise at 70% of HR_{peak}. To reach this goal, 5±1 sessions were required on average.

Study Procedures

All resting cardiovascular measurements were performed in the morning, in a semi-darkened temperature-controlled room, after a minimum of 20 minutes of supine quiet rest. In accordance to recently published guidelines (33), subjects abstained from alcohol, caffeine, medication use and food intake (including fluids other than water) for at least 12-hours prior to data collection.

Aortic pulse wave velocity (PWV)—Aortic PWV, commonly measured as carotid to femoral PWV (cfPWV), is considered to be the gold standard method of assessing arterial stiffness in humans. cfPWV was measured using the SphygmoCor MM3 system (AtCor Medical, New South Wales, Australia) as we have previously described (10) and according to recently published guidelines (33). Briefly, cfPWV was determined by recording pressure pulse waves at the carotid and femoral arteries using a high-fidelity micromanometer (Millar Instruments, Houston, TX) and calculating the distance between the recording sites divided by the time delay between the carotid and femoral pulse waves. The distance was measured using a non-stretchable tape from the suprasternal notch to the carotid recording site and from the suprasternal notch to the femoral recording site; the former distance was subtracted from the latter and used in the calculation of cfPWV. The average of three high-quality measures, as defined by the manufacturer, was used for analysis. The reliability of cfPWV measures was previously examined in our lab in adults 21 to 79 years of age (n=22) using repeated measures obtained within 1 week (unpublished data). Cronbach's alpha intra-class reliability coefficient was 0.974, $P<0.0001$ and mean±SE was 6.50±0.30 vs. 6.53±0.30 m/s for day 1 vs. day 2, $P=0.8$.

Carotid artery compliance and structure—Carotid artery compliance, an established measure of arterial stiffness, was assessed by recording images of the common carotid artery using high-resolution ultrasonography (Aplio XV; Toshiba Medical Systems, Otawara, Japan) and simultaneous contralateral carotid pressure using applanation tonometry (TCB-500, Millar Instruments), as we have previously described (10). Briefly, the carotid

pressure waveforms were obtained with a pencil-type tonometry transducer and the signal was calibrated by the brachial diastolic and mean arterial pressure using the SphygmoCor MM3 software (AtCor Medical). The common carotid artery was imaged with the ultrasound transducer placed at a 90° angle to the vessel so that the near and far walls were clearly visualized. Common carotid artery diameters and intima-media thickness (IMT) were measured approximately 2 cm proximal to the carotid bulb using a commercially available wall tracking software (Vascular Analysis Tools 5.8.2, Medical Imaging Applications). Carotid arterial compliance (C), a measure of arterial buffering capacity (20), was calculated as:

$$C = [(D1-D0)/D0]/[2(P1-P0)]\pi(D0)^2$$

where D1 and D0 are the maximal and minimal carotid diameters and P1 and P0 are the highest and lowest carotid pressures. IMT was measured at the far wall following established guidelines (28). IMT and lumen diameter for normalizing wall thickness were measured at end diastole.

Central and peripheral blood pressures—Aortic systolic pressure was determined non-invasively using the SphygmoCor MM3 device (AtCor Medical) as we have previously described (10). Briefly, radial artery pressure waveforms were recorded using a high-fidelity micromanometer (Millar Instruments) and were calibrated using the brachial diastolic and mean arterial pressure. Aortic pressure waveforms were generated from the radial waveforms by the SphygmoCor software (AtCor Medical) by applying proprietary digital signal processing and a mathematical transfer function. Only high quality recordings, as defined by the manufacturer, were used for analysis. Peripheral blood pressure was measured over the brachial artery using an automated oscillometric device (Dinamap, GE). Aortic and brachial pulse pressures were calculated as the difference between the corresponding systolic and diastolic pressures.

Maximal exercise test—The maximal exercise test was performed on the treadmill because walking is a familiar exercise modality for sedentary aged individuals and treadmill test results are a significant mortality predictor in older adults (30). The graded exercise test protocol consisted of a 6-minute warm-up at a walking speed corresponding to 70~80% of the age-predicted maximal heart rate followed by grade increases of 2.5% every 2 minutes until volitional exhaustion (3, 9, 11). To allow determination of improvements in time to exhaustion (i.e., maximal exercise test duration) in response to the intervention, post-intervention testing for each participant was performed by replicating their pre-intervention protocol. Oxygen consumption was measured using computer-assisted open-circuit spirometry. Peak oxygen consumption (VO_{2peak}) is reported because not all subjects attained at least 3 of the following criteria for establishing maximal oxygen consumption: 1) a plateau in oxygen consumption (<100 ml) with increasing exercise intensity; 2) a maximal respiratory exchange ratio of at least 1.15; 3) achievement (±10bpm) of age-predicted max heart rate (220–age); and 4) a rating of perceived exertion of at least 18 on Borg's scale. HR_{peak} was defined as the highest heart rate recorded during the maximal exercise test.

Height, weight, body mass index and waist circumference—Body weight was measured to the nearest 0.1 kg with an electronic scale (Tanita, Arlington Heights, IL, USA) and height was measured three times to the nearest mm with a stadiometer while subjects were barefoot and dressed in light clothing. Body mass index was determined as weight divided by height squared (kg/m^2). Waist circumference, a surrogate measure of abdominal adiposity, was measured at the iliac crest using a non-stretchable tape and the average of three measures was used in the analysis.

Blood lipids—Fasting blood samples were analyzed by a clinical laboratory via spectrophotometry using standard procedures.

Statistical Analyses

Statistical analyses were performed using SPSS version 23 and power calculations were performed using G*Power version 3.0.1. Statistical significance for all analyses was set at $P< 0.05$. Because of the novelty of our intervention there were no previous data on which to base formal *a priori* calculations for effect size and sample size for our primary outcomes of cfPWV and carotid artery compliance. *Post hoc* power calculations indicate that for $\alpha=0.05$, our study had >80% power to demonstrate a significant effect of the intervention on cfPWV for effect sizes ≤ 0.08 and on carotid artery compliance for effect sizes ≤0.22. Data normality and outliers were evaluated using the Explore procedure in SPSS. To compare baseline group differences, one-way analysis of variance was used. To examine the effect of the intervention, 3×2 analysis of variance with repeated measures was used to test the group (CONT, MICT and HIIT) by time (pre- vs. post-intervention) interaction. Significant group by time interactions were followed by post hoc pairwise multiple comparisons adjusted using the Bonferroni correction. Data are reported as mean ± S.E.M.

RESULTS

Exercise intervention

Nine of the 49 subjects who were randomized (i.e., 18%) did not complete the intervention for the following reasons: 3 subjects in HIIT, due to family issues (n=1) and schedule conflict (n=2); 4 in MICT, due to family issues (n=1), schedule conflict (n=1) or lack of motivation (n=2); and 2 in CONT due to inability to contact for follow-up measures (n=2). Two subjects were excluded from the analysis: 1 in MICT due to illness unrelated to the intervention and 1 in CONT due to non-compliance. All-extremity exercise training was well-tolerated and there were no adverse events. Exercise training compliance was similar for MICT and HIIT (90±4% vs. 90±2%, respectively; P=0.9). The caloric expenditure per exercise session was also similar for MICT and HIIT (241±15 kcal vs. 226±15 kcal, respectively; P=0.5).

Arterial stiffness, carotid artery structure, and blood pressure

There were no significant baseline differences in subject characteristics (P≥0.1; Table 1) or measures of arterial stiffness, carotid artery structure and blood pressure (P≥0.1; Tables 2 and 3). In response to the intervention, arterial stiffness improved in MICT as indicated by decreases in cfPWV (P=0.04 vs. pre-intervention; Table 2) and increases in common carotid

artery compliance (P=0.001 vs. pre-intervention; Table 2 and Figure 1). However, common carotid artery compliance and cfPWV did not change in HIIT (P=0.3 and P=0.99, respectively) and CONT (P=0.8 and P=0.06). Common carotid artery diameter and IMT were unaffected by the intervention (P≥0.7 for group × time interaction; Table 2). Aortic and brachial pressures and heart rate did not change with the intervention (P=0.5 for group × time interaction; Table 3).

Physical activity and other subject characteristics

Physical activity measured by accelerometry was not different pre- vs. post-intervention indicating that our results are not confounded by changes in physical activity beyond the prescribed exercise sessions (P≥0.4 for group × time interaction; Table 1). Time to exhaustion during the maximal exercise test improved in both HIIT and MICT by 2.2±0.4 min and 1.0±0.4 min, respectively (P<0.0001 and P=0.02 vs. pre-intervention), but remained unchanged in CONT (P=0.5 vs. pre-intervention; P=0.008 for group × time interaction). VO_{2peak} improved in HIIT by 2.8±0.5 $ml \cdot kg^{-1} \cdot min^{-1}$ (P<0.0001 vs. pre-intervention; Table 1), but did not change in MICT (P=0.7) and CONT (P=0.9). Body weight, body mass index, waist circumference and blood lipids remained unchanged (P≥0.1 for group × time interaction; Table 1).

DISCUSSION

This is the first study to compare the effect of HIIT and MICT on arterial stiffness (i.e., aortic PWV and common carotid artery compliance) in older adults. Our main finding was that all-extremity MICT, but not HIIT, improved aortic PWV (i.e., cfPWV) and common carotid artery compliance in previously sedentary older adults who were free of overt cardiovascular and other major clinical disease. Improvements in arterial stiffness occurred over a relatively brief period of exercise training (8 weeks) and were not confounded by changes in aortic and brachial blood pressure, heart rate, body mass index and abdominal adiposity, blood lipids or aerobic fitness.

Arterial stiffness, carotid artery structure, and blood pressure

A change in aortic PWV of 1 m/s is associated with ~14% change in CVD risk (35). In our study, aortic PWV improved by 0.5 m/s following 8 weeks of all-extremity MICT and this change was independent of changes in heart rate or blood pressure. We are aware of only one previous aerobic exercise intervention focusing on aortic PWV in older adults, but this study resulted in no improvements in PWV following 1 year of moderate-intensity cycling (21). The conflicting findings could be due to differences in our exercise modalities (lower extremity exercise in the previous study vs. all-extremity exercise in current study) and in the younger age of our subjects (average age 70 vs. 64 years in our study). In agreement with our data, aortic PWV improved following moderate-intensity walking/jogging in middle-aged men (7) and moderate-intensity cycling in middle-aged women (39).

Carotid artery compliance improved by ~30% following all-extremity MICT in sedentary older adults in our study. Our results are in accordance with previous reports on the effect of moderate-intensity brisk walking on arterial compliance in sedentary middle-aged men (7)

and older men and women (27, 19, 29, 31). It is not surprising that carotid artery diameter, IMT and IMT normalized to lumen diameter were not affected by our intervention. Our data are consistent with other short-term studies in middle-aged and older men and postmenopausal women which did not result in significant structural changes in carotid artery (19, 29, 31). Substantially longer interventions may be required to result in carotid artery IMT modification.

In earlier studies, arterial stiffness improved following 12 to 16 weeks of moderate intensity lower body exercise in middle-aged and older adults (7, 19, 31, 39), whereas, in our study improvements in arterial stiffness occurred over a relatively shorter training duration (8 weeks). This could be due to the larger amount of active skeletal muscle mass involved in all-extremity exercise, but this remains to be determined by directly comparing all-extremity vs. lower-extremity exercise in the same cohort.

Central aortic pressures are increasingly recognized as being more important contributors to the pathogenesis of CVD than peripheral pressures (34). In our intervention, aortic and brachial blood pressure did not significantly change which is in agreement with previous short-term aerobic exercise interventions in middle-aged and older adults (1, 7, 22, 31). Our data suggest that improvements in aortic PWV can occur independent of blood pressure lowering effects of exercise. MICT resulted in improvements in time to exhaustion but not aerobic fitness in our study, which is consistent with previous reports in middle-aged and older adults (22, 31). Based on this finding, it appears that improvements in aerobic fitness are not a prerequisite for improvements in arterial stiffness (aortic PWV and carotid artery compliance). Our results are also not confounded by weight loss or changes in total and abdominal adiposity or blood lipids. Collectively, our data suggest that the exercise-induced improvements in arterial stiffness are likely due to direct vascular effects as opposed to being secondary adaptations to improvements in traditional CVD risk factors.

As expected, aerobic fitness improved more in response to HIIT than MICT in our study which is consistent with previous reports (8, 9, 18, 24, 26, 32, 38). Improvements in aerobic fitness are associated with reductions in CVD risk (12, 15), but cfPWV and carotid artery compliance did not improve with HIIT in our study. To the best of our knowledge, there are no published data on the effect of HIIT on arterial stiffness in older adults. However, in young and middle-aged patients with hypertension and young women at high familial risk for hypertension, HIIT but not MICT, resulted in significantly improved cfPWV (4, 6). Our discrepant results may be due to differences in our exercise interventions; the exercise intensity, duration, and frequency, intervention length and the exercise ergometer (lower extremity weight-bearing exercise on treadmill vs. all-extremity non-weight-bearing exercise on cycle ergometer) were different in our studies. Differences in the subjects' age and health status may also have contributed to our conflicting results.

Mechanisms of exercise-induced improvements in arterial stiffness

Advancing age is associated with arterial stiffening due to alterations in vascular structure and vascular smooth muscle function which affects vascular tone (recently reviewed in Santos-Parker et al. (25)). Age-related structural changes include increases in elastin fragmentation and collagen deposition and cross-linking of these proteins by advanced

glycation end products leading to additional stiffening (25). Age-related decreases in nitric oxide bioavailability, increases in vasoconstrictor activity (endothelin), decreases in carotid baroreflex sensitivity and increases in sympathetic nerve activity lead to increased vascular tone which contributes to arterial stiffening (25). These functional and structural changes have been linked to age-related oxidative stress and inflammation (13, 14, 36, 37).

The mechanisms by which all-extremity MICT improves cfPWV and carotid artery compliance are not clear. Currently, there is inadequate information regarding the mechanisms responsible for the effects of aerobic exercise on arterial stiffness in humans. This is largely due to the limited experimental tools that can be used to provide mechanistic insight (25) and the inability to obtain arterial wall samples from large elastic arteries (e.g., aorta and carotid artery) in healthy humans at pre- and post-intervention. Moreover, there is lack of consistent strong associations between measures of arterial stiffness and circulating blood factors including markers of oxidative stress and inflammation.

Given the relatively short duration of our intervention we speculate that improvements in arterial stiffness in our study are not likely to be due to changes in arterial wall composition of elastin and collagen because adaptations are thought to require a long period of time. It is reasonable to hypothesize that the mechanisms by which MICT improved arterial stiffness in our study may possibly include any of the following adaptations: decreases in oxidative stress and inflammation, increases in nitric oxide bioavailability, decreases in vasoconstrictor activity, increases in cardiovagal baroreflex sensitivity or decreases in sympathetic nervous system activity. Any of these potential changes could lead to vascular smooth muscle relaxation and reductions in vascular tone and stiffness, but the exact mechanisms remain to be elucidated.

It is not clear why arterial stiffness improved in response to all-extremity MICT but not HIIT. We have demonstrated that caloric expenditure and exercise compliance did not differ between the two forms of exercise, however, other differences may have possibly led to the disparate effects on arterial stiffness. First, the pattern or magnitude of increase in arterial wall shear stress may have been different during HIIT and MICT resulting in divergent local and systemic adaptations: HIIT consisted of intermitted high-intensity exercise interspersed with periods of active recovery while MICT consisted of continuous moderate-intensity exercise. Second, the duration of MICT per session was longer in order to match the higher caloric expenditure of HIIT which likely influenced the duration of augmented arterial shear stress. Third, each bout of HIIT may have resulted in greater acute increases in blood pressure or sympathetic nervous system activity compared with MICT which may have counteracted any potential improvements in arterial stiffness. In support of this concept, intensive resistance exercise, which is known to intermittently increase blood pressure, has previously been shown to have unfavorable effects on arterial compliance (17).

Study strengths and limitations

Our study has several strengths: 1) novelty of our exercise intervention and findings; 2) randomized controlled design; 3) heart rate monitoring/recording during supervised exercise; 4) and use of standardized testing procedures and blinding; 5) rigorous screening and exclusion of subjects with major clinical disease or subjects who were not previously

sedentary or weight stable; and 6) changes in cfPWV and carotid artery compliance were not confounded by changes in heart rate, blood pressure or other CVD risk factors. Our study also has some potential limitations. We can only speculate on the mechanisms responsible for the exercise-induced improvements in cfPWV and carotid artery compliance. Additional studies are needed to directly investigate the underlying mechanisms. It is also important to reproduce our results in larger cohorts which allow adequately powered sex-specific analysis. However, based on a recent meta-analysis, there is no indication of sex-differences in the effect of exercise on arterial stiffness (2).

CONCLUSIONS

This is the first study to demonstrate that 8 weeks of all-extremity non-weight-bearing MICT improved arterial stiffness (i.e., cfPWV and carotid artery compliance) in previously sedentary older adults free of major clinical disease. However, all-extremity non-weight-bearing HIIT did not result in changes in arterial stiffness. Our findings are not confounded by changes in other CVD risk factors such as reductions in aortic and brachial blood pressure, body mass index and abdominal adiposity or improvements in aerobic fitness and blood lipids. Our results have important implications for optimizing exercise recommendations for CVD prevention in aging, especially for aged individuals who might be unable to engage in weight-bearing exercise.

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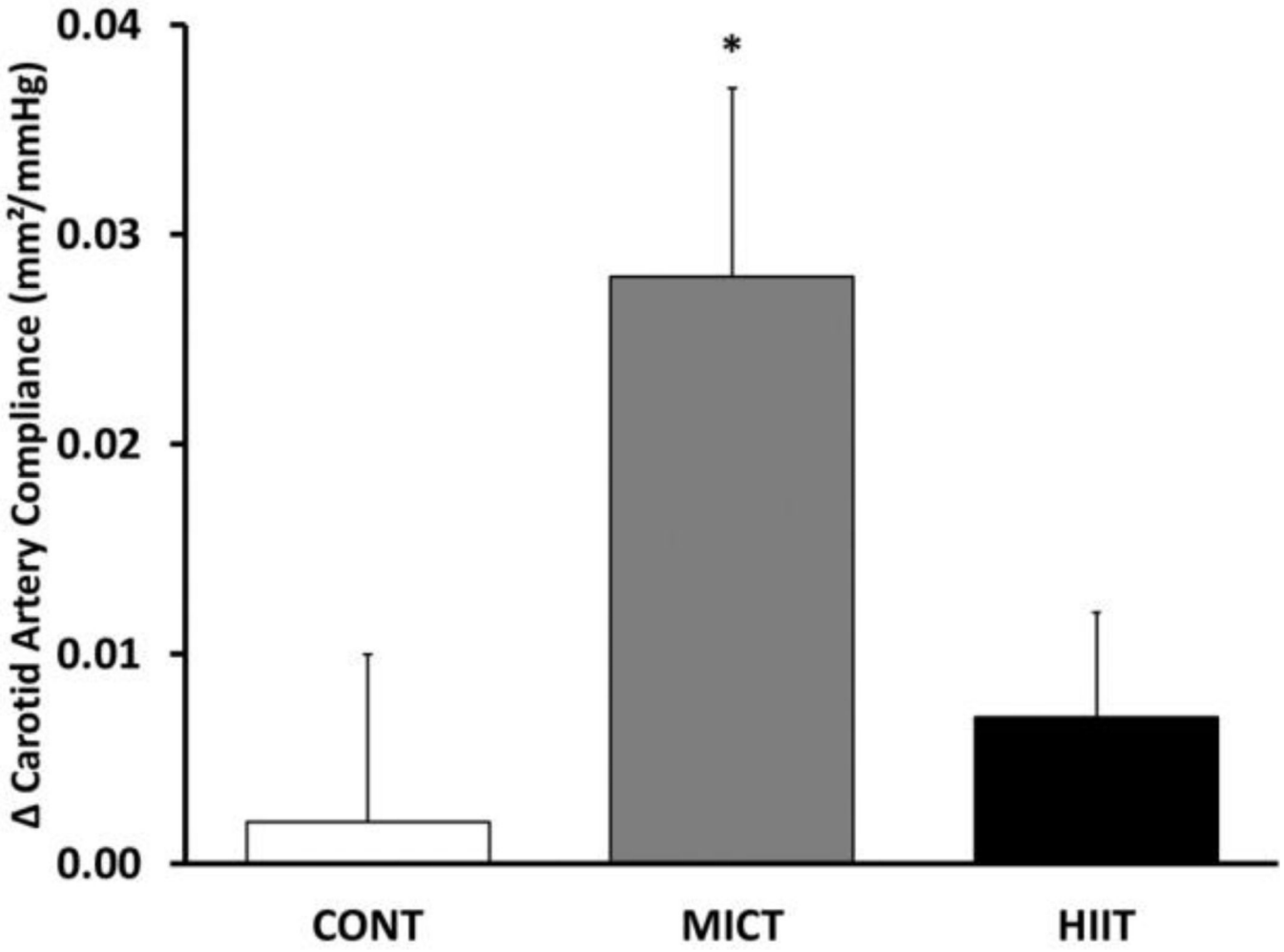

FIGURE 1.

Change in carotid artery compliance in response to the intervention. CONT, non-exercise controls; MICT, moderate-intensity continuous training; HIIT, high-intensity interval training. *P<0.05; post- vs. pre-intervention.

TABLE 1

Subject characteristics at pre- and post-intervention.

	CONT (n=11)		MICT (n=13)		HIIT (n=14)		P values group × time
	Pre	Post	Pre	Post	Pre	Post	
Age (years)	63±2	-	65±2	-	65±1	-	
Height (cm)	163.9±2.4	-	163.4±2.3	-	160.8±3.1	-	
Weight (kg)	68.2±4.3	68.7±4.4	76.6±2.8	76.0±2.6	72.9±4.0	72.8±3.8	0.4
Body mass index (kg/m^2)	25.3±1.4	25.5±1.4	28.7±1.0	28.5±0.9	28.1±1.2	28.0±1.1	0.4
Waist circumference (cm)	88.9±4.5	88.6±4.1	97.6±3.4	95.7±3.2	96.6±4.2	95.4±3.2	0.7
Total cholesterol (mg/dL)	179±12	188±12	210±14	208±9	202±11	190±10	0.1
HDL cholesterol (mg/dL)	56±4	62±5	56±4	55±4	66±6	66±6	0.1
LDL cholesterol (mg/dL)	103±9	103±11	130±12	129±7	114±7	104±7	0.5
Triglycerides (mg/dL)	89±12	115±16	117±14	119±17	103±21	96±13	0.2
VO_{2peak} (ml/kg/min)	25.1±1.7	25.2±1.6	26.0±1.8	26.2±1.8	22.9±0.8	25.8±0.9*	0.001
HR_{peak} (beats/min)	158±6	154±6	164±4	163±4	154±4	156±3	0.3
Physical activity							
Counts/min/day	475±41	468±34	439±38	477±52	446±23	490±32	0.4
Steps/day	5910±439	5853±515	5460±697	5612±667	5850±350	5996±569	0.9
Medication use for							
Hypertension, n	3	-	2	-	3	-	
Lipid lowering, n	3	-	5	-	5	-	

Values are mean ± SEM. P values for group × time interaction are based on 3 × 2 ANOVA with repeated measures.

*P<0.05 vs. pre-intervention are based on multiple pairwise comparisons adjusted by Bonferroni correction.

CONT, non-exercise controls; MICT, moderate-intensity continuous training; HIIT, high-intensity interval training; VO_{2peak}, peak oxygen consumption; HR_{peak}, peak heart rate; HDL, high-density lipoprotein; LDL, low-density lipoprotein.

TABLE 2

Arterial stiffness and carotid artery structure at pre- and post-intervention.

	CONT		MICT		HIIT		P values group × time
	Pre	Post	Pre	Post	Pre	Post	
cfPWV (m/s)	8.86±0.68	9.36±0.64	9.26±0.39	8.75±0.35 *	9.28±0.26	9.28±0.35	0.02
Carotid Compliance (mm^2/mmHg)	0.12±0.02	0.12±0.02	0.11±0.01	0.14±0.02 *	0.11±0.01	0.12±0.01	0.04
Carotid diameter (mm)	6.76±0.16	6.82±0.18	7.09±0.18	7.14±0.21	6.97±0.18	7.01±0.15	0.9
Carotid IMT (mm)	0.59±0.02	0.59±0.02	0.61±0.03	0.61±0.03	0.61±0.03	0.62±0.02	0.9
Carotid IMT/ lumen diameter	0.09±0.004	0.09±0.003	0.09±0.004	0.08±0.003	0.09±0.005	0.09±0.003	0.7

Values are mean ± SEM. P values for group × time interaction are based on 3 × 2 ANOVA with repeated measures.

* P<0.05 vs. pre-intervention are based on multiple pairwise comparisons adjusted by Bonferroni correction.

CONT, non-exercise controls; MICT, moderate-intensity continuous training; HIIT, high-intensity interval training; cfPWV, carotid-femoral pulse wave velocity; C, compliance; IMT, intima-media thickness; lumen; diameter.

TABLE 3

Central and peripheral blood pressure and heart rate at pre- and post-intervention.

	CONT		MICT		HIIT		P values group × time
	Pre	Post	Pre	Post	Pre	Post	
Aortic SBP (mmHg)	110±5	111±4	106±2	107±3	116±3	114±4	0.5
Aortic DBP (mmHg)	69±2	70±2	69±2	69±2	71±2	71±1	0.4
Aortic PP (mmHg)	42±4	41±4	37±2	38±4	45±3	44±3	0.5
Brachial SBP (mmHg)	116±5	118±5	112±2	112±3	122±3	120±4	0.6
Brachial DBP (mmHg)	68±2	69±2	69±2	69±2	70±1	70±1	0.8
Brachial PP (mmHg)	48±4	48±5	44±2	43±3	52±3	50±3	0.7
Heart rate (beats/min)	63±3	64±2	60±1	61±1	63±1	63±2	0.8

Values are mean ± SEM. P values for group × time interaction are based on 3 × 2 ANOVA with repeated measures.

CONT, non-exercise controls; MICT, moderate-intensity continuous training; HIIT, high-intensity interval training; SBP, systolic blood pressure; DBP, diastolic blood pressure; PP, pulse pressure.