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Post-Exercise Arterial Stiffness Responses Are Similar After Acute Eccentric and Concentric Arm Cycling

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ABSTRACT

International Journal of Exercise Science 15(2): 884-895, 2022. Upper-body resistance exercise effectively increases muscular strength, but may concomitantly increase arterial stiffness. Eccentric exercise can lead to muscle soreness and arterial stiffness in untrained participants. However, it is unclear if upper-body eccentric exercise could reduce arterial stiffness in a single session for participants that have undergone progressive training. Our purpose was to compare acute responses to upper-body eccentric (novel, ECCarm) and concentric (traditional, CONarm) steady state arm cycling. We hypothesized that arm arterial stiffness would be reduced after both ECCarm and CONarm. Twenty-two young healthy individuals performed either ECCarm ($n = 11$) or CONarm ($n = 11$) at ~70% of peak heart rate for 20 min after a training period. Heart rate, central pulse wave velocity (cPWV), and peripheral pulse wave velocity (pPWV; i.e., arm arterial stiffness) were assessed before, 10 min, and 30 min after exercise. Heart rate was not elevated at 10 min post ECCarm, but was elevated at 10- and 30-min post CONarm ($p < 0.01$). After exercise, pPWV was decreased at 10 min post for both ECCarm (7.1 ± 0.3 vs. 6.5 ± 0.2 m/s) and CONarm (7.0 ± 0.2 vs. 6.5 ± 0.2 m/s; $p < 0.05$), while both groups returned to baseline values 30 min post. cPWV did not change in either group. Our results indicate that acute ECCarm provides a high-force, low energy cost form of resistance exercise that acutely reduces arm arterial stiffness. The reduction in pPWV and rapid heart rate recovery suggests that ECCarm is a safe form of exercise for overall and cardiovascular health.

KEY WORDS: Arm ergometry, eccentric exercise, pulse wave velocity, steady state exercise

INTRODUCTION

Arterial stiffness is a contributor to hypertension (8), and increases the risk for cardiovascular disease (41). The American College of Sports Medicine (ACSM) recommends that healthy adults perform moderate to vigorous intensity aerobic exercise at least 5 times per week, and resistance exercise 2-3 times per week (16). Aerobic exercise can decrease arterial stiffness after both acute (18, 36) and chronic (17, 42) interventions. However, both acute (34) and chronic (24) resistance exercise may increase arterial stiffness. Thus, resistance exercise, particularly for the upper-body (13), may need to be carefully prescribed on an individual basis for those with cardiovascular risk factors.

Adequate upper-body strength can improve quality of life in clinical populations via improved upper-body and respiratory muscle strength (38). Upper-body strength is also critical for manual laborers (2, 37) and can enhance athletic performance (28). Furthermore, grip strength (15) and upper-body power (23) are associated with a reduction in all-cause mortality. However, upper-body resistance exercise increases arterial stiffness both acutely (22) and chronically (32) to an even greater extent than lower-body resistance exercise. Accumulating evidence (10, 30) indicates that eccentric exercise (i.e., active muscle lengthening contractions) has the potential to improve upper-body muscle function without the negative side effect of arterial stiffness. In a ground-breaking study, Okamoto and colleagues (30) demonstrated that 8 weeks of eccentric elbow flexion increased strength without increasing arterial stiffness, whereas concentric elbow flexion increased strength and arterial stiffness. These authors later reported that acute eccentric exercise was associated with an attenuated blood pressure and endothelin-1 responses compared to concentric resistance exercise (31). These results are promising and imply that attenuated circulatory adjustments to eccentric muscle contractions might help to offset the effects of arterial stiffening associated with traditional resistance exercise including concentric muscle contractions.

It is well established that unaccustomed eccentric exercise can give rise to significant muscle soreness and damage (9). Previous authors (4, 7) have reported that eccentric-induced muscle soreness and damage are linked to changes in pulse wave velocity 48 hours after exercise. This is especially noteworthy for upper-body exercise prescription because the magnitude of eccentric-induced damage is generally greater for upper-body compared to lower-body muscles (20). While soreness and damage are common, neither are necessary to trigger improvements in muscle size and strength (14) and can be avoided with careful progression of eccentric loading over time. Minimizing muscle damage has been shown to have no effect on arterial stiffness following eccentric and concentric leg cycling (29), furthering the point that muscle soreness is not a requirement for progress. Indeed, we (10) demonstrated that 7 weeks of eccentric arm cycling (i.e., repetitive, high-force, muscle lengthening contractions performed at moderate aerobic intensities) increased strength and power without changing aortic or arm arterial stiffness. Importantly, with the progressive nature of the training protocol, muscle soreness was very low throughout the study. However, the acute responses to upper-body eccentric exercise in individuals who progressively train are not documented. Evaluation of arterial stiffness following acute upper-body eccentric exercise without the associated muscle soreness would provide new insights to exercise prescription and cardiovascular health.

In this investigation, participants performed five weeks of heart rate matched eccentric or concentric arm cycling. We chose to compare eccentric arm cycling (continuous resistance exercise performed at aerobic intensities) to the more common mode of concentric arm cycling (continuous aerobic exercise) to utilize the same muscle groups and primary active joints (i.e., shoulders, elbows, and wrists). Our purpose was to evaluate changes in central and peripheral arterial stiffness following acute eccentric or concentric arm cycling in the respective groups of trained participants. Previous work (29, 36) has shown that peripheral arterial stiffness is reduced after concentric arm cycling and leg cycling VO_2 max protocols, and that central arterial stiffness remains unchanged. Therefore, we hypothesized that arm arterial stiffness would be reduced following both steady state eccentric and concentric arm cycling, but that central arterial stiffness would remain unchanged. Determining if upper-body eccentric exercise minimizes arterial stiffness is clinically relevant because repeated bouts of acute exercise training could have cumulative benefits over time (39).

METHODS

Participants

Twenty-two healthy individuals between 18-44 years of age volunteered to participate in this study. A power analysis determined that a sample of 18 participants (9 in each group) was needed to detect a 0.67 m/s change in cPWV, which is an estimated 10% change in mortality (41), based on 0.80 power and alpha of 0.05. Participants were recreationally active but did not regularly perform upper-body aerobic or resistance exercise. Experimental procedures used in this investigation were reviewed and approved by the Michigan Technological University Institutional Review Board. This research was carried out fully in accordance to the ethical standards of the International Journal of Exercise Science (25). The protocol and procedures were verbally described and all participants provided written informed consent prior to testing. Participants were clustered together in such a way as to create two similar groups of eleven participants based on the pre-experimental assessments (further described below) with comparable body composition, upper-body cardiorespiratory capacity, and maximum upper-body power (Table 1). The eccentric arm cycling training group (n = 11) had 8 men and 3 women, and the concentric arm cycling training group (n = 11) had 9 men and 2 women.

Pre-Experimental Assessments: Body composition was assessed using dual energy x-ray absorptiometry (DEXA; Lunar Prodigy, General Electric Company, Fairfield, CT, USA). Upper-body cardiorespiratory capacity was assessed during an incremental concentric arm cycling test ($15 + 15\ W \cdot min^{-1}$). Gas exchange data were measured continuously using open circuit spirometry (True Max 2400, Parvo Medics, Sandy, UT, USA). The metabolic measurement system was calibrated with a 3-L calibration syringe (Hans Rudolph, Kansas City, MO, USA) and medical gases of known concentrations (16.00 % O_2, 4.00 % CO_2, balance N_2). Upper-body peak oxygen consumption (VO_{2peak}), peak heart rate (HR_{peak}), and peak power output (W_{max}) were determined. Maximum upper-body power was assessed during maximal concentric arm cycling trials (5 s, 120 rpm). Participants were then assigned to one of the following exercise conditions: 1) eccentric arm cycling, or 2) concentric arm cycling.

Table 1: Participant demographic, anthropometric, and physiological characteristics.

Variable	Eccentric (n = 11)	Concentric (n = 11)	P value
Age (yr)	23 ± 1	24 ± 1	0.53
Height (m)	1.74 ± 0.03	1.77 ± 0.03	0.60
Body mass (kg)	74 ± 4	79 ± 5	0.40
BMI ($kg \cdot m^{-2}$)	24 ± 1	25 ± 1	0.58
Body Fat (%)	22 ± 4	25 ± 4	0.62
Systolic Arterial Pressure (mmHg)	110 ± 4	111 ± 3	0.86
Diastolic Arterial Pressure (mmHg)	60 ± 3	61 ± 2	0.86
Resting Heart Rate ($b \cdot min^{-1}$)	64 ± 3	60 ± 3	0.33
$\dot{V}O_{2peak}$ ($L \cdot min^{-1}$)	2.2 ± 0.2	2.3 ± 0.2	0.74
$\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	29 ± 3	29 ± 2	0.82
HR_{peak} (bpm)	185 ± 3	181 ± 3	0.37
W_{peak} (W)	134 ± 12	134 ± 12	1.00
P_{max} (W)	599 ± 59	591 ± 60	0.94

Values are reported as Mean ± SE. Body mass index (BMI), upper-body peak oxygen consumption ($\dot{V}O_{2peak}$), upper-body peak heart rate (HR_{peak}), peak power reached at the end of the upper-body $\dot{V}O_{2peak}$ test (W_{peak}), and maximal upper-body concentric power (P_{max}).

Training Period: Both the eccentric and concentric arm cycling groups exercised at 65-70% of upper-body peak heart rate 3x/week for five weeks. Specifically, participants exercised continuously for 5 and 8 min/session during the first and second weeks, respectively. After this, participants trained continuously for 10 and 13 min/session during the third and fourth weeks and for 17 min/session during the fifth week. Muscle soreness associated with eccentric arm cycling or concentric arm cycling was monitored using a visual analog scale (0-10 cm; 10 cm representing the most soreness possible (12, 21)). Specifically, 24 to 48 hours after each exercise session, participants performed a standardized bilateral elbow extension movement (i.e., bench dip) during which they indicated the level of perceived muscle soreness in their arms by placing a mark on the visual analog scale. Perceived muscle soreness was quantified by measuring the distance to the mark on the line to the nearest 0.1 cm. During the 5 weeks of training, mean muscle soreness ranged from 0.4 ± 0.1 to 0.6 ± 0.2 cm and 0.2 ± 0.1 to 0.4 ± 0.2 cm for the eccentric and concentric arm cycling groups, respectively. Thus, participants tolerated the exercise sessions well and were reasonably adapted with their respective modality.

Protocol

For the experimental visit, participants were instructed to avoid exercise and caffeine for 12 h preceding the experiment which was performed at least 3 h post-prandial. This experimental visit occurred at least 48 h after the final training session of week 5 for all participants. Baseline measures of heart rate, blood pressure, and pulse wave velocity were recorded before exercise (described below). Subsequently, participants performed either eccentric arm cycling or concentric arm cycling on an isokinetic ergometer (described below) continuously at ~70% of HR_{peak} for 20 min at an arm cranking rate of 60 rpm. Arm cycling power output and heart rate (Polar CE O537, Polar Electro Inc., Lake Success, New York, USA) were recorded and averaged over the 20-min exercise trial. Overall rating of perceived exertion (RPE_{body}), as well as arm specific RPE (RPE_{arm}), were assessed during the final min of exercise using a Borg 6-20 scale (6). Heart rate, blood pressure, and pulse wave velocity were reassessed at 10 min and 30 min post exercise. These time points were selected because previous studies report arterial stiffness may be altered from 10 to 30 min post-exercise (18, 36). Our experimental protocol is depicted in Figure 1.

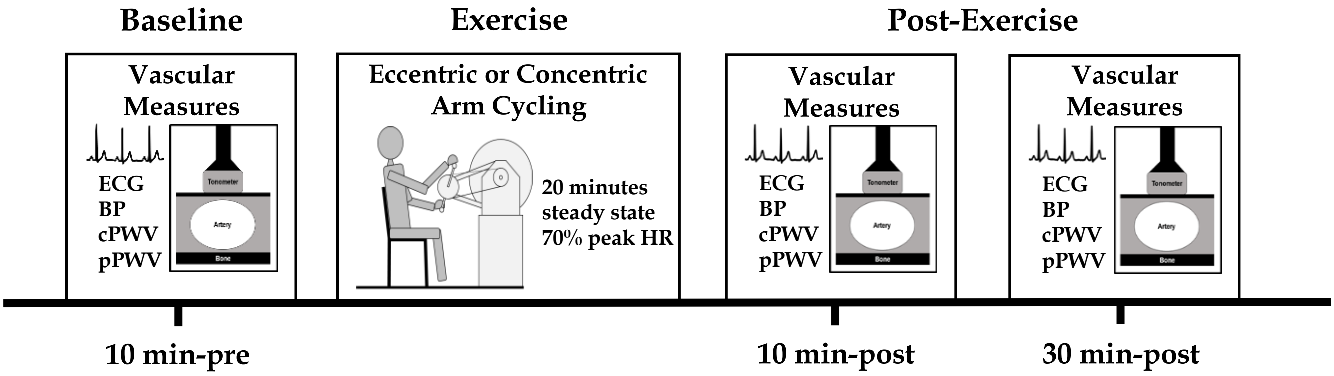

Figure 1. Vascular measures including blood pressure, central pulse wave velocity (cPWV), peripheral pulse wave velocity (pPWV), and electrocardiography (ECG) were performed 10 minutes before, 10 minutes after, and 30 minutes after a 20-minute bout of steady state eccentric or concentric arm cycling.

Cardiovascular Parameters: All measurements were completed following the guidelines from the Scientific Statement from the American Heart Association (40). At baseline, brachial blood pressures were taken in triplicate after at least 15 minutes of supine rest with an automated cuff (Omron HEM-907XL, Omron Health Care, Vernon Hills, IL, USA) with one minute between each recording. Average systolic arterial pressure (SAP) and diastolic arterial pressure (DAP) were used to calibrate the SphygmoCor CPVH system (AtCor Medical, West Ryde, Australia) for pulse wave analysis measurements. A single supine blood pressure was taken to calibrate directly before recordings at 10- and 30-min post exercise. A small pressure transducer (Millar Instruments, Houston, TX, USA) was placed at the radial pulse site to record consecutive waveforms during pulse wave analysis. The SphygmoCor system was used to estimate aortic blood pressures. Recordings were completed in duplicate with an operator index of ≥ 80 for all readings. Values are reported as an average of the two recordings. Peripheral pulse wave velocity (pPWV) was measured from waveforms at the radial and carotid pulses to indicate arm arterial stiffness. Central pulse wave velocity (cPWV) was measured from waveforms at the carotid and femoral pulses to indicate aortic arterial stiffness. The pressure waveforms were gated to the R-waves of a three-lead electrocardiogram recording, which was also used to obtain heart rate. Distances between the suprasternal notch and carotid artery pulse site, radial pulse site, and femoral pulse site were measured as straight lines with a tape measure. Pulse wave velocity recordings were taken in duplicate with ≤ 10% standard deviation and a heart rate difference of ≤ 5 beats/min in between. Values are reported as an average of the two recordings.

Arm Cycle Ergometer: The isokinetic arm cycle ergometer used in this investigation has been previously described in detail (12). Briefly, the flywheel of the ergometer was driven in either the forward direction by the participant (concentric arm cycling), or in the reverse direction (eccentric arm cycling) by a 560 W three-phase electric motor (Leeson, C4T17PT2C; Santa Fe Springs, CA, USA). The cranks (170 mm) were positioned in the asynchronous fashion and power delivered to the ergometer crank was quantified using a power meter (Schoberer Rad Messtechnik, SRM, Jülich, Germany), a system that serves as an accurate method to quantify cycling power (1). Pedaling rate was set to 60 rpm and the SRM power meter (sampled at 2 Hz) displayed the power that the participant was producing (concentric arm cycling trials) or absorbing (eccentric arm cycling trials). The SRM power meter was calibrated using static calibration procedures (11) and a zero offset ($f_{unloaded}$) was obtained before all arm cycling trials. Ergometer seat position was carefully standardized such that the: 1) crank axle was set just below the level of the heart, 2) elbow was positioned at a comfortable angle when the cranks were horizontal (~20° ulnar notch to humeral head), and 3) legs were positioned to help stabilize the torso (~90° lateral malleolus to greater trochanter). Finally, for the concentric arm cycling trials, participants were instructed to "propel" the handles of the ergometer at a power output monitored by the investigator that elicited the specified target heart rate whereas for the eccentric arm cycling trials, participants were instructed to “resist” the motor-driven handles of the ergometer at the specified target heart rate. Note that muscle activation patterns during concentric and eccentric arm cycling have been described previously (12).

Statistical Analysis

Independent t-tests were used to test for differences in participant demographic data, power output, heart rate, and RPE values between eccentric arm cycling and concentric arm cycling. A 2 (exercise group) x 3 (time) repeated measures analysis of variance (ANOVA) was used to assess differences in heart rate, brachial blood pressures, aortic blood pressures, and pulse wave velocity (cPWV, pPWV). If the ANOVA procedures revealed a significant main effect or group x time interaction, then post-hoc paired t-tests were performed to determine where differences occurred. Data are presented as mean ± standard error and the a priori alpha was set to 0.05.

RESULTS

Muscular, cardiorespiratory, and perceptual responses to the 20-min exercise trial are reported in Figure 2. Power absorbed during eccentric arm cycling was ~2x that produced during concentric arm cycling (125 ± 13 vs. 67 ± 7 W, $p < 0.01$). These powers corresponded to 94 ± 5 and 50 ± 2% of the peak power reached during the concentric arm cycling VO_{2peak} test (W_{peak}) and to 22 ± 2 and 12 ± 1% of maximal concentric arm cycling power (P_{max}), respectively. Mean absolute and relative heart rates during eccentric arm cycling (122 ± 4 bpm, 66 ± 2% of HR_{peak}) and concentric arm cycling (122 ± 2 bpm, 67 ± 1% of HR_{peak}) did not differ ($p = 0.87$ and $p = 0.68$, respectively) and were close to the prescribed target of 70% of HR_{peak}. Rating of perceived exertion for the whole-body during eccentric and concentric arm cycling was between a “light” and “somewhat hard” effort and did not differ between groups (13 ± 0 vs. 12 ± 1, $p = 0.20$). Rating of perceived exertion for the arms during eccentric and concentric arm cycling was between a “somewhat hard” and “hard” effort and did not differ between groups (14 ± 0 vs. 13 ± 1, $p = 0.38$).

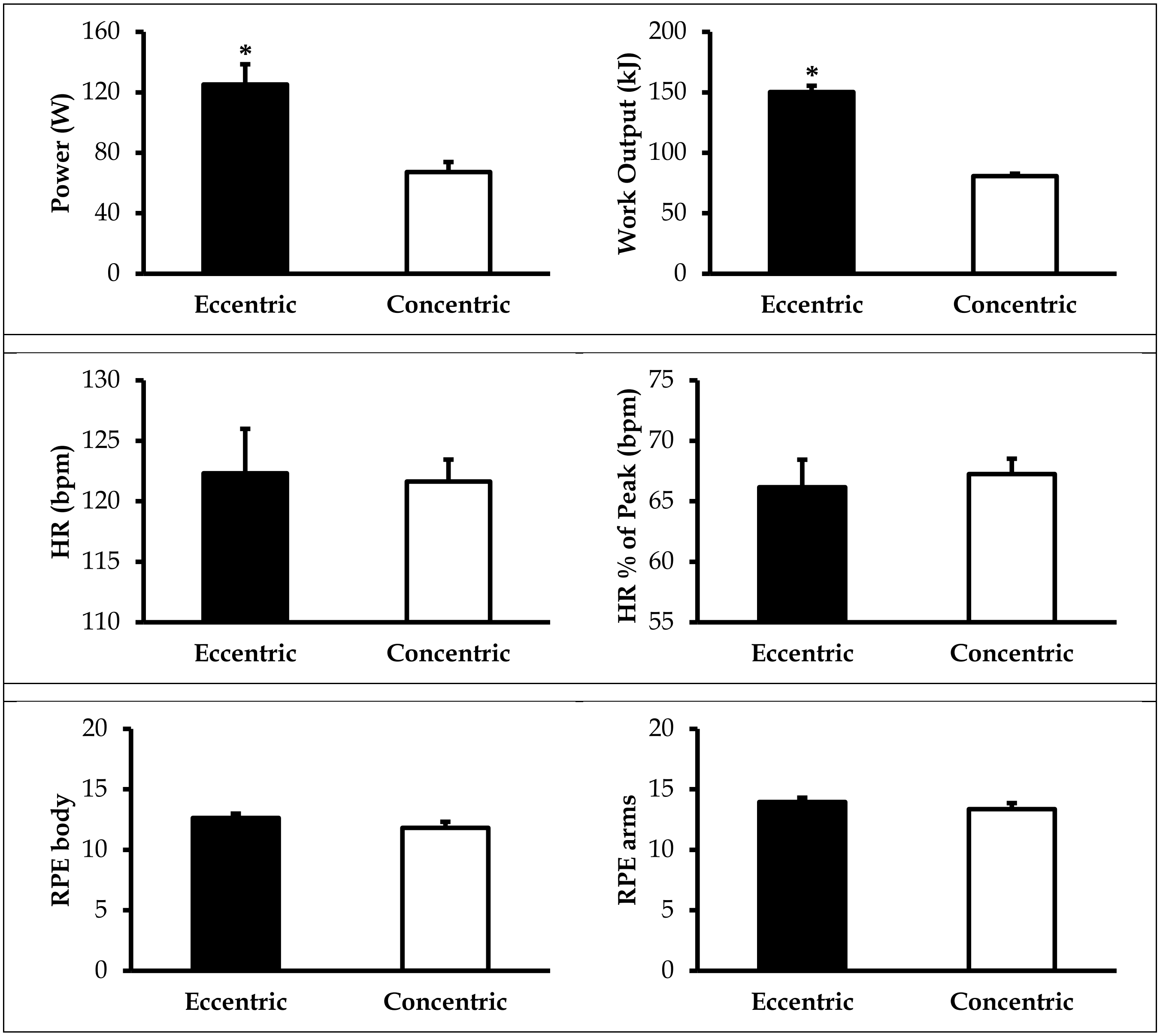

Figure 2. Muscular, cardiorespiratory, and perceptual responses during exercise. *$p < 0.05$ vs. concentric arm cycling.

Data presented in Table 2 indicate that heart rate was not significantly elevated at 10 min post-exercise for eccentric arm cycling ($p = 0.08$) and did not differ from baseline at 30 min post-exercise. Heart rate was elevated at both 10- and 30-min post-exercise for concentric arm cycling ($p < 0.01$). Mean arterial pressure did not differ from baseline at 10- or 30-min post-exercise in either group. Table 2 also depicts aortic blood pressure values for before, 10 min post, and 30 min post-exercise for both groups. Aortic pulse pressure was elevated at 10 min post for both groups, but did not differ from baseline at 30 min post for either group. As illustrated in panel A of Figure 3, pPWV was decreased at 10 min post-exercise for both eccentric and concentric arm cycling ($p < 0.05$), while both groups returned to baseline values by 30 min post. cPWV did not significantly change in either group (panel B of Figure 3).

Table 2: Cardiovascular responses to acute exercise session.

	Eccentric (*n* = 11)			**Concentric (*n* = 11)**		
Variable	**Pre-Exercise**	**10 min Post-Exercise**	**30 min Post-Exercise**	**Pre-Exercise**	**10 min Post-Exercise**	**30 min Post-Exercise**
HR (bpm)	64 ± 3	68 ± 3	61 ± 2	60 ± 3	71 ± 4*	66 ± 3*
bMAP (mmHg)	76 ± 3	79 ± 2	75 ± 2	77 ± 2	72 ± 2	74 ± 2
aSAP (mmHg)	91 ± 3	96 ± 2	93 ± 2	92 ± 2	89 ± 2	87 ± 3
aDAP (mmHg)	61 ± 3	59 ± 2	59 ± 2	63 ± 2	52 ± 2	54 ± 2
aMAP (mmHg)	74 ± 3	76 ± 2	74 ± 2	74 ± 2	69 ± 2	69 ± 2
aPP (mmHg)	31 ± 1	38 ± 1*	35 ± 1	31 ± 2	37 ± 2*	35 ± 2

Values are reported as Mean ± SE. Heart rate (HR), brachial mean atrial pressure (bMAP), aortic systolic blood pressure (aSAP), aortic diastolic blood pressure (aDAP), aortic mean blood pressure (aMAP), aortic pulse pressure (aPP). * $p < 0.05$ vs. pre-exercise baseline.

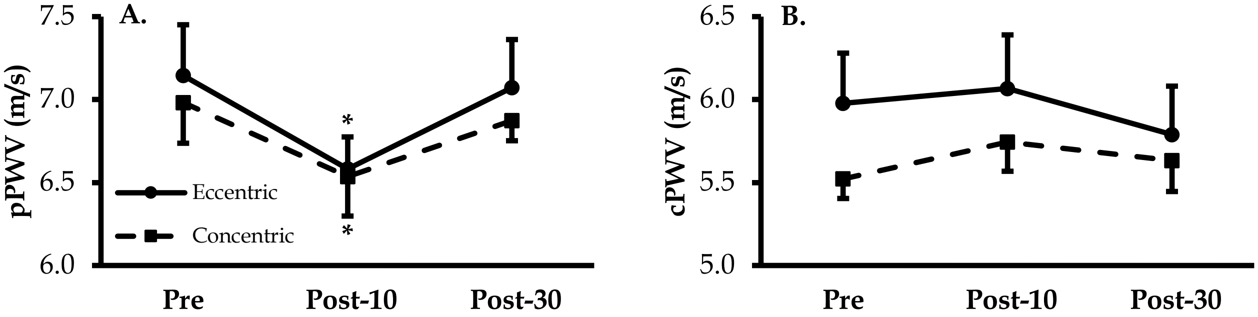

Figure 3. Alterations in peripheral (i.e., arm) pulse wave velocity (pPWV) in panel A and central (i.e., aortic) pulse wave velocity (cPWV) in panel B. *$p < 0.05$ vs. pre-exercise baseline.

DISCUSSION

This study compared arterial stiffness responses to steady state eccentric and concentric arm cycling in trained participants and resulted in three novel findings. First, arm arterial stiffness (i.e., pPWV) was acutely reduced after both eccentric and concentric arm ergometry but returned to pre-exercise values by 30 min post-exercise. Second, aortic arterial stiffness (i.e., cPWV) was not elevated at 10- or 30-min post-eccentric or post-concentric arm ergometry. Third, heart rate was not different from baseline after eccentric arm ergometry, but remained elevated until 30 minutes post concentric arm cycling.

Clinically relevant work demonstrates that pPWV is elevated in prehypertensive adults compared to normotensive controls, and that pPWV can be reduced by about 10-11% through 8-weeks of exercise training (5). Our participants reduced pPWV by about 6 and 8% at 10 min post-exercise in the concentric and eccentric groups, respectively. Furthermore, our pPWV results are in agreement with a previous study (36) that reported concentric arm ergometry performed to VO_2peak can acutely decrease arm arterial stiffness. We extend their findings by indicating that pPWV was not only decreased at 10 min post-concentric steady state arm cycling, but also at 10 min post-eccentric steady state arm cycling. These findings, in conjunction with our recent 7-week training study that indicated no change in pPWV (10), show that arm cycling does not appear to negatively influence arm arterial stiffness. These results are promising, considering that eccentric arm cycling participants increased their upper body strength and power in our longitudinal exercise study (10), whereas traditional upper body resistance training is reported to increase arterial stiffness both acutely (22) and over 10-weeks (32).

Carotid-femoral pulse wave velocity (reported as cPWV in the present study) is strongly associated with cardiovascular disease risk in those with normotension and hypertension (26), and even as little as a 1 m/s increase is noted to increase the risk for cardiovascular events and death by about 15% (41). Neither the eccentric nor concentric arm cycling in the present study altered cPWV as depicted in panel B of Figure 3. The lack of change in cPWV could be due to the relatively short duration (i.e., 20 min) and moderate intensity exercise that our participants experienced (33). Future work could address longer duration and / or higher intensity eccentric or concentric upper-body exercise protocols. Nonetheless, results from the current study along with our previous longitudinal results (10), indicate that eccentric arm cycling could potentially lower cPWV (both 30 minutes after a training session and after 7 weeks of training), and at the very least does not appear to have a negative effect.

Heart rate returned to baseline values by 10 min post-eccentric arm ergometry, but was still elevated at 30 min post-concentric arm ergometry. A more rapid recovery of heart rate after exercise could indicate improved vagal activation and sympathetic withdrawal (19). Previous work has shown that heart rate recovery is more rapid after upper-body ergometry, than lower-body ergometry (35). Our findings provide new indications that heart rate recovery is more rapid after eccentric arm ergometry than concentric arm ergometry. Elevated heart rate, and / or pulse pressure, can increase the pulsatility to end organs such as the brain and kidney and lead to long-term damage (3). Increases in aortic pulse pressure were similar at 30 min post-exercise for the eccentric and concentric groups (~4 mmHg). Because heart rate recovered more rapidly after eccentric than concentric exercise (see Table 2), and aortic pulse pressures were comparable between groups, pulsatile stress should be lower following eccentric arm ergometry. Decreasing aortic pulsatility could help to reduce cardiovascular disease risk (27).

A potential limitation of this study is that we did not test arterial stiffness beyond 30 minutes post exercise. Other studies with eccentric upper-body (4) and lower-body (7) exercise have tracked muscle soreness and arterial stiffness for 48 hours post exercise. However, those studies did not include a significant training period, thus induced significant muscular damage. Muscle soreness ratings were about 7 to 8 on a 10-point scale (4, 7). Changes in pulse wave velocity have been linked to changes in muscle soreness (7). The present study carefully trained participants and their peak muscle soreness ratings were less than 1 on a 10 cm analog scale. Thus, our protocol did not induce delayed onset muscle soreness, and therefore we would not expect a significant change in arterial stiffness more than 30 minutes beyond the acute exercise session.

The results of the present study, and those of our recent longitudinal study (10), indicate that eccentric arm cycling appears to be safe for healthy individuals in regard to arterial stiffness. It is currently unknown if these findings will extend to those with pre-clinical, or clinical, conditions such as hypertension or coronary artery disease.

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REFERENCES

1. Abbiss CR, Quod MJ, Levin G, Martin DT, Laursen PB. Accuracy of the Velotron ergometer and SRM power meter. Int J Sports Med 30(2): 107-112, 2009.

2. Anton D, Mizner RL, Hess JA. The effect of lift teams on kinematics and muscle activity of the upper extremity and trunk in bricklayers. J Orthop Sports Phys Ther 43(4): 232-241, 2013.

3. Augustine JA, Yoon ES, Choo J, Heffernan KS, Jae SY. The relationship between cardiorespiratory fitness and aortic stiffness in women with central obesity. J Womens Health (Larchmt) 25(7): 680-686, 2016.

4. Barnes JN, Trombold JR, Dhindsa M, Lin HF, Tanaka H. Arterial stiffening following eccentric exercise-induced muscle damage. J Appl Physiol (1985) 109(4): 1102-1108, 2010.

5. Beck DT, Martin JS, Casey DP, Braith RW. Exercise training reduces peripheral arterial stiffness and myocardial oxygen demand in young prehypertensive subjects. Am J Hypertens 26(9): 1093-1102, 2013.

6. Borg GA. Psychophysical bases of perceived exertion. Med Sci Sports Exerc 14(5): 377-381, 1982.

7. Burr JF, Boulter M, Beck K. Arterial stiffness results from eccentrically biased downhill running exercise. J Sci Med Sport 18(2): 230-235, 2015.

8. Carthy ER. Autonomic dysfunction in essential hypertension: A systematic review. Ann Med Surg (Lond) 3(1): 2-7, 2014.

9. Clarkson PM, Hubal MJ. Exercise-induced muscle damage in humans. Am J Phys Med Rehabil 81(11 Suppl): S52-69, 2002.

10. Elmer SJ, Anderson DJ, Wakeham TR, Kilgas MA, Durocher JJ, Lindstedt SL, LaStayo PC. Chronic eccentric arm cycling improves maximum upper-body strength and power. Eur J Appl Physiol 117(7): 1473-1483, 2017.

11. Elmer SJ, Danvind J, Holmberg HC. Development of a novel eccentric arm cycle ergometer for training the upper body. Med Sci Sports Exerc 45(1): 206-211, 2013a.

12. Elmer SJ, Marshall CS, McGinnis KR, Van Haitsma TA, LaStayo PC. Eccentric arm cycling: physiological characteristics and potential applications with healthy populations. Eur J Appl Physiol 113(10): 2541-2552, 2013b.

13. Fahs CA, Heffernan KS, Fernhall B. Hemodynamic and vascular response to resistance exercise with L-arginine. Med Sci Sports Exerc 41(4): 773-779, 2009.

14. Flann KL, LaStayo PC, McClain DA, Hazel M, Lindstedt SL. Muscle damage and muscle remodeling: No pain, no gain? J Exp Biol 214(Pt 4): 674–679, 2011.

15. Gale CR, Martyn CN, Cooper C, Sayer AA. Grip strength, body composition, and mortality. Int J Epidemiol 36(1): 228-235, 2007.

16. Garber CE, Blissmer B, Deschenes MR, Franklin BA, Lamonte MJ, Lee IM, Nieman DC, Swain DP. American College of Sports Medicine position stand. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: Guidance for prescribing exercise. Med Sci Sports Exerc 43(7): 1334-1359, 2011.

17. Hayashi K, Sugawara J, Komine H, Maeda S, Yokoi T. Effects of aerobic exercise training on the stiffness of central and peripheral arteries in middle-aged sedentary men. Jpn J Physiol 55(4): 235-239, 2005.

18. Heffernan KS, Jae SY, Echols GH, Lepine NR, Fernhall B. Arterial stiffness and wave reflection following exercise in resistance-trained men. Med Sci Sports Exerc 39(5): 842-848, 2007.

19. Imai K, Sato H, Hori M, Kusuoka H, Ozaki H, Yokoyama H, Takeda H, Inoue M, Kamada T. Vagally mediated heart rate recovery after exercise is accelerated in athletes but blunted in patients with chronic heart failure. J Am Coll Cardiol 24(6): 1529-1535, 1994.

20. Jamurtas AZ, Theocharis V, Tofas T, Tsiokanos A, Yfanti C, Paschalis V, Koutedakis Y, Nosaka K. Comparison between leg and arm eccentric exercises of the same relative intensity on indices of muscle damage. Eur J Appl Physiol 95(2-3): 179-185, 2005.

21. LaStayo PC, Pierotti DJ, Pifer J, Hoppeler H, Lindstedt SL. Eccentric ergometry: Increases in locomotor muscle size and strength at low training intensities. Am J Physiol Regul Integr Comp Physiol 278(5): R1282-1288, 2000.

22. Li Y, Bopp M, Botta F, Nussbaumer M, Schafer J, Roth R, Schmidt-Trucksass A, Hanssen H. Lower body vs. upper body resistance training and arterial stiffness in young men. Int J Sports Med 36(12): 960-967, 2015.

23. Metter EJ, Talbot LA, Schrager M, Conwit RA. Arm-cranking muscle power and arm isometric muscle strength are independent predictors of all-cause mortality in men. J Appl Physiol (1985) 96(2): 814-821, 2004.

24. Miyachi M, Kawano H, Sugawara J, Takahashi K, Hayashi K, Yamazaki K, Tabata I, Tanaka H. Unfavorable effects of resistance training on central arterial compliance: A randomized intervention study. Circulation 110(18): 2858-2863, 2004.

25. Navalta JW, Stone WJ, Lyons TS. Ethical issues relating to scientific discovery in exercise science. Int J Exerc Sci 12(1): 1-8, 2019.

26. Niiranen TJ, Kalesan B, Hamburg NM, Benjamin EJ, Mitchell GF, Vasan RS. Relative contributions of arterial stiffness and hypertension to cardiovascular disease: The Framingham Heart Study. J Am Heart Assoc 5(11): 1-8, 2016.

27. Nishijima T, Nakayama Y, Tsumura K, Yamashita N, Yoshimaru K, Ueda H, Hayashi T, Yoshikawa J. Pulsatility of ascending aortic blood pressure waveform is associated with an increased risk of coronary heart disease. Am J Hypertens 14(5 Pt 1): 469-473, 2001.

28. Ofsteng S, Sandbakk O, van Beekvelt M, Hammarstrom D, Kristoffersen R, Hansen J, Paulsen G, Ronnestad BR. Strength training improves double-poling performance after prolonged submaximal exercise in cross-country skiers. Scand J Med Sci Sports 28(3): 893-904, 2018.

29. Okamoto T, Kobayashi R, Hashimoto Y, Nosaka K. Changes in arterial stiffness after eccentric versus concentric cycling. Appl Physiol Nutr Metab 44(5): 533–538, 2019.

30. Okamoto T, Masuhara M, Ikuta K. Cardiovascular responses induced during high-intensity eccentric and concentric isokinetic muscle contraction in healthy young adults. Clin Physiol Funct Imaging 26(1): 39-44, 2006.

31. Okamoto T, Masuhara M, Ikuta K. Relationship between plasma endothelin-1 concentration and cardiovascular responses during high-intensity eccentric and concentric exercise. Clin Physiol Funct Imaging 28(1): 43-48, 2008.

32. Okamoto T, Masuhara M, Ikuta K. Upper but not lower limb resistance training increases arterial stiffness in humans. Eur J Appl Physiol 107(2): 127-134, 2009.

33. Okamoto T, Min SK, Sakamaki-Sunaga M. Acute effect of interval walking on arterial stiffness in healthy young adults. Int J Sports Med 39(7): 495-501, 2018.

34. Pierce DR, Doma K, Leicht AS. Acute effects of exercise mode on arterial stiffness and wave reflection in healthy young adults: A systematic review and meta-analysis. Front Physiol 9(73): 1-20, 2018.

35. Ranadive SM, Fahs CA, Yan H, Rossow LM, Agiovlasitis S, Fernhall B. Heart rate recovery following maximal arm and leg-ergometry. Clin Auton Res 21(2): 117-120, 2011.

36. Ranadive SM, Fahs CA, Yan H, Rossow LM, Agiovlasitis S, Fernhall B. Comparison of the acute impact of maximal arm and leg aerobic exercise on arterial stiffness. Eur J Appl Physiol 112(7): 2631-2635, 2012.

37. Sesto ME, Radwin RG, Block WF, Best TM. Upper limb dynamic responses to impulsive forces for selected assembly workers. J Occup Environ Hyg 3(2): 72-79, 2006.

38. Silva C, Gomes Neto M, Saquetto MB, Conceicao CSD, Souza-Machado A. Effects of upper limb resistance exercise on aerobic capacity, muscle strength, and quality of life in COPD patients: A randomized controlled trial. Clin Rehabil 32(12): 1636-1644, 2018.

39. Thompson PD, Crouse SF, Goodpaster B, Kelley D, Moyna N, Pescatello L. The acute versus the chronic response to exercise. Med Sci Sports Exerc 33(6 Suppl): S438-445, 2001.

40. Townsend RR, Wilkinson IB, Schiffrin EL, Avolio AP, Chirinos JA, Cockcroft JR, Heffernan KS, Lakatta EG, McEniery CM, Mitchell GF, Najjar SS, Nichols WW, Urbina EM, Weber T. Recommendations for improving and standardizing vascular research on arterial stiffness: A scientific statement from the American Heart Association. Hypertension 66(3): 698-722, 2015.

41. Vlachopoulos C, Aznaouridis K, Stefanadis C. Prediction of cardiovascular events and all-cause mortality with arterial stiffness: A systematic review and meta-analysis. J Am Coll Cardiol 55(13): 1318-1327, 2010.

42. Yoshizawa M, Maeda S, Miyaki A, Misono M, Saito Y, Tanabe K, Kuno S, Ajisaka R. Effect of 12 weeks of moderate-intensity resistance training on arterial stiffness: A randomised controlled trial in women aged 32-59 years. Br J Sports Med 43(8): 615-618, 2009.