1-20-2017

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Jamie F. Burr
University of Guelph

Jenny L. Beck
University of Prince Edward Island

John J. Durocher
Michigan Technological University, jjduroch@mtu.edu

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Journal of Sport and Health Science xx (2017) 1–6
www.jshs.org.cn

Original article

The relationship of high-intensity cross-training with arterial stiffness

Jamie F. Burr [a,b,*], Jenny L. Beck [b], John J. Durocher [c]

[a] *Department of Human Health and Nutritional Sciences, University of Guelph, Guelph, ON N1G 2W1, Canada*
[b] *Applied Human Sciences, University of Prince Edward Island, Charlottetown, PE C1A 4P3, Canada*
[c] *Department of Biological Sciences, Michigan Technological University, Houghton, MI 49931, USA*

Received 20 July 2016; revised 25 October 2016; accepted 20 December 2016
Available online

Abstract

Purpose: Central arterial stiffness is a cardiovascular risk factor that can be readily affected through engagement in physical exercise training, with resistance and aerobic exercise having disparate affects. Despite the growing popularity of high-intensity cross-training (HICT), little is currently known about the effects of this mixed modality exercise stimulus on arterial stiffness. Therefore, the purpose of this study was to characterize the arterial stiffness of habitual HICT participants *vs.* aerobically active and sedentary controls using a cross-sectional design.
Methods: A total of 30 participants were recruited: 10 middle-aged long-term participants of HICT (CrossFit) and 20 age, sex, and height matched controls (10 recreationally active, 10 sedentary). Central and peripheral pulse wave velocities were measured for the carotid-femoral and femoral-dorsalis pedis arterial segments. Aerobic fitness (maximal oxygen uptake, VO_{2max}) was measured and typical exercise participation rates were self-reported for each group.
Results: HICT participants manifested central pulse wave velocity (PWV) (5.3 ± 1.0 m/s) and VO_{2max} (43 ± 6 mL/kg/min) values nearly identical to active controls. Both active groups had significantly better values than sedentary controls (7.1 ± 1.0 m/s, $p \le 0.001$; and 32 ± 7 mL/kg/min, $p = 0.01$). No differences were observed in peripheral PWV between groups.
Conclusion: Habitual participation in HICT exercise was not associated with increased central nor peripheral arterial stiffness. Long-term HICT participants presented with similar fitness and arterial stiffness as compared with participants who practiced traditional aerobic exercise. Compared to sedentary living, HICT may offer musculoskeletal and cardiovascular health benefits without negatively impacting arterial stiffness.

Keywords: Circuit training; CrossFit; Pulse wave velocity; Resistance exercise; Vascular; Weight training

1. Introduction

Moderate intensity physical activity is recommended for both the prevention and treatment of a number of chronic conditions.[1–4] Among the many specific cardiovascular benefits of regular physical activity is a decrease of arterial stiffness,[5] or an offset of the expected age-related stiffening.[6] Stiffening of the central arteries is generally considered a cardiovascular risk factor, as it leads to a greater overall demand on the heart through an elevation of pulse pressure and wall stress,[7,8] and may be associated with arteriosclerosis and reduced coronary artery perfusion.[7] These underlying cardiovascular changes at least partially explain the relationship of elevated baseline pulse wave velocity (PWV) with increased morbidity and mortality.[9]

High-intensity interval training has gained recent popularity for its demonstrated capacity to evoke substantial alterations in fitness, while remaining a time-efficient training option.[10] Of particular popularity is high-intensity cross-training (HICT), such as "CrossFit", which combines constantly variable exercise intensities and multiple exercise modalities. A defining feature of HICT workouts is a consistent aerobic stimulus, which results from the consecutive ordering of multiple exercises without rest, and the engagement in resistance-based exercises performed at a high percentage of maximum until failure. CrossFit HICT workouts have been reported to be extremely vigorous, in the range of 90% maximal heart rate (HR_{max}) or 80% maximal oxygen uptake (VO_{2max}).[11]

In contrast to the protective effects of moderate intensity exercise on arterial stiffening, extremely high-intensity exercise has

Peer review under responsibility of Shanghai University of Sport.
* Corresponding author.
E-mail address: burrj@uoguelph.ca (J.F. Burr)

http://dx.doi.org/10.1016/j.jshs.2017.01.009
2095-2546/

been shown to cause a transient increase in PWV,[12,13] and regular participation in progressive high-intensity resistance training leads to a persistent elevation in resting arterial PWV.[14] The recognized vascular alterations associated with repeated high-volume resistance training could be a result of a number of factors including engagement of the Valsalva maneuver,[15] compression of vasculature caused by high intramuscular pressures,[16] eccentric loading,[17,18] or inflammation and stress as part of the recovery process.[19] It is conceivable that some, or all, of these factors could be accentuated by regular participation in a HICT program that promotes high repetitions of heavy weights with little recovery. Previous research has demonstrated HICT exercise to be effective in stimulating adaptations in both strength[15] and aerobic fitness,[16] but controversy around the safety of HICT exists,[17] with some reports of exertional vascular insult.[18] Whether alterations in the vasculature might occur as a result of participation in HICT remains unknown. By the nature of the typical workout, which combines variable intensity resistance and aerobic exercise, HICT thus represents an interesting and poorly understood "dose" of exercise. In particular, the effect of HICT on human vasculature is to present a unique stimulus as it encompasses exercise attributes expected to both increase and decrease resting PWV. During HICT there is no specific ordering of exercises such that resistance or aerobic exercise are performed first, which is an important distinction because an order effect has been shown to influence the resultant PWV.[20]

The primary purpose of this investigation was to compare measures of both central and peripheral arterial PWV of long-term habitual HICT exercise participants with recreationally active and sedentary controls. It was hypothesized that progressive HICT training over many years would be associated with an increased stiffness of the central arteries, and thus HICT participants would demonstrate higher baseline stiffness compared to more moderately active controls. It was also hypothesized that despite a relative stiffening in HICT, both HICT and recreationally active controls would present with less arterial stiffness than persons who participated in no exercise training regime. The effects of training on peripheral PWV were an exploratory outcome to address whether a localized segment (femoral to dorsalis-pedis) was differentially affected in persons who regularly perform HICT.

2. Materials and methods

2.1. Participants

We employed a single measure cross-sectional study design. A total of 30 participants, matched for sex, blood pressure (BP), age, and height were recruited primarily from the local community and comprised the following groups: (1) habitual HICT participants ($n = 10$), (2) active controls ($n = 10$), and (3) sedentary controls ($n = 10$). Inclusion criteria for habitual HICT participation required local CrossFit club members to have been actively involved for >3 years with regular attendance, and participants were members of clubs within the province. Given the shared nature of the online, published workout of the day, a typical CrossFit HICT workout was similar across clubs and included a consistently variable range of activities, with an average duration of 60 min. An example of a HICT workout might include sets of 5–15 pull-ups, paired with squats and push-ups, performed at a maximal pace for a set period of time (e.g. 20 min), with the outcome being the maximal number of rounds completed. As such, the specific "dose" of exercise is variable between days, but also between subjects of differing ability, fitness, or motivation. All subjects were required to be generally healthy, normotensive, and free of overt acute or chronic illness that would preclude safe exercise or exercise testing (confirmed using the Physical Activity Readiness Questionnaire (PARQ), or PARQ+). Active controls were required to participate in regular exercise that typified normal recreational involvement, according to health guidelines and excluding HICT or high-volume resistance training, and match 1:1 as closely as possible with a HICT participant for age, sex, height, and BP. Recreationally active was defined as someone who exercised most days of the week, at a moderate to vigorous intensity (for at least 10 min at a time), and would commonly meet the guideline of ≥150 min of aerobic activity of any type per week. Sedentary controls had the same inclusion criteria with the exception of physical activity participation.

2.2. General procedures

Prior to their laboratory visit for cardiovascular evaluation, participants were instructed to abstain from heavy meals, nicotine, and caffeine for >3 h, alcohol consumption for >12 h, and exercise for >24 h. All participants provided written informed consent in accordance with the ethical standards of this journal and conformed to the guidelines of the University of Prince Edward Island Institutional Human Research Ethics Board, who approved this study. Each participant described his or her own exercise participation habits using the Godin Exercise Questionnaire.[21] The questionnaire asks participants to consider the frequency of exercise over the past 7 days, with anchored descriptions (i.e., "heart beats rapidly, work up a sweat") for intensity. A single score calculated by multiplying self-report data allowed for general comparison of group participation rates.

Upon arrival in the laboratory, measures of anthropometry, seated BP, and PWV were performed prior to exercise for characterization of subject fitness. Height was recorded to the nearest 0.5 cm using a standard portable stadiometer, and weight was measured with a digital scale that was recalibrated before each measurement (Tanita TBF-300 WA; Tanita, Arlington Heights, IL, USA). BP was measured manually while participants rested in the seated position with the left arm supported at the level of the heart. All measures were taken in triplicate, with the first measures discarded and an average of the remaining 2 used for analysis.

2.3. PWV

Measures of central PWV (cfPWV) from the descending aorta were collected while the participant lay supine on an examination table using consecutive recordings of the carotid and femoral arteries, gated to cardiac systole using a standard electrocardiogram. Following the confirmation of a sufficient quality signal at each site, a 10 s recording of pulse waves was collected using a high sensitivity Millar Tonometer included with the Sphygmocor CPVH system (Atcor Medical, Sydney, Australia). Pulse wave arrival time was determined using the intersecting tangent method to decide the foot of each wave, while velocity was calculated using the straight-line distance between measurement sites, with an adjustment for the distance from the suprasternal notch (aortic arch) to the carotid measurement site. A marking was placed on the skin at each measurement site with a felt tip marker to ensure consistency in repeated measures. Reproducibility data from our laboratory, using repeated measures, indicates an ability to accurately detect changes ≥0.16 m/s for cfPWV. Peripheral pulse wave velocity (dpPWV) was similarly calculated using a straight-line distance between measurement sites, with the proximal measurement being recorded from the superficial femoral artery at the groin and the distal site recorded from the dorsalis-pedis on the anterior aspect of the foot. Each participant had PWV measured in triplicate, with the average of all 3 measures used for analysis.

2.4. Fitness

Aerobic fitness was quantified using open-circuit spirometry with analysis of expired gases (COSMED Quark, Rome, Italy) during a graded exercise test on a mechanically driven treadmill. Prior to each testing session both the flowmeter and chemical analyzers of the metabolic cart were calibrated using a standard 3-L syringe and calibration gas of a known concentration. The test began with a 3-min warm-up at 3.5 mph, followed by a progressive increase in speed of 1 mph and 2% grade every 2 min until exhaustion. The test was terminated when oxygen consumption (VO_2) did not increase at least 150 mL/min with an increase in workload, when the respiratory exchange ratio was greater than 1.15, when HR did not increase with increases in exercise intensity, or when the participant reached volitional fatigue and had a rating of perceived exertion greater than 17 on the Borg 6–20 scale.[22]

2.5. Statistical analysis

Comparisons of group mean age, height, weight, body mass index (BMI), BP, aerobic power, and PWV (cfPWV and dpPWV) between HICT participants, active participants, and sedentary controls were made using simple ANOVA, with *post hoc* Bonferroni comparisons. To examine the relationships between potential predictor variables (e.g., anthropometry, exercise exposure, and VO_{2max}) as a confound to PWV by group allocation, Pearson correlations were employed using pooled data across groups. Significance was set, *a priori*, at $p < 0.05$. All data are presented as mean ± SD.

3. Results

Descriptive participant statistics are presented in Table 1. Among the HICT athletes, participants reported an average of 4.7 ± 1.8 years of structured experience. No differences were apparent between groups for participant age, height, or BP as per the study design. Differences in weight were observed between the sedentary controls who were on average 22 kg heavier than the HICT and recreationally active groups ($p = 0.002$). Accordingly, given the similarity in height between groups, BMI was also significantly higher in the sedentary group ($p \le 0.001$). No body mass differences were found between the HICT and active groups.

Table 1
Descriptive statistics of exercisers who habitually participate in regular HICT compared with both recreationally active and sedentary controls.

	HICT (*n* = 10)	Recreationally active (*n* = 10)	Sedentary (*n* = 10)
Male	5	5	5
Female	5	5	5
Age (year)	36 ± 7	36 ± 6	36 ± 4
Height (cm)	168 ± 8	169 ± 10	169 ± 9
Weight (kg)	73 ± 11*	73 ± 12*	95 ± 18
BMI (kg/m^2)	26 ± 4**	25 ± 4**	33 ± 4
Systolic BP (mmHg)	120 ± 6	117 ± 4	119 ± 11
Diastolic BP (mmHg)	75 ± 5	78 ± 5	80 ± 8
Pulse Press (mmHg)	45 ± 5	39 ± 6	39 ± 12
MAP (mmHg)	90 ± 5	91 ± 4	92 ± 7

* $p < 0.01$, ** $p \le 0.001$, compared with sedentary group.
Abbreviations: BP = blood pressure; HICT = high-intensity cross-training; MAP = mean arterial pressure; BMI = body mass index.

3.1. Physical activity

Using the Godin activity report, a difference was observed between the HICT participants and the sedentary control ($p = 0.002$) in overall activity score (27 points); whereas no difference was observed between the active control and either the sedentary group or the HICT group (Fig. 1A). There was no difference in aerobic fitness (Fig. 1B) between HICT and active groups ($p = 0.94$), but the sedentary controls had a substantially lower VO_{2max} than the other 2 groups (−11 mL/kg/min, $p = 0.01$) (Fig. 1B). Descriptive reports of activity type confirmed that the activity participation of active controls was primarily of aerobic origin (walking, jogging, running, and swimming) with only 2 participants reporting irregular participation in weight training. Importantly, this limited exposure to resistance exercise has been shown not to have an effect on arterial stiffening in a similar manner to high-volume progressive resistance training,[23] and participants were included as we were not specifically looking to compare to an aerobic exercise only control. The sedentary controls similarly did not engage in regular activity, with small amounts of walking being the most common activity reported. Estimated weekly breakdowns by group and intensity category are presented in Fig. 1C.

3.2. PWV

The cfPWV of habitual HICT participants (5.3 ± 0.7 m/s) did not differ from normally active participants (5.3 ± 0.5 m/s) who generally performed more aerobic type activity (Fig. 2A). However, both groups demonstrated a significantly lower cfPWV compared to the sedentary control (−1.8 m/s, $p \le 0.001$). *Post hoc* power calculations (G*Power, Institutfür Experimentelle Psychologie, Düsseldorf, Germany) revealed a power of >95% for our ANOVA model. To observe a significantly different

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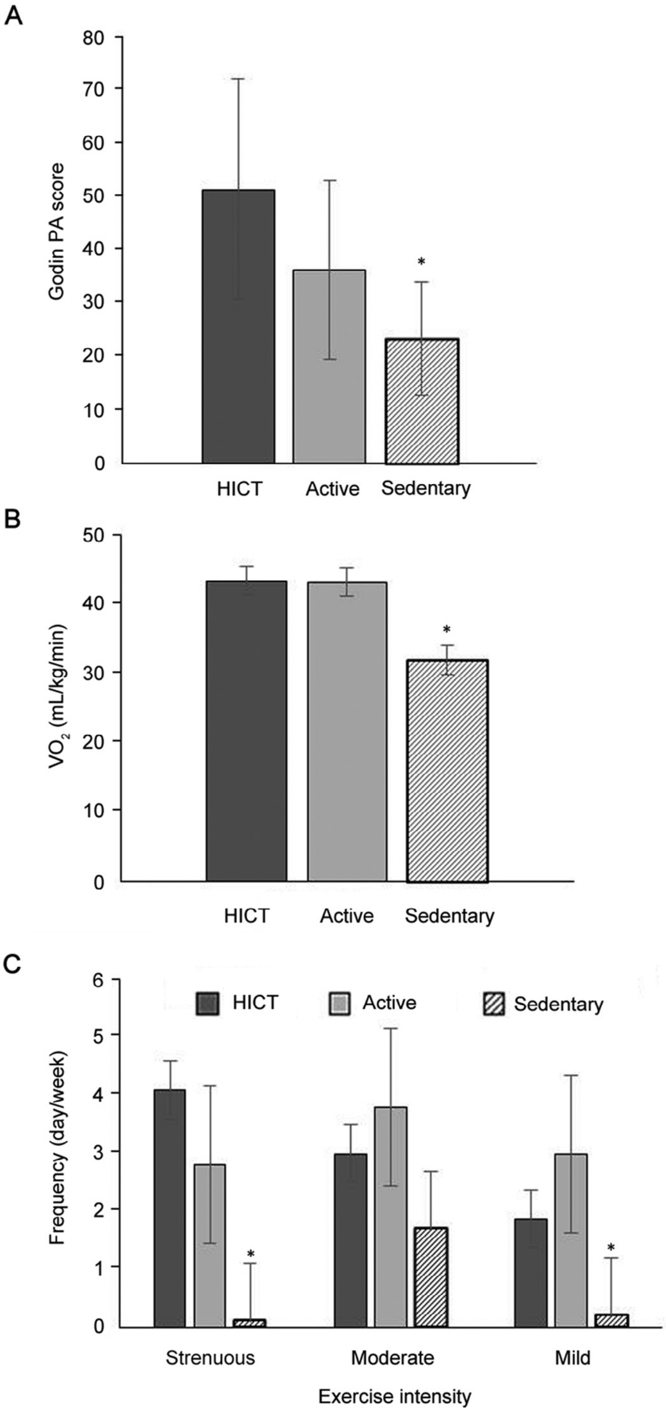

Fig. 1. (A) Group mean activity scores using the Godin Physical Activity Questionnaire, (B) directly measured VO_{2max} values, and (C) frequency of exercise participation divided by self-reported intensity for 3 groups: regular participants of high-intensity cross-training (HICT), moderate recreationally active exercise participation (Active), or sedentary control who did no formal training (Sedentary). *$p < 0.05$, compared with HICT. PA = physical activity; VO_{2max} = maximal oxygen uptake.

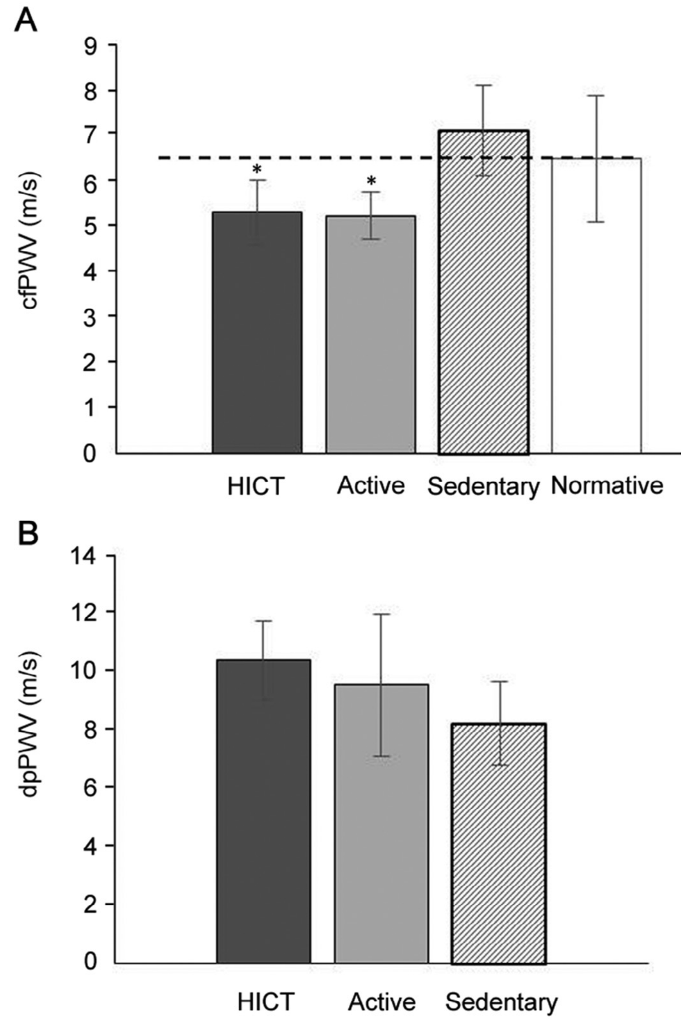

Fig. 2. (A) Carotid to femoral pulse wave velocity (cfPWV) of participants who regularly undertake high-intensity cross-training (HICT) exercise, a typical program of recreation exercise (Active), or who do not participate in regular exercise (Sedentary). Referent normative data ($n = 560$) from The Reference Values for Arterial Stiffness' Collaboration[26] are included as a comparator only. (B) Peripheral pulse wave velocity (dpPWV) from the femoral to dorsalis-pedis sites of the leg. *$p < 0.05$, compared with sedentary group.

alteration between the HICT and aerobic exercise groups an effect size of 0.85 was required, but not achieved as the groups' cfPWV differed by only 0.07 m/s. Moderate-to-strong correlations between cfPWV were found for expected predictor variables including diastolic BP ($r = 0.5, p = 0.01$), weight ($r = 0.66$, $p < 0.001$), and VO_{2max} ($r = 0.42$, $p = 0.03$), but none of these variables differed between active exposure groups, suggesting this relationship did not differentially mediate the finding by group. No differences between HICT, active, or sedentary controls were observed in the dpPWV (Fig. 2B); however, note that measures could only be obtained for 6 participants in the sedentary control group for dpPWV.

4. Discussion

The primary aim of this investigation was to compare measures of resting arterial stiffness between long-term participants in HICT with representative controls who either performed typical exercise regimens or were predominantly sedentary. The major novel finding was that persons who regularly participated in HICT exercise did not differ compared with those who

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performed a typical moderate-intensity exercise program that approximates physical activity guidelines. In fact, the arterial stiffness of the HICT group was nearly identical to the active group who performed more moderate-intensity aerobic type activity, and arterial stiffness was lower than that for similarly aged controls who did not exercise and were obese. As such, we reject our hypothesis that HICT would be associated with higher levels of arterial stiffness compared to persons who perform more aerobically-based moderate-intensity exercise.

Mean self-reported exercise data confirmed proper allocation of participants to activity groups. From the data presented in Fig. 1C, it can be seen that some variations existed in the amounts of strenuous, moderate, and mild activity, and these differences may help to explain why the HICT group manifested similar fitness scores to a more aerobically focused group, based on the efficacy of high-intensity exercise to stimulate changes in VO_{2max}.[10] The finding of no difference in VO_{2max} between the HICT and the recreationally active group is important from a comparative standpoint, indicating that in the current investigation fitness was not influencing the main outcome variable (cfPWV), and this was confirmed with correlational analysis across groups.

Unexpectedly, the HICT group demonstrated similar cfPWV to the recreationally active group, despite a strong representation of both high-intensity aerobic and progressive resistance-training stimuli. Previous research has demonstrated that many of the exercise characteristics that comprise a typical HICT training program (e.g., high-intensity,[12] high-volume progressions,[23,24] and eccentric contractions[17,18]) are related to increased PWV, yet a higher degree of stiffness was not observed at baseline in HICT exercisers. The finding that both active groups (HICT and moderate activity) had similar resting central PWV, and both groups had more compliant central arteries compared to the inactive overweight group, suggests no deleterious effect of HICT inclusion on the well-recognized beneficial effects of (most) exercise training. It is established that aerobic exercise performed prior to heavy resistance training is ineffective for avoiding training related elevations in arterial stiffness, whereas aerobic exercise performed after resistance training has the ability to offset stiffening.[20] Thus, it would appear possible that for programs such as HICT, wherein aerobic and resistance training are intermixed and varied in order, that the protective effect of the aerobic stimulus may remain effective. In a comparable cross-sectional investigation of PWV that considered rowers *vs.* sedentary controls, it has similarly been demonstrated that athletes who perform an aerobically-based repetitive resistance task manifest lower baseline cfPWV.[25] Alterations were also not observed in PWV of the rowers, which matches the observation in HICT athletes and is in line with previous reports that aerobic training alters central, but not peripheral, values.[5]

Comparing the cfPWV of the groups currently described with age and ethnicity matched normative data (>1400 healthy subjects) from the European Society of Cardiology,[26] it can be seen that the observed cfPWV of 5.3 m/s falls below the referent 6.5 m/s. Combined with the finding that HICT participants and recreationally active controls were both well below the matched sedentary control group (7.1 m/s) there is compelling evidence to suggest long-term participants of HICT have lower resting arterial stiffness than what would be normally expected with the absence of regular exercise. The magnitude of difference between the active groups and both the normative and sedentary control is in the range of 1.2–1.8 m/s, and differences of only 1 m/s have been shown to be associated with a 15% increase in the risk of future cardiovascular events in large scale epidemiological data.[9] As such, the observed difference between the HICT and active and sedentary control groups could be considered of a clinically meaningful magnitude. However, it is important to note that the stability of these alterations (between and within the different exercise modes) and the long-term implications for health in the HICT population remains unclear and warrants further investigation.

A limitation of the current study is that cause and effect cannot be demonstrated with cross-sectional design. As such, future work using longitudinal design and careful quantification of both the intervening training load distribution and overall volume should be considered. It is also worth noting that although the control group of non-exercisers were matched on a number of variables (age, sex, BP, and height), matching for BMI in a group that did not exercise was challenging, given the association of physical activity with weight control. As such, discrepancy between subjects existed on this variable. The current study employed typical amateur HICT CrossFit athletes, which is a strength in that the results are applicable to the broadest population of this growing exercise segment. However, it remains unknown if the same results would hold with elite level participants for whom it is conceivable that the training stimuli and associated physical adaptations may differ.

HICT may offer additional musculoskeletal and cardiometabolic health benefits compared with purely aerobic exercise programs[27,28] while apparently avoiding an increase in arterial stiffening as might occur with pure weight training. Such benefits could be realized through the efficiency of high-intensity training, the engagements of large amounts of muscle mass, and associated improvements in muscle mass and strength. An avoidance of arterial stiffening while still using high-load training could have important implications for helping to offset arterial stiffening in weight lifters who commonly employ less HICT and manifest stiffness. This new finding could also be highly applicable for the training of certain sub-sections of athletes and exercisers for whom deleterious alterations in arterial stiffness, even transiently, could have health or performance implications.

5. Conclusion

Regular participation in HICT exercise is not associated with central nor peripheral arterial stiffness. In fact, HICT participation was associated with similar decreases in cfPWV as was observed in a regularly active group who primarily undertook aerobic type activity. Irrespective of the inclusion of resistance type activity, both active groups in the current investigation manifested important reductions in cfPWV when compared to sedentary controls and large scale normative data, reaffirming the vascular benefit of exercise for reducing this cardiovascular

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risk factor. We conclude that persons who engage in typical and continued exposure to HICT manifest improvements in fitness and arterial stiffness, compared with their nontrained counterparts, in a similar manner to those doing more aerobically based training. Given the well-accepted benefits of both aerobic and resistance training, it is possible that HICT may offer additional musculoskeletal benefits above those accrued in a primarily aerobic exercise program without negatively impacting arterial stiffness.

Acknowledgments

The authors would like to acknowledge the support and assistance of B. MacEwen, A. Rainnie, and T. Wakeham in data collection. J. Burr is supported by a Discovery Grant (No. 03974) from the Natural Sciences and Engineering Research Council (NSERC) of Canada.

Authors' contributions

JFB conceived of the study and participated in design, data analysis and manuscript preparation; JLB performed primary data collection, analysis, and drafted the initial manuscript; JJD contributed to data collection, interpretation, and manuscript revisions. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

The authors declare that they have no competing interests.

References

1. Warburton DE, Nicol CW, Bredin SS. Health benefits of physical activity: the evidence. *CMAJ* 2006;**174**:801–9.
2. Warburton DE, Nicol CW, Bredin SS. Prescribing exercise as preventive therapy. *CMAJ* 2006;**174**:961–74.
3. Burr JF, Rowan CP, Jamnik VK, Riddell MC. The role of physical activity in type 2 diabetes prevention: physiological and practical perspectives. *Phys Sportsmed* 2010;**38**:72–82.
4. Sigal RJ, Kenny G, Oh P, Perkins BA, Plotnikoff RC, Prud'homme D, et al. Physical activity and diabetes. *Can J Diabetes* 2008;**32**(Suppl. 1):S37–9.
5. 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* 2005;**55**:235–9.
6. Tanaka H, DeSouza CA, Seals DR. Absence of age-related increase in central arterial stiffness in physically active women. *Arterioscler Thromb Vasc Biol* 1998;**18**:127–32.
7. Kass DA, Saeki A, Tunin RS, Recchia FA. Adverse influence of systemic vascular stiffening on cardiac dysfunction and adaptation to acute coronary occlusion. *Circulation* 1996;**93**:1533–41.
8. Belz GG. Elastic properties and Windkessel function of the human aorta. *Cardiovasc Drugs Ther* 1995;**9**:73–83.
9. 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* 2010;**55**:1318–27.
10. Gibala MJ, Little JP, MacDonald MJ, Hawley JA. Physiological adaptations to low-volume, high-intensity interval training in health and disease. *J Physiol* 2012;**590**:1077–84.
11. Babiash PE. *Determining the energy expenditure and relative intensity of two Crossfit workouts*. La Crosse, WI University of Wisconsin; 2013. [Thesis].
12. Rakobowchuk M, Stuckey MI, Millar PJ, Gurr L, Macdonald MJ. Effect of acute sprint interval exercise on central and peripheral artery distensibility in young healthy males. *Eur J Appl Physiol* 2009;**105**:787–95.
13. DeVan AE, Anton MM, Cook JN, Neidre DB, Cortez-Cooper MY, Tanaka H. Acute effects of resistance exercise on arterial compliance. *J App Physiol (1985)* 2005;**98**:2287–91.
14. Miyachi M. Effects of resistance training on arterial stiffness: a meta-analysis. *Br J Sports Med* 2013;**47**:393–6.
15. Heffernan KS, Jae SY, Edwards DG, Kelly EE, Fernhall B. Arterial stiffness following repeated Valsalva maneuvers and resistance exercise in young men. *Appl Physiol Nutr Metab* 2007;**32**:257–64.
16. Heffernan KS, Edwards DG, Rossow L, Jae SY, Fernhall B. External mechanical compression reduces regional arterial stiffness. *Eur J Appl Physiol* 2007;**101**:735–41.
17. Burr JF, Boulter M, Beck K. Arterial stiffness results from eccentrically biased downhill running exercise. *J Sci Med Sport* 2015;**18**:230–5.
18. Barnes JN, Trombold JR, Dhindsa M, Lin HF, Tanaka H. Arterial stiffening following eccentric exercise-induced muscle damage. *J App Physiol (1985)* 2010;**109**:1102–8.
19. Vlachopoulos C, Dima I, Aznaouridis K, Vasiliadou C, Ioakeimidis N, Aggeli C, et al. Acute systemic inflammation increases arterial stiffness and decreases wave reflections in healthy individuals. *Circulation* 2005;**112**:2193–200.
20. Okamoto T, Masuhara M, Ikuta K. Combined aerobic and resistance training and vascular function: effect of aerobic exercise before and after resistance training. *J App Physiol (1985)* 2007;**103**:1655–61.
21. Godin G, Shephard RJ. Godin leisure-time exercise questionnaire. *Med Sci Sports Exerc* 1997;**29**:36–8.
22. Heyward VH. Chapter 4: assessing cardiorespiratory fitness. *Advanced fitness assessment and exercise prescription*. Champaign, IL: Human Kinetics; 2006.
23. Casey DP, Beck DT, Braith RW. Progressive resistance training without volume increases does not alter arterial stiffness and aortic wave reflection. *Exp Biol Med (Maywood)* 2007;**232**:1228–35.
24. Burr JF, Drury CT, Phillips AA, Ivey A, Ku J, Warburton DE. Long-term ultra-marathon running and arterial compliance. *J Sci Med Sport* 2014;**17**:322–5.
25. Cook JN, DeVan AE, Schleifer JL, Anton MM, Cortez-Cooper MY, Tanaka H. Arterial compliance of rowers: implications for combined aerobic and strength training on arterial elasticity. *Am J Physiol Heart Circ Physiol* 2006;**290**:H1596–600.
26. Collaboration RVfAS. Determinants of pulse wave velocity in healthy people and in the presence of cardiovascular risk factors: 'establishing normal and reference values'. *Eur Heart J* 2010;**31**:2338–50.
27. Reid R, Tulloch H, Sigal RJ, Kenny GP, Fortier M, McDonnell L, et al. Effects of aerobic exercise, resistance exercise or both, on patient-reported health status and well-being in type 2 diabetes mellitus: a randomised trial. *Diabetologia* 2010;**53**:632–40.
28. Pollock ML, Franklin BA, Balady GJ, Chaitman BL, Fleg JL, Fletcher B, et al. Resistance exercise in individuals with and without cardiovascular disease benefits, rationale, safety, and prescription an advisory from the committee on exercise, rehabilitation, and prevention, council on clinical cardiology, American Heart Association. *Circulation* 2000;**101**:828–33.

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