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Research article

Vascular Responses to High-Intensity Battling Rope Exercise between the Sexes

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Abstract
The purpose of the study was to assess high-intensity battling rope exercise (HI-BRE) on hemodynamics, pulse wave reflection and arterial stiffness during recovery and between sexes. Twenty-three young, healthy resistance-trained individuals (men: n = 13; women: n = 10) were assessed for all measures at Rest, as well as 10-, 30-, and 60-minutes following HI-BRE. A one-way repeated measures ANOVA was used to analyze the effects of HI-BRE across time (Rest, 10, 30, and 60-minutes) on all dependent variables. Significant main effects were analyzed using paired t-tests with a Sidak correction factor. Significance was accepted *a priori* at $p \leq 0.05$. There were significant reductions in hemodynamic measures of diastolic blood pressure (BP) in women, but not men following HI-BRE at 30 minutes. Further, measures of pulse wave reflection, specifically those of the augmentation index (AIx) and wasted left ventricular energy (ΔE_w), were significantly increased in both men and women for 60 minutes, but changes were significantly attenuated in women suggesting less ventricular work. There were also significant increases in arterial stiffness in regard to the aorta and common carotid artery that were fully recovered by 30 and 60 minutes, respectively with no differences between men and women. Thus, the primary findings of this study suggest that measures of hemodynamics and pulse wave reflection are collectively altered for at least 60 minutes following HI-BRE, with women having attenuated responses compared to men.

Key words: Vigorous activity, blood pressure, pulse wave reflection, heart workload, arterial stiffness.

Introduction

High-intensity (HI) exercise acutely alters vascular function during the recovery period (Babcock et al., 2015; Kingsley et al., 2017; Rakobowchuk et al., 2009; Rossow et al., 2010; Wong et al., 2020). In particular, HI exercise results in an increase in heart rate (HR) (Kingsley et al., 2017; Rakobowchuk et al., 2009; Rossow et al., 2010; Wong et al., 2020), that may (Dennis et al., 2017; Rakobowchuk et al., 2009) or may not be accompanied by changes in blood pressure (BP) (Kingsley et al., 2017) following an exercise bout. It is unclear, however, whether these acute changes also influence other vascular measures such as those of pulse wave reflection and arterial stiffness. To date, studies have reported transient changes in measures of hemodynamics in parallel with those of pulse wave reflection (Kingsley et al., 2017; Rakobowchuk et al., 2009; Rossow et al., 2010) following HI-exercise. These studies suggest that changes in measures of pulse wave reflection may, or may not, be influenced by acute increases in arterial stiffness (Kingsley et al., 2017; Rakobowchuk et al., 2009; Rossow et al., 2010). It is unclear whether these changes may, or may not be deleterious. However, given the relationship of these measures to cardiovascular disease (CVD) and CVD-related events (Hashimoto et al., 2008; Mattace-Raso et al., 2006; Roman et al., 2009), particularly pulse wave reflection and arterial stiffness, understanding the relationship between these measures and modalities that modulate them is essential.

Changes in pulse wave reflection directly affect the shape of the arterial pulse (O'Rourke and Pauca, 2004). For example, one study has suggested that HI-cycling exercise (HI-CE) results in augmentation of the arterial pulse specific to that of the Augmentation Index Normalized to 75 bpm (AIx@75) (Kingsley et al., 2017). The AIx@75 illustrates the degree to which the measured arterial pressure wave is augmented above the initial due to increases in magnitude (i.e. augmentation pressure (AP)) and timing of pulse wave reflection (T*r*) (Butlin and Qasem, 2017), while controlling for HR (Wilkinson et al., 2000). Interestingly, changes in measures of pulse wave reflection more indicative of left ventricular function have not been widely reported, but may provide additional insight into the effects of HI exercise on the vascular system. These measures include the subendocardial viability ratio (SEVR), an index of myocardial oxygen supply and demand (Buckberg et al., 1972), and the wasted left ventricular energy (ΔE_w) representative of additional ventricular work in part due to dyssynchronous ventricular contraction patterns (Nichols, 2005). Further, studies have investigated changes in stiffness of the aorta and the common carotid artery (CCA), indicating increased (Babcock et al., 2015; Rakobowchuk et al., 2009; Rossow et al., 2010) or no change in stiffness (Kingsley et al., 2017). Thus, of the limited literature available, it appears that a HI modality alters vascular function in terms of pulse wave reflection and conceivably arterial stiffness during the recovery period.

Discrepancies amongst studies may be due to methodological differences. However, the use of the cycling modality itself may be limited in application to other HI-exercise modalities that involve a greater active muscle mass, such as the battling rope. It is plausible that augmented active muscle mass may prolong cardiovascular recovery, but this is speculative (Seals, 1993) . Further, studies have primarily included men (Kingsley et al., 2017; Rakobowchuk et al., 2009; Wong et al., 2020), or a combination of both men and women (Babcock et al., 2015; Rossow et al., 2010). It is well known that several

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differences (i.e., body composition, sex hormones, BP, etc.) exist between men and women that may directly or indirectly influence vascular responses (Collier, 2008; Doonan et al., 2013). However, based on the current literature, vascular responses between the sexes following a HI exercise modality has been relatively unexplored.

Therefore, the purpose of this study was two-fold. The first and primary purpose of this study was to examine vascular responses in terms of hemodynamics, pulse wave reflection, and arterial stiffness responses to a novel HI-battling rope exercise (HI-BRE) at rest and at 15-, 30-, and 60-minutes during recovery in resistance-trained (RT) men and women. The secondary purpose of this study was to elucidate responses between the sexes. It was hypothesized that measures of 1) hemodynamics, specifically HR would be augmented during recovery, 2) pulse wave reflection and left ventricular function would be altered by an increase in the AIx, AIx@75, and ΔEw, as well as a decrease in the SEVR, for at least 30 minutes, and 3) arterial stiffness of the aorta and CCA would be increased for at least 10 minutes. Further, it was hypothesized that men in comparison to women would demonstrate greater alterations in vascular measures, such as increased brachial BP, measures of pulse wave reflection, particularly the AIx and AP, in addition to increased arterial stiffness of the aorta and CCA during recovery.

Methods

Study Design

Twenty-three RT men (n = 13) and women (n = 10) participated in this study. All were non-smokers, non-obese (body mass index (BMI) < 30kg/m^2), non-hypertensive (brachial systolic BP (bSBP) <130 and brachial diastolic BP (bDBP) <80 mmHg), and free of cardiovascular or metabolic diseases. Participants came to the laboratory for orientation and one additional visit for data collection. Women were tested during the early follicular phase (Days 1-4) of their menstrual cycle, determined by the start of their menses or first day of placebo if taking oral contraceptives. All participants signed a written informed consent prior to data collection. Ethics approval was granted by the Kent State University Institutional Review Board and corresponded to the Declaration of Helsinki.

Anthropometrics

During orientation, participants' height and weight were assessed using a stadiometer and balance beam scale (Detecto 448; Cardinal Scale Manufacturing, Web City, MO, USA). Height and weight were measured to the nearest 0.1 centimeter or pound and used to compute BMI. Body composition was measured by seven site skinfolds (Lange; Beta Technology, Santa Cruz, CA, USA).

Hemodynamic Assessment

On the day of data collection, participants arrived between the hours of 6 am to 12 pm to control for diurnal variation. Participants rested for 10 minutes in the supine position in a dim, temperature-controlled (19-22°C) laboratory. Beat-to-beat BP was recorded via finger photoplethysmography (NexfinCC, BMEYE, Amsterdam, Netherlands). The pressure waveforms obtained via the Model flow technique (Wesseling et al., 1993) were used to assess HR, stroke volume (SV), and cardiac output (CO), as well as the derivation of total peripheral resistance (TPR). Following collection, measures of SV and CO were used to calculate the SV index (SVI) and CO index (CI) relative to body surface area (BSA). BSA was calculated according to Mosteller (Mosteller, 1987). Other measures of hemodynamics (bSBP, bDBP, brachial mean arterial pressure (bMAP)) were assessed using an automated oscillometric cuff placed on the right arm (AtCor Medical, SphygmoCor EXCEL Technology, Sydney, Australia). Blood pressure (BP) assessments were made in duplicate until exactly two values were within at least five mmHg of each other for both bSBP and bDBP. Values were first averaged then used for subsequent analysis.

Assessment of Pulse Wave Reflection and Left Ventricular Function

Measures of pulse wave reflection were obtained via a valid transfer function (Pauca et al., 2001), which has been reported to be reliable (r = 0.75) to previous non-invasive methods (i.e. SphygmoCor CvMS). Measures of pulse wave reflection included the AIx, AIx@75, T*r*, AP, and central pulse pressure (cPP). The AIx was calculated as the ratio between AP and PP. The AIx was also normalized (i.e. AIx@75) given its inverse relationship with HR (Wilkinson et al., 2000). The AP is determined as the difference between systolic pressure and inflection pressure while T*r* represents the transit time of the pulse wave from the left ventricle to the periphery and back (Butlin and Qasem, 2017). Central PP was calculated as the difference between central systolic BP (cSBP) and central diastolic BP (cDBP). Measures of pulse wave reflection indicative of left ventricular function included SEVR, derived from the systolic pressure time tension index (SPTI) and the diastolic pressure time tension index (DPTI), as well as ΔE_w. The ratio of the area under the central pressure waveform for systole (SPTI) and diastole (DPTI) were used to determine SEVR (Tsiachris et al., 2012). Wasted myocardial work, ΔE_w, is representative of energy that contributes to left ventricular ejection calculated as:

$$\Delta E_w = 1.333 \text{ x AP (ventricular ejection duration - T}r\text{) x } (\pi / 4)$$

where 1.333 is the conversion factor for mmHg/s to dynes-seconds/cm^2 (Casey et al., 2011).

Assessment of arterial stiffness

Stiffness of the aorta was assessed via carotid-femoral pulse wave velocity (cf-PWV) (Townsend et al., 2015) utilizing applanation tonometry and volumetric cuff displacement (AtCor Medical, SphygmoCor EXCEL Technology, Sydney, Australia), which is valid and reliable (Butlin et al., 2013). Cf-PWV was calculated as the difference of the foot-to-foot transit time of the pulse wave from the right common CCA and right femoral pulse divided by the estimated length of the aortic path (Butlin and Qasem, 2017). A single, high fidelity transducer was placed on right common CCA with an automated cuff on the right leg to measure pressure waveforms over a 10-second epoch. The distance of the aortic path was obtained with straight line tape measurement and calculated using the subtraction method (Butlin and Qasem, 2017). Cf-PWV measurements were made in duplicate, with no more than 0.1 m/s. Stiffness of the CCA was measured via CCA compliance and ß-stiffness, according to previously described methods (Miyachi et al., 2004). The CCA was assessed longitudinally using a 10MHz linear array transducer attached to a high-resolution ultrasound machine (GE Ultrasound A/S, Horton, Norway) with simultaneous assessment of BP. Images of the common CCA were recorded and transferred to a digital viewing software (Vascular Imager, Medical Imaging Applications, Coralville, Iowa) where pulsatile changes in CCA diameters were analyzed (Brachial Analyzer for Research, Medical Imaging Applications, Coralville, Iowa). CCA compliance was calculated as:

$$\text{CCA compliance} = [(D_1 - D_0)/D_0]/\ [2(P_1 - P_0)]\ \cdot\pi\cdot D_0^2$$

ß-stiffness was calculated as:

$$\text{ß-stiffness} = (\ln P_1/P_0)/\ [(D_1 - D_0)/D_0]$$

where D_1 and D_0 are the maximum and minimum CCA diameters measured from intima to intima, and P_1 and P_0 are estimates of cSBP and cDBP, respectively, obtained with a general transfer function, which has been validated to tonometry techniques (Pauca et al., 2001). Central BPs were presumed to reflect the CCA based upon the fact that BP in the CCA is often used as a surrogate for BP in the ascending aorta given the two are anatomically adjacent with little differences in PP amplification (~2 mmHg) (Avolio et al., 2009). All scans were performed by the same investigator.

HI-BRE Protocol

Following collection of resting measures, participants completed a four-minute warm-up on the cycle ergometer (Schwinn Air Dyne; Boulder, Colorado). The HI-BRE consisted of 6 sets of 15-second exercise bouts using a double wave pattern, separated by 30-seconds of seated passive recovery. The exercise pace was set at 180 bpm. Both men and women used a battling rope that was approximately 10 kg and 50 feet in length. Previous studies involving the battling rope have utilized similar loading patterns (Ratamass et al., 2009; Ratamess et al., 2015; Wong et al., 2020).

Statistical Analyses

Prior to ANOVA analyses, all data were assessed for normality, homogeneity of variance, and sphericity assumptions. If the assumption of Mauchly's sphericity test was violated, a Greenhouse-Geisser correction was applied (Greenhouse and Geisser, 1959). Participant characteristics for men and women, as well as differences at rest, were conducted using independent samples t-tests. Men and women differed at rest for bSBP, cSBP, CPP, CI, and SVI. Thus, a two-way repeated analysis of covariance (ANCOVA) was performed to determine the effects of HI-BRE between sexes (men and women) on measures of hemodynamics (bSBP, SVI, and CI) and pulse wave reflection (cSBP, cPP) across time (10 minutes, 30 minutes, and 60 minutes) with Rest as a covariate. Following, a two-way repeated measures analysis of variance (ANOVA) was used to investigate the effects of HI-BRE between sexes (men, women) across time (Rest, 10 minutes, 30 minutes, and 60 minutes) on measures of hemodynamics (HR, bDBP, bMAP, TPR), pulse wave reflection (AIx, AIx@75, T*r*, AP, CPP, cSBP, cDBP, cMAP, SEVR, SPTI, DPTI, ΔE_w) and arterial stiffness (cf-PWV, CCA compliance, ß-stiffness). If the ANOVA was significant, pairwise comparisons were conducted post hoc with a Šidák correction factor. Partial eta squared (η_p^2) was used to assess effect size. Statistical significance was defined *a priori* as $p \leq 0.05$. Values are presented as mean ± standard deviation (SD). All statistical analyses were completed using IBM SPSS (Version 25, Armonk, NY, USA). The sample size of the present study was based on HR pilot data collected after HI-BRE using 8 participants. The G*Power sample size calculator, version 3.1.9.2 (Faul et al., 2007), was used to estimate a minimum sample size of eight participants to achieve a power of 80% based on an effect size of 0.96 and an alpha of 0.05.

Results

Participant characteristics

Participant characteristics are presented in Table 1. Men were significantly ($p \leq 0.05$) older, taller, and heavier, with a greater BMI and lesser body fat than women.

Table 1. Participant characteristics. Data are mean ± standard deviation.

	Men (N=13)	Women (N=10)
Age, yrs	24 ± 2*	22 ± 2
Height, m	1.8 ± 0.1*	1.6 ± 0.1
Weight, kg	84.6 ± 10.1*	61.1 ± 7.4
BMI, kg/m²	26.5 ± 2.2*	22.8 ± 2.2
Body Fat, %	11.5 ± 4.2*	19.7 ± 4.5

BMI, Body mass index. * $p \leq 0.05$, significantly different from women.

Changes in measures of hemodynamics

Measures of hemodynamics during recovery from HI-BRE, and between sexes are presented in Table 2. There were significant sex by time interactions for bDBP ($p < 0.001$, $\eta_p^2 = 0.3$) and bMAP ($p = 0.013$, $\eta_p^2 = 0.2$). bDBP was attenuated at 10 minutes compared to Rest and was also augmented in men compared to women while the bMAP was augmented in men compared to women at 10 and 30 minutes. There were also main effects of time for HR ($p < 0.001$, $\eta_p^2 = 0.8$) and TPR ($p < 0.001$, $\eta_p^2 = 0.8$). The HR was increased at all time points during recovery compared to Rest and did not recover while TPR was increased for at least 30 minutes. Further, there were significant main effects of sex ($p = 0.007$, $\eta_p^2 = 0.3$) for bSBP, such that bSBP was augmented in men compared to women at 60 minutes. There were no significant ($p > 0.05$) main effects or interactions for SVI or CI.

Changes in measures of pulse wave reflection and left ventricular function

Measures of pulse wave reflection during recovery from

HI-BRE, and between sexes are presented in Table 3. There were significant sex by time interactions for AIx ($p = 0.008$, $\eta_p^2 = 0.2$), AIx@75 ($p = 0.002$, $\eta_p^2 = 0.2$), AP ($p = 0.003$, $\eta_p^2 = 0.2$), cPP ($p = 0.002$, $\eta_p^2 = 0.3$), cMAP ($p = 0.003$, $\eta_p^2 = 0.2$), DPTI ($p = 0.031$, $\eta_p^2 = 0.1$), and ΔE_w ($p = 0.002$, $\eta_p^2 = 0.2$). The AIx was augmented at 10 minutes during recovery compared to Rest and attenuated at 30, and 60 minutes such that it was similar to Rest. The AIx@75 was also augmented, but at both 10- and 30-minutes during recovery compared to Rest, which then decreased at 60 minutes, such that it was similar to Rest. Additionally, the AIx and AIx@75 were further augmented in men compared to women at 60 minutes. The AP was augmented at 10 minutes during recovery compared to Rest and further attenuated at 30 and 60 minutes such that it was similar to Rest. AP in men was also augmented compared to women at both 10 and 60 minutes. After controlling for differences at Rest, there was a significant difference in

Table 2. Measures of hemodynamics at rest and during recovery from high-intensity battling rope exercise. Data ar- mean ± standard deviation.

		Rest	10 minutes	30 minutes	60 minutes
HR, bpm	Men	57 ± 10	83 ± 13†	76 ± 13†‡	68 ± 10†‡§
	Women	65 ± 10	83 ± 6†	76 ± 6†‡	71 ± 7†‡§
SVI, mL/m²	Men	43 ± 3‖	44 ± 3	43 ± 3	43 ± 3
	Women	49 ± 3	49 ± 6	50 ± 3	49 ± 4
CI, L/min/m²	Men	4.4 ± 0.6‖	4.1 ± 0.5	3.9 ± 0.6	3.4 ± 0.5
	Women	4.5 ± 0.4	4.3 ± 0.3	4.0 ± 0.4	3.9 ± 0.5
TPR, mmHg•min/L	Men	951.7 ± 137.3	749.8 ± 79.6†	819.6 ± 83.5†‡	858.6 ± 87.7
	Women	1012.6 ± 107.0	832.7 ± 67.6†	905.7 ± 75.9†‡	991.7 ± 46.6
bSBP, mmHg	Men	123 ± 6‖	125 ± 7	123 ± 7	123 ± 5††
	Women	111 ± 9	112 ± 9	113 ± 6	109 ± 6
bDBP, mmHg	Men	66 ± 9	66 ± 8†¶	66 ± 7	66 ± 8
	Women	68 ± 6	61 ± 5†	63 ± 5	66 ± 6
bMAP, mmHg	Men	85 ± 7	86 ± 6¶	85 ± 6**	85 ± 6
	Women	82 ± 6	78 ± 4	80 ± 4	80 ± 5

Brachial Diastolic Blood Pressure; bMAP, Brachial Mean Arterial Pressure; bSBP, Brachial Systolic Blood Pressure; CI, Cardiac Output Index; HR, Heart Rate; SVI, Stroke Volume Index; TPR; Total Peripheral Resistance. †p ≤ 0.05, significantly different from Rest; ‡p ≤ 0.05, significantly different from 10 minutes; §p ≤ 0.05, significantly different from 30 minutes; ‖p ≤ 0.05, significantly different from women at Rest; ¶p ≤ 0.05 significantly different from women at 10 minutes; **p ≤ 0.05 significantly different from women at 30 minutes; ††p ≤ 0.05 significantly different from women at 60 minutes.

Table 3. Measures of pulse wave reflection at rest and during recovery from high-intensity battling rope exercise. Data are mean ± standard deviation.

		Rest	10 minutes	30 minutes	60 minutes
AIx, %	Men	9 ± 10	30 ± 13†	18 ± 13‡	18 ± 8‡††
	Women	11 ± 12	22 ± 11†	13 ± 8‡	7 ± 6‡
AIx@75, %	Men	0 ± 8	34 ± 13†	19 ± 13†‡	15 ± 10‡§††
	Women	7 ± 12	26 ± 10†	13 ± 6†‡	5 ± 7‡§
Tr, ms	Men	145.9 ± 8.5	149.8 ± 4.7	149.6 ± 6.1	117.0 ± 3.8†‡§
	Women	150.2 ± 5.6	149.0 ± 5.7	148.5 ± 4.2	113.5 ± 5.0†‡§
AP, mmHg	Men	4 ± 4	14 ± 5†¶	8 ± 5‡	7 ± 4‡††
	Women	4 ± 4	8 ± 5†	5 ± 3‡	2 ± 2‡††
cPP, mmHg	Men	40 ± 5‖	44 ± 8	40 ± 7	41 ± 6††
	Women	30 ± 6	37 ± 8	34 ± 6	28 ± 4
cSBP, mmHg	Men	106 ± 6‖	112 ± 7¶	108 ± 7	107 ± 4††
	Women	99 ± 6	99 ± 6	99 ± 5	96 ± 5
cDBP, mmHg	Men	67 ± 8	68 ± 8†¶	67 ± 6	67 ± 8
	Women	69 ± 6	62 ± 5†	68 ± 11	67 ± 5
cMAP, mmHg	Men	81 ± 7	87 ± 7¶	83 ± 6**	82 ± 7
	Women	81 ± 6	78 ± 4	77 ± 7	79 ± 5
SEVR, %	Men	148.9 ± 26.9	92.8 ± 14.7†	104.7 ± 28.5†‡	129.1 ± 23.2†‡§
	Women	141.9 ± 27.2	81.7 ± 16.3†	104.6 ± 19.0†‡	126.1± 18.6†‡§
SPTI, ms	Men	1887.4 ± 212.2	2721.7 ± 267.2†	2480.6 ± 400.7†‡	2179.5 ± 231.3†‡§
	Women	2038.9 ± 350.6	2604.1 ± 226.2†	2304.7 ± 200.4†‡	2150.6 ± 202.8†‡§
DPTI, ms	Men	2690.3 ± 391.8	2501.1 ± 307.0†¶	2504.3 ± 464.3†	2760.4 ± 358.5†‡§
	Women	2813.1 ± 252.5	2100.4 ± 292.6†	2381.7 ± 282.8†	2640.6 ± 264.0†‡§
ΔEw, dynes/cm2	Men	305.5 ± 228.6	2048.4 ± 804.0†¶	1177.5 ± 779.6†‡	1147.3 ± 564.3†‡††
	Women	277.1 ± 267.1	1276.6 ± 709.4†	715.4 ± 481.2†‡	313.9 ± 310.6†‡

AIx, Augmentation Index; AIx@75, Augmentation Index Normalized to 75 BPM; bDBP, cAP, Central Augmentation Pressure; cDBP, Central Diastolic Blood Pressure, cPP, Central Pulse Pressure, cSBP, Central Systolic Blood Pressure, DPTI, Diastolic Pressure Time Index, SEVR, Subendocardial Viability Ratio, SPTI, Systolic Pressure Time Index; Tr, Time of the Reflected Wave; ΔE_w, Wasted Left Ventricular Energy. †p ≤ 0.05, significantly different from Rest; ‡p ≤ 0.05, significantly different from 10 minutes; §p ≤ 0.05, significantly different from 30 minutes; ‖p ≤ 0.05, significantly different from women at Rest; ¶p ≤ 0.05 significantly different from women at 10 minutes; **p ≤ 0.05 significantly different from women at 30 minutes; ††p ≤ 0.05 significantly different from women at 60 minutes.

cPP between men and women at 60 minutes, such that cPP was augmented in men compared to women. cMAP was also augmented in men compared to women at 10 and 30 minutes. Further, the DPTI was attenuated at all time points compared to Rest and also differed between men and women such that it was further attenuated in women at 10 minutes. Finally, ΔE_w was augmented at all time points during recovery compared to Rest with men having greater augmentations compared to women at both 10 and 60 minutes.

Further, there were significant main effects of time for T*r* ($p < 0.001$, $\eta_p^2 = 0.9$), SEVR ($p < 0.001$, $\eta_p^2 = 0.8$) and SPTI ($p < 0.001$, $\eta_p^2 = 0.7$). The SPTI was augmented, while the SEVR was attenuated at all time points during recovery compared to Rest. Further, the T*r* was attenuated at 60 minutes compared to Rest, 10-, and 30-minutes during recovery. There were also significant main effects of sex for cSBP ($p < 0.001$, $\eta_p^2 = 0.4$), such that cSBP was augmented in men compared to women at 10 and 30.

Changes in measures of arterial stiffness

Measures of arterial stiffness at Rest, during recovery from HI-BRE, and between sexes are presented in Table 4. There was a significant main effect of time for cf-PWV ($p < 0.001$, $\eta_p^2 = 0.3$), CCA compliance ($p < 0.001$, $\eta_p^2 = 0.3$), and ß-stiffness ($p = 0.002$, $\eta_p^2 = 0.2$). The cf-PWV was augmented at 10 minutes, but attenuated at 30 and 60 minutes compared to 10 minutes, and from 30 to 60 minutes. CCA compliance and ß-stiffness were attenuated and augmented, respectively at 10 minutes and 30 minutes, compared to Rest. CCA compliance and ß-stiffness were augmented and attenuated, respectively, at 30 and 60 mins compared to 10 mins and also from 30 to 60 minutes.

Table 4. Measures of arterial stiffness at rest and during recovery from high-intensity battling rope exercise. Data are mean ± standard deviation.

		Rest	10 minutes	30 minutes	60 minutes
cf-PWV, m/s	Men	5.9 ± 0.7	6.2 ± 0.7†	6.0 ± 0.8	5.7 ± 0.8‡§
	Women	5.4 ± 0.8	5.7 ± 1.0†	5.4 ± 0.7	5.1 ± 0.5‡§
CCA compliance, mm²/kPa	Men	0.22 ± 0.07	0.18 ± 0.09	0.20 ± 0.06†	0.23 ± 0.09‡§
	Women	0.26 ± 0.10	0.18 ± 0.6	0.16 ± 0.06†	0.27 ± 0.09‡§
ß-stiffness, U	Men	3.2 ± 1.1	4.0 ± 1.5	3.5 ± 1.6	3.3 ± 1.5§
	Women	2.6 ± 1.0	3.6 ± 1.6	4.3 ± 1.7	2.4 ± 0.8§

Cf-PWV, Carotid-femoral pulse wave velocity; CCA, Common carotid artery. †p ≤ 0.05, significantly different from Rest; ‡p ≤ 0.05, significantly different from 10 minutes; §p ≤ 0.05, significantly different from 30 minutes.

Discussion

The major findings of the present study suggest that measures of hemodynamics, pulse wave reflection, and arterial stiffness are collectively altered following HI-BRE, but with different patterns of recovery. In this study, HR did not recover within 60 minutes following HI-BRE and women appeared to have a reduction in bDBP and bMAP early in the recovery period, which was not demonstrated by men. Further, in terms of pulse wave reflection, the AIx and AIx@75 were increased at all time points during recovery and this appeared to be primarily influenced by an increase in AP, with men having greater augmentations. Further, similar to peripheral BP changes, cDBP and cMAP were decreased early in the recovery period with men having augmented measures compared to women. In terms of left ventricular function, there was a collective reduction in the SEVR at all time points with concomitant increases and decreases in SPTI and ΔE_w, as well as DPTI, respectively with men having greater alterations in ΔE_w. Finally, HI-BRE resulted in a modest increase in arterial stiffness of the aorta during early recovery with no meaningful changes in carotid stiffness for both men and women.

In this study, HR was augmented for at least 60 minutes. This HR recovery is longer in duration compared to a previous study by Wong et al. (2020) where HR was increased for at least 30 minutes. Thus, HR recovery following this modality is unknown, but appears to exceed 60 minutes. Further, alterations in bSBP and bMAP during recovery in the present study were unremarkable, but this is dissimilar to the data reported by Wong et al. (2020), which suggested reductions in both bSBP and bDBP. This is likely to due to differences in volume between study protocols where in the present study, participants completed 6 sets of 15 seconds of HI-BRE. However, in the study by Wong et al. (2020), 10 sets of 30 seconds of HI-BRE was performed. Previous studies suggest that the post-exercise hypotension phenomenon following anaerobic modalities is typically observed when a greater number of sets are performed (Polito and Farinatti, 2009), which could explain these differences. Additionally, in the study by Wong et al. (2020), only men were included. While we report no changes in measures of BP for men, we did observe reductions in measures of BP in women. Specifically, women exhibited decreased bSBP and bMAP compared to men at similar time points, which may be attributable to differences in BP control mechanisms. It has been documented that young women, in comparison to age-matched men, demonstrate reduced sympathetic vasoconstriction due to augmented β-adrenergic vasodilator effects (Kneale et al., 2000). However, whether sympathetic activity played a significant role in these changes is unknown, as this was not directly measured in this study. In the study conducted by Wong et al. (2020), increases in measures of sympathovagal balance following HI-BRE were observed in men, which might imply an increase in sympathetic outflow, but this is unclear due to the complex nature of the two autonomic arms (Task Force of the European Society of Cardiology and the North American Society of Pacing and

Electrophysiology, 1996). Further, the fact that there were no differences between men and women in terms of CI and SVI further support this assumption. Additionally, while it is expected that sympathetic activity and TPR would correspond linearly, this relationship remains complex and tends to vary among the sexes and with age. For instance, in young women there is reportedly no relationship between the two as β-adrenergic vasodilator effects serve to offset α-adrenergic mediated vasoconstriction (Hart et al., 2009), which may explain the lack of differences in TPR between sexes. Collectively, these findings agree with the current literature that men and women exhibit differential brachial BP responses and further suggests that these difference influence patterns of vascular recovery following HI-BRE.

Similar to previous findings (Kingsley et al., 2017), the AIx@75 was augmented post-exercise prior to recovery indicating an earlier return of the reflected wave. The magnitude of change in AIx@75 in the present study (Men: +3300%; Women: +271%), however appears to be greater compared to changes in the AIx@75 following the HI-CE (+444.5%) by Kingsley et al. (2017). To our knowledge, this is only the second study to report changes in pulse wave reflection following a high-intensity interval modality. It is possible that increasing the total number of exercise bouts may increase the magnitude of change in measures of pulse wave reflection, particularly the AIx@75, but this is speculative.

Both the AIx@75 and AIx measures in this study appear to be predominately affected by the magnitude (i.e. AP, cPP), rather than reflection time (i.e. T*r)* of the pulse wave. However, again, Kingsley et al. (2017) reported that neither magnitude nor reflection time were associated with changes in the AIx@75. These authors speculated that the absence of these changes may have been due to increases in reservoir pressure, which has been shown to independently influence measures of the AIx (Davies et al., 2010). Whether the reservoir pressure influenced measures of the AIx in the present study is unclear. However, there does seem to be an influence of the reflected pulse wave contributing to increases in measures of the AIx. Although differences between men and women were only reported at 60 minutes following HI-BRE, it is reasonable to suggest that changes in the AIx are indeed sex specific and profoundly influenced by the AP. Again, the fact that women exhibit greater vasodilator effects may explain these differences. Moreover, sex differences seem to have driven changes in the AIx and AP between men and women, which are increased following HI-BRE.

Changes in hemodynamics and pulse wave reflection may have collectively or independently altered left ventricular function by increasing and decreasing the SPTI and DPTI, respectively, thus attenuating SEVR. While there were no sex differences in the SEVR, men in comparison to women had reportedly greater time spent in diastole (DPTI) in comparison to women. However, it is suspected that this may be due to differences in heart size alone. Changes in the SEVR following HI-BRE may be significant. The SEVR, which reflects oxygen supply and demand of the myocardium, typically experiences ischemia when reduced by ~50% (Tsiachris et al., 2012). Thus, although the present study does not suggest ischemia, there is still a significant reduction in oxygen supply to the myocardium at 60 minutes. Additionally, unlike Kingsley et al. (2017) the present study demonstrated an increase in ΔE_w which was greater in men due to augmented AP. Thus, the vasodilator effects in women seem to offset AP thereby decreasing AIx, as well as reducing heart workload.

In the literature, changes in stiffness of the aorta following HI-CE are mixed. For example, Rakobowchuk et al. (2009) reported increases in cf-PWV at similar time points in recreationally active men. However, Kingsley et al. (2017) reported no changes in cf-PWV in RT men. The present study, which also used RT individuals, reported a modest increase in cf-PWV for at least 10 minutes. The fact that the present study did observe changes in cf-PWV while others have not could be due the fact that exercise performed in this study was mainly in the upper-body (Okamoto et al., 2009). This would suggest that in RT individuals, the addition of the upper-body, or an increase in active muscle mass stimulates an increase in stiffness of the aorta. Interestingly, there were no changes in stiffness of the CCA. Both the aorta and CCA are categorized as elastic vessels, but their properties are inherently different. It is suggested that the aorta is more sensitive to changes in load bearing properties due to its' higher content of cross-linked collagen peptides that would increase stiffness. (Dobrin, 1995; Dobrin and Rovick, 1969). Collectively, these structural differences may help to explain these changes.

This study has several limitations. First, the Valsalva maneuver was not controlled for, which may have independently influenced results (Heffernan et al., 2007). Secondly, an absolute load was used for each participant suggesting varying exercise intensities between individuals.

Conclusion

In summary, HI-BRE augmented HR and this was accompanied by augmented pulse wave reflection magnitude and adverse alterations in left ventrticular function. Further, these measures were augmented in men in comparison to women, which seem to have been mediated by differences in vasodilatory effects. Further, HI-BRE acutely augmented stiffness of the aorta, but not the CCA. Future research is needed to fully elucidate time to recovery following HI-BRE, especially in terms of measures of wave reflection and left ventricular function. Additionally, studies should continue to further examine modalities or interventions that may attenuate these cardiovascular responses, as well as sex-specific differences.

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Key points

- Battling rope exercise increases wave reflection magnitude and left ventricular work.
- At similar time points, women demonstrate reduced alterations in these measures, which may be explained by lower diastolic blood pressures.
- Sex may determine recovery in men and women after battling rope exercise.

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