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The effects of a 12-week jump rope exercise program on abdominal adiposity, vasoactive substances, inflammation, and vascular function in adolescent girls with prehypertension

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Abstract

Introduction Childhood obesity is strongly associated with cardiovascular disease (CVD) development. It is necessary to combat unfavorable outcomes of obesity at a young age by utilizing effective interventions, such as exercise.

Purpose We sought to examine the effects of a jump rope exercise program on CVD risk factors, including body composition, vasoactive substances, inflammation, and vascular function in prehypertensive adolescent girls.

Methods Forty girls (age 14–16) were recruited and randomly assigned to a jump rope exercise group (EX, $n = 20$) or control group (CON, $n = 20$). Body composition, nitrate and nitrite levels, endothelin-1 (ET-1), C-reactive protein (CRP), systolic blood pressure and diastolic blood pressure (SBP, DBP), and arterial stiffness were measured before and after 12 weeks.

Results There were significant group by time interactions following the 12-week program for body composition (from 33.8 ± 3.6 to 30.2 ± 3.1%), central adiposity (from 86.4 ± 4 to 83.3 ± 5 cm), SBP (from 126 ± 3.3 to 120 ± 2.1 mmHg), and brachial-to-ankle pulse wave velocity (from 8.2 ± 1.0 to 7.4 ± 0.2 m/s). Nitrate/nitrite levels increased (from 54.5 ± 5.1 to 57.2 ± 5.2 µmol) along a reduction in CRP levels (from 0.5 ± 0.4 to 0.2 ± 0.1 mg/L). There were no significant changes in ET-1 ($P = 0.22$).

Conclusions These findings indicate that jump rope exercise may be an effective intervention to improve these CVD risk factors in prehypertensive adolescent girls. Jumping rope is an easily accessible exercise modality that may have important health implications for CVD prevention in younger populations.

Keywords Arterial stiffness · Central adiposity · C-reactive protein · Endothelin-1 · Nitric oxide · Pulse wave velocity

Abbreviations

ANOVA	Analysis of variance
baPWV	Brachial-to-ankle pulse wave velocity
BIA	Bioelectrical impedance analysis
BMI	Body mass index
BP	Blood pressure
bpm	Beats per minute
CON	Control group
CRP	C-reactive protein
CVD	Cardiovascular disease
DBP	Diastolic blood pressure
ET-1	Endothelin-1
EX	Exercise intervention group
HRR	Heart rate reserve
NO	Nitric oxide
RPE	Rating of perceived exertion
SD	Standard deviation of the mean
SBP	Systolic blood pressure
WC	Waist circumference

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Introduction

Obesity is strongly associated with a higher incidence of cardiovascular disease (CVD) and other various metabolic dis- orders in both youth and adult populations (Akil and Ahmad 2011; Chorin et al. 2015). Increased central adiposity specifically, defined as fat mass around the abdominal region, is positively associated with increases in risk factors for CVD such as increased blood pressure (BP) (Jansen et al. 2016), arterial stiffness (Strasser et al. 2015), and C-reactive protein (CRP) levels (Saijo et al. 2004). Greater measurements of arterial stiffness can indicate an increased risk for atherosclerosis and heart diseases, and brachial-to-ankle pulse wave velocity (baPWV), a measure of arterial stiffness, has been associated with BP increases in children (Hvidt 2015). Previous studies suggested that children and adolescents with high levels of adiposity and high BP are at a substantial risk for the development of coronary heart disease and other cardiovascular risk factors later in life (Ewart et al. 1998; Freedman et al. 2007).

Exercise training has been used to improve overall health and to reduce risk factors for CVD (Myers 2003). Previous studies indicate that exercise alone may reduce fat mass, CRP levels, BP, and arterial stiffness in obese young adults and children (Arikawa et al. 2011; Beck et al. 2013; Ewart et al. 1998). These studies incorporated about 40–50 min of moderate-to-vigorous intensity aerobic exercise 3–5 times per week (Arikawa et al. 2011; Beck et al. 2013; Ewart et al. 1998). The reduced arterial stiffness in these studies may be attributed to exercise-induced increases in nitric oxide (NO) bioavailability, a potent vasodilator, and reduced levels of endothelin-1 (ET-1), a potent vasoconstrictor (Maeda et al. 2003; Son et al. 2017). By increasing exercise in children, measures of arterial stiffness, NO bioavailability, and ET-1 may improve, thus potentially improving overall vascular health which would reduce the risk for the development of CVD occurrences later in life.

We have previously demonstrated that different modes of combined resistance and aerobic exercise training may have beneficial effects on measurements of BP, insulin resistance, arterial stiffness, central adiposity, leptin, and adiponectin levels, and other CVD risk factors in obese adolescent girls (Bharath et al. 2018; Son et al. 2017). However, the combined exercise training equipment may not be the most easily accessible for this specific population. Thus, identifying an exercise modality that is simple to use, easily accessible, and able to improve CVD risk factors may be integral to improving the health of obese adolescents. Adolescents, distinctively girls, state that they would be more motivated to participate in exercise if it is perceived as fun (Robbins et al. 2003; Taylor et al. 1999). Jumping rope is an easily accessible and enjoyable exercise modality that may increase exercise program adherence in adolescent girls. Additionally, jumping rope is an inexpensive exercise modality and also requires only limited space for performance that may promote better exercise adherence in this population (Withall et al. 2011). Jump rope exercise has been shown to improve cardiorespiratory endurance and coordination in both preadolescents and adolescents (Ozer et al. 2011), and improvements in cardiorespiratory fitness have also been shown to reduce blood pressure (Liu et al. 2014). However, to our knowledge, no prior studies have examined the effects of jump rope exercise on risks for CVD development in adolescence girls, including levels of vasoactive substances (ET-1, NO), inflammation (CRP), central adiposity, percent body fat, high blood pressure, and arterial stiffness. Taken together, determining the impact(s) of jump rope exercise on body composition and cardiovascular function may be beneficial for this population. Therefore, the purpose of this study was to examine the effects of a 12-week jump rope exercise program to test the hypothesis that this specific exercise modality would reduce levels of ET-1 and CRP, and improve central adiposity, percent body fat, NO bio- availability, arterial stiffness, and BP in sedentary adolescent girls with prehypertension.

Methods

Participants

Forty girls (age 14–16) volunteered to participate in this research study. All participants were classified as prehypertensive (120–140 mmHg systolic BP and/or 80–90 mmHg diastolic BP) and had abdominal obesity (waist > 80 cm, BMI equal to or greater than the 95th percentile for age and sex). All participants were considered to be inactive, meaning they participated in less than 1 h of regular physical activity per week within the last 6 months. Other exclusion criteria included a previous musculoskeletal injury within the last year that may negatively affect participation, as well as cardiovascular, pulmonary, adrenal, pituitary, and thyroid diseases. Participants who were already involved in a regular exercise program, on daily medication(s), including antioxidants and fat loss supplements, or weight loss diet plans were also excluded from participation. All procedures performed in this study were in accordance with the ethical standards of the institutional research committee at Pusan National University (PNU IRB/2016_105_HR) and with the tenets of the Declaration of Helsinki. This study was registered in Clinicaltrials.gov (NCT03534427). Informed consent was obtained from all individual participants and their parent/guardian(s) included in this study. Participant characteristics can be seen in Table 1.

Study design

A two-armed, parallel experimental design was used. The jump rope exercise intervention took place during the months of March–June during the school year. Blood samples, anthropometrics, and vascular function parameters were assessed before (baseline) and after the 12-week jump rope exercise program at 8:00 AM (± 1 h) following an over- night fast. After baseline measurements were performed, the participants were randomly assigned to either the jump rope exercise group (EX, n = 20) or the control group (CON, n = 20). The participants in the EX group participated in an exercise program (50 min per day, 5 times per week for 12 weeks) that consisted of jump rope variations. Exercise was performed at 2:00 PM (± 1 h) Monday-Friday. The EX group did not perform any additional exercise outside of this prescribed program during the 12 weeks. The participants in the CON group did not participate in the exercise intervention, or any outside exercise during the 12-week period, but were present and supervised in the laboratory at the same frequency, duration, and time of day as the EX group throughout the entire study period. Both groups of participants were advised weekly not to change their diet habits (~ 1920 kcal/day) for the duration of the study, and diet logs were obtained every week to keep track of dietary intake. Water intake was not recorded, however, participants were encouraged to consume approximately 2.5 L of water per day (Sawka et al. 2005). All exercise sessions were super- vised by trained professionals and all measurements were taken by qualified researchers.

Table 1 Participant

	Control (n=20)			Exercise (n=20)			Cohen's *d*
	Pre	**Post**	Δ	**Pre**	**Post**	Δ	
Age (years)	15±1	–	–	15±1	–	–	–
Tanner stage	2-3	–	–	2-3	–	–	–
Height (cm)	161±3	162±4	–	160±3	161±3	–	–
Body mass (kg)	68±8	70±8.9*	2.0±1.2	69±9.4	66±7.3*†	-3.0±1.5	0.3
BMI (kg/m²)	25±2	26±2	1.0±0.2	26±3	25±2	-1.0±0.5	0.4
Heart rate (bpm)	69±2	68±3	1.0±1.0	67±3	64±2*†	-3.0±1.0	0.7
SBP (mmHg)	126±4	127±5.3	1.0±0.8	126±3.3	120±2.1*†	-5.0±1.0	1.2
DBP (mmHg)	82±2	84±1.9	2.0±0.3	82±0.4	80±2	-2.0±1.0	1.3

Values are mean ± SD
BMI body mass index, *SBP* systolic blood pressure, *DBP* diastolic blood pressure, *Δ* changes between pre and post
*$p \leq 0.05$ different than Pre
†$p \leq 0.05$ different than Control

Blood sampling and analysis

Blood samples were collected at 8:00 AM (± 1 h) after an overnight fast at baseline and after 12 weeks from an antecubital vein. Each sample was centrifuged for 15 min at 3000 rpm stored at − 80 °C for later analysis. Using the provided reagents, each blood sample was run in duplicate in accordance with the manufacturer's instructions for total nitrate and nitrite levels, which were analyzed using a Griess assay kit from Cayman Chemical (Ann Arbor, MI, USA) (Giovannoni et al. 1997). The amount of nitrate and nitrite produced in the reaction mixture was determined spectrophotometrically at 540 nm (OD540) using a microplate reader (Edwards et al. 2004; Masaki and Yanagisawa 1992). Levels of endothelin-1 (ET-1) in blood samples were measured with an enzyme immunoassay kit (Endothelin-1 Enzyme Immunoassay Kit, Cayman Chemical, Ann Arbor, MI, USA). The detection range for ET-1 using this assay was from ≥ 1.5 µmol/mL (Hodeib et al. 2010). C-reactive protein (CRP) was assessed using an enzyme immunoassay kit (C-Reactive Protein Enzyme Immunoassay Kit, Cayman Chemical, Ann Arbor, MI, USA) according to the manufacturer's instructions (Druwe et al. 2012).

Pubertal development

Pubertal development was assessed using Tanner staging (breast and pubic hair stage) by self-reporting at the beginning of the study. Standard line drawings and writ- ten descriptions were provided, and participants selected the picture that most accurately reflected their appearance (Morris and Udry 1980).

Anthropometrics

Anthropometric measurements were taken at baseline and after 12 weeks. Height was measured without shoes using a stadiometer to the nearest 1.0 cm. Body composition was measured using bioelectrical impedance analysis (BIA) (InBody 230, Biospace, Seoul, Korea), which simultaneously recorded total body mass (nearest 0.1 kg), percent body fat (nearest 0.1%), and fat-free mass (nearest 0.1 kg) (Seo et al. 2012). The InBody 230 specifically has been validated to be consistent with the doubly labeled water method (Beato et al. 2018) and dual X-ray absorptiometry for measurements of total fat mass, total lean mass, and percent body fat measurements (Karelis et al. 2013). For BIA, the intra- assay coefficient of variation (repeated measures within individual) was 0.8 ± 0.9% and the inter-assay coefficient of variation (repeated measures between different days) was 0.3 ± 0.2%. BMI was calculated as body mass divided by the square of height (kg/m^2). Waist circumference was recorded using a standard tape measure to the nearest 0.1 cm at the midpoint between the iliac crest and the lower rib. These values were used to determine adiposity in absolute terms; however, there are no standard values that are considered to represent high adiposity in children and adolescents (Flegal et al. 2010).

Vascular function

Resting systolic and diastolic blood pressure (mmHg) and resting heart rate (bpm) were both measured in duplicate using an automatic sphygmomanometer (HEM-7113 INT; Omron Corp., Kyoto, Japan) and radial artery palpation, respectively, at baseline and after 12 weeks. The measurements were recorded after participants were in a seated position for 5 min. The average of the two measurements was recorded as the resting blood pressure and resting heart rate. Brachial-to-ankle pulse wave velocity (baPWV, m/s), an indicator of peripheral arterial stiffness, was measured using applanation tonometry (SphygmoCor CPV system, AtCor Medical Ltd, Sydney, Australia), followed by data analysis (version 8.0, SphygmoCor Cardiovascular

Management Suite, AtCor Medical Ltd, Sydney, Australia). Two measurements were collected, one at each time point, and averaged as previously described (Weber et al. 2004; Yambe et al. 2007).

Jump rope exercise program

Participants in the EX group participated in a jump rope exercise program for 12 weeks, 5 days per week, for 50 min per day (Table 2). This program was divided into a warm-up (5 min), the main exercise session (40 min of rope jumping variations), and a cool-down (5 min). Both the warm-up and the cool-down consisted of stretching, walking, and jogging. There were seven main rope jumping exercises, including one line two jump, jumping feet together, running jumping, open side jump, open back and forth jump, and rock paper scissor jump. The jump rope exercise program intensity incrementally increased every 4 weeks: weeks 1–4 were at 40–50% HRR and 11–12 RPE, weeks 5–8 were at 50–60% HRR and 13–14 RPE, and weeks 9–12 were at 60–70% HRR and 15–16 RPE. These exercise intensities, frequencies, and durations were chosen to reflect previous studies that reduced fat mass, BP, and arterial stiffness in various populations (Arikawa et al. 2011; Beck et al. 2013; Ewart et al. 1998). The exercise intensity of the jump rope program was monitored using heart rate reserve (HRR) and Borg's rating of perceived exertion scale (RPE) of 6–20. Participant heart rate was monitored using a wearable Polar heart monitor (Electro, Oy, Kempele, Finland) during all exercise sessions to sustain the proper training intensity. There were five trainers supervising each exercise session, each specifically assigned to four participants. Heart rate monitors and RPE were checked every 5 min during the 40-min training session. If heart rate or RPE were either too low or too high, participants were encouraged to either increase or decrease their effort during the session.

Statistical analysis

The Shapiro–Wilk test was used to determine the normality of the data. Independent *t* tests were used to determine base- line differences between the two groups. A two-way analysis of variance (ANOVA) with repeated measures [group (CON and EX) × time (before and after 12 weeks)] was used to compare the difference of changes between pre- and post- jump rope exercise program within and between groups on the dependent variables. Bonferroni correction was used to determine the effects of the jump rope training program over time. When a significant main effect or interaction was noted, paired *t* tests were used for post-hoc comparisons. An effect size analysis was performed using eta-squared (η^2) for the two-way ANOVA, and interpreted 0.01, 0.06, and 0.14 as small, medium and large, respectively. Cohen's *d* was used for the *t* tests, interpreted as 0.20, 0.50, and 0.80 as small, medium and large, respectively (Lee et al. 2018). All analyses were performed using SPSS 25.0 (SPSS Inc., Chicago, IL, USA). Data are presented as Mean ± SD. Statistical significance was set at $p \leq 0.05$. It was estimated that 40 participants would enable 80% power to detect a 5% decrease in baPWV after the jump rope exercise program based on previous literature (Figueroa et al. 2011).

Table 2 Jump rope exercise program

Order	Exercise	Duration (min)	Week	Intensity	Frequency
Warm-up	Static stretching	5			
	Walking				
	Jogging				
Main exercise	1 line 2 jump	40	1-4	40-50% HRR	5 times/week
	Jumping feet together			(RPE 11-12)	
	Running jumping		5-8	50-60% HRR	
	Open side jump			(RPE 13-14)	
	Open back and forth jump		9-12	60-70% HRR	
	Rock paper scissor jump			(RPE 15-16)	
Cool-down	Static stretching	5			
	Walking				
	Jogging				

Results

Vasoactive substances

Post-exercise program nitrate and nitrite levels in the EX group significantly increased ($p \leq 0.05$) after 12 weeks (from 54.5 ± 5.1 μmol to 57.2 ± 5.2 μmol, respectively). Pre- and post-levels in the CON group were not different. Post-nitrate and nitrite levels increased significantly ($p \leq 0.05$) in the EX group in comparison to the CON group (Table 3). There were no significant differences ($p = 0.22$) in endothelin-1 (ET-1) levels pre- and post-exercise intervention between the EX group (from 0.37 ± 0.21 to 0.38–0.33 μmol/mL) and the CON group (from 0.41 ± 0.21 to 0.40–0.31 μmol/mL) (Table 3).

C-reactive protein

Post-exercise program C-reactive protein (CRP) levels in the EX group were significantly reduced ($p \leq 0.05$) following 12 weeks of jump rope exercise (from 0.5 ± 0.4 to 0.2 ± 0.1 mg/L, respectively). Pre-and post-CON levels were not significantly different after 12 weeks. Post-CRP levels were significantly reduced after 12 weeks ($p \leq 0.05$) in the EX group in comparison to the CON group (EX post vs. CON post: 0.2 ± 0.1 vs. 0.7 ± 0.4 mg/L, respectively)(Table 3).

Anthropometrics

There were significant group by time interactions following the 12 weeks jump rope exercise program. Total body mass, percent body fat, and waist circumference were significantly reduced ($p \leq 0.05$) after 12 weeks of jump rope exercise in the EX group **(**Fig. 1**)**. In the EX group, total body mass significantly decreased (from 69 ± 9.4 to 66 ± 7.3 kg), percent body fat significantly decreased (from 33 ± 3.6 to 30.2 ± 3.1%), and waist circumference significantly decreased (from 86.4 ± 0.4 to 83.3 ± 0.6 cm). The EX group also had significantly increased lean body mass ($p \leq 0.05$) after 12 weeks (from 44.9 ± 4.5 to 46.8 ± 4.2 kg) **(**Fig. 1**)**. However, the CON group had an increase in total body mass after 12 weeks (from 68 ± 8.4 to 70 ± 8.9 kg) (Table 1). Baseline measurements between the EX and CON group were not significantly different ($p > 0.05$) (Table 1).

Vascular function

Systolic blood pressure (SBP) was significantly reduced ($p \leq 0.05$) in the EX group following 12 weeks of the jump rope exercise program (from 126 ± 3.3 to 120 ± 2.1

mmHg). Post-SBP decreased significantly ($p \leq 0.05$) in the EX group in comparison to the CON group (EX post vs. CON post: 120 ± 2.1 mmHg vs. 127 ± 5.3 mmHg, respectively). How- ever, diastolic blood pressure (DBP) did not significantly differ between groups (Table 1). Resting heart rate was significantly reduced ($p \leq 0.05$) in the EX group after 12 weeks of jump rope exercise (from 67 ± 3 to 64 ± 2 bpm). Post-rest- ing heart rate was reduced significantly ($p \leq 0.05$) in the EX group in comparison to the CON group (EX post vs. CON post: 68 ± 3 bpm vs. 64 ± 2 bpm, respectively). Brachial-to-ankle pulse wave velocity (baPWV) significantly decreased ($p \leq 0.05$) in the EX group (from 8.2 ± 1 to 7.4 ± 0.2 m/s). Post-baPWV decreased significantly ($p \leq 0.05$) in the EX group in comparison to the CON group (EX post vs. CON post: 7.4 ± 0.2 mmHg vs. 8.1 ± 0.2 mmHg, respectively) (Table 3).

Table 3 Changes in vasoactive substances, arterial stiffness, and inflammation before and after a 12-week period of control ($n = 20$) and exercise intervention ($n = 20$)

	Control (*n*=20)		**Exercise (*n*=20)**		**Eta-squared (η^2)**		
	Pre	**Post**	**Pre**	**Post**	**Group**	**Time**	**Interactional**
Total nitrate and nitrite (µmol)	53.3±4.3	53.5±5.2	54.5±5.1	57.2±5.2*†	0.06	0.11	0.04
Endothelin-1 (µmol/mL)	0.41±0.21	0.4±0.31	0.37±0.21	0.38±0.33	0.02	0.04	0.02
baPWV (m/s)	8.2±0.5	8.1±0.2	8.2±1	7.4±0.2*†	0.06	0.14	0.04
CPR (mg/L)	0.5±0.3	0.7±0.4	0.5±0.4	0.2±0.1*†	0.03	0.12	0.03

Values are mean ± SD

baPWV brachial-to-ankle pulse wave velocity, *CRP* C-reactive protein, *eta-squared (η^2)* effect size analysis

*$p \leq 0.05$ different than Pre

†$p \leq 0.05$ different than Control

Discussion

The objective of this study was to examine the effects of a 12-week jump rope exercise program on body composition, central adiposity, vasoactive substances (NO bioavailability and ET-1), inflammation (CRP), and vascular function (BP and arterial stiffness) in adolescent girls with prehypertension. There are multiple novel findings from this study that are beneficial for this population. First, BP was reduced from prehypertensive to normotensive values along with a significant reduction in arterial stiffness following the 12-week jump rope exercise program. Second, total blood nitrate and nitrite levels, an indicator of NO bioavailability, increased along with a significant decrease in CRP, a blood marker for systemic inflammation. Additionally, central adiposity and body composition were favorably improved. To our knowledge, this is the first study to show the effects of a 12-week jump rope exercise intervention on body composition, central adiposity, vasoactive substances, inflammation, and vascular function in prehypertensive adolescent girls.

Exercise has been proven to be beneficial as a non- pharmacological intervention in both children and adults to improve cardiovascular function and to reduce risks for clinical conditions, such as coronary heart disease (Hakim et al. 1999; Tan et al. 2017). In the present study, we examined the use of a 12-week jump rope exercise program, an inexpensive and easily accessible exercise modality, and its effects on prehypertensive adolescent girls. One of the notable findings of this study is that jump rope exercise reduced systolic blood pressure (SBP) by ~ 6 mmHg. This reduction of SBP is clinically significant because a mere reduction in SBP of 2 mmHg has been shown to reduce mortality from stroke by nearly 6% and coronary heart disease by 4% (Chobanian et al. 2003). Thus, a reduction of 6 mmHg in this present study may have an effect on preventing cardio- vascular complications that may arise later in adulthood. In addition to the reduction in SBP, arterial stiffness decreased by ~ 0.8 m/s in this study. This is significant, as an increase of only 1 m/s in baPWV has been shown to be associated with a 12% increase in the risk of cardiovascular events, especially in individuals who are already at a high risk for CVD (Vlachopoulos et al. 2012). This decrease in SBP is likely due to the improved vasodilatory function, signified by increased levels of circulating nitrate and nitrite

(Goto et al. 2007). Increased levels of nitrate and nitrite are indicative of increased NO bioavailability, and NO is a potent vasodilator and is crucial for regulating vascular resistance (Park et al. 2016). Increased NO bioavailability may also decrease levels of arterial stiffness (Kinlay et al. 2001), which may have been a cause of the BP reduction in these prehypertensive adolescent girls. However, the endothelium-derived potent vasoconstrictor ET-1 was not changed following the 12 weeks exercise intervention. Thus, these results regarding reduced blood pressure and arterial stiffness indicate that jump rope exercise may be a useful intervention for improving vascular function via improving NO bioavailability in prehypertensive adolescents.

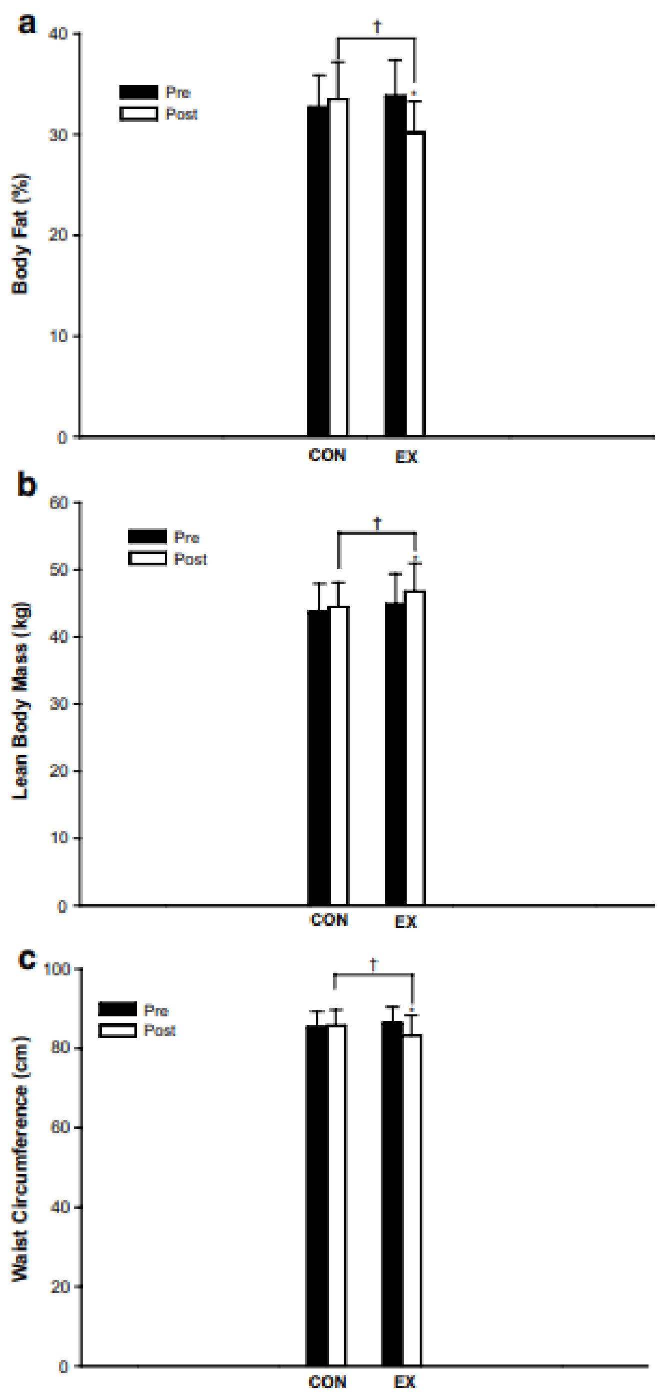

Fig. 1 Changes in anthropometric parameters after 12 weeks of jump rope training (EX) compared to a control (CON). **a** Body fat (%) decreased in the EX group and was lower than the CON group after post-testing. **b** Lean body mass (kg) increased in the EX group and was greater than the CON group after post-testing. **c** Waist circumference (cm) decreased in the EX group and was lower than the CON group after post-testing. **a** Effect size analysis: η^2 group: 0.06, time: 0.14, interactional: 0.04. **b** Effect size analysis: η^2 group: 0.05, time: 0.16, interactional: 0.07. **c** Effect size analysis: η^2 group: 0.05, time: 0.12, interactional: 0.05. *$p \leq 0.05$ vs. Pre. $^{\dagger}p \leq 0.05$ vs. CON. Data are mean ± SD

In addition to the blood pressure-lowering effects of vasodilation caused by NO, another potential mechanism responsible for lowering BP may be an increase in micro- vascular density following the 12-week jump rope exercise program. High blood pressure, specifically hypertension, is associated with an increase in peripheral vascular resistance which is mainly from microvascular dysfunction and/or reduced microvascular density (Mayet and Hughes 2003). A previous study also indicated that increases in total peripheral resistance in hypertensive populations may result from reduced microvascular density (Greene et al. 1989). In general, aerobic exercise activity improves microvascular density by vascular remodeling (Evans 1985). Thus, by increasing regular aerobic exercise activity, microvascular density may be increased and can potentially decrease BP. In the case of the present study, skeletal muscle microvascular density may have improved and could have had an effect on the reduction in SBP. Potentially, a reduced baPWV may indicate that decreased peripheral arterial stiffness may be associated with improved microvascular density; however, this warrants further investigations.

Previous studies suggested that increased levels of CRP indicate higher levels of inflammation and are validated clinical predictors for CVD and coronary artery disease (Danesh et al. 2004; Hamer et al. 2010). Furthermore, elevated CRP levels are also associated with increased endothelial dysfunction (Singh et al. 2007) and greater levels of arterial stiffness, which can result in the development of atherosclerosis (Hage 2014). For instance, previous studies suggested that high levels of CRP inhibit endothelial nitric oxide synthase (eNOS) activity (Venugopal et al. 2002), which can cause vascular endothelial cell dysfunction. This is supported in our study, as CRP levels decreased and NO bioavailability increased. This increase in NO bioavailability may be attributed to the decreased levels of CRP in these prehypertensive adolescent girls. Thus, CRP reduction in this study may indicate improved eNOS functioning. Considering that eNOS deficiency is a pivotal factor in atherogenesis (Venugopal et al. 2002), this specific effect of the jump rope exercise program may be clinically relevant in the prevention of atherosclerosis.

Exercise, specifically aerobic exercise, has been shown to reduce CRP in both men and women (Arikawa et al. 2011; Lakka et al. 2005). Additionally, exercise interventions longer in duration (16-week and 12-month interventions) have been shown to significantly decrease CRP levels in various populations (Arikawa et al. 2011; Campbell et al. 2009). Our current results are well-aligned with the findings from these previous studies. Interestingly, our results suggest that a 12-week jump rope exercise program is a sufficient duration and mode for an exercise intervention to reduce CRP levels, specifically in prehypertensive adolescent girls. It has been proposed that consistent, regular exercise attenuates inflammatory markers, such as CRP, by reducing body fat (You et al. 2004), which may also be the case in the present study, for we revealed significant decreases in CRP levels, percent body fat, and waist circumference in the EX group. Obesity and increased abdominal adiposity are associated with increased levels of inflammation (Kalkhoff et al. 1983), and increased amount of fat tissues in the liver specifically may cause a greater secretion of CRP (Ellulu et al. 2017).

Additionally, in girls aged 13–18 years, increased waist circumference (WC) was found to be strongly associated with increased levels of serum CRP (Harmse and Kruger 2010), which is closely associated with risks for the development of CVD (Ellulu et al. 2017). In the present study, WC, a well-confirmed measurement of abdominal adiposity in younger individuals (Brambilla et al. 2006), and per- cent body fat were both significantly reduced following the 12-week jump rope exercise program. These reductions may be associated with the CRP reduction in this study. Moreover, one study found that reducing WC by a minimum of 3 cm may be beneficial for reducing the risk for metabolic syndrome (Miyatake et al. 2008). Following the jump rope exercise program, WC was reduced by ~ 3.1 cm; thus, this exercise intervention may also be helpful in reducing the risks for the development of CVD in these adolescent girls. However, the mechanism(s) underlying the relationship between the reduction in CRP and central adiposity warrant further investigation.

Conclusion

This study showed that body composition, central adiposity, NO bioavailability, inflammation, and vascular function were favorably improved after a 12-week jump rope exercise program in adolescent girls with prehypertension. Although various modes of exercise are believed to improve a number of these parameters, to our knowledge, this is the first study that shows the effects of a jump rope exercise program on these CVD risk factors in this population. Therefore, our results suggest that jump rope exercise is a useful, easily accessible, and cost-effective exercise modality to improve cardiovascular health and weight management in adolescent girls with prehypertension.

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Author contributions Authors' roles: conception and design of the study: KDS and SYP. Collection, assembly, analysis and interpreta- tion of data: KDS, EJP, WMS and SYP. Drafting the article or revising it critically for important intellectual content: KDS, EJP, WMS, and SYP. Final approval of the version to be submitted: KDS, EJP, SDS, WMS and SYP.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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