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Pulse wave reflection responses to bench press with and without practical blood flow restriction

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Abstract

Resistance exercise is recommended to increase muscular strength, but may also increase pulse wave reflection. Resistance exercise combined with practical blood flow restriction (pBFR) on pulse wave reflection is unknown. **PURPOSE**: To evaluate the differences between bench press with pBFR and traditional high-load bench press on pulse wave reflection characteristics in resistance-trained men. **METHODS:** Sixteen resistance-trained men participated in the study. Pulse wave reflection characteristics were assessed before and after low-load bench press with pBFR (LL-pBFR), traditional high-load bench press (HL), and a control (CON). A repeated measures ANOVA was used to evaluate the conditions across time on pulse wave reflection characteristics. **RESULTS:** There were significant ($p \leq 0.05$) interactions for heart rate, augmentation index, augmentation index normalized at 75bpm, augmentation pressure, time-tension index and wasted left ventricular energy such that they were increased after LL-pBFR and HL compared to rest and CON, with no differences between LL-pBFR and HL. Aortic pulse pressure ($p<0.001$) was only elevated after LL-pBFR compared to rest. In addition, there was a significant ($p \leq 0.05$) interaction for aortic diastolic blood pressure (BP) such that it was decreased after LL-pBFR compared to rest and CON but not HL. The subendocardial viability ratio and diastolic-pressure-time index were significantly different between LL-pBFR and HL compared to rest and CON. There were no significant interactions for brachial systolic or diastolic BP, aortic systolic BP, or time of the reflected wave. **CONCLUSION:** Acute bench press resistance exercise using LL-pBFR or HL, significantly altered pulse wave reflection characteristics without differences between LL-pBFR and HL.

Word count: 250

Key words: augmentation index, blood pressure, resistance exercise, KAATSU, Venous occlusion, knee wraps

Introduction

Resistance exercise (RE) is suggested to increase muscular strength, endurance (Kraemer et al. 2002; Position-Stand 2009), as well as hypertrophy (Tesch 1988). It has been demonstrated that utilizing a resistance greater than 70% 1-repetition maximum (1RM) is necessary to induce hypertrophy (Kraemer and Ratamess 2004; Position-Stand 2009). However, previous studies have demonstrated that performing RE combined with blood flow restriction (BFR) increases muscular strength, muscular endurance, and hypertrophy with resistance set as low as 20-30% 1RM (Abe et al. 2005; Madarame et al. 2008; Sumide et al. 2009). A recent meta-analysis by Lixandrao et al. (2018) demonstrated that high-load RE to failure resulted in muscular strength gains that were greater to or equal low-load RE with BFR to failure, but both conditions produced muscular hypertrophy in a similar fashion (Lixandrao et al. 2018). Moreover, Farup et al. (2015) and Fahs et al. (2015) reported that muscular strength and hypertrophy can be enhanced by low-load RE to failure with or without BFR to failure; however, the number of repetitions and exercise volume are significantly greater in low-load RE without BFR compared to low-load RE with BFR. Recently researchers have demonstrated that practical BFR (pBFR), using knee wraps in lieu of a KAATSU device or blood pressure (BP) cuff, resulted in an acute increase in skeletal muscle thickness after an acute bout of leg press (Wilson et al. 2013) and also a chronic increase in muscle thickness after 4 and 8 weeks of biceps curl resistance training (Lowery et al., 2013).

Evaluation of cardiovascular risk factors after RE, such as pulse wave reflection characteristics [augmentation index (AIx), Alx normalized at 75 bpm (AIx@75)], is novel and provides valuable information that is currently lacking in the literature. Previous researchers have evaluated pulse wave reflection characteristics in response to lower-body RE with BFR induced by KAATSU (Rossow et al. 2012) or a BP device (Figueroa and Vicil 2011). However, upper-body RE with pBFR on pulse wave reflection characteristics have not been investigated. Especially, the bench press is a very popular upper-body RE for novice and trained individuals to enhance muscular strength and hypertrophy, it is important to understand the cardiovascular responses to bench press with pBFR in order to provide insight information to the public because increased pulse wave reflection characteristics are strongly and independently connected with an increased risk for cardiovascular events as well as increased morbidity and mortality (Weber et al. 2004; Weber et al. 2005; Roman et al. 2009). The AIx and AIx@75 appear to play an important role in left ventricular (LV) contractile function (Segers et al. 2007; Denardo et al. 2010), LV afterload, the subendocardial viability ration (SEVR) (Tsiachris et al. 2012), a measure of myocardial perfusion, and wasted LV pressure energy (ΔE_w) (Hashimoto et al. 2008), indicative of myocardial workload.

Previous researchers have reported that acute RE increases AIx (Fahs et al. 2009) and AIx@75 (Fahs et al. 2009; Yoon et al. 2010; Thiebaud et al. 2016). However, decreases in pulse wave reflection characteristics have been observed after lower-body RE with and without BFR (Figueroa and Vicil 2011) as well as upper-body RE (Okamoto et al. 2014) at low-load that utilized no BFR. The effects of solely upper-body, low-load RE with BFR compared to traditional high-load RE on pulse wave reflection characteristics have not been examined. Resistance exercises combined with pBFR, is applicable, allowing for individuals who do not have access to specialized equipment to utilize BFR at home or in gyms (Loenneke and Pujol 2009).

The hemodynamic responses after RE are controversial. Previous studies have demonstrated that traditional high-load RE induces significant increases in brachial systolic BP

(BSBP) and aortic systolic BP (ASBP) (Fahs et al. 2009; Figueroa and Vicil 2011), but this is not a consistent finding as researchers have also reported no change in BSBP and ASBP after RE (Yoon et al. 2010; Tai et al. 2018). Interestingly, some data have shown acute RE significantly decreased BSBP (Rezk et al. 2006; Duncan et al. 2014) and brachial diastolic BP (BDBP) (DeVan et al. 2005; Fahs et al. 2009; Lefferts et al. 2014). On the other hand, previous studies reported no change in BSBP and BDBP 10-15 min after upper- (Maior et al. 2015) and lower-body (Rossow et al. 2012; Poton and Polito 2016) resistance exercise with BFR. The acute increases in BSBP, BDBP, ASBP, ADBP during RE may result in an increased ΔE_w for at least 30 minutes, which is associated with increased cardiovascular risk (Tai et al. 2018); currently no researchers have evaluated how BFR may affect ΔE_w. In addition, high-load resistance exercise without BFR induces higher pressure responses than low-load resistance exercise with BFR (Brandner et al. 2015; Poton and Polito. 2016). However, no studies have evaluated how upper-body, low-load BFR compared to traditional high-load RE alters brachial and aortic BP responses. Despite the fact that the data are severely lacking, the use of pBFR has far reaching implications in almost any gym due to it's ease of use and sheer practicality. Understanding the effects of pBFR on pulse wave reflection characteristics and hemodynamics is pertinent to understand how, or if, acute use of pBFR has deleterious effects on the cardiovasculature.

Therefore, the purpose of the present study was to evaluate the differences between bench press with pBFR and traditional high-load bench press on pulse wave reflection characteristics and hemodynamics in resistance-trained men. It was hypothesized that pulse wave reflection characteristics would not change after low-load bench press with pBFR but would be significantly increased after traditional high-load bench press, compared to low-load bench press with pBFR. Furthermore, it was hypothesized that hemodynamics would not change after an acute bout of low-load bench press with pBFR or traditional high-load bench press.

Materials and methods

Subjects. Sixteen, young, healthy men (20-30 yrs old) self-reported that they had been engaging in resistance training (6±4 yrs) at least 3 days per week for a minimum of 1 year assessed via a questionnaire. Participants were excluded if they were taking any medications or supplements known to affect HR, BP or vascular function (for example, stimulants or nitric oxide products). Exclusion criteria included a recent smoking history (< 6 months), obesity (defined as a body mass index (BMI) ≥ 30 kg/m^2), orthopedic problems, open wounds, history of blood clots, cancer, metabolic disease, known cardiovascular disease, uncontrolled hypertension (resting brachial BP ≥ 140/90 mmHg), or vascular dysfunction as assessed via the Physical Activity Readiness Questionnaire (PAR-Q) and a Health Participant Questionnaire. This research was approved by the Kent State University Institutional Review Board and was completed in accordance with the Declaration of Helsinki. Informed consent was obtained from all individual participants included in the study.

Procedures. The initial visit consisted of anthropometric measurements and muscular strength assessment on the bench press. The second visit was separated by at least 72 hours and consisted of muscular strength verification on the bench press. The remaining three visits were performed in a counterbalanced fashion in which the participants reported to the Cardiovascular Dynamics Laboratory for either low-load bench press RE with pBFR (LL-pBFR), traditional high-load bench press (HL), or a quiet control (CON). All testing occurred between the hours of 6am-noon in order to control for diurnal variation. All participants were ≥ 3 hours postprandial (Figueroa and Vicil 2011; Rossow et al. 2012; Thiebaud et al. 2016) and had avoided caffeine, alcohol, and strenuous exercise for at least 24 hours prior to testing. The modalities were separated by 1 week, with no more than 10 days between them. Each participant also completed testing at the same time of day (±1 hour). Upon arriving to the laboratory, participants rested quietly in the supine position for a period of 10 min. Pulse wave reflection characteristics were assessed over the next 10 min. After completion of either LL-pBFR, HL, or CON, the participants returned to the supine position, and pulse wave reflection characteristics were reassessed after 10 min. In order to compare data with different studies, we chose 10 minutes to match our previous research (Tai et al. 2018) and the timeline from other reports (Maior et al. 2015; Neto et al. 2015, 2016; Poton and Polite 2016).

Anthropometric measurement. Height and weight were measured using a stadiometer and a beam balance platform scale, respectively. Body composition was determined using 7-site skinfold analysis (ACSM. 2018). Each site was measured twice. If the measurements were different than 1 mm, a third measurement was conducted. Body fat percentage was calculated using the Brozek equation (Brozek et al. 1963). Since we recruited resistance-trained individuals, the purpose of body fat percentage measurement was to indicate their level of conditioning.

Muscle Strength. Muscle strength was assessed by the 1RM test for bench press. The 1RM was assessed within five attempts following a warm-up with 50% of the participant's body weight based on recommendations from the National Strength and Conditioning Association (Haff and Triplett 2015). The highest resistance lifted between the two days of the 1RM assessment was used to determine the workload for the LL-pBFR and HL conditions.

Pulse wave reflection characteristics. After 10 min of supine rest, BSBP and BDBP were measured at least twice using a SphygmoCor (AtCor Medical, Sydney, Australia) device, separated by 1 min. The two readings were no more than 5mmHg difference. If there was more than a 5 mmHg difference, a third measurement was taken. If the third measurement was greater than 5 mmHg, the resting BP measurements were started over from the beginning. Once two BP measurements were obtained that were with 5 mmHg, and they were averaged. The average of these measurements was used to calibrate the pressure waveforms obtained from a 10-sec epoch using a high-fidelity tonometer (SPT-301B; Millar Instruments, Houston, Texas, USA). BP measurements were derived from the aortic waveform using an intrinsic generalized transfer function from the software which has been shown to be valid (Pauca et al. 2001). All the pulse wave reflection characteristics were measured twice. If the quality of the pressure waveform was lower than 90% (an operator index score), a third measurement was obtained. The two pulse wave reflection characteristics measurements were averaged for data analysis. The aortic waveforms are comprised of a forward moving wave (P1), caused by the ejection of stroke volume, as well as a reflected wave (P2) that returns to the aorta from peripheral sites. The AP was calculated as the differences between the peaks of forward and reflecting waves (AP=P2-P1) of ASBP, expressed as a percentage of aortic PP (APP). In addition, APP has been demonstrated to be strongly associated with subclinical heart disease (Roman et al. 2007; Roman et al. 2009). A strong inverse relationship exists for the AIx and HR, therefore AIx@75 was calculated by the software. The transit time of the reflected wave (T*r*) was also derived from the pressure waveform and is defined as the time of the pressure wave travel to the peripheral reflecting sites and back to the aorta (Nichols and Singh 2002). The SEVR was calculated as the ratio of diastolic area under the curve [diastolic-pressure-time index (DPTI)) to systolic area under the curve (time-tension index (TTI)] and has been shown to be an estimate of myocardial perfusion (Tsiachris et al. 2012). We also measured ΔE_w, a measurement of additional myocardial workload (Casey et al. 2008) due to the early reflection of the systolic wave, and is dependent on the amplitude of aortic pressure augmentation. This was calculated using the equation 1.333 x AP [ventricular ejection duration – T*r*] x $\pi/4$, such that 1.333 allows for the conversion of mmHg/s to dynes s/cm^2 (Casey et al. 2011).

Resistance Exercise. The LL-pBFR consisted of 4 sets of 30, 15, 15, and 15 repetitions at 30% of the 1RM with 30sec of rest between sets. Participants' arms were wrapped using knee wraps just below the shoulder. Three pairs of knee wraps were used between participants, and the width of knee wraps was 8 cm (Harbinger, Austin, TX) with a length of 183 cm. A rating of perceived pressure at 7 out of 10 on a 10-point Visual Analog Scale (Lowery et al. 2013; Wilson et al. 2013) was used to determine tension of the wrap. We chose our perceived pressure based on work by Lowery et al. (2013) and Wilson et al. (2013), which used knee wraps as a method of pBFR. The work by Lowery et al. (2013) used pBFR on the arms, using the same rationale from a previous study from the same laboratory, Wilson et al. (2013), as did the present study. Wilson et al. (2013) monitored the presence of blood flow via ultrasonography at the following perceived pressures: control (0 out of 10), moderate (7 out of 10), and tight (10 out of 10) using pBFR on the legs. In their study, the moderate condition was chosen because the ultrasonography showed occlusion of venous blood flow with arterial blood flow still present under the moderate condition. The control condition did not restrict venous blood flow or arterial blood flow, while the tight condition occluded both venous and arterial blood flow. The HL consisted of 4 sets of 8 repetitions at 70% of the 1RM with 1 min of rest between sets. The CON had the participants rest in the supine position for 10 min, matching the body position of the RE.

Statistical analysis. A one-way ANOVA was used to determine if there were any significant differences at rest between conditions. A 3 x 2 repeated measures ANOVA was used to test the effects of condition (LL-pBFR, HL, and CON) across time (rest and recovery) on pulse wave reflection characteristics [HR, BSBP, BDBP, PP, ASBP, aortic diastolic BP (ADBP), APP, AIx, AIx@75, AP, T*r*, SEVR, DPTI, TTI, and ΔE_w]. If the interactions were deemed significant using the aforementioned ANOVA, Tukey Honest Significant Difference (HSD) tests were used to determine significance post hoc. Significance was set *a priori* at $p \leq 0.05$. Values are presented as mean ± standard deviation (SD), percent change (%) are calculated as (recovery-rest)/rest x 100%. All statistical analyses were completed using IBM SPSS version 21 (Armonk, NY, USA). Our sample size was based on data in our laboratory that was collected under identical conditions using 7 healthy, resistance-trained participants. From our pilot data an effect size for the outcome variables AIx@75 estimated a sample size of 15 participants giving us an effect size of 0.95, respectively, with an alpha of 0.05, and a power of 80%.

Results

The 16 participants in the present study were 23±3 yrs old, 1.77±0.05 m height, and weighed 80.2±9.3 kg with a body fat percentage of 13.3±4.8%. The average number of years of resistance training was 6±4 yrs, and the average 1RM on the bench press was 117±20 kg. The exercise volume in LL-BFR and HL was similar between the two conditions ($p>0.05$), 2563±408 kg and 2308±409 kg, respectively.

Pulse wave reflection characteristics are presented in Table 1, with the exception of AIx (percent change (%): LL-pBFR= 734; HL: 725; CON: -43.8) and AIx@75 (percent change (%): LL-pBFR=550; HL: 305; CON: -150) (Figure 1). There were no significant ($p>0.05$) interactions or main effects for BSBP, BDBP, ASBP, or T*r*. There were significant condition-by-time interactions for HR ($F_{2,26}$=44.2, p<0.001), AP ($F_{2,26}$=29.5, p<0.001), AIx ($F_{2,26}$=39.8, p<0.001), AIx@75 ($F_{2,24}$=50.0, p<0.001), TTI ($F_{2,26}$=20.4, p<0.001), and ΔE_w ($F_{2,24}$=23.4, p<0.001) such that they were increased after LL-pBFR and HL compared to rest and CON. There was also a significant interaction for APP ($F_{2,26}$=10.8, p<0.001) such that it was elevated after LL-BFR compared to rest and CON, with no difference between LL-BFR and HL, or HL and CON. There were significant condition-by-time interactions for SEVR ($F_{2,26}$=32.2, p<0.001) and DPTI ($F_{2,26}$=6.3, p=0.006) such that they were decreased after LL-pBFR and HL compared to rest and CON. Main effects of time were also noted for HR ($F_{1,13}$=19.1, p=0.001), AP ($F_{1,13}$=20.8, p=0.001), AIx ($F_{1,13}$=17.2, p=0.001), AIx@75 ($F_{1,12}$=17.2, p=0.001), TTI ($F_{1,13}$=11.8, p=0.004), and ΔE_w ($F_{1,12}$=15.1, p=0.002) such that they were attenuated after the CON and augmented after LL-pBFR and HL.

Discussion

The primary finding of the present study is that 10 min after an acute bout of either bench press with pBFR or traditional high-load bench press, pulse wave reflection characteristics significantly change in relation to rest, in similar fashions, without altering aortic or brachial SBP, or T*r*, in young, healthy, resistance-trained men. Specifically, our data demonstrated significant increases in the AIx, AIx@75, AP, TTI, and ΔE_w, concomitant with significant decreases in SEVR and DPTI. To our knowledge, this is the first study to evaluate the differences between low-load bench press with pBFR compared to traditional high-load bench press on pulse wave reflection characteristics in resistance-trained men.

In agreement with a previous study (Rossow et al. 2012), we observed no significant changes 10 min after an acute bout of RE in BSBP, BDBP, and ASBP, be it either pBFR or traditional high-load RE. Maior et al. (2015) and Neto et al. (2016) found significant reductions in BDBP up to 40 and 60 min respectively followed by low-load RE with BFR (Maior et al. 2015; Neto et al. 2016). Previous studies that have examined the hemodynamic responses after low-load RE with BFR have demonstrated no difference in hemodynamics at 30 min after RE with BFR compared to rest (Figueroa and Vicil 2011; Rossow et al. 2012; Brandner et al. 2015; Poton and Polito 2016). Brandner et al. (2015) and Rossow et al. (2012) utilized different muscle groups, but similar BFR protocols, that consisted of 4 sets of 30, 15, 15, and 15 repetitions at 20% 1RM in young individuals. Brandner et al. (2015) reported no changes in BSBP and BDBP up to 60 min after acute bout of bicep curls with BFR using 130% of resting BSBP in order to achieve BFR (Brandner et al. 2015). Rossow et al. (2012) utilized 130% of resting BSBP to achieve BFR while using both a narrow cuff (5 cm) and a wide cuff (13.5 cm) to restrict blood flow and reported no changes in BSBP, BDBP, ASBP, and ADBP at 5 and 15 min after an acute bout of knee extension (Rossow et al. 2012) with either cuff size. Figueroa and Vicil (2011) had a crossover design such that participants performed 3 sets of leg extension and flexion with, or without BFR, which was accomplished by inflating a cuff to a pressure of 100 mmHg, and exercising at 40% 1RM until volitional fatigue in young healthy individuals. They reported significant changes in BSBP, BDBP, ASBP, and ADBP immediately after the acute bouts of low-load RE, either with or without BFR, with no change reported at 30 min during recovery. However, there was no difference between the RE conditions (traditional high-load or low-load with BFR). Based on these data, it appears that just performing upper- or lower-body RE is insufficient to alter BP, and that both limbs are necessary, which further highlights that the amount of muscle mass used during acute RE plays a critical role (Bentes et al. 2015). Also, the time points of measurement were different across studies, we measured hemodynamics 10 min after acute resistance exercise with and without pBFR while other studies measured from immediately (Figueroa and Vicil 2011; Maior et al. 2015; Poton and Polito 2016; Rossow et al. 2012), 5-15 min (Brandner et al. 2015; Maior et al. 2015; Neto et al. 2015; Poton and Polito 2016; Rossow et al. 2012), 20-30 min (Brandner et al. 2015; Figueroa and Vicil 2011; Maior et al. 2015; Neto et al. 2015; Rossow et al. 2011), 40-50 min (Brandner et al. 2015; Maior et al. 2015; Neto et al. 2015), to 60 min (Brandner et al. 2015; Maior et al. 2015; Neto et al. 2015; Rossow et al. 2012). In addition, the present study, and the other published studies, all utilized different means to restrict blood flow which further limits direct comparisons.

The present study demonstrates that an acute bout of RE with pBFR and traditional high-load RE have similar, significant impacts on pulse wave reflection characteristics in resistance-trained men which rejects our hypothesis, and both acute bout of RE with pBFR and traditional high-load RE might increase the risk of cardiovascular events, however the data are unclear. The similar responses between pBFR and traditional high-load might be the resistance exercise we chose, bench press. Due to this exercise utilizing only the upper-body, and due to the close proximity to the heart, direct impacts on the heart may cause similar responses in pulse wave reflection characteristics. Since there are no previous studies that have examined an acute bout of upper-body RE with pBFR on AIx and AIx@75, we can only compare to studies that have performed an acute bout of lower-body RE with BFR. Rossow et al. (2012) observed a significant decrease in AIx immediately after an acute bout of lower-body RE with BFR using the aforementioned protocol of BFR, with no change after 5 min recovery. However, Figueroa and Vicil (2011) did not find any significant change in AIx immediately after an acute bout of lower-body RE with intermittent BFR, which deflated the cuffs between sets and exercises, might increase venous return compared to continuous BFR, but they did report a significant reduction in AIx after 30 min recovery. The reduction 30 min later was attributed to peripheral vasodilation, a major determinant of the reflected wave and thus AIx (Kelly et al. 2001; Munir et al. 2008). Nevertheless, our data demonstrate a significant increase in AIx (170%) 10-15 min after an acute bout of upper-body RE with pBFR. Since AIx is associated with HR (Wilkinson et al. 1998) as well as LV preload (Heffernan et al. 2010), the significant change in AIx might result from different changes in HR and LV preload across studies. Although HR increases, the increase in AIx is due to decreases in T*r* after acute RE with (Figueroa and Vicil 2011) BFR and traditional high-load RE (Fahs et al. 2009; Tai et al. 2018). However, we did not observe any change in T*r* in the present study, and our data are in agreement with a previous study (Rossow et al. 2012). As previously mentioned, BFR decreases venous return, LV preload, stroke volume, and cardiac output which may lead to greater contractile force, thereby increasing cardiac workload. This is in agreement with the present study, as we observed significant increases in SEVR, DPTI, TTI, and ΔE_w after an acute bout of RE with BFR. However, no data have been published, to our knowledge, examining alterations in arterial blood flow using knee wraps as a means of achieving BFR.

To our knowledge, this is the first study to exam myocardial workload (SEVR, DPTI, TTI, and ΔE_w) after acute bout of bench press with pBFR or traditional high-load bench press. Our data suggest there were significant decreases in SEVR and DPTI, with increases in TTI and ΔE_w 10-15 min after an acute bout of bench press regardless of condition. Since SEVR is the ratio of DPTI to TTI, the significant reduction in SEVR resulted from a decrease in DPTI and an increase in TTI, which suggests that an acute bout of bench press with pBFR and traditional high-load bench press significantly decreased oxygen supply and increased oxygen demand of the myocardium for at least 15 min post-exercise. This is further exemplified with the increased ΔE_w, a measure of myocardial workload that is not affected by BP and/or HR. It is important to note that the immediate negative effect (sustained increased cardiac workload post-exercise) we observed in the present study might be temporary as Beck et al. (Beck et al. 2013) reported regular resistance training significantly reduces myocardial oxygen demand in young individuals, as measured via SEVR, DPTI, and TTI. However, since the present study was an acute bout of RE, not a resistance training design, this is not possible to ascertain.

Individuals who want to perform BFR exercise should be mindful of the differences between traditional methods of BFR and pBFR. The purpose of using BFR as a means to alter blood flow during RE is to eliminate venous return and still allow arterial blood flow to transport oxygen to exercising muscles. Some studies have used absolute pressure (Figueroa and Vicil 2011) or relative pressure (Brandner et al. 2015; Maior et al. 2015; Neto et al. 2016; Rossow et al. 2012). In addition, some some studies have used internittent pressure (Brandner et al. 2015; Figueroa and Vicil 2011; Neto et al. 2016) between sets, or exercises, while other studies have used continuous pressure throughout the RE (Brandner et al. 2015; Maior et al. 2015; Rossow et al. 2012). On the other hand, there is no set standard for pBFR as of yet. Since we do not know the effects of pBFR on limbs blood flow, it is difficult to qualify the tightness. In addition, the altherations in blood flow due to pBFR would be changed after every repetition/set as the knee wraps are unable to maintain the same amount of blood flow throughout all of the exercises due their elastic material, which would not be the case with the vinyl BP cuff used in some BFR studies. Despite this shortcoming, the benefits of using pBFR is that it is more practical and cheaper for individuals to use during their RE sessions compared to traditional methods of BFR.

The present study is not without limitations. First, we determined the tension of the knee wraps using a rating of perceived pressure, and the pain tolerance might have a high amount of inter-individual variability. The rating of perceived pressure at 7 of 10 may restrict different percentages of arterial blood flow per each individual, causing different cardiovascular responses. Secondly, based on data by Wilson et al. (2013) a moderate perceived pressure (7 out of 10) was associated with venous occlusion and moderate arterial flow, however we cannot be certain that this applied to our participants. Thirdly, we recruited resistance-trained men only; we did not recruit untrained, aerobic-trained, or women. The different fitness level, training statues, or sex may cause different physiological impacts in response to an acute bout of RE with pBFR. Finally, it is unclear how our pBFR compare to other traditional known pressure BFR methods that which have many studies demonstrating the chronic benefits.

In conclusion, the present study demonstrated that low-load bench press with pBFR and traditional high-load bench press induce significant alterations in pulse wave reflection characteristics in a similar fashion without any changes in hemodynamics except ADBP and APP. Our data demonstrated that the similar cardiovascular responses between pBFR and traditional high-load RE. However, high-load RE requires heavy weights and equipment. The pBFR is a more practical exercise modality with RE load is relatively low such that individuals may use small dumbbells or resistance bands at home. The pBFR using knee wraps may be a cheaper and more accessible method to achieve BFR than an expensive rapidly inflated cuff system. However, the pressure of knee wraps on arms might be changed due to different numbers of knee wraps were wrapped, time of use (loss elasticity), and circumference of individual’s limb. It is imperative that future studies exam the different responses between acute and chronic effects of low-load RE with pBFR on pulse wave reflection characteristics, and how these responses may affect cardiovascular function.

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Conflict of interest Statement

The authors have no conflicts of interest to report

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Table 1. Hemodynamics and pulse wave reflection characteristics at rest and recovery in 3 different conditions

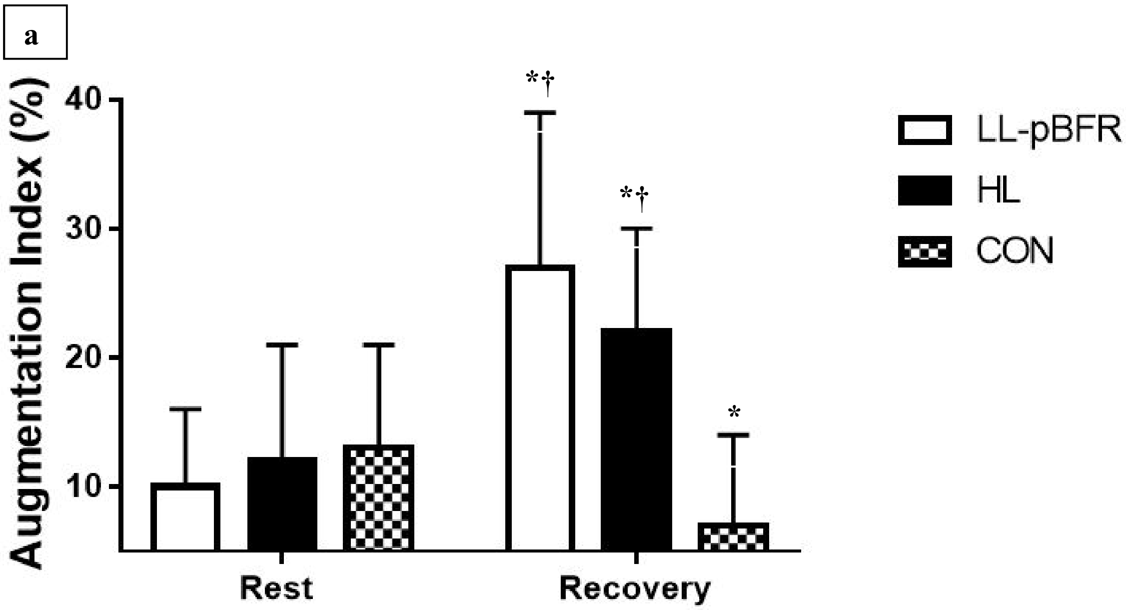
	LL-pBFR			HL			CONTROL		
	Rest	Recovery	Change (%)	Rest	Recovery	Change (%)	Rest	Recovery	change (%)
HR (bpm)	56±10	61±12*†‡	8.8±9.7	57±14	69±13*†	22.3±9.8	57±10	53±7*	-6.3±7.6
BSBP (mmHg)	119±7	121±7	2.5±6.5	121±10	121±10	0.1±9.0	121±8	120±6	-0.8±5.8
BDBP (mmHg)	63±8	59±5	-6.4±9.4	63±10	62±8	-0.7±9.1	65±8	64±8	-0.7±8.4
ASBP (mmHg)	103±7	108±7	4.1±6.8	105±10	106±9	1.7±0.9	106±8	104±7	-1.5±5.4
ADBP (mmHg)	65±9	60±6*	-7.1±9.3	64±10	63±8	-0.5±10.2	66±8	65±8	-0.2±7.7
APP (mmHg)	39±5	48±5*†	26.1±20.1	41±5	43±5†	6.2±13.0	40±4	38±4	-3.1±11.9
AP (mmHg)	4.0±2.3	14.0±7.0*†	982±2624	5.2±3.9	9.6±3.7*†	2910±9999	6.1±2.4	3.4±2.7*	-42.5±42.9
T*r* (ms)	149.6±5.1	150.9±8.0	0.8±5.6	149.0±6.1	153.0±14.2	2.7±8.3	147.9±3.7	151.3±5.1	-3.4±23.5
SEVR (%)	155.5±30.1	129.8±37.3*†	-16.8±11.9	154.8±42.2	117.1±29.8*†	-23.3±8.4	152.0±32.8	170.3±31.7*	12.0±13.7
DPTI (ms)	2811±314	2583±267*†	-8.3±9.9	2784±379	2525±226*†	8.4±8.6	2855±375	2925±347	2.9±7.9
TTI (ms)	1864±371	2085±391*†	11.3±11.2	1905±510	2253±484*†	20.0±12.0	1926±324	1754±262*	-7.2±8.3
ΔE_w (dynes s/cm^2)	810±475	3126±1842*†	942±2650	1000±778	1958±936†	2700±9282	1280±534	688±589*	-46.8±44.3

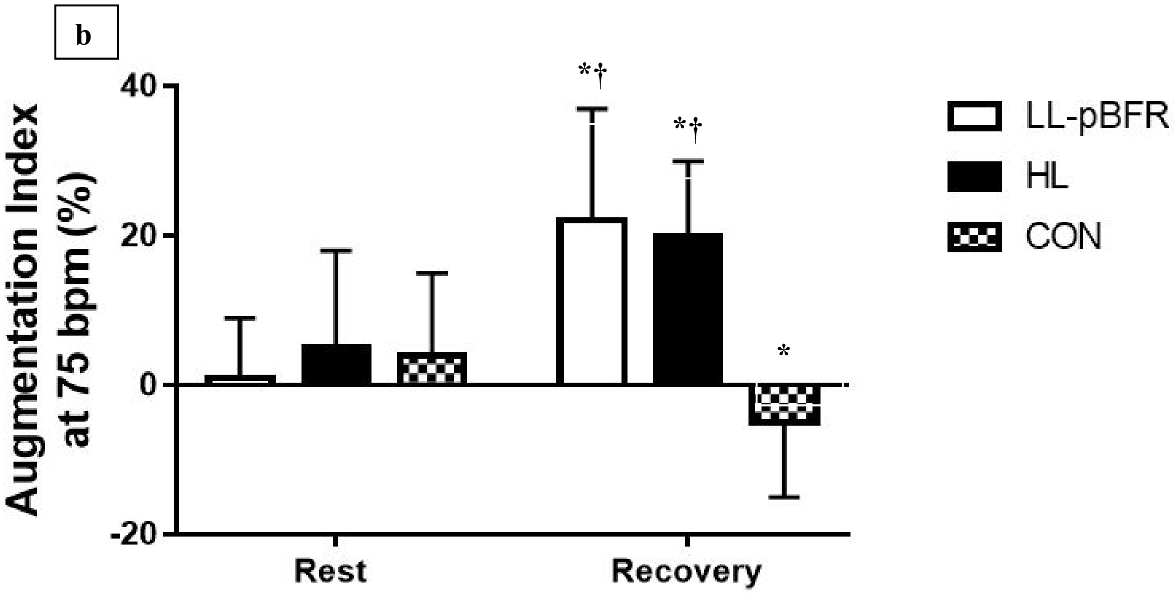
Data are mean ± SD

*p<0.05, different from rest, †p<0.05, difference from Control, ‡p<0.05, difference from HL

ADBP aortic diastolic blood pressure, AP augmentation pressure, APP aortic pulse pressure, ASBP aortic systolic blood pressure, BDBP brachial diastolic blood pressure, BSBP brachial systolic blood pressure, DPTI diastolic pressure time index, HL high-load bench press without blood flow restriction, HR heart rate, LL-pBFR low-load bench press with practical blood flow restriction, SEVR subendocardial viability ratio, T*r* transit time of the reflected wave, TTI time tension index, ΔE_w wasted left ventricular energy

Fig. 1 Changes in a) Augmentation Index and b) Augmentation Index at 75bpm at rest and during recovery from an acute bout of low-load resistance exercise with practical blood flow restriction (LL-pBFR), traditional high-load resistance exercise without blood flow restriction (HL), and a quiet control (CON) in young, resistance trained individuals (N=16). Data are mean ± SD. $^*p \le 0.05$, significantly different from rest; $^\dagger p < 0.05$, significantly different from CON


a
Augmentation Index (%)
40
30
20
10
*†
*†
*
Rest
Recovery
LL-pBFR
HL
CON


b
Augmentation Index at 75 bpm (%)
40
20
0
-20
*†
*†
*
Rest
Recovery
LL-pBFR
HL
CON