Shafer et al. (2025) *Int J Res Ex Phys*. 21(1):37-54.

International Journal of Research in Exercise Physiology

Original Research Article

Frequency of Blood-Flow Restriction Resistance Training on Maximal Leg Strength and Arterial Stiffness in Resistance-Trained Young Adults

Chase Shafer[1], Jacob Baldwin[1], Carter Sundeen[1], Sebastian de la Toba[1], Zak McPhee[1], Nicholas Beltz[1], Jeffrey Janot[1]

[1]Department of Kinesiology, University of Wisconsin-Eau Claire, WI, USA

Abstract

Introduction: While the benefits of traditional resistance training (TRT) have been demonstrated in past research, the high intensity often used in this type of training has been shown in some studies to acutely increase vasoconstriction and chronically increase arterial stiffness. Blood flow restriction training (BFRT) may mitigate this increase or even decrease arterial stiffness while providing similar training benefits. This study aimed to compare the effects of BFRT once per week (along with another day of TRT; BFRT+TRT) vs. twice per week (BFRT+BFRT) on knee extensor/flexor isokinetic strength and arterial stiffness. **Methods:** Fifteen participants were randomly assigned to either BFRT+TRT or BFRT+BFRT. Outcome variables included augmentation index normalized to a heart rate of 75 beats per minute (AIx75), pulse-wave velocity (PWV), and isokinetic peak torque of the knee flexors and extensors at both 60 and 180 degrees per second (°/s). The intervention involved leg extension and leg curl exercises at 30% one repetition maximum (1RM) for BFRT and 70% 1RM for TRT, performed two days per week for six weeks with each session separated by at least 48 hours. **Results:** A two-way repeated measures analysis of variance revealed no significant Group or Time effects on arterial stiffness. There was a significant Time effect, but no Group effect, on all isokinetic strength measures except peak torque extension at 180°/s. **Conclusions:** The findings of the study suggest that BFRT and TRT have similar effects in increasing peak torque with no adverse effects on arterial stiffness. Two days a week of BFRT can be implemented safely among healthy young adults.

Key Words: Augmentation Index, Cardiovascular, Kaatsu, Programming, Pulse-Wave Velocity

INTRODUCTION

Increased arterial stiffness (i.e., a loss of elasticity in the arteries, which are the blood vessels that carry blood away from the heart) is associated with the development of peripheral artery disease (PAD), a form of cardiovascular disease involving the accumulation of atherosclerotic plaque within arteries of the extremities. PAD, which affects more than 200 million people worldwide, can be closely linked to risk factors such as obesity, diabetes, hypertension, smoking, poor diet, and physical inactivity[1,2]. Regular exercise and physical activity have been shown to treat and reduce the risk of developing PAD[1].

One common modality of exercise is traditional resistance training (TRT), which strengthens muscles, stimulates muscle growth, enhances muscle endurance, and promotes overall health and wellbeing[3]. TRT involves voluntary contractions of specific skeletal muscles against some form of external resistance (e.g., weight machines, free weights, resistance bands, and/or gravity). The current American College of Sports Medicine guidelines on TRT state that the general population should participate in these exercises two to three days a week targeting each major muscle group and allowing at least two days of rest between sessions targeting the same muscle groups. These guidelines also specify the optimal set and repetition range for the untrained general population as 1-2 sets of 8-12 repetitions per exercise. The eventual target intensity for most TRT is 60-80% of an individual's one-repetition maximum (1RM; the heaviest load that can be successfully lifted for one repetition) for that exercise. TRT makes a significant contribution to the maintenance of functional abilities, improvement of muscular strength and endurance, and avoidance or management of chronic disease and disability[4]. TRT is especially beneficial for older adults, as researchers observed that there may be a link between the decline in physical function during older adulthood and an increased risk of death[5].

While the benefits of TRT have been demonstrated in past research, the high intensity often used in this type of training has been shown in some studies to acutely increase vasoconstriction and chronically increase arterial stiffness, the latter of which is a risk factor for PAD[6,7]. When performed chronically, low to moderate intensities of TRT may be beneficial for arterial stiffness but may not provide sufficient training stimuli for the fitness goals of trained individuals[8,9]. However, recent experimental studies have found that a relatively new resistance training modality, blood flow restriction training (BFRT), mitigates this increase[6,10] or even decreases arterial stiffness[11] in adults. This suggests that BFRT could be a safer alternative to TRT from a cardiovascular health standpoint, an essential implication for populations with PAD.

BFRT involves placing a tourniquet-like device around a muscle to reduce blood flow through it prior to exercising. While this may seem counterintuitive, research suggests that restricting blood flow by 40-80% of an individual's limb occlusion pressure (the pressure required to entirely stop blood flow through a limb) produces the safest, and most effective, improvements in muscular strength and mass during BFRT[12]. This unique stimulus allows for similar muscle adaptations to be elicited with only a fraction of the weight used in TRT (20-50%

1RM compared to 60-80%), as is supported by various review articles[10,13,14,15,16,17]. One such review analyzed 10 studies comparing the effects of TRT and BFRT and found a similar mean percentage gain in muscle mass between the two modalities[14]. A more recent systematic review and meta-analysis of seven studies determined that BFRT actually produced higher follow-up scores in knee extensor maximum voluntary contraction than did TRT. The review also presents findings that there were no significant differences noted between the modalities in maximal dynamic muscle strength (i.e., 1RM) of the knee extension and the leg press exercises[18]. This makes BFRT appealing for diverse populations including those in rehabilitation or those seeking performance improvements[19]. The hypertrophic and strength-inducing effects of BFRT are attributed to increased levels of metabolic stress (i.e., build-up of metabolites because of the ischemic/hypoxic environment) rather than mechanical stress (i.e., heavy loads from external resistance) as in TRT. This is theorized to induce muscle growth and strength increases by influencing other factors such as the increased recruitment of fast-twitch muscle fibers, elevated systemic anabolic hormones, reduced myostatin (to promote muscle growth), reduced muscle ring-finger protein 1 (MuRF1; to inhibit muscle atrophy), stimulated cell swelling (which increases protein synthesis by activation of protein kinase signaling pathways), and increased rate of protein translation[12,20,21] (the production of proteins).

Aside from the extensive research on BFRT and its effect on muscle strength and hypertrophy, the authors could find no studies comparing the effects that different frequencies of BFRT have on strength or arterial stiffness outcomes. Furthermore, the lack of a consensus on BFRT's effect on arterial stiffness highlights a need for additional research in this area.

This study is the first to examine the effects of two different frequencies of BFRT on both leg strength and arterial stiffness. The information yielded can be used to develop best practices for BFRT implementation that consider both efficiency (i.e., greatest benefit with least time cost) and safety (i.e., positive long-term effects on arterial stiffness), which can be applied to various settings from rehabilitation to strength and performance training. This study aimed to determine whether it is more optimal to perform BFRT once per week (along with another day of TRT) or twice per week from both a strength and arterial stiffness perspective. It is hypothesized that two days per week of BFRT will lead to similar strength improvements as a combination of BFRT and TRT while eliciting a lessor increase in arterial stiffness.

METHODS

Subjects

Participants were recruited from kinesiology classes at the University of Wisconsin-Eau

Claire. The researchers gave recruitment presentations to approximately 450 kinesiology students across 11 different classes. The target population of this study was resistance-trained (operationally defined as having participated in resistance training of all major muscle groups an average of at least twice per week for at least the past six months), 18–29-year-old students. To maximize participant safety and control for some confounding variables, the following exclusion criteria were set for eligibility to participate:

- Body mass index of greater than 35 kg/m^2 (kilograms per meter squared)
- Signs or symptoms (or a known condition) of cardiovascular, musculoskeletal, or nervous system diseases
- Any other uncontrolled chronic conditions
- Major injury to a muscle or joint in the past six months
- Current infection, inflammation, or injury to the lower extremity
- Surgery of any kind within the past six months
- Spinal fusion procedure at any point in life
- Smoking or vaping within the past six months
- Current use of blood thinners or blood pressure medications
- Current pregnancy
- Family history of deep vein thrombosis
- Personal history of reactions to compression (such as swelling in areas distal to compression, bruising, pain, nerve damage, or numbness)
- Personal history of metabolic conditions (e.g., type I or II diabetes mellitus) or difficulty regulating blood sugar levels (e.g., hyperglycemia or hypoglycemia).

Of the 66 students who expressed interest in participating, 20 scheduled an initial meeting to complete the informed consent form and health history questionnaire. Three prospective participants were excluded during this phase for failing one or more exclusion criteria, resulting in an initial sample size of 17 (12 males and five females). Table 1 describes the initial participant characteristics. Over the course of the eight-week study, two participants withdrew due to soreness from the BFRT and scheduling conflicts. As a result, the final sample size of the study was 15 (11 males and four females). Table 2 describes the final participant characteristics. Participants were randomly assigned to either a one day of BFRT and one day of TRT per week group (BFRT+TRT) or two days of BFRT group (BFRT+BFRT) using a simple random team generator prior to the first training intervention. BFRT+TRT performed TRT to ensure that the training stimulus was adequate for trained individuals (as only one day of training per muscle group per week is insufficient for this population). The

Institutional Review Board of the University of Wisconsin-Eau Claire reviewed this study and granted approval on August 27, 2025. Additionally, each participant completed an informed consent form prior to any data collection or health history inquiries.

Table 1. Initial participant characteristics by group

	BFRT+TRT (*n*=9)	BFRT+BFRT (*n*=8)	Total (*N*=17)
Age (years)	20.78 ± 3.46	19.63 ± 1.41	20.24 ± 2.68
Height (cm)	172.73 ± 8.74	179.41 ± 8.99	175.88 ± 9.24
Weight (kg)	80.21 ± 14.62	79.42 ± 11.99	79.83 ± 13.04
Body Mass Index (kg·m^{-2})	26.71 ± 3.09	24.57 ± 2.19	25.70 ± 2.85

Note. cm = centimeters; kg = kilograms; kg·m^{-2} = kilograms per meter squared.

Experimental Design

This study was an eight-week pretest-posttest randomized groups design that involved two groups (BFRT+TRT and BFRT+BFRT) and two independent variables (the frequency of BFRT and time).

Procedures

Isokinetic Dynamometer

The CSMi Humac Norm (Computer Sports Medicine Inc. Solutions, Stoughton, Massachusetts) isokinetic dynamometer was used to measure the isokinetic (constant-speed) strength of the quadriceps (i.e., extensors) and hamstrings (i.e., flexors) muscle groups. This involved five consecutive repetitions of maximal effort extension and flexion of the right knee while seated in the machine. The machine is programmed to move only at a speed of 60 and then 180 degrees per second (°/s), with compensatory changes in the resistance applied by the machine based on the force applied into the pad by the subject (to maintain the programmed speed). Isokinetic strength at 60°/s is indicative of muscular strength and most closely mimics the movement of the joint during TRT. At 180°/s, isokinetic strength is a greater indicator of power output and explosivity. Peak torque (the maximum amount of rotational force applied into the pad of the machine during a single repetition) was measured by the machine (based on the amount of resistance the machine must apply to maintain the programmed speed) and provided on screen as a report. This assessment measures four dependent variables: peak torque extension and peak torque flexion at both 60°/s and 180°/s. Isokinetic dynamometry is widely regarded as the gold-standard assessment of muscular strength and is often the reference criterion for novel devices. The Humac Norm specifically has been found to have good to excellent intrarater reliability[22] and strong inter-machine reliability with the Biodex System 3 model[23], which itself has been found to have reliability and validity levels appropriate for both clinical and research uses[24]. See Figure 1 for the setup for an isokinetic dynamometry assessment using the Humac Norm.

SphygmoCor XCEL

The SphygmoCor XCEL (Cardiex Ltd, Sydney, Australia) device was used to measure arterial stiffness via two different dependent variables: augmentation index normalized for a heart rate of 75 beats per minute (AIx75) and pulse-wave velocity (PWV). With each contraction of the heart, a pressure wave is created which travels through the proximal arteries to the more distal ones. When this wave reaches a fork of an artery, part of the pressure wave is reflected back towards the heart, resulting in the augmentation pressure (a temporary increase in blood pressure at the intersection of the opposing blood flow and reflected pressure wave forces). AIx75 is the ratio between this augmentation pressure and the pulse pressure (the difference between systolic and diastolic blood pressures) standardized to a heart rate of 75 beats per minute. Pulse pressure is an especially significant aspect of AIx75, as a large difference between systolic and diastolic pressure values is indicative of poor cardiovascular health. The larger the difference, the greater the risk of atherosclerosis, stroke, or other cardiac events. PWV is the speed at which the original pressure wave travels through the arterial system. AIx75 is measured via the brachial artery by applying a blood pressure cuff to the upper arm while the subject lies supine. See Figure 2 for the setup for the AIx75 assessment using the SphygmoCor XCEL. PWV is measured via the application of a cuff to the upper thigh (to detect the femoral pulse) and a gentle application of a probe to the carotid artery in the neck while the participant lies supine. PWV is considered the gold-standard non-invasive technique for measuring arterial stiffness[13,25]. See Figure 3 for the setup for the PWV assessment using the SphygmoCor XCEL. Additionally, the SphygmoCor XCEL has been found to be highly valid and reliable in its measurements of these two factors of arterial stiffness[26].

Initial Test

Upon completion of the informed consent and health history documents, participants scheduled their baseline data collection session. These sessions were held during the mornings of the first week of the study and were conducted at the McPhee Physical Education Center at the University of Wisconsin-Eau Claire. Prior to the start of data collection, both the isokinetic and the SphygmoCor Xcel devices were calibrated. Additionally, all data collection was conducted by qualified investigators. To minimize the risks for confounding variables, participants were instructed to arrive at the assessment having obtained a typical night of sleep (based on their individual habits) and not eaten, exercised, or consumed caffeine since at least midnight. Participants were also told to consume a typical amount of water leading up to the assessment (based on their individual habits).

After the participants had their height and weight measured and recorded, they were provided with a standard granola bar then asked to lie in a supine position for 10 minutes to achieve a resting state. The first assessment was the "Pulse-Wave Analysis" on the SphygmoCor XCEL, which yielded the AIx75. Immediately after this, the "Pulse-Wave Velocity" assessment was performed, measuring the PWV. While remaining in the supine position, limb occlusion pressure was then measured. This process involved the gradual increase in pressure in a cuff applied to the upper thigh until the posterior tibial (back of ankle) pulse could no longer be palpated.

Next, to prepare for the isokinetic strength test, participants were guided through a five-minute dynamic warmup that consisted of three minutes of stationary cycling followed by 15 yards of each of the following exercises: lunges with a rotation towards the front leg, carioca (down and back), hamstring scoops, hip open the gate/close the gate, high knees, butt kicks, and single-leg Romanian deadlifts. Following the warmup, participants were seated into the isokinetic machine and strapped into position. Only the right leg was measured for efficiency. Four practice reps were allowed at each movement speed prior to any data collection to allow participants to adjust to the procedure. Following the practice repetitions, five consecutive maximal effort repetitions were measured at each speed. A full recovery was allowed between the completion of the 60°/s assessment and the practice reps for the 180°/s assessment (rather than a set time) to ensure readiness in all participants.

Lastly, participants completed a two-to-five repetition maximum assessment for both the bilateral leg extension and bilateral leg curl exercises. After completing two warmup sets (of 10, then five repetitions) of progressively higher intensity and fully recovering, participants performed as many repetitions as possible (with full range of motion) up to five repetitions with 10-20% more weight than the second warmup set (depending on the rating of perceived exertion of the second warmup set). If more than five repetitions could be completed, participants again were allowed to fully recover before another attempt with 10-20% higher resistance (again depending on the rating of perceived exertion). This process was repeated until only two to five repetitions could be completed with full range of motion and proper technique. A conversion chart published by the National Strength and Conditioning Association was used to estimate each participant's 1RM[27]. This value was only used to determine training intensity of the BFRT and TRT workouts during the intervention and is not a dependent variable in this study.

Of note, the two-to-five repetition maximum procedure was repeated after each participant's sixth workout session (i.e., the midpoint of the study) to allow for compensatory changes in training intensity during the second half of the intervention if participants had changed their strength levels in either of the exercises (i.e., if the predicted 1RM went up, so would their training weight for the last three weeks).

This mid-point assessment was scheduled at least 48 hours after the sixth workout and at least 48 hours before the seventh.

The entire pre-intervention process took approximately 90 minutes per participant, as it involved the most assessments. The midpoint reassessment required around 20 minutes due to it only testing the two-to-five-repetition maximum for both exercises. Because the post-intervention assessment included only the SphygmoCor XCEL and isokinetic tests, it required about 45 minutes to complete.

Resistance Training Sessions

At the end of the pre-intervention assessment, each participant scheduled their two workouts for the next week (or further if their schedule allowed), separated by at least 48 hours. Participants in the BFRT+TRT group completed one BFRT workout and one TRT workout (in that order) each week. Participants in BFRT+BFRT completed two BFRT workouts each week. Regardless of group assignment, participants began the workout with the same warmup as used prior to the isokinetic test. All participants then performed the bilateral leg extension exercise followed by the bilateral leg curl exercise, and each session took about 20 minutes. In accordance with the published recommendations, the BFRT workouts consisted of four sets (of 30, 15, 15, and 15 repetitions) for each exercise at 30% of the participants' predicted 1RM for the specific exercise, separated by 30 seconds of rest. Blood pressure cuffs were applied to the upper thighs of both legs and inflated to 60% of the individual's measured limb occlusion pressure. This pressure was maintained throughout all four sets of the same exercise before being deflated (to restore blood flow) while switching to the leg curl or after completion of the workout[15,17]. Since standard thigh blood pressure cuffs were used rather than BFRT-specific cuffs, muscle actions during each repetition (expansion and relaxation) made it impossible to maintain an exact pressure throughout the set. However, for maximal consistency the researchers ensured proper cuff inflation before each set while the muscles were tensed and the pads of the exercise equipment were pressed against the cuffs. TRT workouts consisted of four sets of 10 repetitions for each exercise at 70% of the participants' predicted 1RM for the specific exercise, separated by 60 seconds of rest (an efficient but appropriate duration for this training intensity). These TRT protocols were selected based on similarity to the BFRT protocols (i.e., four sets of a moderate number of repetitions) while remaining in accordance with published recommend-ations for the intermediately trained population[4]. Although intensities above 70% 1RM (and thus repetition targets of fewer than 10) are optimal for strength-focused training programs and are also most strongly associated with increased arterial stiffness, 70% was used since it was within the recommendations for the intermediately trained general population[4] (and thus more generalizable) and was found to elicit both strength improvements[12] and arterial stiffness increases[9] in previous studies. Differences in inter-set rest times between the types of resistance training are attributable to the different mechanisms underlying each modality: the higher loads in TRT require longer rest periods whereas the emphasis on a hypoxic environment in BFRT necessitates shorter rests. In both groups, training resistances were rounded up to the nearest five pounds to accommodate the selectivity of the available exercise machines. The same weight was used for the first three weeks and then updated for the last three weeks based on the baseline and midpoint 1RM values. Sets were completed until reaching the prescribed number of repetitions or until reaching failure, whichever occurred first. Table 3 summarizes these protocols. Figure 4 demonstrates the setup for the BFRT leg extension and leg curl exercises.

These workouts were completed at the same frequency of twice-per-week for six weeks, maintaining at least 48 hours of separation between workouts. At least one researcher was present for all workouts, although due to time constraints the same researcher could not attend every session. Participants were required to avoid any form of resistance training of the quadriceps and hamstrings muscle groups during the eight-week study (i.e., throughout both rounds of testing and the intervention).

Figure 1. Humac Norm isokinetic dynamometry setup

Figure 2. SphygmoCor XCEL augmentation index normalized for 75 heartbeats per minute assessment setup

Figure 3. SphygmoCor XCEL pulse-wave velocity assessment setup

Figure 4. Leg extension and leg curl exercise with blood flow restriction setup
Note. The setup for these exercises is the same for traditional resistance training, only the BFR cuffs are removed.

Statistical Analyses

A two-way repeated measures analysis of variance (ANOVA) was used to analyze all four dependent variables regarding isokinetic strength (peak torque [PT] flexion [flex] and PT extension [ext] at both movement speeds) and both variables regarding arterial stiffness (AIx75 and PWV). The significance level was set at .05, and the IBM SPSS version 31.0 software was used to conduct the statistical analysis.

RESULTS

Two participants withdrew from the study (due to delayed onset muscle soreness and scheduling constraints) during the six-week intervention and thus were not included in the final statistical analysis (leaving a total of 15 participants; nine in the BFRT+TRT group, six in the BFRT+BFRT group). All other participants exhibited full adherence and participation. Due to experimenter error, six participants were excluded from the data analyses for isokinetic strength outcomes (leaving a total of nine participants for these variables; five in the BFRT+TRT group, four in the BFRT+BFRT group). The final participant characteristics are presented in Table 2. Table 4 displays the mean and standard deviation values of AIx75, PWV, PT ext at 60°/s, PT flex at 60°/s, PT ext at 180°/s, and PT flex at 180°/s by Group and Time.

Table 2. Final participant characteristics by group

	BFRT+TRT (*n*=9)	BFRT+BFRT (*n*=6)	Total (*N*=15)
Age (years)	20.78 ± 3.46	19.00 ± 0.89	20.07 ± 2.81
Height (cm)	172.73 ± 8.74	179.55 ± 10.33	175.46 ± 9.68
Weight (kg)	80.42 ± 15.04	82.54 ± 12.68	81.27 ± 13.71
Body Mass Index (kg·m^{-2})	26.78 ± 3.18	25.48 ± 1.88	26.26 ± 2.74

Note. cm = centimeters; kg = kilograms; kg·m^{-2} = kilograms per meter squared.

Table 3. Training protocols by modality

	BFRT	TRT
Resistance (% one repetition maximum)	30	70
Cuff inflation (% limb occlusion pressure)	60	n/a
Sets	4	4
Reps	30, 15, 15, 15	10, 10, 10, 10
Rest	30	60

Note. BFRT = blood flow restriction training; TRT = traditional resistance training; % = percentage. BFR+BFR group performed two days of BFRT each week; BFR+TRT group performed one day of BFRT and one day of TRT each week.

Table 4. Arterial stiffness outcomes by group and time

	BFRT+TRT (*n*=9)		BFRT+BFRT (*n*=6)	
	Pre	**Post**	**Pre**	**Post**
AIx75 (%)	7.22 ± 11.31	0.78 ± 13.65	5.00 ± 10.30	5.17 ± 15.55
PWV (m/s)	5.76 ± 0.69	5.40 ± 1.30	5.63 ± 0.45	5.65 ± 1.09

Note. AIx75 = (augmentation pressure/pulse pressure) x correction factor x 100% = augmentation index at a heart rate of 75 beats per minute; m/s = meters per second; PWV = pulse wave velocity; % = percentage.

Arterial Stiffness Outcomes

Augmentation Index at 75 heartbeats per minute

Using an alpha of .05, the two-way repeated measures ANOVA indicated Time (pretest, posttest) and Group (BFRT+TRT, BFRT+BFRT) were not significant predictors of AIx75, $F(1,13) = 1.58$, $p = .232$ and $F(1,13) = 0.03$, $p = .865$, respectively. In addition, no significant interaction effect was examined, F(1,13) = 1.75, p = .209.

Pulse-Wave Velocity

Using an alpha of .05, the two-way repeated measures ANOVA indicated Time (pretest, posttest) and Group (BFRT+TRT, BFRT+BFRT) were not significant predictors of PWV, $F(1,13) = .38$, $p = .550$ and $F(1,13) = 0.02$, $p = .884$, respectively. In addition, no significant interaction effect was examined, $F(1,13) = 0.45$, $p = .512$. See Table 4 for descriptive statistics for AIx75 and PWV by Group and Time.

Isokinetic Strength of Quadriceps and Hamstrings

Peak Torque Extension at 60 degrees per second

Using an alpha of .05, the two-way repeated measures ANOVA indicated that Time (pretest, posttest) was a significant predictor of PT ext at 60°/s, $F(1,7) = 8.22$, $p = .024$. However, Group (BFRT+TRT, BFRT+BFRT) was not a significant predictor of PT ext at 60°/s, $F(1,7) = 0.12$, $p = .740$. In addition, no significant interaction effect was examined, $F(1,7) = 0.11$, $p = .751$.

Peak Torque Flexion at 60 degrees per second

Using an alpha of .05, the two-way repeated measures ANOVA indicated that Time (pretest, posttest) was a significant predictor of PT flex at 60°/s, $F(1,7) = 8.39$, $p = .023$. However, Group (BFRT+TRT, BFRT+BFRT) was not a significant predictor of PT flex at 60°/s, $F(1,7) = 0.31$, $p = .594$. In addition, no significant interaction effect was examined, $F(1,7) = 0.08$, $p = .788$.

Peak Torque Extension at 180 degrees per second

Using an alpha of .05, the two-way repeated measures ANOVA indicated Time (pretest, posttest) and Group (BFRT+TRT, BFRT+BFRT) were not significant predictors of PT ext at 180°/s, $F(1,7) = 1.63$, $p = .242$ and $F(1,7) = 0.66$, $p = .442$, respectively. In addition, no significant interaction effect was examined, $F(1,7) = 0.38$, $p = .559$.

Peak Torque Flexion at 180 degrees per second

Using an alpha of .05, the two-way repeated measures ANOVA indicated that Time (pretest, posttest) was a significant predictor of PT flex at 180°/s, $F(1,7) = 17.08$, $p = .004$. On the other hand, Group (BFRT+TRT, BFRT+BFRT) was not a significant predictor of PT flex at 180°/s, $F(1,7) = 0.55$, $p = .484$. In addition, no significant interaction effect was examined, $F(1,7) = 0.27$, $p = .619$. See Table 5 for descriptive statistics for PT ext and flex at 60°/s and 180°/s by Group and Time.

Table 5. Lower extremity isokinetic strength by group and time

	BFRT+TRT (*n*=5)		BFRT+BFRT (*n*=4)	
	Pre	**Post**	**Pre**	**Post**
PT ext at 60°/s (ft·lbs)	148.40 ± 28.52	163.20 ± 40.25*	141.75 ± 37.42	153.50 ± 37.31*
PT flex at 60°/s (ft·lbs)	89.8 ± 20.32	98.60 ± 24.72*	81.50 ± 30.51	88.75 ± 22.87*
PT ext at 180°/s (ft·lbs)	102.60 ± 24.84	107.00 ± 23.58	82.50 ± 48.68	95.00 ± 23.37
PT flex at 180°/s (ft·lbs)	61.80 ± 12.95	75.00 ± 17.82*	50.25 ± 29.50	67.25 ± 19.72*

Note. ft·lbs = foot-pounds; PT = peak torque; PT ext at 60°/s = peak leg extension torque at 60 degrees per second; PT ext at 180°/s = peak leg extension torque at 180 degrees per second; PT flex at 60°/s = peak leg flexion torque at 60 degrees per second; PT flex at 180°/s = peak leg flexion torque at 180 degrees per second; * indicates a significant difference compared to pre-test value at $p < 0.05$.

DISCUSSION

Previous studies have highlighted evidence that TRT provides numerous benefits for physical fitness. However, some studies have found TRT to increase arterial stiffness when performed chronically at a high enough intensity, which may increase the risk for cardiovascular diseases such as PAD[6,7]. Recent studies have found that chronic BFRT, on the other hand, may elicit a smaller increase in arterial stiffness[6,10] or even decrease arterial stiffness[11]. BFRT has also been shown to be a safe alternative to TRT in individuals who may not be able to do high load training due to injury, recent surgery, or other contraindications[19]. To our knowledge, no studies have compared the effects of different frequencies of BFRT on arterial stiffness and maximal leg strength. Our study found that there was a significant increase in PT ext at 60°/s and in PT flex at both 60°/s and 180°/s from pre- to post-intervention amongst both groups. There were no significant differences in PT ext at 180°/s, AIx75, or PWV from pre- to post-intervention in either group or between groups.

In disagreement with our hypothesis, the two-way repeated measures ANOVA found no statistically significant Group or Time effects on AIx75 or PWV, suggesting that arterial stiffness was unaffected by group assignment or time. However, no statistically significant difference was detected between groups at either time point in any of the four isokinetic strength measures (PT ext at 60°/s, PT flex at 60°/s, PT ext at 180°/s, PT flex at 180°/s), which supports our hypothesis. Additionally, a statistically significant increase in three of these four variables (PT ext at 60°/s, PT flex at 60°/s, and PT flex at 180°/s) was observed in both groups. Taken together, these strength findings suggest a significant Time, but not Group, effect on isokinetic strength in all measures except PT ext at 180°/s.

Arterial Stiffness Findings

A six-week experimental study found that three sessions per week of high-intensity upper-body TRT led to a statistically significant increase in arterial stiffness, whereas three weekly sessions of upper-body BFRT led to no changes in males aged 22 to 32 years[6]. The differences in TRT's effect on arterial stiffness between this study and the present study may be explained by the use of lower extremity exercises, reduced training frequency, and/or slightly lower TRT intensity (of 70% compared to 75% 1RM) employed by the present study. Another experimental study found that after four weeks of four weekly training sessions, 18- to 30-year-old males undergoing BFRT experienced a five percent reduction in PWV (representing a decrease in arterial stiffness) whereas the TRT group saw no significant changes[11]. The differences in BFRT's effect on PWV between this study and the present study may be explained by differences in treatment duration, as research suggests that after four weeks of training BFRT no longer significantly benefits arterial stiffness[10]. Two systematic reviews on a combination of young and old adults and two experimental studies on young adults found no significant differences in arterial stiffness changes between BFRT and TRT after at least four weeks of training, which support the findings of the present study[10,16,28,29].

Isokinetic Strength Findings

A systematic review on both young and old adults had contrasting results to the present study, finding that BFRT produces significantly greater improvements in lower limb strength, specifically regarding maximal knee extensor voluntary contraction, when compared to TRT[18]. These opposing findings may be attributable to differences in selected exercises and intensities. Likewise, a separate review on 19- to 26-year-olds analyzed nine studies on the strength improvements of BFRT versus TRT and found that seven of these demonstrated significantly greater gains in the BFRT group[30]. This difference in results may stem from the large differences in the length of the study intervention as well as the limb occlusion pressure utilized during BFRT. Of note, regarding isokinetic strength at the faster speed setting (180°/s), the present study revealed a significant improvement in PT flex, but not PT ext. This anomaly may be due to participants having a disproportionately greater degree of knee extensor (i.e., quadriceps) strength than knee flexor (i.e., hamstrings) strength at baseline, which may have made the flexors more responsive to the intervention.

The strength improvements seen in both groups undergoing BFRT, despite the training intensity (i.e., percentage of 1RM) being much lower than in TRT, are likely the result of a greater level of metabolic stimuli to compensate for the lessor mechanical stimuli. This metabolic stress elicits a training response largely through increases in fast-twitch muscle fiber recruitment, systemic anabolic hormone levels, and protein synthesis and through reductions in catabolic hormones[12,20,21].

Participant Tolerance of Intervention

Although tolerance and muscle soreness were not measured during the intervention, it is important to note that participants expressed a significant level of discomfort associated with the first few BFRT sessions, as this was a new stimulus for all participants. However, participants also indicated that there were substantial reductions in discomfort and muscle soreness as the intervention progressed and could tolerate the BFRT well by the final week. Based on the initial level of discomfort in this trained sample, it may be unrealistic to apply this exact training protocol to populations such as untrained or elderly individuals. It may be more practical for these demographics to use a percentage of 1RM and/or limb occlusion pressure that is closer to the low end of their respective recommended ranges, although it is unknown whether the results of this study are generalizable to a protocol with these changes.

Limitations

There were several limitations of this study. First, the sample size was small (*n*=9 for valid isokinetic strength data, *n*=15 for valid arterial stiffness data), especially for females (*n*=3 for valid isokinetic strength data, *n*=4 for valid arterial stiffness data), and only included resistance-trained and apparently healthy young adults, which may limit the validity and generalizability of these findings. The use of a convenience sample may further limit generalizability of the findings. Another limitation was the potential for a wide range of participant training statuses, as this study only included a minimum training history of six months of regular training as an inclusion criterion. This may have led to differences in recovery rates and perceived exertion and thus performance in workouts, which could impact the training stimulus received. Additionally, physical activity levels outside of the study were not controlled except for resistance training of the quadriceps and hamstrings muscle groups. The use of standard blood pressure cuffs to occlude blood flow was also a restraint, as these cannot maintain an exact occlusion pressure throughout a set as well as automated BFRT cuffs. The biggest limitation was human error when operating the isokinetic machine, resulting in the exclusion of six participants' isokinetic data (which was compromised due to experimenter error).

CONCLUSION

The results of our study suggest that both frequencies of BFRT have similar effects in increasing PT (as measured by the Humac Norm isokinetic dynamometer) and no statistically significant effect on AIx75 or PWV (as measured by the SphygmoCor XCEL). Thus, concerns of the effects of frequency of BFRT on arterial stiffness and strength development may not need to be considered when prescribing a resistance training program that involves both TRT and BFRT. Additionally, these findings suggest that BFRT may be safe for those who are unable to perform TRT and have risk factors for cardiovascular diseases. Future research should explore this topic with a larger and more diverse sample to improve overall generalizability and examine the effects of a wider range of BFRT training frequencies on arterial stiffness and strength.

ACKNOWLEDGEMENTS

We would like to offer a special thank you to Katie Chung for her assistance with the intervention and data collection processes and to Makenna and Lisa Hawkins for designing and producing uniforms for the researchers.

ADDRESS FOR CORRESPONDENCE

Shafer, C. University of Wisconsin-Eau Claire, 105 Garfield Ave. Eau Claire, WI, 54702, USA; Phone: (715) 928-1534; FAX: (715) 836-4074; Email: chaseshafer22@gmail.com.

REFERENCES

1. Ehrman, J., Gordon, P., Visich, P., & Keteyian, S. (n.d.). *Clinical Exercise Physiology* (Fifth). Human Kinetics.
2. Mayo Clinic Staff. (2024). Peripheral artery disease (PAD)—Symptoms and causes. Mayo Clinic. https://www.mayoclinic.org/diseases-conditions/peripheral-artery-disease/symptoms-causes/syc-20350557
3. Winett, R. A., & Carpinelli, R. N. (2001). Potential health-related benefits of resistance training. *Preventive Medicine*, *33*(5), 503–513. https://doi.org/10.1006/pmed.2001.0909
4. American College of Sports Medicine. (2026). ACSM's guidelines for exercise testing and prescription (12th ed.). Wolters Kluwer.
5. Landré, B., Fayosse, A., Ben Hassen, C., Machado-Fragua, M. D., Dumurgier, J., Kivimaki, M., Sabia, S., & Singh-Manoux, A. (2021). Terminal decline in objective and self-reported measures of motor function before death: 10 year follow-up of Whitehall II cohort study. *BMJ (Clinical Research Ed.)*, *374*, n1743. https://doi.org/10.1136/bmj.n1743
6. Ozaki, H., Yasuda, T., Ogasawara, R., Sakamaki-Sunaga, M., Naito, H., & Abe, T. (2013). Effects of high-intensity and blood flow-restricted low-intensity resistance training on carotid arterial compliance: Role of blood pressure during training sessions. *European Journal of Applied Physiology*, *113*(1), 167–174. https://doi.org/10.1007/s00421-012-2422-9
7. Miyachi, M. (2013). Effects of resistance training on arterial stiffness: A meta-analysis. *British Journal of Sports Medicine*, *47*(6), 393–396. https://doi.org/10.1136/bjsports-2012-090488
8. Jurik, R., Żebrowska, A., & Stastny, P. (2021). Effect of an acute resistance training bout and long-term resistance training program on arterial stiffness: A systematic review and meta-analysis. *Journal of Clinical Medicine*, *10*(16), 3492. https://doi.org/10.3390/jcm10163492
9. Zhang, Y., Zhang, Y.-J., Ye, W., & Korivi, M. (2021). Low-to-moderate-intensity resistance exercise effectively improves arterial stiffness in adults: Evidence from systematic review, meta-analysis, and meta-regression analysis. *Frontiers in Cardiovascular Medicine*, *8*. https://doi.org/10.3389/fcvm.2021.738489

10. Liu, Y., Jiang, N., Pang, F., & Chen, T. (2021). Resistance training with blood flow restriction on vascular function: A meta-analysis. *International Journal of Sports Medicine*, *42*(7), 577–587. https://doi.org/10.1055/a-1386-4846
11. Horiuchi, M., Stoner, L., & Poles, J. (2023). The effect of four weeks blood flow restricted resistance training on macro- and micro-vascular function in healthy, young men. *European Journal of Applied Physiology*, *123*(10), 2179–2189. https://doi.org/10.1007/s00421-023-05230-3
12. Martin, P. M., Bart, R. M., Ashley, R. L., Velasco, T., & Wise, S. R. (2022). An overview of blood flow restriction physiology and clinical considerations. *Current Sports Medicine Reports*, *21*(4), 123. https://doi.org/10.1249/JSR.0000000000000948
13. Amorim, S., Rolnick, N., Schoenfeld, B. J., & Aagaard, P. (2021). Low-intensity resistance exercise with blood flow restriction and arterial stiffness in humans: A systematic review. *Scandinavian Journal of Medicine & Science in Sports*, *31*(3), 498–509. https://doi.org/10.1111/sms.13902
14. Lixandrão, M. E., Ugrinowitsch, C., Berton, R., Vechin, F. C., Conceição, M. S., Damas, F., Libardi, C. A., & Roschel, H. (2018). Magnitude of muscle strength and mass adaptations between high-load resistance training versus low-load resistance training associated with blood-flow restriction: A systematic review and meta-analysis. *Sports Medicine*, *48*(2), 361–378. https://doi.org/10.1007/s40279-017-0795-y
15. Patterson, S. D., Hughes, L., Warmington, S., Burr, J., Scott, B. R., Owens, J., Abe, T., Nielsen, J. L., Libardi, C. A., Laurentino, G., Neto, G. R., Brandner, C., Martin-Hernandez, J., & Loenneke, J. (2019). Blood flow restriction exercise: Considerations of methodology, application, and safety. *Frontiers in Physiology*, *10*. https://doi.org/10.3389/fphys.2019.00533
16. Pereira-Neto, E. A., Lewthwaite, H., Boyle, T., Johnston, K., Bennett, H., & Williams, M. T. (2021). Effects of exercise training with blood flow restriction on vascular function in adults: A systematic review and meta-analysis. *PeerJ*, *9*, e11554. https://doi.org/10.7717/peerj.11554
17. Rolnick, N., & Schoenfeld, B. J. (2020). Blood flow restriction training and the physique athlete: A practical research-based guide to maximizing muscle size. *Strength & Conditioning Journal*, *42*(5), 22. https://doi.org/10.1519/SSC.0000000000000553
18. Jørgensen, S. L., Kierkegaard-Brøchner, S., Bohn, M. B., Høgsholt, M., Aagaard, P., & Mechlenburg, I. (2023). Effects of blood-flow restricted exercise versus conventional resistance training in musculoskeletal disorders—A systematic review and meta-analysis. *BMC Sports Science, Medicine and Rehabilitation*, *15*(1), 141. https://doi.org/10.1186/s13102-023-00750-z
19. Erickson, L. N., Lucas, K. C. H., Davis, K. A., Jacobs, C. A., Thompson, K. L., Hardy, P. A., Andersen, A. H., Fry, C. S., & Noehren, B. W. (2019). Effect of blood flow restriction training on quadriceps muscle strength, morphology, physiology, and knee biomechanics before and after anterior cruciate ligament reconstruction: Protocol for a randomized clinical trial. *Physical Therapy*, *99*(8), 1010–1019. https://doi.org/10.1093/ptj/pzz062
20. Cognetti, D. J., Sheean, A. J., & Owens, J. G. (2022). Blood flow restriction therapy and its use for rehabilitation and return to sport: Physiology, application, and guidelines for implementation. *Arthroscopy, Sports Medicine, and Rehabilitation*, *4*(1), e71–e76. https://doi.org/10.1016/j.asmr.2021.09.025
21. Pearson, S. J., & Hussain, S. R. (2015). A Review on the mechanisms of blood-flow restriction resistance training-induced muscle hypertrophy. *Sports Medicine*, *45*(2), 187–200. https://doi.org/10.1007/s40279-014-0264-9
22. Habets, B., Staal, J. B., Tijssen, M., & van Cingel, R. (2018). Intrarater reliability of the Humac NORM isokinetic dynamometer for strength measurements of the knee and shoulder muscles. *BMC Research Notes*, *11*, 15. https://doi.org/10.1186/s13104-018-3128-9
23. de Araujo Ribeiro Alvares, J. B., Rodrigues, R., de Azevedo Franke, R., da Silva, B. G. C., Pinto, R. S., Vaz, M. A., & Baroni, B. M. (2015). Inter-machine reliability of the Biodex and Cybex isokinetic dynamometers for knee flexor/extensor isometric, concentric and eccentric tests. *Physical Therapy in Sport: Official Journal of the Association of Chartered Physiotherapists in Sports Medicine*, *16*(1), 59–65. https://doi.org/10.1016/j.ptsp.2014.04.004
24. Drouin, J. M., Valovich-mcLeod, T. C., Shultz, S. J., Gansneder, B. M., & Perrin, D. H. (2004). Reliability and validity of the Biodex system 3 pro isokinetic dynamometer velocity, torque and position measurements. *European Journal of Applied Physiology*, *91*(1), 22–29. https://doi.org/10.1007/s00421-003-0933-0
25. Rolnick, N., Licameli, N., Moghaddam, M., Marquette, L., Walter, J., Fedorko, B., & Werner, T. (2023). Autoregulated and non-autoregulated blood flow restriction on acute arterial stiffness. *International Journal of Sports Medicine*, *45*, 23–32. https://doi.org/10.1055/a-2152-0015
26. Hwang, M.-H., Yoo, J.-K., Kim, H.-K., Hwang, C.-L., Mackay, K., Hemstreet, O., Nichols, W. W., & Christou, D. D. (2014). Validity and reliability of aortic pulse wave velocity and augmentation index determined by the new cuff-based

SphygmoCor Xcel. *Journal of Human Hypertension*, *28*(8), 475–481. https://doi.org/10.1038/jhh.2013.144

27. National Strength and Conditioning Association. (2016). *Essentials of Strength Training and Conditioning* (G. Haff & T. Triplett, Eds.; Fourth). Human Kinetics.
28. Fahs, C. A., Rossow, L. M., Loenneke, J. P., Thiebaud, R. S., Kim, D., Bemben, D. A., & Bemben, M. G. (2012). Effect of different types of lower body resistance training on arterial compliance and calf blood flow. *Clinical Physiology and Functional Imaging*, *32*(1), 45–51. https://doi.org/10.1111/j.1475-097X.2011.01053.x
29. Tai, Y. L., Marshall, E. M., Parks, J. C., & Kingsley, J. D. (2022). Hemodynamic response and pulse wave analysis after upper- and lower-body resistance exercise with and without blood flow restriction. *European Journal of Sport Science*, *22*(11), 1695–1704. https://doi.org/10.1080/17461391.2021.1982018
30. Wortman, R. J., Brown, S. M., Savage-Elliott, I., Finley, Z. J., & Mulcahey, M. K. (2021). Blood flow restriction training for athletes: A systematic review. *The American Journal of Sports Medicine*, *49*(7), 1938–1944. https://doi.org/10.1177/0363546520964454