SEONZ
SPORT & EXERCISE SCIENCE
NEW ZEALAND

*The Journal of Sport and Exercise Science, Vol. 8, Issue 1, 33-42 (2024)*

*www.jses.net*

JSES
ISSN: 2703-240X

# Effects of three weeks of aerobic blood flow restriction completed before daily training on running performance and resting hemodynamic measures in trained runners

Alexander H. K. Montoye[1*], Jackson T. Nordbeck[1], Benjamin A. Cox[2], Munni Begum[3], Drew M. Lazar[3], Jennifer R. Vranish[1]

[1]Department of Integrative Physiology and Health Science, Alma College, USA
[2]Cox Sports Medicine and Orthopedic Surgery, USA
[3]Department of Mathematical Sciences, Ball State University, USA

ARTICLE INFO

*Received: 16.12.2023*
*Accepted: 17.07.2024*
*Online: 24.09.2024*

*Keywords:*
*Limb occlusion pressure*
*Arterial occlusion pressure*
*Ischemic preconditioning*
*Ergogenic aid*
*Sport science*

ABSTRACT

*Our study investigated the effects of a daily, pre-training aerobic blood flow restriction (BFR) protocol on 2.4 km running time trial performance and resting cardiovascular measures and hemodynamics. Runners on a collegiate cross country team (n = 13, 61.5% female, aged 18 – 23 years) participated in a two-group randomized crossover design, completing a maximal 2.4 km running time trial and resting cardiovascular (heart rate, brachial blood pressure) and hemodynamic (popliteal artery: diameter, velocity, blood flow, shear rate) measures at baseline. One group (Group B) performed BFR for 10 – 15 minutes at 65% of limb occlusion pressure while engaging in light-intensity walking prior to completing a team-prescribed running workout on at least five days/week for three weeks, while another group (Group A) completed the same light-intensity walking and same running workout but without BFR. After three weeks, the running and resting cardiovascular and hemodynamic measures were repeated. Following a 2- to 3-day washout period, the groups reversed, with Group A in the intervention condition and Group B in the control condition for three weeks. Final running and resting cardiovascular and hemodynamic measures were then taken. There were no significant treatment effects for any measured outcome variables. However, changes in 2.4 km running time in the intervention condition exceeded the smallest worthwhile change (-20.8 ± 24.7 seconds, 95% CI [-34.2, -7.3]), with no improvement in the control condition (-7.2 ± 18.7 seconds, 95% CI [-17.4, 3.0]). Daily, pre-training aerobic BFR at 65% of limb occlusion pressure may elicit a meaningful, favorable change in 2.4 km time trial performance in trained collegiate runners. If future studies confirm our findings, our protocol may be appealing for use in field-based settings.*

## 1. Introduction

Blood flow restriction (BFR) is a technique that uses restrictive cuffs, wraps, or similar equipment on the arm or leg to reduce blood flow during exercise. Initially popularized in resistance training, BFR has gained significant attention for its potential to enhance muscle hypertrophy and strength gains with lower exercise intensities compared to traditional high-load training (Hughes et al., 2017; Pignanelli et al., 2021; Scott et al., 2015; Slysz et al., 2016). BFR techniques have also been incorporated into low-intensity aerobic exercises such as cycling, walking, and rowing. Evidence in this research area suggests that, in non-athletes, aerobic BFR training may induce a range of physiological adaptations including improved aerobic capacity ($VO_2$max), muscular strength and endurance, and vascular function (Abe et al., 2006; 2010; de Oliveira et al., 2016). One systematic review found evidence of superior $VO_2$max and aerobic performance outcomes with aerobic BFR training

*Corresponding Author: Alexander H. K. Montoye, Alma College, USA, montoyeah@alma.edu

(Bennett & Slattery, 2019), and another review found greater muscular fitness (strength, endurance) benefits of aerobic BFR training (de Lemos Muller et al., 2024). Of note, both of these reviews focused on healthy non-athletes and comparing BFR training to absolute intensity-matched training without BFR. However, endurance athletes differ from non-athletes in many ways and, therefore, may not experience the same adaptations with BFR training.

Peak endurance exercise performance is determined by a number of factors such as $VO_2$max, muscle function, exercise economy, and lactate threshold. Vascular function is an important determinant of oxygen and nutrient delivery to tissues as well as lactate clearance and, therefore, influences many of these aforementioned factors. Two studies in elite rowers found improvements in $VO_2$max when incorporating BFR during low-intensity rowing training compared to control groups completing similar training without BFR (Held et al., 2020; 2024). However, one of these studies also assessed 1-repetition maximum squat performance, finding no difference between intervention and control groups (Held et al., 2020), and the other study also examined peak power output and time trial performance and found no difference in these variables between intervention and control groups (Held et al., 2024). A similar study in elite rowers found improvements in $VO_2$max and time trial performance with four weeks of aerobic BFR training but lacked a control group in order to determine if and how much the BFR element played in the performance improvements (Thompson et al., 2024). A study in masters level cyclists found that supplementing normal training with aerobic BFR enhanced cycling time trial performance, but this could have been due to the increased training volume in the BFR group compared to the control group (Tangchaisuriya et al., 2022). In contrast, a study which utilized sprint interval training in trained cyclists found similar improvement in time trial performance regardless of whether the training was conducted with or without BFR (Giovanna et al., 2022). Finally, two related studies in endurance runners found improvements in $VO_2$max, running performance, and muscular strength and endurance with an eight-week running BFR training program when compared to an absolute intensity-matched control group without BFR (Chen, Hsieh, Ho, Ho, et al., 2022; Chen, Hsieh, Ho, Lin, et al., 2022). In many of these studies, the BFR training was done in place of normal training rather than as a supplement to a typical training routine. Additionally, the studies which specified when they were conducted took place in athletes' off-season, offering little insight as to whether BFR training can be beneficial when supplemented into in-season training. In summary, the available evidence provides intriguing but limited and mixed evidence as to if and how training with BFR may affect exercise performance in athletes.

When evaluating the current evidence determining the effectiveness of aerobic BFR training in enhancing endurance athletes' exercise performance, a number of noteworthy limitations exist. First, much of the current work has evaluated aerobic BFR training to absolute intensity-matched exercise without BFR, with these protocols serving as the main training stimulus. Studies examining the effects of resistance training with BFR demonstrate superior training adaptations with BFR when compared to absolute intensity-matched exercise without BFR (Pignanelli et al., 2021; Scott et al., 2015; Wortman et al., 2021), whereas resistance training with BFR typically produces smaller training adaptations than high-load training without BFR (Lixandrao et al., 2018). In both of these cases, magnitude and directionality of training adaptations with aerobic BFR likely mirror those of resistance BFR training. Therefore, from an athlete training perspective it is of more value to evaluate the use of aerobic BFR training as a supplement, rather than a replacement, for their normal training when seeking to optimize training adaptations. Second, the efficacy of BFR training during an athlete's season (in contrast to use in the off-season) is unknown.

Finally, mixed evidence is available evaluating the effects of aerobic BFR on hemodynamic and vascular changes in endurance athletes. A review which evaluated evidence of resistance BFR training found superior changes in muscle capillarization compared to absolute intensity-matched training without BFR (Ferguson et al., 2021). Another review found some evidence of superior improvement in endothelial function but no difference in changes in resting heart rate or blood pressure with resistance BFR training compared to absolute intensity-matched training without BFR (Maga et al., 2023). However, both of these reviews included studies with primarily non-athlete populations. Given the potential for maladaptive changes to vascular function with BFR training noted in several recent reviews (da Cunha Nascimento et al., 2020; Spranger et al., 2015) and the lack of research examining such potential changes in athletes, more work is needed to determine potential changes in cardiovascular and hemodynamic function in athletic populations.

With these research gaps in mind, our study's primary purpose was to assess the effects of three weeks of almost daily walking with BFR prior to normal training on 2.4 km running time trial performance in collegiate cross country runners. Our secondary purpose was to assess the effects of this walking BFR program on resting cardiovascular and hemodynamic measures.

## 2. Methods

### *2.1. Participants*

Males and females aged 18 – 23 years who were active members of a collegiate Division III cross country team and who reported 3 – 11 years of competitive endurance running experience were recruited for this study. Potential participants were excluded if they had a known cardiovascular, renal, or metabolic disease; were known to be at increased risk of blood clotting; had any bone or muscle injuries in the lower limbs that prevented full participation in their training schedule; or had COVID-19 in the previous 4 weeks. Although 19 participants (9 male, 10 female) started the study, only 13 (5 male, 8 female) completed training sessions and all testing to be included in the final analysis. Of note, data collection was performed during the 7-week fall cross country season, and dropout from this study was due to injuries, illness, or other factors unrelated to study participation. No injuries or negative side effects due to the BFR protocol were noted. All participants in this study completed an informed consent form and were given the ability to ask questions prior to and during the study. This study was approved by the Alma College Institutional Review Board (IRB#: R_2VrKwENd78z7MHQ) prior to beginning testing.

*2.2. Procedure*

Participants completed several resting measures within a laboratory setting at three time points: baseline, mid-point, and post. For these assessments, participants were asked to abstain from food, caloric drinks, exercise, caffeine, and tobacco for at least three hours prior to laboratory visits. Upon arrival, participant height and weight were taken using a stadiometer (Seca GmbH & Co. KG., Hamburg, Germany) and scale (Tanita Corp., Tokyo, Japan), respectively, and age was self-reported. Thigh circumference was assessed at one third of the distance from the inguinal crease to the top of the patella for each thigh. Following 3 – 5 minutes of supine rest, resting heart rate and blood pressure were assessed using a Welch Allyn ProBP 3400 system (Hillrom, Skaneateles Falls, New York, USA), with the cuff placed on the left arm.

Next, resting blood flow through the popliteal artery of each leg while supine was determined by a researcher (JRV) with extensive training in ultrasound-based vascular measures (Vranish et al., 2017). For blood flow determination, a GE LOGICe ultrasound machine (GE Healthcare, Chicago, IL, USA) with a 9 MHz linear probe was used to measure the diameter and blood velocity in the popliteal artery. Using screen capture software (QuikTime Pro, Apple Inc., Cupertino, CA, USA), 30-second videos of blood flow in the popliteal artery were recorded, and Cardiovascular Suite (Quipu, Pisa, Italy) was used to obtain indices of average artery diameter and blood velocity during the measurement period, from which total blood flow was calculated using the following equations (Gnasso et al., 2001; Secomb, 2016):

$$Blood\ flow = \left(\pi \left[Diameter \times \frac{1}{2}\right]^2\right) \times (Blood\ velocity) \times 60\ sec$$

Additionally, shear rate was calculated as:

$$Shear\ rate = 8 \times \frac{Mean\ blood\ velocity}{Diameter}$$

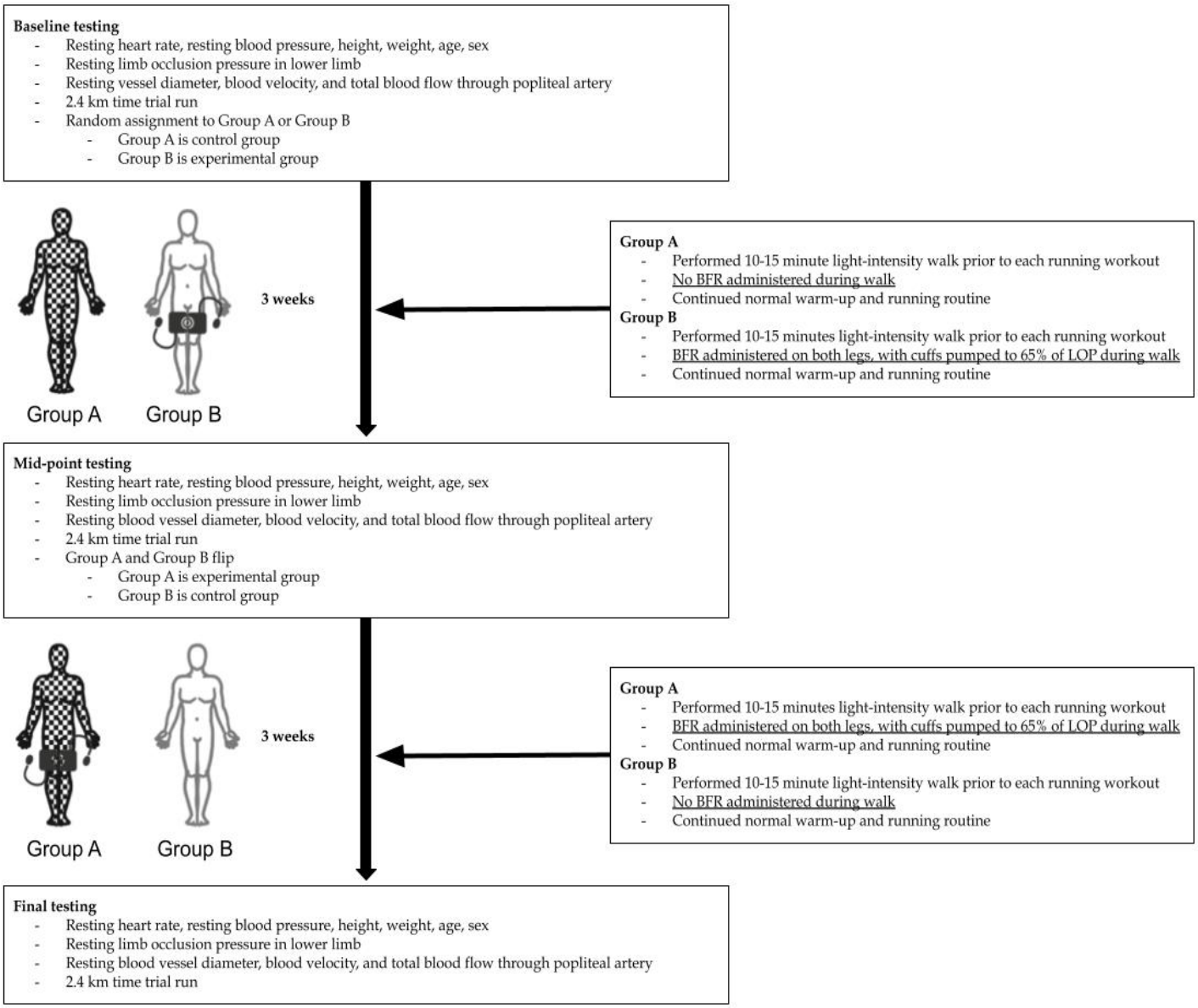
To determine participants' LOP, a lower body Personalized Tourniquet System (Delfi Medical Innovations, Inc., Vancouver, BC, Canada) was connected to a 11.5 cm width cuff, which was placed as proximally as possible on the thigh (choice of right vs. left as the first measure was randomized across participants), and the "Personalized Tourniquet Pressure" protocol was run on the Delfi system. Following 5 – 7 minutes of supine rest, the same procedure was conducted for the other thigh. The LOP measures obtained from the two legs were then averaged, and 65% of LOP was calculated for use in the aerobic BFR protocol. Past work has shown the efficacy of using cuff pressures of 50 – 75% of LOP (Montoye et al., 2023), and we selected a percentage near the middle of this range since participants would be in charge of inflating cuffs during the protocol, thus allowing for some user error while still remaining in the 50 – 75% of LOP range.

In addition to the resting laboratory measures, participants completed an outdoor, 2.4 km running time trial at baseline, mid-point, and post. Prior to the time trial, participants completed a 10-minute dynamic stretching protocol and a self-paced 2.4 km jogging warm-up. Then, participants completed a 2.4 km time trial as quickly as possible on an out-and-back (1.2 km in each direction), paved trail which was flat and had extensive tree cover to shield participants from the wind. Spotters ensured that participants reached the 1.2 km mark before turning around. The total time to complete the 2.4 km course, measured to the nearest second, was recorded for each participant by a trained research assistant. Participants were then allowed a self-paced cool-down.

Our study's purpose was to assess the effects of pre-training, aerobic BFR on the aforementioned time trial and laboratory outcomes. To accomplish this purpose, our study used a 2 × 2 crossover design where, following baseline testing, participants were split into two groups. One group (Group A) received the control condition for the first three weeks (baseline to mid-point) followed by the intervention for the next three weeks (mid-point to post). The other group (Group B) received the intervention for the first three weeks (baseline to mid-point) followed by the control condition for the next three weeks (mid-point to post). Both groups had a 2- to 3-day washout period (depending on availability for performing laboratory testing following the time trial) between conditions. Groups were assigned at random, and this study design was chosen to account for seasonal, training, or learning effects. Figure 1 provides a schematic of the overall structure of the study.

In brief, all participants underwent baseline laboratory and time trial testing as described above. Then, the intervention group (Group B) was instructed to wear blood pressure cuffs (21 cm width; EverDixie, Dixie EMA Supply Co., Brooklyn, NY, USA) as proximally as possible on both thighs and to inflate them simultaneously to 65% of LOP. They were to walk at a self-determined light intensity (described as an intensity which was comfortable and did not cause them fatigue) for 10 – 15 minutes (while wearing the inflated cuffs) immediately prior to each running practice, for at least five days/week, over an approximately 3-week span. Participants needed to complete at least 10 minutes with the cuffs applied; because multiple participants were doing the cuff restriction simultaneously it was not always possible to control exact start/stop times, and some participants likely had a few extra minutes of restriction. Upon arrival at practice, participants removed the cuffs and completed a standardized, 10-minute dynamic warm-up that consisted of exercises such as high knees, skipping, and lunges performed at a controlled speed for 15 meters in a straight line. Next, participants completed their normal team running workouts. The control group (Group A) completed the same 10 – 15 minutes light-intensity walk, standardized 10-minute dynamic warm-up, and team running workout but did not complete any BFR prior to practice. All walking and warm-up exercises were completed by Groups A and B at the same time. Following the three weeks, a mid-point set of time trial and laboratory tests were completed. Then, participants switched conditions, so Group A became the intervention group and Group B became the control group for the next three weeks. Following three weeks in the new conditions, a third and final set of laboratory and time trial tests (post) were performed. Research staff were present at all workouts to ensure compliance to the BFR protocol and answer questions from participants. Research staff also informally asked participants about potential pain/discomfort or fatigue from the BFR protocol that affected their workouts. Finally, participant race times throughout their racing season were collected from online Michigan Intercollegiate Athletic Association cross country race results.

Figure 1: Flow chart of study procedure.




### *2.3. Statistical approach*

To investigate the effects of a low-intensity, aerobic BFR protocol performed at least five days/week for three weeks on 2.4 km running time trial performance and resting cardiovascular and hemodynamic measures, we applied linear mixed effects models (LMEM; Singer & Willett, 2003) with a random intercept and unstructured covariance. Separately for each outcome of interest (2.4 km run time, resting heart rate, resting systolic and diastolic blood pressure, popliteal artery diameter, popliteal artery blood velocity, popliteal artery blood flow, popliteal artery shear rate), the LMEM includes period, treatment, and baseline measure of each outcome of interest.

In a 2 × 2 crossover study, the period effect implies that the effect of the same treatment received at two different periods may be different for a specific period (Lim & In, 2021). The LMEM for assessing the direct effect of the intervention includes indicator variables for the intervention (treatment) and period effects after adjusting for the baseline outcome measure.

In addition to the LMEM, effect size analyses were conducted, and effect sizes were considered negligible if < 0.20, small if 0.20 – 0.49, medium if 0.50 – 0.79, and large if ≥ 0.80 (Cohen, 1988). With an alpha level of $p < 0.05$, a desired power of 80%, and a sample size of 13, our study was powered to detect only large effect sizes (≥ 0.84). Thus, a smallest worthwhile change analysis was also conducted in order to detect smaller but potentially meaningful changes between conditions. For the smallest worthwhile change analysis, a meaningful difference was denoted as when the mean difference between trials exceeded 0.6 × standard deviation of the difference between trials (Buchheit, 2016; Marocolo et al., 2019). Analyses were conducted in R (R Core Development Team, Vienna, Austria) and Microsoft Excel 365 (Microsoft Corp., Redmond, WA, USA).

## 3. Results

Independent-samples *t*-tests confirmed that participants in Group A and B were not significantly different at baseline for any of the measured variables except for resting heart rate, which was significantly lower in Group B (Table 1).

Table 1: Baseline anthropometric, hemodynamic, and running time trial data for Group A and B.

| | Group A ($n$ = 6, 4 female) | | Group B ($n$ = 7, 4 female) | |
|---|---|---|---|---|
| | *M* | SD | *M* | SD |
| Age (years) | 20.0 | 1.4 | 19.1 | 0.7 |
| Height (cm) | 166.2 | 11.2 | 170.8 | 14.3 |
| Weight (kg) | 61.6 | 9.4 | 65.6 | 7.4 |
| Body mass index (kg/m$^2$) | 22.2 | 2.2 | 22.7 | 3.1 |
| Resting heart rate (beats/minute) | 62.5 | 5.8 | 56.0* | 8.9 |
| Resting mean arterial pressure (mmHg) | 117.8 | 9.2 | 116.1 | 6.3 |
| Resting diastolic blood pressure (mmHg) | 65.8 | 2.9 | 67.4 | 3.9 |
| Popliteal artery blood flow (ml/second) | 116.8 | 58.3 | 132.7 | 66.0 |
| Popliteal artery diameter (mm) | 5.1 | 1.1 | 6.1 | 0.9 |
| Popliteal artery blood velocity (cm/second) | 9.4 | 3.6 | 7.4 | 2.6 |
| Popliteal artery shear rate (1/seconds) | 155.3 | 83.3 | 98.8 | 33.0 |
| 2.4 km run time (seconds) | 606.8 | 85.3 | 608.1 | 111.7 |
| Average limb occlusion pressure (mmHg) | 179.2 | 18.1 | 187.9 | 14.5 |
| 65% of average limb occlusion pressure (mmHg) | 116.5 | 11.5 | 122.2 | 8.6 |

*Notes: M* = mean, SD = standard deviation, *Significant difference from Group A ($p < 0.05$).

Results of the LMEM analyses are shown in Table 2, with data plotted by group and time shown in Figure 2 (also shown in table format in Table 3). For 2.4 km time trial completion time, there was a significant main effect with times decreasing from baseline. However, sequence, time, and treatment were not statistically significant. Resting heart rate and diastolic blood pressure were significantly lower in Group B than Group A, and there was a main effect for heart rate decreasing from baseline, but time and treatment were not statistically significant. For systolic blood pressure, popliteal artery blood flow velocity and shear rate, there were significant main effects but no significant effects of sequence, time, or treatment. For popliteal artery blood flow and popliteal artery diameter, there were no significant main effects nor effects of sequence, time, or treatment.

Table 2: Results of 2 × 2 (group × time) linear mixed models analyses for run time, resting heart rate and blood pressure, and resting popliteal artery outcome variables.

| Predictors | Estimates | 95% CI | *p* |
|---|---|---|---|
| Run time | | | |
| Intercept | 90.59 | [30.91, 150.28] | 0.005* |
| Seq[IC] | -9.79 | [-27.36, 7.78] | 0.258 |
| P | -13.67 | [-26.86, -0.48] | 0.043* |
| T | -5.67 | [-18.86, 7.52] | 0.380 |
| Run b | 0.84 | [0.75, 0.93] | < 0.001* |
| Marginal $R^2$/Conditional $R^2$ = 0.947/0.962 | | | |
| Resting heart rate | | | |
| Intercept | 28.28 | [1.35, 55.21] | 0.041* |
| Seq[IC] | -8.10 | [-14.65, -1.55] | 0.018* |
| P | -1.05 | [-5.96, 3.86] | 0.660 |
| T | -0.62 | [-5.53, 4.29] | 0.795 |
| RHR b | 0.63 | [0.21, 1.05] | 0.005* |
| Marginal $R^2$/Conditional $R^2$ = 0.576 / 0.656 | | | |
| Systolic blood pressure | | | |
| Intercept | 37.77 | [-31.71, 107.24] | 0.269 |
| Seq [IC] | -3.34 | [-10.79, 4.11] | 0.360 |
| P | 3.45 | [-1.27, 8.17] | 0.142 |
| T | -2.12 | [-6.84. 2.60] | 0.359 |
| SBP b | 0.67 | [0.08, 1.25] | 0.027* |
| Marginal $R^2$/Conditional $R^2$ = 0.363 / 0.610 | | | |
| Diastolic blood pressure | | | |
| Intercept | 58.19 | [23.82, 92.55] | 0.002* |
| Seq [IC] | -4.92 | [-9.10, -0.74] | 0.023* |
| P | -0.31 | [-3.68, 3.68] | 0.850 |
| T | -0.02 | [-3.39, 3.35] | 0.988 |
| DBP b | 0.13 | [-0.38, 0.65] | 0.602 |
| Marginal $R^2$/Conditional $R^2$ = 0.224/ 0.366 | | | |
| Popliteal artery blood flow | | | |
| Intercept | 96.05 | [54.35, 196.16] | 0.002* |
| Seq [IC] | -24.29 | [-73.77, 25.29] | 0.317 |
| P | -29.21 | [-77.94, 19.52] | 0.225 |
| T | -15.73 | [-64.47, 33.00] | 0.507 |
| BF b | 0.42 | [0.00, 0.84] | 0.052 |
| Marginal $R^2$/Conditional $R^2$ = 0.213/ 0.218 | | | |
| Popliteal artery diameter | | | |
| Intercept | 3.22 | [1.15, 5.28] | 0.004* |
| Seq [IC] | 0.27 | [-0.51, 1.06] | 0.478 |
| P | -0.12 | [-0.40, 0.16] | 0.394 |
| T | 0.14 | [-0.14, 0.42] | 0.308 |
| DBP b | 0.38 | [-0.02, 0.77] | 0.059 |
| Marginal $R^2$/Conditional $R^2$ = 0.360/ 0.813 | | | |
| Popliteal artery blood flow velocity | | | |
| Intercept | 6.69 | [-0.37, 13.75] | 0.062 |
| Seq [IC] | -1.79 | [-5.63, 2.04] | 0.340 |
| P | -2.20 | [-5.79, 1.39] | 0.216 |
| T | -2.14 | [-5.74, 1.45] | 0.227 |
| BV b | 0.83 | [0.19, 1.46] | 0.014* |
| Marginal $R^2$/Conditional $R^2$ = 0.362/0.369 | | | |
| Popliteal artery shear rate | | | |
| Intercept | 86.27 | [-17.84, 190.4] | 0.099 |
| Seq [IC] | -17.19 | [-84.77, 50.39] | 0.601 |
| P | -35.39 | [-95.83, 25.06] | 0.235 |
| T | -40.96 | [-101.4, 19.49] | 0.172 |
| SR b | 0.97 | [0.43, 1.50] | 0.001* |
| Marginal $R^2$/Conditional $R^2$ = 0.488/NA | | | |

*Notes*: Seq, sequence; P, period (time); T, treatment; *$p < 0.05$.

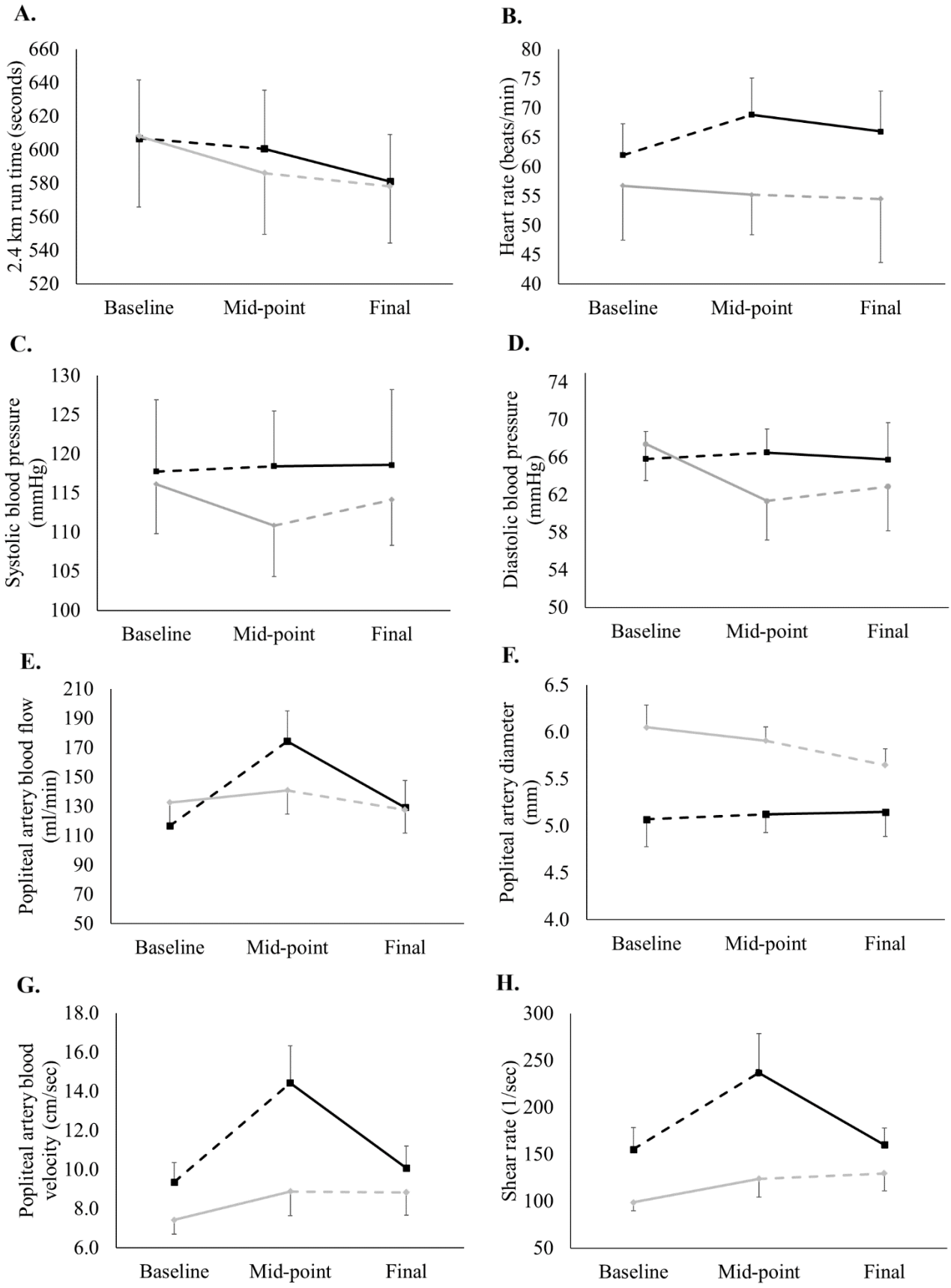



Figure 2: Outcome variables at each time point, shown by group and condition. Error bars represent standard error. Dotted line indicates time where participants were in control condition. Solid line indicates time where participants were in intervention condition.

Table 3: Table with data from which Figure 2 was created.

| | Baseline *M* (SD) | | Mid-point *M* (SD) | | Post *M* (SD) | |
|---|---|---|---|---|---|---|
| Outcome variables | Group A | Group B | Group A | Group B^ | Group A^ | Group B |
| 2.4 km time trial (seconds) | 606.8 (85.3) | 608.1 (111.7) | 600.5 (85.8) | 586.1 (96.8) | 581.2 (68.2) | 578.1 (89.7) |
| Heart rate (beats/minute) | 62.0 (5.3) | 56.8 (9.3) | 68.8 (6.3) | 55.2 (6.8) | 66.0 (8.9) | 54.5 (10.8) |
| Systolic blood pressure (mmHg) | 117.8 (9.2) | 116.1 (6.3) | 118.4 (7.1) | 110.9 (6.5) | 118.6 (9.6) | 114.1 (5.8) |
| Diastolic blood pressure (mmHg) | 65.8 (2.9) | 67.4 (3.9) | 66.5 (2.5) | 61.4 (4.2) | 65.8 (3.9) | 62.9 (4.7) |
| Popliteal artery blood flow (ml/second) | 116.8 (58.3) | 132.7 (66.0) | 174.3 (75.0) | 140.9 (58.3) | 129.3 (65.7) | 127.5 (56.3) |
| Popliteal artery vessel diameter (mm) | 5.1 (1.1) | 6.1 (0.9) | 5.1 (0.7) | 5.9 (0.5) | 5.2 (1.0) | 5.7 (0.6) |
| Popliteal artery blood velocity (cm/second) | 9.4 (3.6) | 7.4 (2.6) | 14.4 (6.9) | 8.9 (4.5) | 10.1 (4.0) | 8.8 (4.2) |
| Popliteal artery shear rate (1/seconds) | 155.3 (53.3) | 98.8 (33.0) | 236.6 (151.6) | 123.8 (70.6) | 160.3 (63.0) | 129.3 (65.7) |

*Notes: M* = mean, SD = standard deviation, ^Portion of the study in which each group received the intervention (Group B for the three weeks between Baseline and Mid-point testing, Group A for the three weeks between Mid-point and Post testing).

Results of the smallest worthwhile change analysis (Table 4) revealed no meaningful changes in resting heart rate, systolic blood pressure, or any of the popliteal artery outcomes despite medium effect sizes for all variables except popliteal artery total blood flow (small) and popliteal artery diameter (negligible). However, the change in diastolic blood pressure in the intervention condition exceeded the smallest worthwhile change (effect size = 0.62), with a non-significant trend toward greater change in the intervention group (drop of 3.6 ± 5.8 mmHg) compared to the control group (increase of 1.1 ± 4.1 mmHg). Additionally, the change in time trial performance during the intervention condition exceeded the smallest worthwhile change (effect size = 0.62), with a non-significant trend toward lower running times in the intervention condition (improvement of 20.8 ± 24.7 seconds, which translates to 8.7 ± 10.3 seconds/km) compared to the control condition (improvement of 7.2 ± 18.7 seconds, or 3.0 ± 7.8 seconds/km). To give context to the extent of participant improvement in the time trial, participants' fastest race of the season was 10.2 ± 7.8 seconds/km faster than their first race of the season.

Table 4: Smallest worthwhile change and effect size analyses for differences in outcome variables across conditions.

| | Control | | Intervention | | |
|---|---|---|---|---|---|
| Outcome variables | SWC | MD | SWC | MD | Effect size |
| 2.4 km time trial (seconds) | 11.2 | -7.2 | 14.8 | -20.8^ | 0.62 |
| Heart rate (beats/minute) | 4.9 | 2.8 | 3.1 | -2.2 | 0.52 |
| Systolic blood pressure (mmHg) | 3.7 | 2.1 | 5.2 | -2.8 | 0.61 |
| Diastolic blood pressure (mmHg) | 2.4 | 1.1 | 3.5 | -3.6^ | 0.62 |
| Popliteal artery blood flow (ml/second) | 47.0 | 19.3 | 47.4 | -16.3 | 0.45 |
| Popliteal artery vessel diameter (mm) | 0.28 | -0.11 | 0.45 | -0.07 | 0.08 |
| Popliteal artery blood velocity (cm/second) | 0.031 | 0.023 | 0.039 | -0.012 | 0.60 |
| Popliteal artery shear rate (1/seconds) | 47.6 | 40.5 | 68.1 | -21.8 | 0.64 |

*Note:* SWC = smallest worthwhile change, MD = mean difference, ^Indicates that difference between trials exceeded the smallest worthwhile change threshold.

## 4. Discussion

Our study evaluated the effects of an aerobic BFR protocol utilizing approximately 10 – 15 minutes restriction duration at 65% of LOP prior to daily running practices for three weeks in collegiate cross country runners during their fall season. Our results found no significant differences in any of the cardiovascular, hemodynamic, or time trial variables between control and intervention conditions. However, the time trial results, while non-significant, did identify a potentially meaningful change in the favorable direction with BFR administration, with the time trial change exceeding the smallest worthwhile change and a medium effect size for differences from the control condition. When participants were in the BFR

condition, point estimates of time trial performance improved by an average of approximately 8.7 seconds/km. For context, by examining published race reports, it was found that our study participants improved race times by 10.2 seconds/km throughout their seven-week season. If such an improvement could be maintained for full race distances (6.0 km for women, 8.0 km for men), our study suggests that the majority (~85%) of the improvement in race times across the season could be accounted for by changes in 2.4 km run times during the three weeks participants were in the intervention group.

Our findings add to a mixed body of evidence when evaluating effects of aerobic BFR training on endurance performance in athletes. One meta-analysis evaluating aerobic BFR in athletes found effect sizes favoring a small additional gain in fitness with aerobic BFR training as compared to similar high-intensity training without BFR, but heterogeneity in findings and a small sample size kept this result from achieving statistical significance (Castilla-López et al., 2022). A recent review study indicated that aerobic BFR training can enhance $VO_2$max, increase the lactate threshold, and possibly improve movement economy, although exact adaptations are likely to be protocol- and population-specific (Smith et al., 2022). Many of the previously-conducted studies match absolute training load and use BFR as a main training modality rather than as a supplement to athletes' normal training, and to our knowledge no previous studies have been conducted on in-season athletes (Chen, Hsieh, Ho, Ho, et al., 2022; Chen, Hsieh, Ho, Lin, et al., 2022; Giovanna et al., 2022; Held et al., 2020, 2024; Tangchaisuriya et al., 2022). Our study builds on this past work by showcasing an active BFR protocol of low intensity as a potential means to improve running time trial performance in collegiate cross country runners during their season, when used in addition to their normally prescribed running training. Yet, more work needs to be done to identify protocols and populations for which such training may have the greatest ergogenic effect.

In examination of our cardiovascular and hemodynamic outcomes, resting systolic blood pressure did not change across the study or between conditions, but resting diastolic blood pressure exceeded the smallest worthwhile change following the intervention condition and had medium effect size, with a non-significant trend toward lower diastolic blood pressure following the intervention condition. It is well-known that blood pressure and heart rate acutely rise to a greater degree during exercise with BFR than absolute intensity-matched exercise without BFR (de Queiros et al., 2023; Domingos & Polito, 2018; Patterson et al., 2019), whereas a recent review found that high-intensity aerobic training without BFR induced larger acute changes in heart rate and blood pressure than lower-intensity aerobic training with BFR (de Queiros et al., 2023). When examining adaptations with BFR training, two recent meta-analyses including mainly normotensive adults found no changes in resting blood pressure or heart rate following 6 – 12 weeks of BFR training (Maga et al., 2023; Russo et al., 2023). However, it has been documented that exercise training is more effective for reducing resting blood pressure in individuals with pre-hypertension or hypertension compared to normal blood pressure (Cornelissen & Smart, 2013), and a similar case may be true for blood pressure changes with BFR. Indeed, one study in hypertensive adults did show a reduction in both resting systolic and diastolic blood pressure following eight weeks of resistance training with BFR (Cezar et al., 2016). We were unable to find research specifically looking at adaptations to aerobic or resistance training with BFR in athletic populations, although our findings and those from non-BFR training suggest that few changes to resting blood pressure or heart rate should be expected.

Our study also found no effect of active BFR on resting popliteal artery characteristics. This finding is in agreement with Hunt et al. (2013), who found no changes in resting popliteal artery size or function following six weeks of plantar flexion training with BFR in apparently healthy adult males. In contrast, studies by Hunt et al. (2012) and Christiansen et al. (2020) have found increases in brachial artery and femoral artery diameter, respectively, following 4 – 6 weeks of BFR training of isolated muscle groups in young adult males. Given the highly trained nature of our participants, endothelial adaptations to exercise training associated with endurance exercise (Green et al., 2017) may supersede any potential adaptations from BFR alone. Protocol differences in duration of restriction, the types of exercise completed with BFR, and the number of days/weeks may also have contributed to the mixed findings. Such possibilities should be explored in future research.

Aerobic BFR exercise causes increased physiologic strain and increased perceived exertion when compared to absolute intensity-matched exercise without restriction (Corvino et al., 2017; Ozaki et al., 2010). By contrast, our BFR protocol took place before each running workout 5+ days per week, and our participants anecdotally reported no fatigue from the protocol and noted no residual effects on their running workouts, suggesting that their self-selected light intensity walk was sufficiently light as to not hinder subsequent workout quality. Consideration of how to optimally design BFR protocols to elicit favorable training adaptations without compromising acute performance is important when planning future protocols aimed at enhancing exercise performance and recovery in rehabilitation, health, and performance settings.

Our study has several notable strengths. First and foremost, our crossover study design minimized the chances that potential effects of having different participants in control and intervention groups, or differences in training prior to beginning the study may have influenced our findings. Furthermore, our field-based time trial adds real-world value to our findings, and may highlight changes that can occur independent of hemodynamic alterations.

However, study limitations must also be acknowledged. Our sample, while of similar size to past studies in this research area, was small and relatively homogenous, and our non-significant trend toward improved running times shows that our study was underpowered to identify a potentially small but meaningful improvement in running performance with aerobic BFR. In order to control for the effects of weather, time trial course, and other potentially extraneous variables, we had to restrict our recruitment to local cross country teams, and our rural geographic location resulted in limited ability to recruit participants meeting our strict inclusion criteria. If our study were replicated using a larger sample (possibly with high school runners or adults in running clubs), it may be sufficiently powered to detect a small benefit of aerobic BFR performed prior to training for endurance running performance. Additionally, although participants acted as their own controls, the control condition did not have a sham protocol (e.g., pumping cuffs to 20 mmHg). This choice was made to reduce burden to the athletes and to reduce risk of confusion to

participants by changing cuff pressures during the study, but it does lend the possibility that the placebo effect could have played a role in our findings. Finally, the short washout period (2 – 3 days) between being in the control and intervention groups may have resulted in a residual effect on our study outcomes, although it is unlikely that it lasted three weeks until the next set of outcome measures were taken.

In conclusion, we found that daily aerobic BFR prior to run training resulted in a non-significant but potentially meaningful trend toward improved 2.4 km time trial performance in collegiate cross country runners without a significant change in resting cardiovascular or hemodynamic measures. More work is needed in this research area to better determine in what sports, populations, and under what BFR parameters such training strategies may elicit a chronic ergogenic effect in order to optimize their use in field-based settings.

**Conflict of Interest**

The authors declare no conflicts of interest.

**References**


Abe, T., Fujita, S., Nakajima, T., Sakamaki-Sunaga, M., Ozaki, H., Ogasawara, R., Sugaya, M., Kudo, M., Kurano, M., Yasuda, T., Sato, Y., Ohshima, H., Mukai, C., & Ishii, N. (2010). Effects of low-intensity cycle training with restricted leg blood flow on thigh muscle volume and VO2max in young men. *Journal of Sports Science & Medicine*, *9*, 452–458.

Abe, T., Kearns, C. F., & Sato, Y. (2006). Muscle size and strength are increased following walk training with restricted venous blood flow from the leg muscle, Kaatsu-walk training. *Journal of Applied Physiology*, *100*(5), 1460–1466. https://doi.org/10.1152/japplphysiol.01267.2005

Bennett, H., & Slattery, F. (2019). Effects of blood flow restriction training on aerobic capacity and performance: A systematic review. *Journal of Strength and Conditioning Research*, *33*(2), 572–583. https://doi.org/10.1519/JSC.0000000000002963

Buchheit, M. (2016). The numbers will love you back in return–I promise. *International Journal of Sports Physiology and Performance*, *11*(4), 551–554. https://doi.org/10.1123/IJSPP.2016-0214

Castilla-López, C., Molina-Mula, J., & Romero-Franco, N. (2022). Blood flow restriction during training for improving the aerobic capacity and sport performance of trained athletes: A systematic review and meta-analysis. *Journal of Exercise Science and Fitness*, *20*(2), 190–197. https://doi.org/10.1016/j.jesf.2022.03.004

Cezar, M. A., De Sá, C. A., Corralo, V. da S., Copatti, S. L., Santos, G. A. G. dos, & Grigoletto, M. E. da S. (2016). Effects of exercise training with blood flow restriction on blood pressure in medicated hypertensive patients. *Motriz: Revista de Educação Física*, *22*, 9–17. https://doi.org/10.1590/S1980-6574201600020002

Chen, Y.-T., Hsieh, Y.-Y., Ho, J.-Y., Ho, C.-C., Lin, T.-Y., & Lin, J.-C. (2022). Running interval training combined with blood flow restriction increases maximal running performance and muscular fitness in male runners. *Scientific Reports*, *12*, 1–9. https://doi.org/10.1038/s41598-022-14253-3

Chen, Y.-T., Hsieh, Y.-Y., Ho, J.-Y., Lin, T.-Y., & Lin, J.-C. (2022). Running training combined with blood flow restriction increases cardiopulmonary function and muscle strength in endurance athletes. *Journal of Strength and Conditioning Research*, *36*(5), 1228–1237. https://doi.org/10.1519/JSC.0000000000003938

Cohen, S. S. (1988). *Statistical power analysis for the behavioral sciences* (2nd Ed.). Lawrence Erlbaum Associates.

Cornelissen, V. A., & Smart, N. A. (2013). Exercise training for blood pressure: A systematic review and meta-analysis. *Journal of the American Heart Association: Cardiovascular and Cerebrovascular Disease*, *2*(1), 1–9. https://doi.org/10.1161/JAHA.112.004473

Corvino, R. B., Rossiter, H. B., Loch, T., Martins, J. C., & Caputo, F. (2017). Physiological responses to interval endurance exercise at different levels of blood flow restriction. *European Journal of Applied Physiology*, *117*(1), 39–52. https://doi.org/10.1007/s00421-016-3497-5

da Cunha Nascimento, D., Schoenfeld, B. J., & Prestes, J. (2020). Potential implications of blood flow restriction exercise on vascular health: A brief review. *Sports Medicine*, *50*(1), 73–81. https://doi.org/10.1007/s40279-019-01196-5

de Lemos Muller, C. H., Farinha, J. B., Leal-Menezes, R., & Ramis, T. R. (2024). Aerobic training with blood flow restriction on muscle hypertrophy and strength: Systematic review and meta-analysis. *Journal of Strength and Conditioning Research*, *38*(7), 1341–1349. https://doi.org/10.1519/JSC.0000000000004800

de Oliveira, M. F. M., Caputo, F., Corvino, R. B., & Denadai, B. S. (2016). Short-term low-intensity blood flow restricted interval training improves both aerobic fitness and muscle strength. *Scandinavian Journal of Medicine & Science in Sports*, *26*(9), 1017–1025. https://doi.org/10.1111/sms.12540

de Queiros, V. S., Rolnick, N., Sabag, A., de França, I. M., Wilde, P., Vieira, J. G., Reis, V. M., Formiga, M. F., Cabral, B. G. de A. T., & Dantas, P. M. S. (2023). Acute responses in blood flow restriction low-intensity aerobic training: A meta-analysis. *International Journal of Sports Medicine*, *44*(8), 545–557. https://doi.org/10.1055/a-2038-3635

Domingos, E., & Polito, M. D. (2018). Blood pressure response between resistance exercise with and without blood flow restriction: A systematic review and meta-analysis. *Life Sciences*, *209*, 122–131. https://doi.org/10.1016/j.lfs.2018.08.006

Ferguson, R. A., Mitchell, E. A., Taylor, C. W., Bishop, D. J., & Christiansen, D. (2021). Blood-flow-restricted exercise: Strategies for enhancing muscle adaptation and performance in the endurance-trained athlete. *Experimental Physiology*, *106*(4), 837–860. https://doi.org/10.1113/EP089280

Giovanna, M., Solsona, R., Sanchez, A. M. J., & Borrani, F. (2022). Effects of short-term repeated sprint training in hypoxia or with blood flow restriction on response to exercise. *Journal of Physiological Anthropology*, *41*(1), 1–13. https://doi.org/10.1186/s40101-022-00304-1

Gnasso, A., Carallo, C., Irace, C., De Franceschi, M. S., Mattioli, P. L., Motti, C., & Cortese, C. (2001). Association between wall shear stress and flow-mediated vasodilation in healthy

men. *Atherosclerosis*, *156*(1), 171–176. https://doi.org/10.1016/s0021-9150(00)00617-1

Green, D. J., Hopman, M. T. E., Padilla, J., Laughlin, M. H., & Thijssen, D. H. J. (2017). Vascular adaptation to exercise in humans: Role of hemodynamic stimuli. *Physiological Reviews*, *97*(2), 495–528. https://doi.org/10.1152/physrev.00014.2016

Held, S., Behringer, M., & Donath, L. (2020). Low intensity rowing with blood flow restriction over 5 weeks increases V̇O2max in elite rowers: A randomized controlled trial. *Journal of Science and Medicine in Sport*, *23*(3), 304–308. https://doi.org/10.1016/j.jsams.2019.10.002

Held, S., Rappelt, L., Rein, R., Deutsch, J.-P., Wiedenmann, T., & Donath, L. (2024). Five-week, low-intensity blood flow restriction rowing improves V̇O2max in elite rowers. *Journal of Strength and Conditioning Research*, *38*(6), e299–e303. https://doi.org/10.1519/JSC.0000000000004755

Hughes, L., Paton, B., Rosenblatt, B., Gissane, C., & Patterson, S. D. (2017). Blood flow restriction training in clinical musculoskeletal rehabilitation: A systematic review and meta-analysis. *British Journal of Sports Medicine*, *51*(13), 1003–1011. https://doi.org/10.1136/bjsports-2016-097071

Lim, C.-Y., & In, J. (2021). Considerations for crossover design in clinical study. *Korean Journal of Anesthesiology*, *74*(4), 293–299. https://doi.org/10.4097/kja.21165

Lixandrao, M. E., Ugrinowitsch, C., Berton, R., Vechin, F. C., Conceicao, 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

Maga, M., Wachsmann-Maga, A., Batko, K., Włodarczyk, A., Kłapacz, P., Krężel, J., Szopa, N., & Sliwka, A. (2023). Impact of blood-flow-restricted training on arterial functions and angiogenesis–A systematic review with meta-analysis. *Biomedicines*, *11*(6), 1–19. https://doi.org/10.3390/biomedicines11061601

Marocolo, M., Simim, M. A. M., Bernardino, A., Monteiro, I. R., Patterson, S. D., & da Mota, G. R. (2019). Ischemic preconditioning and exercise performance: Shedding light through smallest worthwhile change. *European Journal of Applied Physiology*, *119*(10), 2123–2149. https://doi.org/10.1007/s00421-019-04214-6

Montoye, A. H. K., McFate, D. G., Cox, B. A., Rider, B. C., & Vranish, J. R. (2023). Acute effects of ischemic preconditioning at different occlusion pressures on athletic performance indicators in male soccer players. *International Journal of Strength and Conditioning*, *3*(1). 1–10. https://doi.org/10.47206/ijsc.v3i1.221

Ozaki, H., Brechue, W. F., Sakamaki, M., Yasuda, T., Nishikawa, M., Aoki, N., Ogita, F., & Abe, T. (2010). Metabolic and cardiovascular responses to upright cycle exercise with leg blood flow reduction. *Journal of Sports Science & Medicine*, *9*(2), 224–230.

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*, 1–15. https://doi.org/10.3389/fphys.2019.00533

Pignanelli, C., Christiansen, D., & Burr, J. F. (2021). Blood flow restriction training and the high-performance athlete: Science to application. *Journal of Applied Physiology*, *130*(4), 1163–1170. https://doi.org/10.1152/japplphysiol.00982.2020

Russo, A., Boppre, G., Schmidt, C., & Bohn, L. (2023). Chronic hemodynamic adaptations induced by resistance training with and without blood flow restriction in adults: A systematic review and meta-analysis. *Sports Medicine and Health Science*, *5*(4), 259–268. https://doi.org/10.1016/j.smhs.2023.09.006

Scott, B. R., Loenneke, J. P., Slattery, K. M., & Dascombe, B. J. (2015). Exercise with blood flow restriction: An updated evidence-based approach for enhanced muscular development. *Sports Medicine*, *45*(3), 313–325. https://doi.org/10.1007/s40279-014-0288-1

Secomb, T. W. (2016). Hemodynamics. *Comprehensive Physiology*, *6*(2), 975–1003. https://doi.org/10.1002/cphy.c150038

Singer, J. D., & Willett, J. B. (2003). Doing data analysis with the multilevel model for change. In J. D. Singer & J. B. Willett (Eds.), *Applied longitudinal data analysis: Modeling change and event occurrence* (pp.75–137). Oxford University Press. https://doi.org/10.1093/acprof:oso/9780195152968.003.0004

Slysz, J., Stultz, J., & Burr, J. F. (2016). The efficacy of blood flow restricted exercise: A systematic review & meta-analysis. *Journal of Science and Medicine in Sport*, *19*(8), 669–675. https://doi.org/10.1016/j.jsams.2015.09.005

Smith, N. D. W., Scott, B. R., Girard, O., & Peiffer, J. J. (2022). Aerobic training with blood flow restriction for endurance athletes: Potential benefits and considerations of implementation. *The Journal of Strength & Conditioning Research*, *36*(12), 3541–3550. https://doi.org/10.1519/JSC.0000000000004079

Spranger, M. D., Krishnan, A. C., Levy, P. D., O'Leary, D. S., & Smith, S. A. (2015). Blood flow restriction training and the exercise pressor reflex: A call for concern. *American Journal of Physiology–Heart and Circulatory Physiology*, *309*(9), H1440–H1452. https://doi.org/10.1152/ajpheart.00208.2015

Tangchaisuriya, P., Chuensiri, N., Tanaka, H., & Suksom, D. (2022). Physiological adaptations to high-intensity interval training combined with blood flow restriction in masters road cyclists. *Medicine and Science in Sports and Exercise*, *54*(5), 830–840. https://doi.org/10.1249/MSS.0000000000002857

Vranish, J. R., Young, B. E., Kaur, J., Patik, J. C., Padilla, J., & Fadel, P. J. (2017). Influence of sex on microvascular and macrovascular responses to prolonged sitting. *American Journal of Physiology. Heart and Circulatory Physiology*, *312*(4), H800–H805. https://doi.org/10.1152/ajpheart.00823.2016

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