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CARDIORESPIRATORY AND METABOLIC RESPONSES TO LOW-INTENSITY BLOOD-FLOW RESTRICTED RUNNING

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Abstract

Low-intensity (LI) aerobic exercise with blood-flow restriction (BFR) increases heart rate (HR), oxygen consumption (VO_2), and ratings of perceived exertion (RPE), sometimes to similar levels as high-intensity (HI) exercise. Distance runners may benefit from LI-BFR running in periods of reduced volume or intensity, possibly due to injury. **PURPOSE:** To compare HR, VO_2, blood lactate (BLa), and RPE during LI-BFR running and HI running without BFR. **METHODS:** Fifteen female distance runners (age 23±4yrs, height 1.67±0.50m, body mass 57.6±5.7kg, VO_2max 51.0±4.5mL•kg^{-1}•min^{-1}) completed three randomized 12-minute running conditions: LI control (40% VO_2max), HI (80% VO_2max), and LI-BFR (40% VO_2max). VO_2, HR, and RPE were measured at rest, and every 3-minutes. BLa was measured at rest, immediately-post (ImmPost), and 3-minutes post-exercise (3minPost). **RESULTS:** VO_2 remained steady among each condition ($p=0.075, \eta_p^2=0.155$). The average VO_2 differed between the conditions ($p<0.001$), as HI (39.4±3.9mL•kg^{-1}•min^{-1}) > LI-BFR (25.3±2.6mL•kg^{-1}•min^{-1}) > LI (22.5±3.1mL•kg^{-1}•min^{-1}). HR increased at the onset of exercise and differed between the conditions ($p<0.001, \eta_p^2=0.745$). The average HR for HI, LI-BFR, and LI were 166±8bpm, 142±13bpm, and 124±11bpm, respectively. BLa was similar in HI and LI-BFR ImmPost and 3minPost ($p>0.05$), and both were higher than LI ($p<0.017$). Average RPE in the HI and LI-BFR conditions were similar ($p=0.236$). **CONCLUSION:** HI elicits greater VO_2 and HR responses than LI-BFR running, suggesting that HI would result in more robust long-term training responses. However, if one cannot engage in HI running because of injury and rehabilitation, LI-BFR running could be a feasible temporary alternative.

Key Words: BFR, aerobic exercise, heart rate, oxygen consumption, blood lactate, rating of perceived exertion.

1. Introduction

Distance running is a popular form of exercise and a competitive sport where overuse injuries are often a result of training (1). Injured runners may need to reduce or sometimes stop their training for several weeks to months (2, 3). During that time, runners may engage in rehabilitative programs focused on slowly progressing back to running along with sport-specific training to mitigate the aerobic training losses, or detraining (4).

Blood flow restricted (BFR) exercise is a rehabilitation modality that allows individuals to gain fitness benefits while working under lower mechanical loads and intensities (5). Most BFR studies focus on resistance training, and few studies have combined it with aerobic exercise. Of those studies investigating aerobic exercise with BFR, most are performed as interval training (6–10) and only three have evaluated aerobic BFR exercise in a continuous bout (11–13). BFR exercise requires a pressurized cuff or torniquet to be placed around the proximal portion of the upper or lower extremities during exercise (14), reducing arterial and venous blood flow, and leading to blood pooling and hemodynamic stress (15, 16). This, in turn, makes BFR exercise difficult to perform, and is therefore done at low-intensities (LI). Oftentimes BFR exercise shows similar physiological responses to high intensity (HI) exercise. LI aerobic exercise with BFR (LI-BFR) has generally been performed at 40% VO_2max compared to about 80% VO_2max in HI training. (6, 7, 11, 17–20). Most LI-BFR aerobic training studies have reported increased muscle size and strength (8, 12, 21), improved cardiorespiratory endurance (12, 16), enhanced exercise tolerance and time to exhaustion (12, 20), greater power output, and angiogenesis (7, 16). Studies displaying the immediate effects of LI-BFR aerobic exercise have demonstrated that it is more vigorous than training at the same LI without BFR, with higher heart rate (HR), VO_2, and ratings of perceived exertion (RPE) values (6, 10, 11). When compared to HI aerobic exercise, however, there are lower VO_2, HR, blood lactate (BLa), and RPE values in LI-BFR aerobic exercise (6, 7, 13, 22, 23). BLa levels are often elevated after BFR exercise in the ischemic muscle, due to increased fast glycolysis, though with aerobic exercise, this BLa could be used in oxidative metabolism, resulting in lower observed levels (6, 11).

The few previous studies comparing aerobic LI-BFR training to HI aerobic interval training have shown that the former elicits lower cardiorespiratory and metabolic responses than HI interval aerobic exercise, though higher than LI controls. However, this could be due to inadequate comparisons between the LI and HI protocols when it comes to intensity, mode, and duration since previous studies have primarily used HI interval training instead of continuous bouts for the HI condition (7, 22, 23). Endurance athletes primarily train in a continuous aerobic bout, not exclusively in HI intervals and therefore, this should be investigated.

LI-BFR aerobic exercise could be a viable exercise mode to combat cardiorespiratory and endurance losses during detraining periods (24–26). First though, studies should be designed to directly compare LI-BFR to HI aerobic exercise in acute bouts of exercise and then apply it throughout training periods since training is a collection of exercise bouts over time. It seems LI-BFR aerobic exercise could be a practical training tool for endurance athletes.

Therefore, the purpose of this study was to compare HR, VO_2, BLa, and RPE during acute sessions of LI-BFR and HI running. It was hypothesized that the cardiorespiratory and metabolic factors of HR, VO_2, BLa, and RPE would be similar in 12 minutes of continuous LI-BFR and HI running.

2. Materials and Methods

Participants

The participants of this study were 15 healthy female distance runners between the ages of 18 and 30 years old, and within the past year had ran a 5k in under 22-minutes. Participant demographics are outlined in Table 1. Those with cardiovascular or neurological conditions, orthopedic injuries within the past 6 months, or implanted medical devices were excluded from the study. The participants were recruited by word of mouth, social media, and local races.

Experimental Design

This study consisted of 4 visits total, attended over approximately 2 weeks. Participants had 3 days rest in between maximal testing and 48 hours between conditions to ensure adequate recovery. During the first visit, they were familiarized with the experimental methods and in visits 2-4, they performed 3 separate conditions in a randomized order, following a within-subjects design. The participants refrained from exercise for 24 hours before visits and had no caffeine on visit days. During all testing sessions, HR and VO_2 were obtained continuously, and RPE (Borg 6-20) measured every 3 minutes. BLa was obtained at rest, immediately after (ImmPost), and in recovery (3minPost). Subjective measures of lower body effort (0-10), pain (0-10), and pleasantness of the running session on a visual analogue scale (0-100, wherein 0 was the least pleasant and 100 was the most pleasant) were obtained after each session. This design allowed us to compare the effects of condition and time, and the interactions between these factors to determine the acute cardiorespiratory and metabolic responses of BFR on LI running.

Visit 1: Familiarization and Maximal Aerobic Testing

Visit 1 consisted of a familiarization session and maximal aerobic testing. The participants completed the written informed consent document approved by the University of New Hampshire's Institutional Review Board, a PAR-Q form, and a running history questionnaire. Participant age, height (m), body mass (kg), and body composition from an InBody machine (InBody770; California, USA) were measured. The arterial occlusion pressure (AOP) to designate pressure of the BFR was determined using B Strong BFR cuffs. A doppler ultrasound (Hokanson Inc. MD6 Bidirectional Doppler; Washington, USA) was placed on the posterior tibial artery in the foot and the cuffs inflated until no pulse was heard. The point of complete occlusion was determined to be the AOP, and this number was used to calculate 50% AOP for the LI-BFR condition. Cuff size was based on each participant's leg circumference, either size #3 or #4 cuffs were chosen to wear for testing.

Participants were fitted with a two-way nonrebreather mask (7450 V2 Series; Kansas, USA) to collect expired air and a heart rate monitor (Polar H10 Heart Rate Sensors). They underwent an incremental VO_2max test (ParvoMedics TrueOne 2400 Metabolic Measurement System; Utah, USAon a treadmill (Fitnex Fitness #3020; Texas, USA). . The protocol started with a 3-minute walking warm-up of 1 minute at 3mph, 3.5mph, and 4mph before starting the test at 5mph and increasing by 1 mph every 3 minutes until VO_2max was reached. VO_2, HR, and subjective effort measured in RPE were recorded every 3 minutes. BLa using a Nova Biomedical Lactate Plus Measurement System was measured at rest and every 3-minutes with a finger stick. VO_2max was used to determine the workloads (40% or 80% VO_2max) for the experimental conditions.

Visits 2-4: Experimental Trials

A schematic representation of the timeline and measurements obtained during each condition of the experimental trials is presented in Figure 1. Upon arriving at the laboratory, participants were informed of the condition that they were going to complete. Participants underwent the first of 3 randomly assigned experimental conditions for visits 2-4: a control LI (40% VO_2max) running, LI running with BFR (LI-BFR: 40% VO_2max), and HI (80% VO_2max) running. Participants rested in a seated position for 5 minutes, while the face mask and heart rate monitor were fitted to the individual. Baseline data was collected and then the same walking warm up done in maximal testing was employed. The LI and HI conditions consisted of 12 minutes of treadmill running at 40% or 80% of VO_2max, respectively, The LI-BFR condition consisted of 12 minutes of treadmill running, using B Strong cuffs on the proximal thighs to restrict blood flow, at the pressure determined during the familiarization session to be a calculation of 50% of the AOP. For this condition, the BFR cuffs were put on and inflated following the 3-minute warm up walk (the treadmill was stopped, and participants told to straddle the belt) to ensure that they were on for exactly 12 minutes total. After 12 minutes of exercise, the treadmill was stopped, and the cuffs deflated immediately.

Statistical Analysis

A power analysis was performed in G*Power version 3.1.9.7 (27) based on the results from the study by Silva et al. (11) that studied aerobic BFR and compared it to low intensity aerobic exercise and high intensity interval training. The researchers reported η^2 values for the condition by time interactions for the variables of VO_2 and HR to be 0.91 and 0.74, respectively.

Based on those effect sizes, an α of 0.05, and power of 0.9 yielded a sample size of 9-15 subjects, respectively.

Statistical procedures were performed in SPSS 27; IBM Inc, NY. Two-way repeated measures analysis of variance (ANOVA) evaluating the differences in condition (HI, LI, LI-BFR) x time were used to test main effects and interactions in cardiorespiratory and metabolic responses. Giesser-Greenhouse corrections were applied in instances when sphericity was violated. Significant interactions were further evaluated with separate 1-way repeated-measures ANOVAs and dependent t-tests with Bonferonni corrections for familywise error rates. Partial eta-squared (η_p^2) was calculated to determine the magnitude of differences when each condition and interaction was partialed out. Data are reported as means ± SD and the level of significance was $p \leq 0.05$.

3. Results

The participants were experienced distance runners who had been running for 11 ± 4 years, and had a mean VO_2max of 51.0 ± 4.5 $mL \cdot kg^{-1} \cdot min^{-1}$. They had an average 5k time of just under 19 minutes, placing them in a competitive distance runner category (see Table 1).

Heart Rate

There was a significant condition ($p < 0.001$, $\eta_p^2 = 0.888$) main effect as the average HR for HI, LI-BFR, and LI were 166 ± 8 bpm, 142 ± 13 bpm, and 124 ± 11 bpm, respectively, wherein HI > LI-BFR > LI. There was a significant time main effect as HR was similar across all conditions at baseline ($p = 0.129$, $\eta_p^2 = 0.136$) then increased at the onset of exercise and differed between the 3 conditions ($p < 0.001$, η_p^2 ranged from 0.840 to 0.896) at each timepoint during the 12 minutes of running (Figure 2). The 3minPost recovery HR for HI and LI-BFR were similar ($p = 0.243$). There was a significant condition by time interaction ($p < 0.001$, $\eta_p^2 = 0.745$) for HR.

Oxygen Consumption

There was a significant condition main effect ($p < 0.001$, $\eta_p^2 = 0.949$) as the average VO_2 (Figure 3) differed between the 3 conditions, where HI (39.4 ± 3.9 mL•kg^{-1}•min^{-1}) was greater than LI-BFR (25.3 ± 2.6 mL•kg^{-1}•min^{-1}) and both of those were higher LI (22.5 ± 3.1 mL•kg^{-1}•min^{-1}). There was also a significant main effect of time ($p = 0.014$, $\eta_p^2 = 0.295$), however, upon post-hoc testing, none of the differences between the time points achieved significance with Bonferroni corrections.

Blood Lactate Concentration

There was a significant condition by time interaction ($p = 0.005$, $\eta_p^2 = 0.296$) for BLa. As depicted in Figure 4, BLa was similar in the HI and LI-BFR conditions immediately following and 3-minutes post-exercise ($p > 0.05$), and both were higher than LI ($p < 0.017$).

Ratings of Perceived Exertion

There was a significant condition main effect ($p = 0.236$, $\eta_p^2 = 0.099$) for RPE. As depicted in Figure 5, average RPE in the HI (11 ± 2) and LI-BFR (12 ± 2) conditions were similar, while LI (9 ± 1) was significantly lower ($p < 0.001$ η_p^2 ranged from 0.688 to 0.783). There was a significant condition by time interaction ($p < 0.001$, $\eta_p^2 = 0.465$) for RPE.

Additional RPE’s for lower-body effort, pain, and pleasantness are depicted in Table 2. For pleasantness, HI and LI did not differ ($p = 0.061$).

4. Discussion

This study compared the acute cardiorespiratory (HR and VO_2), metabolic (BLa), and perceptual (RPE) responses of LI-BFR, LI, and HI running. The key findings from this research indicate that the greatest responses in HR and VO_2 resulted from HI running, followed by LI-BFR and then LI. BLa and RPE were similar in HI and LI-BFR, and both were higher than LI. This indicates that adding BFR to LI running is effective in increasing the cardiorespiratory and metabolic responses to exercise, while not to the same magnitude as HI running.

Similar to our study, Silva et al. (2021) found that the addition of BFR to aerobic treadmill exercise elicits similar ratings of discomfort to HI interval exercise, while evoking lower VO_2 and HR values (11). However, runners do not always train in HI intervals, so comparing a continuous bout for the HI condition allows for more comparable and realistic results. Our study focused on steady-state continuous exercise for each condition as distance runners spend a considerable amount of training this way.. Additionally, our study took a more robust approach with continuous data for HR and VO_2 throughout sessions that was averaged each 3-minute period instead of just at each 3-minute mark.

Frechette et al. (2022) studied the acute physiological responses to steady-state arm cycling ergometry with and without upper extremity BFR (13). There were four randomized conditions consisting of high-workload (60% maximal power output), low-workload (30% maximal power output), low-workload with BFR, and a control no-exercise condition. The greatest responses in HR, VO_2, BLa, and RPE were seen in the high-workload condition. Average VO_2 was 25 and 26% greater in the high-workload condition as compared to low-workload and low-workload BFR conditions. This study found no significant differences between the low-workload conditions with and without BFR (13). Our study found average VO_2 was 75 and 56% greater in the HI condition compared to LI and LI-BFR. HR, however, was 35% and 17% greater in HI condition compared to LI and LI-BFR. There may therefore be different responses to continuous aerobic exercise when BFR is applied to the upper versus lower extremities.

Another study looking at LI rowing interval exercise found that LI rowing exercise with BFR elicits significantly higher HR, decreased muscle oxygen saturation, and increased RPE than at LI without BFR (6). Mahoney et al. (2019) reported to be about 10 $\pm$ 2 for the control LI and about 12 $\pm$ 2 for the LI-BFR condition (6). BLa was measured pre and post-exercise and did not significantly differ between timepoints or conditions (6). Mahoney et al. found a 6.9% increase in HR with the addition of BFR to the LI rowing (6), whereas another study with Renzi et al. found almost a 20% increase in HR during walking with BFR compared to walking without BFR (10). These values compare to our study where there was a 15.0% increase in HR and 12.3% increase in VO_2 with the addition of BFR to LI running. An interesting finding was that the 3minPost HR for HI and LI-BFR running did not differ. Future studies should further investigate this relationship as LI-BFR running may continue to have other longer-term effects that may be similar to that of HI.

It's important to note that the LI condition of 40% VO_2max was really slow for the runners in the study. For example, the LI and LI-BFR paces were an average of 7.0 $\pm$ 0.7 km•h^{-1}

compared to HI pace which was 12.5 ± 1.2 km•h^{-1}. This study modeled the previous literature using 40% for LI, but ultimately this was a walkable pace that was uncomfortably slow to run at, and is much slower than the runners would typically deem LI in training. The HI condition of 80% VO_2max was generally about average or slightly above average running pace for the runners. This could have accounted for a larger portion of the significant differences in the HR and VO_2 values between LI-BFR and HI conditions. Future studies could assess using a LI condition that is still LI for running but may be more in the range of 60% VO_2max, though the feasibility of running with BFR at this pace is unknown.

The majority of the previous BFR studies investigating aerobic exercise have used populations of healthy, recreationally active, and mostly male adults (6–8, 10–13, 22, 28) and no known study has used trained endurance athletes. It's important to note that the subjects in this study did not enjoy performing the LI-BFR exercise as it was the most painful, least pleasant, and required the most lower body effort. However, all but one subject said they would use BFR if it would help with their training or rehabilitation from injury. Competitive endurance athletes, like runners, engage in several months to years of regular aerobic training to reach peak performance (29). However, within only 3 weeks of stopping training, perhaps due to injury, endurance-trained athletes experience a significant 7% decrease in VO_2max (29, 30).

Cross-training or HI training may be used to maintain training-induced adaptations of VO_2max for several months that otherwise would be lost with detraining (24, 25, 29, 30). This is, however, heavily based on maintaining training intensity, or effort (7, 29). For runners, some cross-training modes that are sport-specific and use similar muscles and movement patterns include deep water running/aqua jogging, and antigravity treadmill training running at a lower percentage of body weight. Other modes such as cycling and swimming may also be effective at maintaining cardiovascular fitness (2, 24). In this population of competitive runners, time is typically limited and there is a need to quickly and efficiently return to sport and competition following injury. The findings from this study are critical in that, while an acute bout of LI-BFR running was lower in VO_2 and HR responses than HI running, it was higher than LI alone and elicited the same BLa and similar RPE responses to HI. In a time of detraining, adding BFR to a LI run could increase the acute physiological and metabolic demands, though there is not currently enough information on using BFR for aerobic exercise during rehabilitation for endurance athletes or as supplemental volume in training.

The practicality and feasibility of running with BFR may not be the same for populations without an urgency to return to sport, wherein the pain and unpleasantness of BFR may not be deemed worth it. Recreational runners may not use BFR if it is painful and unpleasant, regardless of any potential benefits. Additionally, not every subject was fully occluded in the standing position (to simulate standing when running) when determining the AOP. Every subject, however, had blood flow reduced at no more than 50% AOP. Pressure in BFR cuffs is typically between the range of 40-80% AOP, though 40% seems to be sufficient to reduce tissue oxygen saturation during exercise (22). Additionally, a strength of this study was the use of within-subjects design to allow for robust comparisons between the conditions for each subject.

This study looked at acute responses to LI-BFR running, and the long-term effects of BFR training are currently unknown. Future training studies are needed to compare these potential long-term adaptations and compliance. This study is a starting place now that we have an adequate comparison with duration and intensity for LI-BFR running.

5. Conclusion

HI running elicits the greatest acute responses in HR and VO_2, compared to LI and LI-BFR, suggesting that HI running may result in more robust long-term training responses. With that said, if one cannot engage in HI running due to injury and rehabilitation, BFR running at LI could be a feasible alternative to HI and LI running in times of decreased training volume and intensity. By comparing the acute responses to continuous aerobic protocols of LI BFR and HI running, these acute responses can be better understood in terms of feasibility and application to future training studies on rehabilitation and return to exercise and sport protocols. Future studies are needed on the long-term physiological effects and compliance of BFR training.

6. Acknowledgements

Conflicts of Interest: There are no conflicts of interest to report.

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Figures

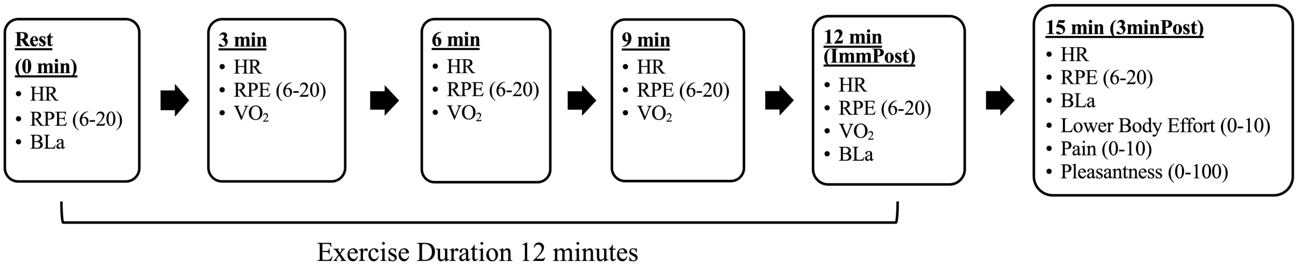

Figure 1. Schematic representation of the timeline and measurements obtained during each condition of the experimental trials. Heart rate, HR; ratings of perceived exertion, RPE; blood lactate, BLa; oxygen consumption, VO_2; immediately post-exercise, ImmPost; 3-minute post-exercise recovery, 3minPost.

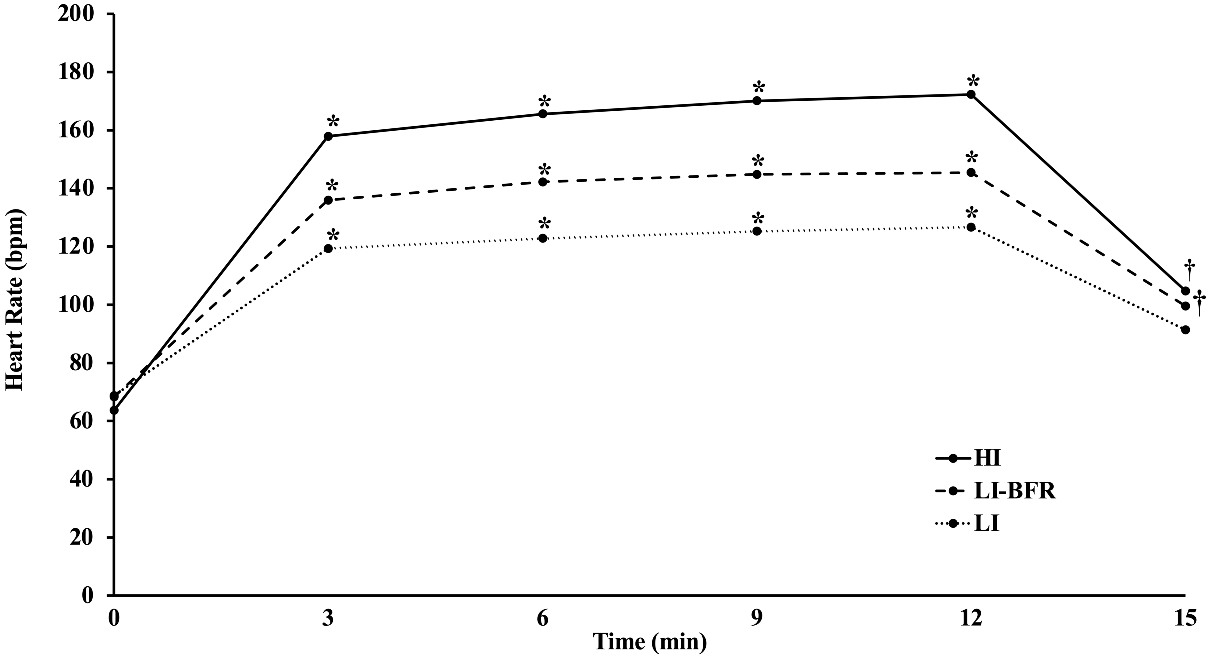

Figure 2. Depicts the mean HR (bpm) for each 3-minute increment during the 3 experimental conditions from rest (0mins) to exercise (3, 6, 9, and 12mins) to 3minPost recovery (15mins). * denotes significantly different between all conditions ($p < 0.001$), and † denotes significantly different from LI ($p < 0.001$). High-intensity running, HI; low-intensity blood-flow restricted running, LI-BFR; low-intensity running, LI.

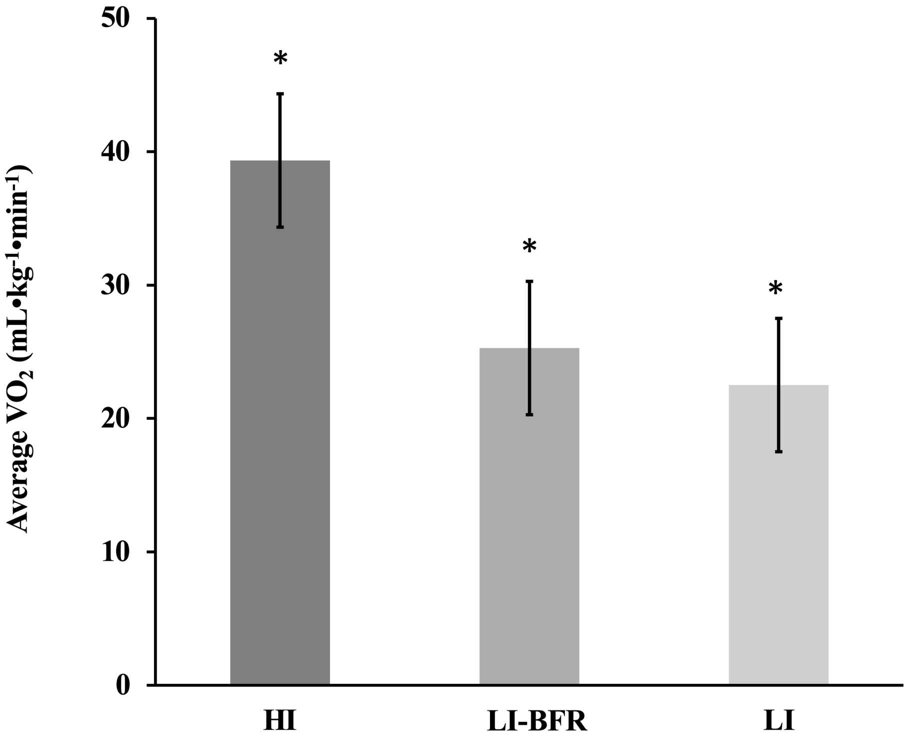

Figure 3. Depicts the mean ± S.D. VO_2 (mL•kg-1•min-1) during each experimental condition. * denotes statistically different between all conditions ($p < 0.001$). Oxygen consumption, VO_2; high-intensity running, HI; low-intensity blood-flow restricted running, LI-BFR; low-intensity running, LI.

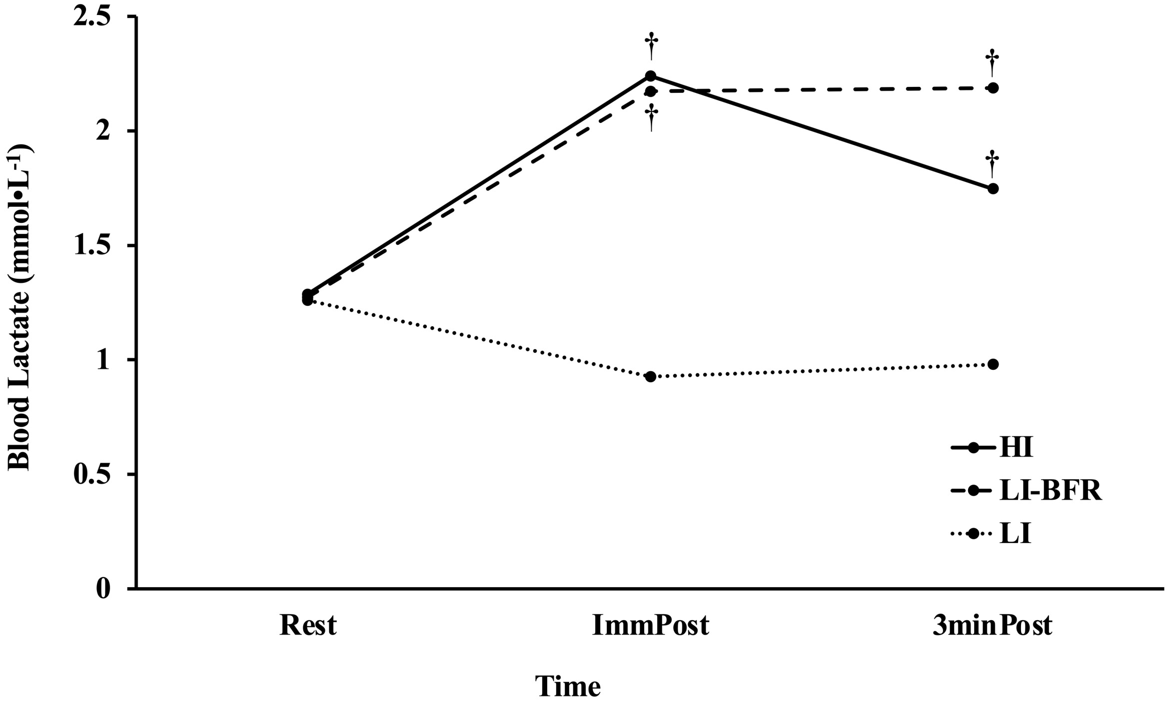

Figure 4. Depicts the mean BLa measurements (mmol•L^{-1}) during the 3 experimental conditions from rest (0min) to ImmPost (12mins) to 3minPost recovery (15mins). † denotes significantly different from LI ($p < 0.017$). High-intensity running, HI; low-intensity blood-flow restricted running, LI-BFR; low-intensity running, LI.

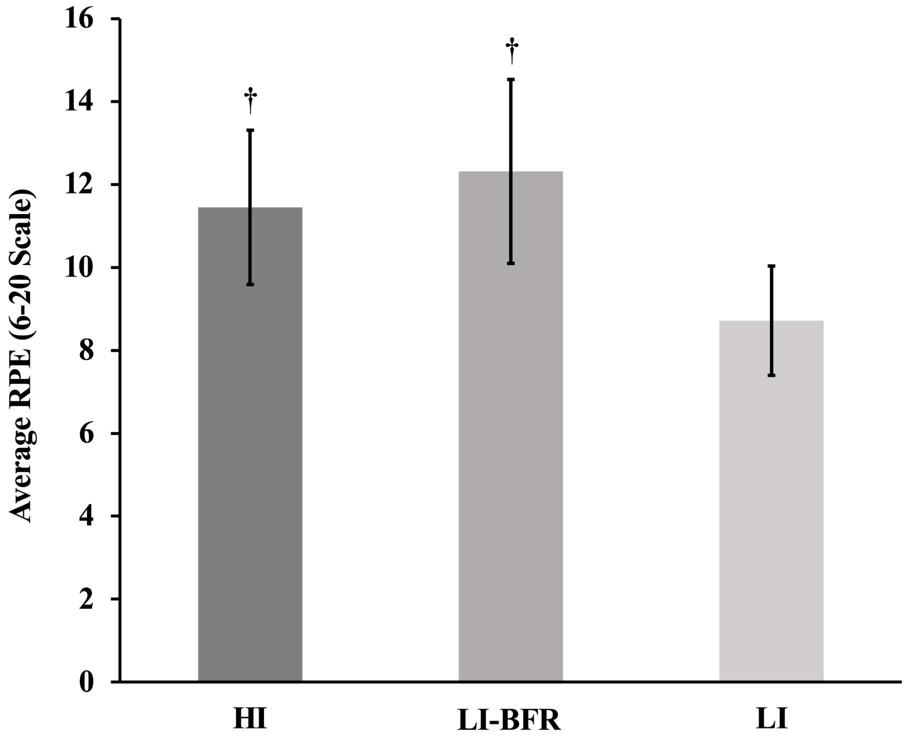

Figure 5. Depicts the mean ± S.D. RPE (6-20) for each experimental condition. † denotes significantly different from LI ($p < 0.001$). Ratings of perceived exertion, RPE; high-intensity running, HI; low-intensity blood-flow restricted running, LI-BFR; low-intensity running, LI.

Tables

Table 1. Participant characteristics are presented as means ± S.D. Maximal oxygen consumption, VO_2max.

N Total	15
Age (yrs)	23 ± 4
Height (m)	1.67 ± 0.5
Body Mass (kg)	57.6 ± 5.7
Body Fat (%)	19.2 ± 4.8
VO_2max ($mL \bullet kg^{-1} \bullet min^{-1}$)	51.0 ± 4.5
5k Time (min)	18.8 ± 1.3
Years Running (yrs)	11 ± 4

Table 2. Describes the mean + S.D. RPE for lower body effort (0-10), pain (0-10), and pleasantness (0-100). * denotes significantly different between all conditions (p < 0.001), and ‡ denotes significantly different from LI-BFR (p < 0.001). High-intensity running, HI; low-intensity blood-flow restricted running, LI-BFR; low-intensity running, LI.

	HI	**LI-BFR**	**LI**
Lower Body Effort (0-10)	3 ± 1*	7 ± 2*	1 ± 1*
Pain (0-10)	2 ± 1*	5 ± 2*	0 ± 1*
Pleasantness (0-100)	76 ± 12‡	19 ± 11	83 ± 13‡