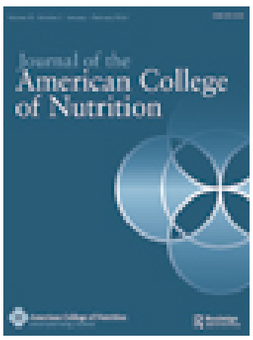

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Distinct Effects of Repeated-Sprint Training in Normobaric Hypoxia and β-Alanine Supplementation

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ABSTRACT

Objective: The present study evaluated the effects of repeated-sprint training in normobaric hypoxia and β-alanine supplementation (BA) on aerobic and anaerobic performance in recreationally active men.

Methods: Participants were randomly assigned to one of the following groups: normoxia/β-alanine (NB, $n = 11$), normoxia/placebo (NP, $n = 8$), normobaric hypoxia/β-alanine (HB, $n = 10$) and normobaric hypoxia/placebo (HP, $n = 9$). All participants completed 8 training sessions over 4 weeks on a cycle ergometer either in normobaric hypoxia (oxygen fraction: $FiO_2 = 14.2\%$) or normoxia ($FiO_2 = 20.9\%$). Participants were instructed to consume a daily dosage of 6.4 g of BA or placebo. Changes in performance in a graded exercise test, repeated-sprint test (RST), and 3-minute all-out test (3MT) were examined before and after training and supplementation.

Results: No between-group differences were observed for training volume or supplementation compliance. Anthropometric and hematological measures remained unchanged before and after intervention in all groups. A main effect of training condition was shown for oxygen consumption and power output at respiratory compensation point, average power output during the last sprint of the RST, heart rate recovery following the RST, and total work during the 3MT. These measures in the normobaric hypoxia groups were significantly ($p < 0.05$) higher than the normoxia groups, except for the heart rate recovery following the RST. A main effect of supplement was detected in anaerobic working capacity, with postintervention values in the BA groups being significantly ($p < 0.05$) higher than the placebo groups.

Conclusions: Repeated-sprint training in hypoxia improved aerobic performance, exercise tolerance, cardiovascular recovery, and overall working capacity, while BA maintained the anaerobic working capacity. However, BA did not provide additional benefits with respect to attenuating fatigue or enhancing repeated-sprint performance.

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Altitude training; training adaptation; exercise performance; fatigue

Introduction

Muscle buffering capacity is a key mechanism related to high-intensity exercise performance. Skeletal muscle acidosis impedes several metabolic processes, such as disruption of phosphorylcreatine resynthesis,[1] inhibition of glycolysis,[2] and dysfunction of muscle contractile process.[3] Muscle buffering capacity derives from several physiological buffers, such as proteins, inorganic phosphate, bicarbonate, and the histidine-containing dipeptide carnosine.[4] Due to the importance of buffering capacity on anaerobic exercise performance, many training programs and dietary supplementation strategies have focused on elevating muscle buffering capacity and improving anaerobic performance.

Training at natural (hypobaric) and simulated (normobaric) altitude has been used for many years in the pursuit of performance enhancement when returning to sea level.[5–7] This type of training is implemented in a variety of forms, including live high–train high, live high–train low, and live low–train high. Recently, interest has focused on the potential of repeated-sprint training in normobaric hypoxia. Several studies have demonstrated the effectiveness of repeated-sprint training in hypoxia based on the repetition of "all-out" efforts of short ($\leq$30 seconds) duration activity interspersed with brief incomplete recoveries.[8–10] Repeated-sprint training in hypoxia uses maximal intensity and relies heavily on the recruitment of fast-twitch muscle fibers under hypoxic conditions.[11] The advantage of repeated-sprint training in hypoxia can be further explained by the greater fractional oxygen extraction from tissue due to decreased oxygen delivery during exercise.[12] Some authors also reported that the addition of a hypoxic stimulus to training modulates phosphorylcreatine resynthesis during exercise,[13] while this is not supported by a recent study examined the impact of 5 days of repeated-sprint training in hypoxia on muscle energy substances.[14] The potential mechanism

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induced by repeated-sprint training in hypoxia is likely to be fiber-type specific and mediated by an oxygen-sensing pathway.[15–18] A newly published meta-analysis concluded that repeated-sprint training in hypoxia improved average repeated-sprint performance to a significantly greater extent than the same training at sea level.[19]

In addition to a well-designed and efficacious training program, the appropriate consumption of dietary nutrients is of vital importance to maintain optimal training and maximize competitive performance. β-Alanine (BA) is commonly employed as an ergogenic aid and has been identified as the rate-limiting precursor to carnosine synthesis, which acts as an intracellular buffer.[20] Numerous studies have demonstrated the effectiveness of BA on improving muscle carnosine content (for detail, see Hobson et al.[21]), which may improve performance during high-intensity intermittent exercise. However, most studies have focused on prolonged high-intensity exercises, and relatively little is known regarding the potential for combined ergogenic aids, especially with prescribed training programs, to improve physiological and performance responses to multi-effort, short-duration exercises such as repeated-sprint training.

Of particular interest is whether the integration of repeated-sprint training in hypoxia and BA is superior to each intervention by itself, in regard to improving exercise performance during various performance testing modalities. Saunders et al.[22] examined the effects of BA on an acute repeated-sprint session and found no differences in performance when compared to placebo. Based upon previous studies, it appears that repeated-sprint training in hypoxia primarily enhances metabolic reactions involved with pH regulation and glycolysis,[19] while the most likely mechanism of action of BA is to increase intracellular buffering capacity.[20] Therefore, the combination of repeated-sprint training in hypoxia and BA may provide independent but additive ergogenic effects on muscle buffering capacity through a variety of potential mechanisms, but it has yet to be evaluated with regard to exercise performance. Considering the lack of research examining the interaction between repeated-sprint training in hypoxia and BA, the purpose of this study was to examine the effects of repeated-sprint training in hypoxia and BA on aerobic, anaerobic, and repeated-sprint performance in recreationally trained men.

Materials and methods

Participants

Fifty-two healthy men were recruited by word of mouth and flyers. Participants were at least recreationally active (most performing weightlifting, cycling, and running) and did not use any supplements that contained BA for at least 9 weeks prior to the study or during the study period. Participants with exposure to altitude over 1,500 m and those who smoked during the previous 6 months were excluded. Among the 52 eligible participants initially recruited, 2 individuals withdrew from the study due to training intolerance, and 12 individuals did not finish the training protocol due to reasons not directly related to the study. Consequently, 38 participants (see Table 1) completed all testing, training, and supplementation protocols and their data were included in the final analysis. They were instructed to maintain their habitual physical activity level (5–7 hours of resistance or endurance training per week) and normal diet throughout the study. This investigation was approved by the university's institutional review board. All participants provided written informed consent after clearing any physical and medical limitations, as determined by the Medical and Activity History Questionnaire and Physical Activity Readiness Questionnaire, and being fully informed about the content of the study and the risks involved.

Table 1. Participant characteristics.

	NB ($n = 11$)	NP ($n = 8$)	HB ($n = 10$)	HP ($n = 9$)
Age (years)	22.6 ± 2.9	22.6 ± 2.9	22.5 ± 2.7	22.7 ± 2.8
Height (cm)	175.2 ± 6.8	174.5 ± 7.4	174.9 ± 6.9	174.8 ± 7.2
Body mass (kg)	78.2 ± 11.6	81.4 ± 7.9	72.4 ± 4.3	72.3 ± 8.4

Note. Data are mean ± standard deviation (SD) and represent baseline characteristics of the participants training in hypoxia while receiving beta-alanine (HB) or placebo (HP) supplementation and participants training in normoxia while receiving beta-alanine (NB) or placebo (NP) supplementation. *n*: Sample size.

Experimental design

This investigation employed a randomized, double-blind, placebo-controlled design for the supplementation component, with a single-blind design for the training component due to the use of hypoxic generators. All participants completed a resting blood draw, body composition assessments, and graded exercise testing on day 1, a lower body repeated-sprint testing on day 2, and a 3-minute all-out cycling testing on day 3. Following the pretesting assessment, participants were randomly (using a random number generator) divided into 4 groups: repeated-sprint training normoxia + BA group (NB), repeated-sprint training in normoxia + placebo group (NP), repeated-sprint training in normobaric hypoxia + BA group (HB), and repeated-sprint training in normobaric hypoxia + placebo group (HP). The fraction of inspired oxygen and simulated altitude were 14.5–14.2% (e.g., 2800–3000 m) for normobaric hypoxia, and 20.9–20.1% (e.g., 0–300 m) for normoxia, respectively. To compare changes in anaerobic performance, each group completed a 4-week training program (2 sessions per week) under the direct supervision of certified strength and conditioning specialists with a concurrent supplementation protocol (6.4 g per day). Participants completed at least 95% of their respective repeated sprints and 95% of the supplementation protocol during the 4-week study period. Posttesting occurred following the completion of the 4-week intervention.

Anthropometric assessments

Anthropometric measurements for all participants were conducted in the following sequence: height, body mass, and body composition. Height (±0.1 cm) was determined using a calibrated medical scale (Health o Meter Professional Model 500 KL, Pelstar, Alsip, IL) with the participants standing barefoot, with feet together, in their normal daily attire. Body mass (±0.1 kg) and body composition were determined using air displacement plethysmography. Participants undressed

down to their undergarments, removed their footwear, including socks, put on a swim cap provided, and sat in the device (BOD POD, COSMED, Rome, Italy) for measurement to determine body composition. Values for body fat percentage were recorded.

Graded exercise testing

An incremental test to volitional exhaustion was performed by each participant on a cycle ergometer to determine maximal oxygen consumption (VO_2peak), gas exchange threshold (GET), and respiratory compensation point (RCP). Prior to testing, each participant completed a standardized warmup consisting of 5 minutes of cycling at 120 W and 10 repetitions of body weight squats, alternating lunges, walking knee hugs, and walking butt kicks. Following the warmup, each participant was fitted with a heart-rate monitor (Garmin, Schaffhausen, Switzerland) to record the participants' heart rates. Participants maintained a pedaling cadence of 70–75 revolutions per minute (RPM) at an initial workload of 60 W. The workload increased 1 W every 3 seconds until the participant was unable to maintain a cadence above 70 RPM for 10 seconds despite verbal encouragement, or volitional fatigue. Prior to each graded exercise test, a metabolic gas analyzer (Quark CPET, COSMED, Rome, Italy) was calibrated with room air and gases of known concentration. Oxygen (O_2), carbon dioxide (CO_2), ventilation (VE), and respiratory exchange ratio were monitored continuously and expressed breath-by-breath. VO_2peak was determined as the highest VO_2 value. The GET was defined as the VO_2 value corresponding to the intersection of two linear regression lines derived separately from the data points below and above the breakpoint in the carbon dioxide production rate (VCO_2 versus VO_2 relationship). The RCP was defined as the VO_2 value corresponding to the point of departure from linearity of the VE versus VCO_2 relationship.[23]

Repeated-sprint testing

Each participant performed a total of six 10-second lower-body cycling Wingate tests with a 7.5% body mass loading, which was interspersed with 60-second active recovery periods.[10] Besides the standardized warmup described previously, the participants also completed 2–3 short sprints on the ergometer (894E, Monark Exercise AB, Vansbro, Sweden) at the same resistance to be used during the test. Following the warmup and prior to each successive sprint, the participants commenced with maximal pedaling at the end of a standardized 10-second countdown. Each sprint started automatically when the cadence reached 120 RPM and continued for 10 seconds thereafter. Verbal encouragement was provided throughout the sprints. At the end of the test, the load was removed and the participant continued to exercise at 60 RPM on the unloaded ergometer for at least 5 minutes. Peak and mean power for each sprint were recorded. Fatigue index was calculated as the percent decline for mean power across all sprints. Heart rate recovery (HRR), defined as the rate at which heart rate declines 60 seconds after the last sprint, was calculated.[24]

3-Minute all-out testing

Each participant performed a 3-minute maximal effort cycling test (3MT) using a calibrated electronically braked cycle ergometer (Excalibur, Lode, Groningen, The Netherlands). Following the aforementioned standardized warmup, the participant completed 60 seconds of unloaded cycling at 90 RPM, followed by an all-out 3-minute effort with resistance being set as a function of pedaling rate. Participants were asked to accelerate to approximately 110 RPM over the last 5 seconds of the baseline period. The resistance was adjusted during the all-out effort using the pedaling rate-dependent linear mode on the cycle ergometer that used a linear factor (power/cadence^2) based on the power output at a given pedaling rate (70 RPM) being equal to 50% of the difference between the power output at GET and VO_2peak assessed during the graded exercise test described previously.[23] To prevent pacing and ensure an all-out effort, the participant was not aware of the elapsed time and strong verbal encouragement was provided. Critical power was calculated as the average power output during the final 30 seconds of the test, and anaerobic working capacity was calculated as the work–time integral above critical power.[23] HRR was also calculated after the 3MT.

Repeated-sprint training intervention

A repeated-sprint training program consisting of 8 training sessions (2 sessions per week for 4 weeks) was employed and each session was separated by at least 48 hours. The NB and NP groups trained under normoxia, while the HB and HP groups trained under normobaric hypoxia. A hypoxic generator (Everest Summit II, Hypoxico, Inc., New York, NY) was used to provide hypoxic or normoxic air to the participants for blinding purpose. The oxygen content of the air inhaled by the participants was monitored with an oxygen analyzer (Handi+, Maxtec, Salt Lake City, UT) throughout each training session. Following a standardized warmup (without the mask) and several short warmup sprints (with the mask), the participants completed three sets of 5×10 seconds all-out repeated-sprints with a 7.5% body mass loading, which was interspersed with 20-second active recovery periods. A 5-minute recovery period was given between sets, and each training protocol ended with a 10-minute recovery period. Subjects were instructed to perform all-out sprints attempting to reach and maintain the highest RPM for every sprint, and strong verbal encouragement was given during each sprint. The participants immediately began the between-sets recovery period if they were unable to complete all 5 sprints for a given set. Heart rate from a wireless device (BioHarness 3, Zephyr Technology Corporation, Annapolis, MD) and arterial oxygen saturation (SpO_2) via pulse oximeter (GO_2, Nonin Medical, Inc., Plymouth, MN) were monitored throughout each training session. SpO_2 decline was calculated as the average of the delta changes between the SpO_2 value before the

Table 2. Anthropometric and hematological variables before (pre-) and after (post-) intervention.

	NB ($n = 11$)		NP ($n = 8$)		HB ($n = 10$)		HP ($n = 9$)	
	Pre-	Post-	Pre-	Post-	Pre-	Post-	Pre-	Post-
BM (kg)	78.2 ± 11.6	77.8 ± 10.2	81.4 ± 7.9	81.7 ± 7.8	72.4 ± 4.3	73.3 ± 4.8	72.3 ± 8.4	72.5 ± 7.5
%BF	20.1 ± 8.1	19.2 ± 8.4	18.8 ± 8.4	18.7 ± 9.3	14.5 ± 4.5	14.8 ± 4.3	15.6 ± 4.8	15.3 ± 5.1
Hb (g dl^{-1})	15.1 ± 0.8	14.9 ± 0.8	14.2 ± 0.9	14.1 ± 1.0	14.5 ± 0.8	14.5 ± 0.9	14.7 ± 1.1	14.5 ± 1.1
Hct (%)	42.8 ± 3.0	44.0 ± 2.5	41.2 ± 2.7	42.2 ± 2.5	41.5 ± 2.2	42.5 ± 2.3	42.2 ± 2.7	42.7 ± 2.6

Note. Data are mean ± standard deviation (SD) and represent raw data measured before and following intervention for the participants training in normoxia while receiving beta-alanine (NB) or placebo (NP) supplementation and participants training in hypoxia while receiving beta-alanine (HB) or placebo (HP) supplementation. *n*: Sample size; BM: body mass; %BF: percent body fat; Hb: hemoglobin; Hct: hematocrit.

first sprint and the value after the last sprint in each training session.

Supplementation intervention

The NB and HB groups received 6.4 g of sustained-release BA (Natural Alternative, Inc., Carlsbad, CA) per day during the 4-week period, while the HP and NP groups received the same amount of placebo (rice powder) throughout the study. The dosing regimen was similar to that reported by Saunders et al.,[22] consisting of two 800-mg BA or placebo tablets (with identical appearance) ingested 4 times per day at 3- to 4-hour intervals for 28 days. Compliance was monitored using supplementation logs. Additionally, participants completed a 3-day dietary recall before and after the intervention.

Blood samples

Blood samples were collected during the testing sessions before and after the 4-week intervention. During day 1, a resting blood sample was obtained by venipuncture of the forearm vein following a 15-minute equilibration period. All blood samples were collected into Vacutainer tubes containing K_3EDTA (4 ml) for determination of hematocrit and hemoglobin concentrations. In addition, blood samples were also obtained by finger-prick before and after the repeated-sprint test and the critical power test to determine blood lactate concentration.

Biochemical analysis

The hemoglobin and hematocrit were measured immediately after the blood draw via a hematology analyzer (Ac T diff2^{TM}, Beckman Coulter, Brea, CA), which was calibrated every day using control reagents. Coefficients of variation for each assay were 6.3% for hemoglobin and 6.1% for hematocrit. Blood lactate concentrations were analyzed using a portable device (Lactate Plus, Nova Biomedical, Waltham, MA) from 20-µl fingertip capillary blood.

Statistical analysis

One-way analysis of variance (ANOVA) was performed to compare training volume, supplementation compliance, and SpO_2 during training between groups. Since there were no baseline differences, one-way ANOVA with repeated measures (pretest vs. posttest) was performed to examine pre–post changes for anthropometric and hematological measures between groups. To account for significant ($p < 0.05$) baseline differences between groups, two-way (training condition × supplement) analysis of covariance (ANCOVA) was performed on posttest values for all performance measures between groups with pretest values serving as the covariate. The assumptions of normality, linearity, homogeneity of variances, homogeneity of regression slopes, and reliable measurement of the covariate were verified. For effect size, the partial eta squared statistic was calculated, and 0.01, 0.06, and 0.14 were interpreted as small, medium, and large effect sizes, respectively. An alpha of $p < 0.05$ was established a priori. All data were reported as mean ± SD. In addition, posttest performance measures were reported as mean ±95% confidence intervals to indicate meaningful changes as compared with covariate adjusted pretest values. Statistical software (IBM SPSS Statistics for Windows, Version 22.0; Armonk, NY: IBM Corp.) was used for all analyses.

Results

Training volume and supplementation compliance

No significant difference was observed between groups for training volume ($F_{3,\ 33} = 1.268$, $p = 0.301$) or supplementation compliance ($F_{3,\ 33} = 1.541$, $p = 0.222$). NB, NP, HB, and HP consumed 179.2 ± 0.0 g, 175.7 ± 4.3 g, 178.6 ± 1.1 g, and 177.2 ± 4.2 g out of 180 g of the provided supplement and completed 120.0 ± 0.0, 115.9 ± 10.5, 119.1 ± 1.7, and 119.8 ± 0.7 of the 120 required sprints, respectively.

Arterial oxygen saturation

Significant differences were noted in SpO_2 measures at rest ($F_{3,\ 33} = 185.299$, $p = 0.01$); during training ($F_{3,\ 33} = 64.695$, $p = 0.01$) and the SpO_2 decline from rest to training ($F_{3,\ 33} = 19.763$, $p = 0.01$) with distinctions between the hypoxic and normoxic training conditions. Resting SpO_2 values for NB (96.4 ± 0.9%) and NP (97.2 ± 0.7%) were significantly higher ($p = 0.01$) than that observed for HB (88.8 ± 1.1%) and HP (89.6 ± 1.1%). Training SpO_2 values for NB (94.1 ± 3.5%) and NP (95.7 ± 0.8%) were significantly greater ($p = 0.01$) than that for HB (78.6 ± 2.7%) and HP (81.5 ± 4.6%).

Anthropometric and hematological measures

No significant main effects or time × group interactions were observed for body mass, percent body fat, hemoglobin concentration, or hematocrit. Results indicated that anthropometric

and hematological measures were unchanged before and following the intervention for all groups (see Table 2 and Table 4).

Graded exercise testing

Unadjusted raw data for graded exercise testing variables are shown in Table 3. ANCOVA results with covariate values are shown in Figure 1 and Table 4. Individual changes before and after the intervention are shown in Figure 2. No significant main effects, or training condition × supplement interaction were noted for maximal oxygen consumption (VO_2max) or peak power output (PPO) during the graded exercise testing (GXT). Greater postintervention values for VO_2max and PPO were noted in all groups, without any between-group differences. Furthermore, no main effects for time or significant training condition × supplement interactions were noted for oxygen consumption (VO_2RCP) and power output at RCP (PRCP). However, main effects for training condition for both VO_2RCP ($F_{1,\ 32} = 5.029$, $p = 0.032$, $\eta^2 = 0.136$) and PRCP ($F_{1,\ 32} = 5.091$, $p = 0.031$, $\eta^2 = 0.137$) were observed. VO_2RCP values pooled for both HB and HP (38.44 ± 3.33 ml-min kg^{-1}) were greater than that of NB and NP (35.96 ± 3.36 ml-min kg^{-1}). For PRCP, pooled values for HB and HP (2.91 ± 0.18 W kg^{-1}) were also greater than that of NB and NP (2.77 ± 0.19 W kg^{-1}).

Repeated-sprint testing

Unadjusted raw data for repeated-sprint testing variables are shown in Table 3. ANCOVA results with covariate values are shown in Figure 3 and Table 4. Individual changes before and after the intervention are shown in Figure 4. No significant main effects or training condition × supplement interactions were noted for average power output of all sprints (RST_AP), best peak power (RST_BPP), and fatigue index (RST_FI). No significant main effect for supplement or training condition × supplement interaction was noted for average power output of the last sprint (RST_AP5). However, a main effect for training condition ($F_{1,32} = 4.107$, $p = 0.050$, $\eta^2 = 0.114$) was noted, with values pooled for HB and HP (8.66 ± 0.51 W kg^{-1}) being greater than that of NB and NP (8.32 ± 0.51 W kg^{-1}). No significant main effect, or training condition × supplement interaction was observed for lactate concentrations after RST (RST_La). No significant main effect for supplement or training condition × supplement interaction was noted for heart rate at 60 seconds after RST (RST_HR60). However, a main effect for training condition ($F_{1,\ 30} = 5.370$, $p = 0.027$, $\eta^2 = 0.152$) was observed, with values pooled for HB and HP (144.79 ± 7.52 bpm) being lower than that of NB and NP (150.29 ± 7.62 bpm).

3-Minute all-out testing

Unadjusted raw data for 3-minute all-out testing variables are shown in Table 3. ANCOVA results with covariate values are shown in Figure 5 and Table 4. Individual changes before and after the intervention are shown in Figure 6. No

Table 3. Exercise performance variables before (pre-) and after (post-) intervention.

	NB ($n = 11$)		NP ($n = 8$)		HB ($n = 10$)		HP ($n = 9$)	
	Pre-	Post-	Pre-	Post-	Pre-	Post-	Pre-	Post-
VO_2max (ml min^{-1} kg^{-1})	41.7 ± 4.8	42.8 ± 4.8	38.0 ± 7.3	40.4 ± 6.3	45.1 ± 6.0	47.8 ± 5.2	41.6 ± 3.1	44.1 ± 2.6
PPO (W)	257 ± 45	272 ± 39	247 ± 32	264 ± 28	262 ± 44	279 ± 43	244 ± 21	260 ± 21
VO_2RCP (ml min^{-1} kg^{-1})	37.0 ± 3.9	36.4 ± 5.3	33.6 ± 6.6	34.3 ± 4.7	38.3 ± 6.3	39.8 ± 4.4	35.8 ± 4.4	38.0 ± 4.0
PRCP (W)	211 ± 37	217 ± 35	205 ± 30	210 ± 21	213 ± 38	222 ± 34	195 ± 18	211 ± 21
RST_AP (W)	649 ± 115	728 ± 123	700 ± 105	780 ± 119	650 ± 94	726 ± 87	642 ± 114	733 ± 110
RST_AP5 (W)	523 ± 121	629 ± 125	559 ± 103	674 ± 99	538 ± 114	656 ± 87	517 ± 106	631 ± 91
RST_BPP (W)	1000 ± 129	1065 ± 151	1073 ± 198	1172 ± 228	1013 ± 160	1017 ± 113	1019 ± 329	1031 ± 163
RST_FI (%)	35.6 ± 10.0	27.3 ± 7.1	35.5 ± 9.9	27.5 ± 8.6	30.7 ± 14.6	19 ± 7.3	33.9 ± 6.3	25.9 ± 9.1
RST_La (mmol L^{-1})	13.2 ± 3.1	12.0 ± 3.3	12.2 ± 3.2	12.9 ± 2.6	13.0 ± 1.9	11.3 ± 1.8	12.0 ± 3.3	12.6 ± 2.6
RST_HR60 (bpm)	147 ± 20	150 ± 19	148 ± 5	150 ± 12	145 ± 18	139 ± 17	150 ± 14	151 ± 10
CP (W)	189 ± 51	203 ± 33	177 ± 46	210 ± 30	186 ± 38	212 ± 35	171 ± 22	202 ± 17
AWC (kJ)	16.8 ± 3.6	17.9 ± 4.4	19.2 ± 6.3	16.0 ± 4.1	18.0 ± 3.9	18.0 ± 3.1	18.3 ± 3.7	17.2 ± 3.7
TW (kJ)	50.8 ± 10.3	54.5 ± 9.5	51.1 ± 7.9	53.7 ± 7.5	51.4 ± 7.5	56.2 ± 8.0	49.0 ± 5.3	53.5 ± 4.7
3MT_La (mmol L^{-1})	15.6 ± 2.5	15.0 ± 3.2	12.6 ± 2.7	14.5 ± 2.2	15.5 ± 2.9	14.5 ± 3.3	13.1 ± 3.7	14.8 ± 2.7
3MT_HR60 (bpm)	164 ± 16	160 ± 18	156 ± 14	150 ± 15	150 ± 17	149 ± 15	155 ± 14	158 ± 9

Note. Data are mean ± standard deviation (SD) and represent raw data measured before and following intervention for the participants training in normoxia while receiving beta-alanine (NB) or placebo (NP) supplementation and participants training in hypoxia while receiving beta-alanine (HB) or placebo (HP) supplementation. *n*: Sample size. VO_2max: maximal oxygen consumption; PPO: peak power output; VO_2RCP: oxygen consumption at respiratory compensation point; PRCP: power output at respiratory compensation point. RST_AP: average power output of all sprints in repeated sprint testing; RST_AP5: average power output of the last sprint in repeated sprint testing; RST_BPP: best peak power output of all sprints in repeated sprint testing; RST_FI: fatigue index during repeated sprint testing; RST_La: lactate concentration after repeated sprint testing; RST_HR60: heart rate at 60 seconds after repeated sprint testing. CP: critical power; AWC: anaerobic working capacity; TW: total work; 3MT_La: lactate concentration after 3-minute all-out testing; 3MT_HR60: heart rate at 60 seconds after 3-minute all-out testing.

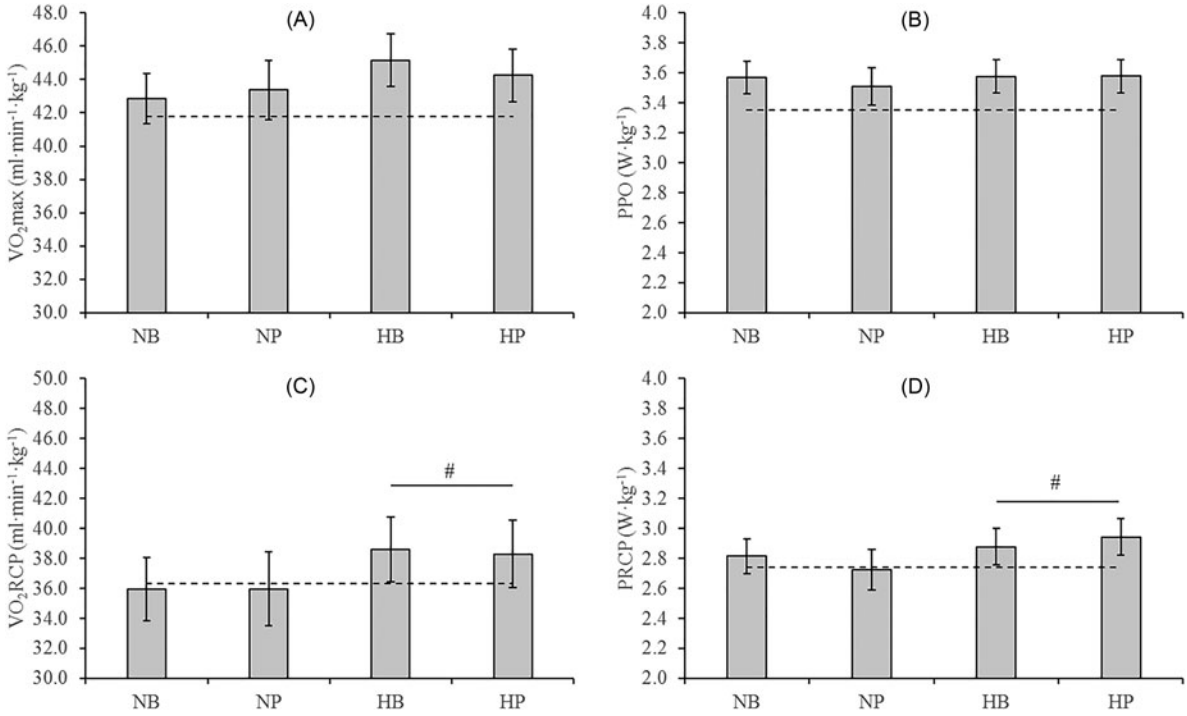

Figure 1. Graded exercise testing variables before (pre-) and after (post-) 4 weeks of training.
Note. Mean values (±95% confidence interval) for posttest adjusted for initial differences in pretest (dash line) for normoxia/beta-alanine group (NB), normoxia/placebo group (NP), normobaric hypoxia/beta-alanine group (HB), and normobaric hypoxia/placebo group (HP): A. Maximal oxygen consumption (VO_2max; covariate: adjusted pretest mean =41.79 ml min^{-1} kg^{-1}). B. Peak power output (PPO; covariate: adjusted pretest mean =3.35 W kg^{-1}). C. Oxygen consumption at respiratory compensation point (VO_2RCP; covariate: adjusted pretest mean =36.34 ml min^{-1} kg^{-1}). D. Power output at respiratory compensation point (PRCP; covariate: adjusted pretest mean =2.74 W kg^{-1}); # indicates main effect for altitude.

Table 4. Statistical results (*F* value, *p* value, partial eta squared) for anthropometric, hematological and exercise performance variables.

	Training condition × Supplement interaction	Main effects for training condition	Main effects for supplement
BM	1.040, 0.315, 0.031	0.697, 0.410, 0.021	0.003, 0.953, 0.001
%BF	2.282, 0.140, 0.065	0.925, 0.343, 0.027	0.002, 0.965, 0.001
Hb	0.646, 0.427, 0.019	0.027, 0.872, 0.001	0.158, 0.684, 0.005
Hct	0.098, 0.756, 0.003	0.152, 0.699, 0.005	0.173, 0.680, 0.005
VO_2max	0.864, 0.360, 0.026	3.842, 0.059, 0.107	0.050, 0.824, 0.002
PPO	0.305, 0.584, 0.009	0.417, 0.523, 0.013	0.275, 0.604, 0.009
VO_2RCP	0.020, 0.888, 0.001	5.029, 0.032, 0.136	0.014, 0.908, 0.001
PRCP	1.754, 0.195, 0.052	5.091, 0.031, 0.137	0.044, 0.834, 0.001
RST_AP	1.252, 0.272, 0.038	2.158, 0.152, 0.063	0.864, 0.360, 0.026
RST_AP5	0.091, 0.765, 0.003	4.107, 0.050, 0.114	0.008, 0.930, 0.001
RST_BPP	0.031, 0.861, 0.001	0.350, 0.558, 0.011	1.064, 0.310, 0.032
RST_FI	1.483, 0.232, 0.044	2.609, 0.116, 0.075	1.777, 0.192, 0.053
RST_La	0.053, 0.819, 0.002	0.284, 0.598, 0.009	2.664, 0.112, 0.077
RST_HR60	2.227, 0.146, 0.071	5.370, 0.027, 0.152	1.484, 0.233, 0.049
CP	0.124, 0.727, 0.004	4.103, 0.051, 0.114	0.691, 0.412, 0.021
AWC	1.561, 0.221, 0.047	2.627, 0.115, 0.076	5.570, 0.025, 0.148
TW	1.640, 0.209, 0.049	9.402, 0.004, 0.227	1.866, 0.182, 0.055
3MT_La	0.109, 0.744, 0.003	0.022, 0.883, 0.001	1.024, 0.319, 0.031
3MT_HR60	2.630, 0.115, 0.078	1.825, 0.187, 0.056	0.150, 0.701, 0.005

Note. Data are presented in the order of *F* value, *p* value, and partial eta squared. BM: body mass; %BF: percent body fat; Hb: hemoglobin; Hct: hematocrit; VO_2max: maximal oxygen consumption; PPO: peak power output; VO_2RCP: oxygen consumption at respiratory compensation point; PRCP: power output at respiratory compensation point. RST_AP: average power output of all sprints in repeated sprint testing; RST_AP5: average power output of the last sprint in repeated sprint testing; RST_BPP: best peak power output of all sprints in repeated sprint testing; RST_FI: fatigue index during repeated sprint testing; RST_La: lactate concentration after repeated sprint testing; RST_HR60: heart rate at 60 seconds after repeated sprint testing. CP: critical power; AWC: anaerobic working capacity; TW: total work; 3MT_La: lactate concentration after 3-minute all-out testing; 3MT_HR60: heart rate at 60 seconds after 3-minute all-out testing.

significant main effects or training condition × supplement interactions were noted for either critical power (CP) or anaerobic working capacity (AWC). However, a main effect for supplement ($F_{1,\ 32} = 5.570$, $p = 0.025$, $\eta^2 = 0.148$) was noted for AWC, with values pooled for HB and NB (0.24 ± 0.04 kJ kg^{-1}) being greater than that of HP and NP (0.21 ± 0.03 kJ kg^{-1}). No significant main effect for supplement, or training condition × supplement interaction was noted for total work (TW). However, a main effect for training condition ($F_{1,\ 32} = 9.402$, $p = 0.004$, $\eta^2 = 0.227$) was noted for TW, with values pooled for HB and HP (0.73 ± 0.03 kJ kg^{-1}) being greater than that of NB and NP (0.70 ± 0.03 kJ kg^{-1}). No significant main effect or training condition × supplement interaction was observed for lactate

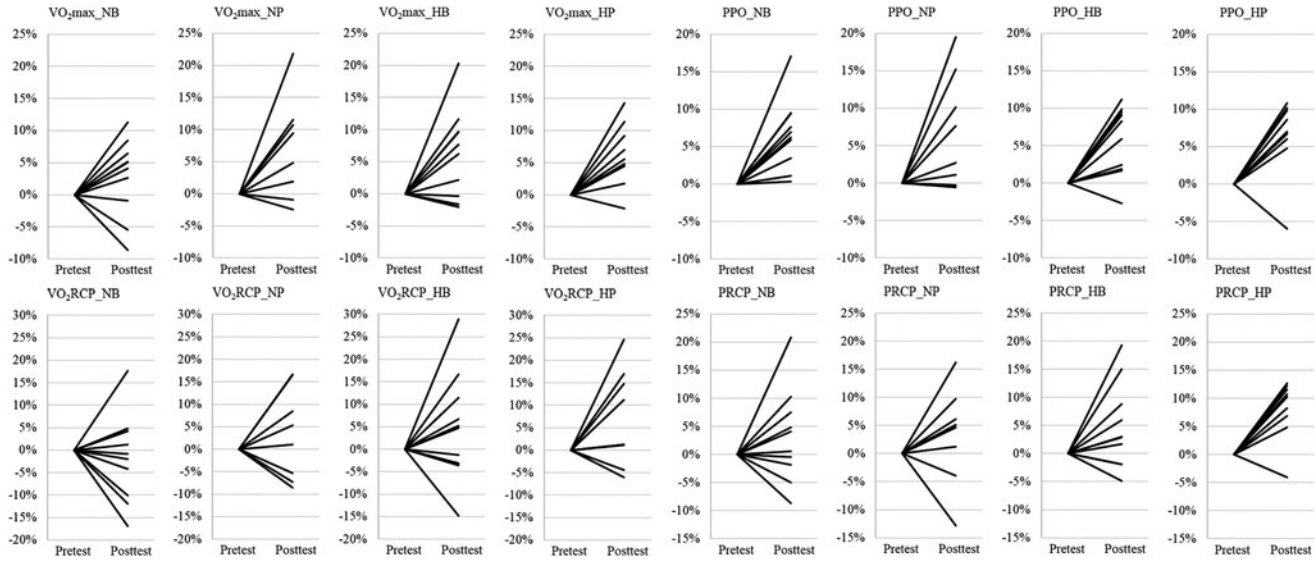

Figure 2. Spaghetti plots for graded exercise testing variables.
Note. VO_2max = maximal oxygen consumption; PPO = peak power output; VO_2RCP = oxygen consumption at respiratory compensation point; PRCP = power output at respiratory compensation point.

concentration after 3MT (3MT_La) and heart rate at 60 seconds following 3MT (3MT_HR60).

Discussion

To the best of our knowledge, the present study is the first randomized, placebo-controlled investigation, conducted in a double-blind manner for supplement and a single-blind manner for training condition, examining the potential additive effects of concurrent repeated-sprint training in hypoxia and BA supplementation on sea-level performance in recreationally trained men. The present study demonstrated that repeated-sprint training in hypoxia and BA benefit performance from different perspectives. Repeated-sprint training in hypoxia resulted in greater postintervention values for fatigue threshold, exercise tolerance, cardiovascular recovery, and overall working capacity than repeated-sprint training in normoxia, while BA resulted in greater anaerobic working capacity compared to placebo following the repeated-sprint training intervention.

Graded exercise testing performance

Greater postintervention values for VO_2max and PPO were noted in all groups, without any between-group differences. However, a trend ($p = 0.059$) for a main effect for training condition was observed for VO_2max. Results from previous studies have reported contradictory findings. Kasai et al.[30] reported that VO_2max did not improve significantly in either repeated-sprint training in hypoxia or normoxia. These conflicting results could potentially result from differences in study design parameters such as duration, intensity and volume, and so on. Contradictory results have also been shown for field-based tests. No significant improvements were noted in an incremental field test for repeated-sprint training in either hypoxia or normoxia.[25] These investigators suggested that the total duration of hypoxic exposure was too short to induce any positive adaptations in hemoglobin concentration and hematocrit. Similarly, the present study demonstrated no changes in hemoglobin and hematocrit values in any group regardless of intervention. Hamlin and colleagues reported no substantial between-group changes in yo-yo intermittent recovery test.[26] Some studies employing other field tests have also reported no advantage of repeated-sprint training in hypoxia over repeated-sprint training in normoxia,[27–29] with one exception.[9] The variation in aerobic adaptation between studies is likely due to the training status of the participants. Untrained individuals are more likely to benefit from repeated-sprint training in hypoxia than well-trained individuals.[28,30] The participants in the current study were recreationally trained and showed greater postintervention values for VO_2RCP and PRCP following training at altitude than the groups training in normoxia, which indicated that participants were able to better maintain steady-state VO_2 and lactate at high-intensity exercise following 4 weeks of repeated-sprint training in hypoxia compared to repeated-sprint training in normoxia.

Repeated-sprint testing performance

Results of this study indicated significant improvements in RST_AP5, but not RST_AP when exercising at altitude compared to the groups training in normoxia. Previously reported changes in repeated-sprint performance after repeated-sprint training in hypoxia and normoxia are inconsistent. Our results are supported by several previously published investigations that showed beneficial changes in repeated-sprint performance after repeated-sprint training in hypoxia compared to repeated-sprint training in normoxia.[8,9,28–30] However, both Goods et al.[27] and Montero et al.[31] reported no advantage of repeated-sprint training in hypoxia over repeated-sprint training in normoxia. It should be noted that the study by Montero et al.[31] employed many tests in a relatively short testing period, which may have

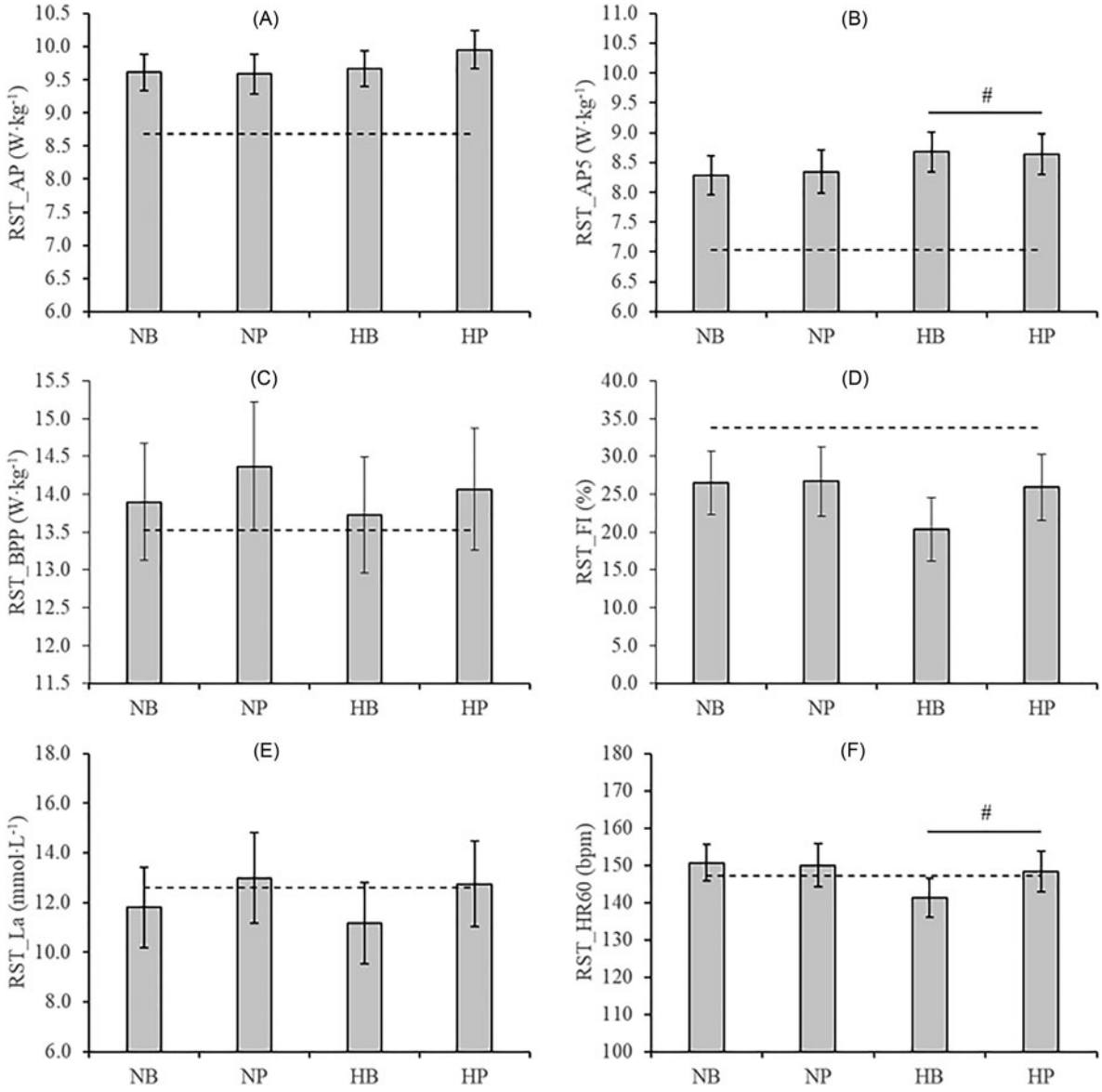

Figure 3. Repeated-sprint testing variables after 4 weeks of training.
Note. Mean values (±95% confidence interval) for posttest adjusted for initial differences in pretest (dash line) for normoxia/beta-alanine group (NB), normoxia/placebo group (NP), normobaric hypoxia/beta-alanine group (HB), and normobaric hypoxia/placebo group (HP): A. Average power output of all sprints (RST_AP; covariate: adjusted pretest mean =8.68 W kg^{-1}). B. Average power output of the last sprint (RST_AP5; covariate: adjusted pretest mean =7.03 W kg^{-1}). C. Lactate concentration after repeated-sprint testing (RST_La; covariate: adjusted pretest mean =12.61 mmol L-1). D. Heart rate at 60 seconds after repeated-sprint testing (RST_HR60; covariate: adjusted pretest mean =147.94 bpm); #indicates main effect for altitude.

induced additional fatigue and affected the posttest. Although the investigation by Hamlin et al.[26] showed similar improvement at the posttesting between repeated-sprint training in hypoxia and normoxia, the follow-up testing conducted 2 weeks after the posttesting indicated a residual effect for repeated-sprint performance in repeated-sprint training in hypoxia, but not in normoxia.

Recently, there has been considerable debate over performance improvement associated with repeated-sprint training in hypoxia.[31–33] Methodological differences, including but not limited to the training status of the participants, the selection and sequence of performance testing, and the calculation of fatigue scores, may contribute to the variation in performance changes. We did not observe any ergogenic effects regarding repeated-sprint performance for BA, which appears to confirm previous findings.[22] It is possible that training-based performance enhancement may have masked any potential ergogenic effects from BA supplementation. The lower limit of 95% confidence intervals far surpassed the adjusted pretest values for RST_AP and RST_AP5, indicating the efficacy of the repeated-sprint training in itself. In support of this notion, it has been previously reported that repeated-sprint ability was significantly correlated with muscle buffering capacity measured from $\Delta[La^-]/\Delta pH$, but not from the titration method.[34] It is possible that non-physiochemical buffering such as metabolic reactions that consume H^+ may have a greater influence on muscle buffering capacity than physiochemical buffering, which would be provided by augmented carnosine concentrations. Additionally, the recovery time (60 seconds) utilized during our repeated-sprint protocol may not have provided a sufficient stimulus to effectively challenge muscle buffering capacity.

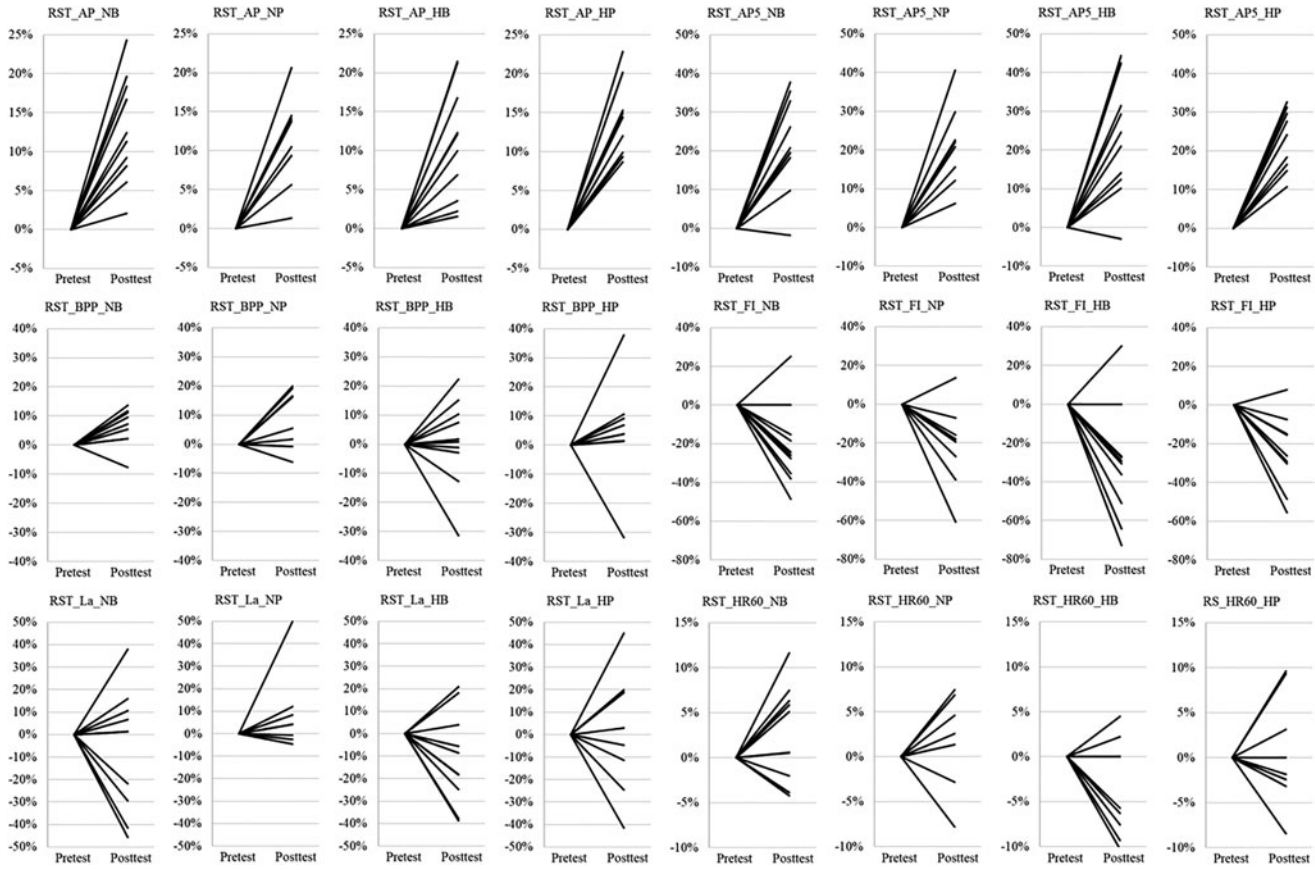

Figure 4. Spaghetti plots for repeated-sprint testing variables.
Note. RST_AP = average power output of all sprints in repeated sprint testing; RST_AP5 = average power output of the last sprint in repeated sprint testing; RST_BPP = best peak power output of all sprints in repeated sprint testing; RST_FI = fatigue index during repeated sprint testing; RST_La = lactate concentration after repeated sprint testing; RST_HR60 = heart rate at 60 seconds after repeated sprint testing.

Reduced HRR was previously reported after maximal exercise, primarily due to the continued sympathetic activation during the early stages of recovery.[35] Research also showed that athletes competing in intermittent sports had faster HRR than endurance athletes.[36] A main effect for training condition was demonstrated for RST_HR60 in the present study, with the 2 groups training in normobaric hypoxia showing significantly lower postintervention values for HRR than those training in normoxia. It has been previously suggested that HRR can be used to predict changes in training status, as well as to monitor the accumulation of fatigue.[24] Results of the current investigation indicated a beneficial effect of repeated-sprint training in hypoxia that may have facilitated physiological adaptations from repeated-sprint training and reduced the accumulation of fatigue during repeated-sprint testing.

3-Minute all-out testing performance

Critical power is considered to represent the highest sustainable rate of oxidative metabolism.[37] Commonly used to demarcate different exercise intensity domains, this threshold has been shown to effectively track changes in aerobic capacity before and after high-intensity intermittent training.[23] The lower limit of 95% confidence intervals exceeded the adjusted pretest value for CP for all groups, suggesting that the training protocol improved CP effectively. Additionally, our results showed a trend ($p = 0.051$) toward a main effect of training condition. It was hypothesized that critical power should benefit from BA. However, our results indicated no effect of BA on critical power. While the underlying mechanism is still unknown and needs to be addressed, performance improvements resulting from BA may have been blunted by repeated-sprint training. It has been suggested that open-endpoint exercise tasks, such as time to exhaustion trials, are more sensitive to BA supplementation as compared to fixed-endpoint tests, such as the 3MT, which may be subject to the influence of intrinsic pacing.[38] In fact, a recent study suggested that participants showed a more conservative pacing strategy during duration-based cycling trials than during distance-based cycling trials, potentially masking any ergogenic potential derived from BA.[39] Saunders et al.[40] suggested that exercise capacity measures, such as open-endpoint exercise tasks, demonstrate a greater effect size than exercise performance measures, such as fixed-endpoint exercise tasks when examining the efficacy of BA.

The work-time integral above critical power, termed AWC (or W'), theoretically represents the maximum amount of work that can be performed above critical power.[37] A closer examination of our results showed that the postintervention values for AWC in the BA groups were significantly higher than in the placebo groups. Due to the two-component model approach utilized during the 3MT and discussed in the next paragraph, the differential responses in AWC may also reflect improved CP in the

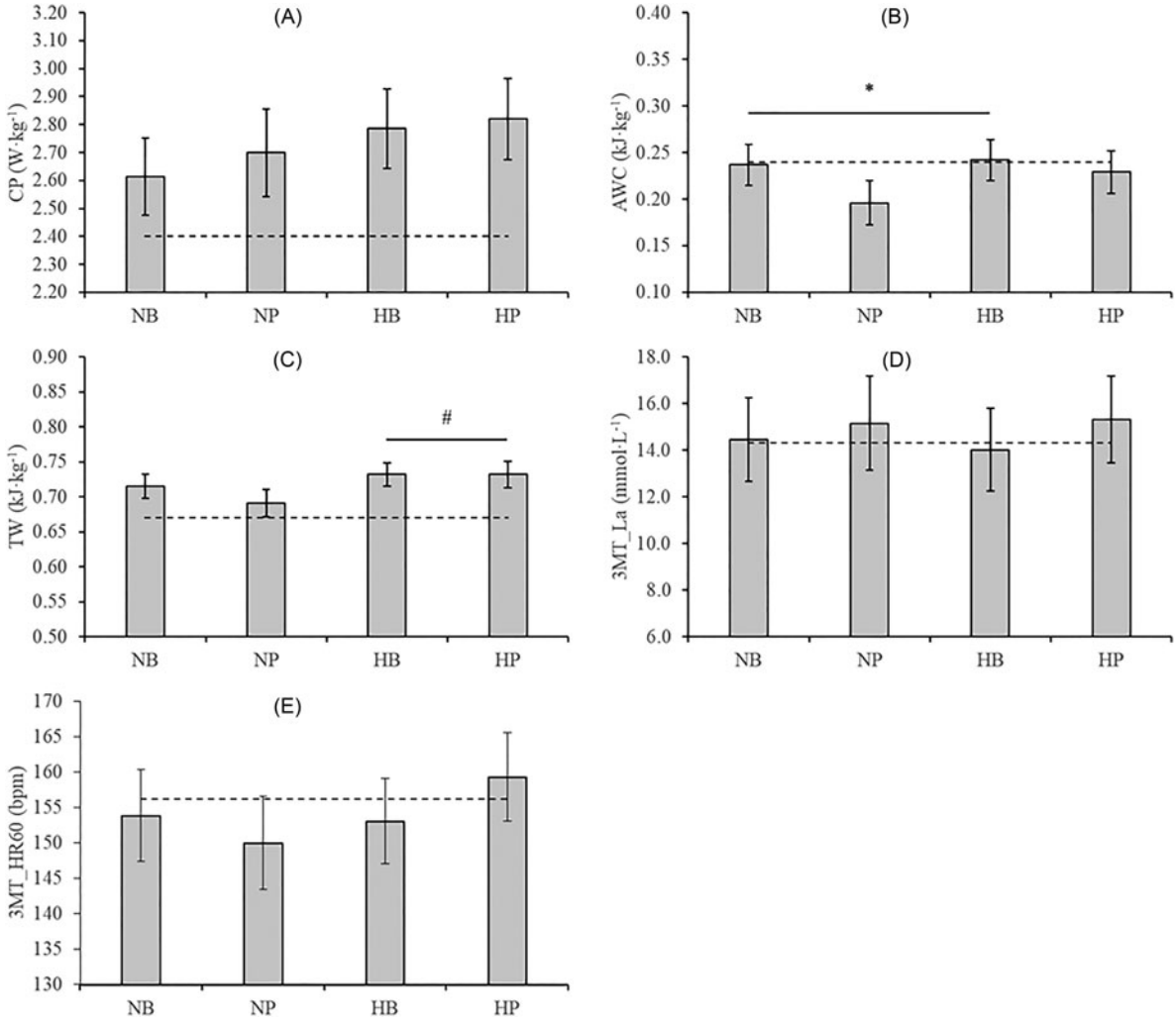

Figure 5. 3-Minute all-out testing variables after 4 weeks of training.
Note. Mean values (±95% confidence interval) for posttest adjusted for initial differences in pretest (dash line) for normoxia/beta-alanine group (NB), normoxia/placebo group (NP), normobaric hypoxia/beta-alanine group (HB), and normobaric hypoxia/placebo group (HP): A. Critical power (CP; covariate: adjusted pretest mean =2.40 W kg^{-1}). B. Anaerobic working capacity (AWC; covariate: adjusted pretest mean =0.24 kJ kg^{-1}). C. Total work (TW; covariate: adjusted pretest mean =0.67 kJ kg^{-1}). D. Lactate concentration after 3-minute all-out testing (3MT_La; covariate: adjusted pretest mean =14.33 mmol L^{-1}). E. Heart rate at 60 seconds after 3-minute all-out testing (3MT_HR60; covariate: adjusted pretest mean =152.22 bpm); # indicates main effect for altitude; * indicates main effect for supplement.

placebo groups. While anaerobic glycolysis is the major contributor to anaerobic capacity during high-intensity exercise, the accumulation of H^+ ions has been shown to inhibit glycolytic enzyme activity, including phosphofructokinase.[41] It is likely that elevated muscle carnosine content from BA contributes to improved glycolytic energy production by buffering H^+ ions and fostering phosphofructokinase activity.[42] When comparing 95% confidence interval of posttest values with the adjusted pretest value, AWC appeared to be maintained in HB and NB, and potentially decreased in NP. However, this finding is not consistent with a previous study, which reported an increased anaerobic capacity from an open-endpoint task following BA when compared with placebo.[43] The underlying mechanism for this inconsistency is unknown and should be addressed in future studies.

The utility of the ratio between AWC and CP has been previously discussed.[37] This ratio indicates the proportion of anaerobic and aerobic contribution to total work, and originated from a two-component mathematical model examining bioenergetics.[37] Calculating this ratio from the mean raw data values provided in Table 3 revealed that it remained unchanged in the normoxic BA group, but decreased in the placebo groups. These results indicated that the normoxic repeated-sprint training protocol utilized may have caused a disproportionate reliance on the aerobic energy supply, yielding a potential deficit in the anaerobic energy supply; however, BA may have alleviated or offset this effect. This finding may have important implications for team sports like rugby, which tend to prioritize anaerobic capacity.

A main effect for training condition was demonstrated when examining the total work completed during the 3MT. The hypoxic groups had greater postintervention values in total work than the normoxic groups. Interestingly, Faiss et al.[8] reported no differences in average power from 3MT following repeated-sprint training in hypoxia and normoxia. Since the time duration is fixed for 3MT, the lack of differences in average power reported would be synonymous with total work as reported in the current investigation. The discrepancy is likely due to variations in the 3MT protocol, which was not reported in detail in their study.[8]

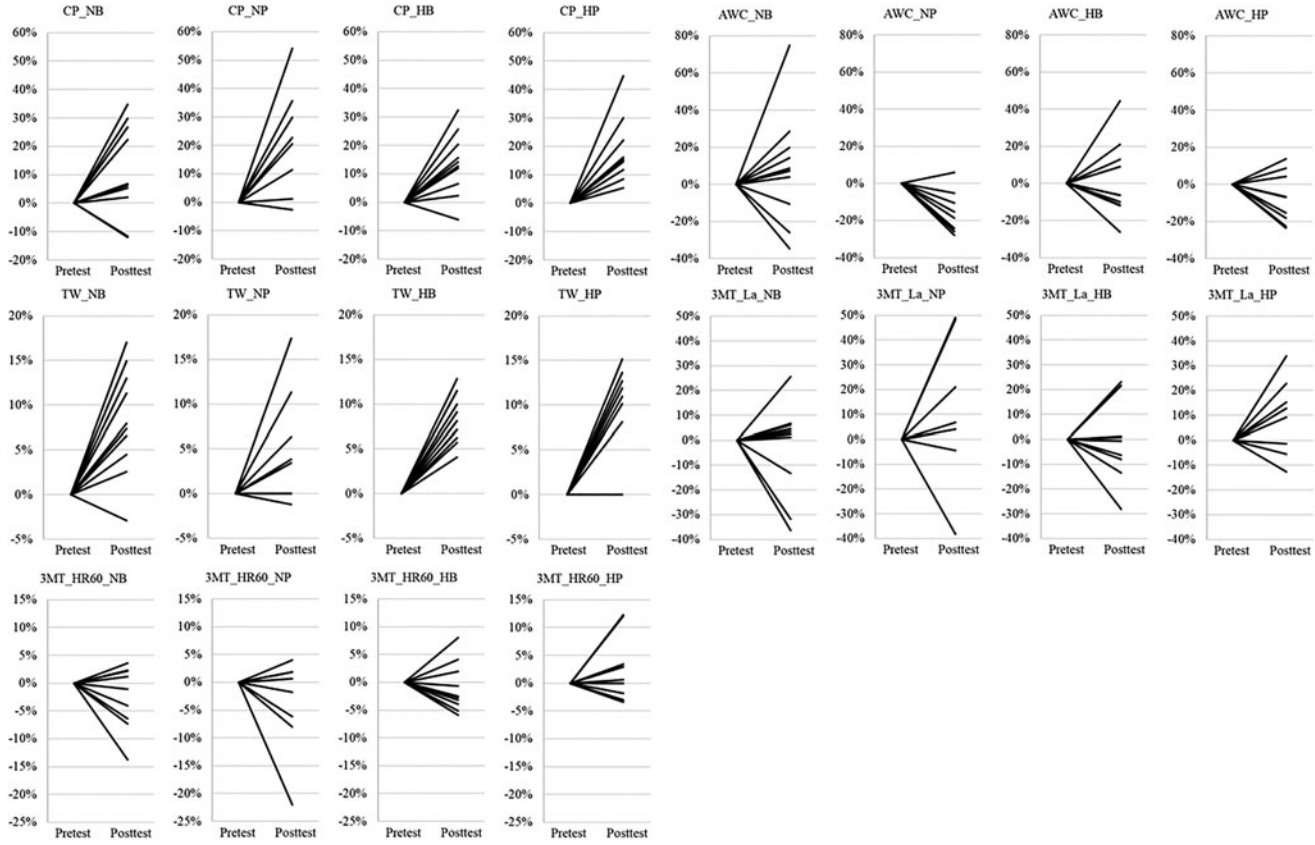

Figure 6. Spaghetti plots for 3-minute all-out testing variables.
Note. CP = critical power; AWC = anaerobic working capacity; TW = total work; 3MT_La = lactate concentration after 3-minute all-out testing; 3MT_HR60 = heart rate at 60 seconds after 3-minute all-out testing.

No difference was noted in the lactate response between groups. This result is consistent with the study by Saunders et al.,[44] who reported no effect of BA on postexercise lactate concentration. Although different from repeated-sprint training, Bellinger et al.[43] reported that BA increased lactate level after sprint-interval training. Blood lactate concentration is the result of lactate production and removal; therefore, it does not necessarily reflect muscle acidosis. Previous investigations have reported that BA can significantly reduce exercise-induced acidosis without affecting blood lactate concentrations.[42] The increased lactate production following BA might be attributable to a lower intramuscular H^+ concentration, allowing for a less inhibited glycolytic metabolism and higher rate of glycogen usage.[45] It has been suggested that the monocarboxylate transporter (MCT) system is mainly responsible for lactate utilization from the circulation (MCT1) and lactate efflux from glycolytic-dependent tissues (MCT4), respectively.[46,47] Faiss et al.[8] demonstrated an upregulation of MCT4 mRNA and a downregulation of MCT1 mRNA in repeated-sprint training in hypoxia, but not in normoxia. In contrast, Brocherie et al.[48] recently reported an upregulation of MCT1 instead of MCT4 in repeated-sprint training in both hypoxia and normoxia when combined with chronic hypoxic exposure. Although speculative, the discrepancy between our study and previous investigations is likely related to the dosage of hypoxic exposure, which may lead to differences in the ratio between MCT1 and MCT4. The duration of performance testing may have also played a role here; however, more detailed mechanistic study is needed.

Different from RST_HR60, changes in 3MT_HR60 did not show any main effects or interaction. Each sprint in RST only lasted for 10 seconds, while the 3MT requires longer (180 seconds) continuous effort, which may partially explain the differences between tests. In addition, the sprint duration during training intervention was also 10 seconds and the participants likely were more familiar with this kind of exercise stimulus following 4 weeks of training.

Limitations

There were some limitations for the present investigation. First, muscle biopsies were not included in this study to provide direct measures for muscle carnosine changes. However, another study conducted in our laboratory with a similar BA protocol showed that skeletal muscle carnosine increased from 8.06 ± 3.60 to 12.22 ± 6.19 mmol kg_{ww}^{-1} following 4 weeks of supplementation.[49] Second, the dropout rate for the current study was relatively high (12 out of 52). Due to the purpose of the study, the participants needed to adhere to both training and supplementation protocols. Last, the participants recruited were recreationally trained men. Therefore, the findings of this study may not be generalized to elite athletes, who may have already achieved large physiological adaptations from years of training. Future studies should examine whether there is an additive effect

for repeated-sprint training in hypoxia and BA in elite athletes.

Conclusion

In summary, the results of the current investigation indicate that normobaric hypoxia improved fatigue threshold, exercise tolerance, cardiovascular recovery, and overall working capacity in recreationally trained men following the repeated-sprint training intervention. Furthermore, it appears that BA maintained the anaerobic working capacity following the repeated-sprint training intervention, which tended to decrease as a result of repeated-sprint training, especially in normoxia. However, BA did not provide additional benefits with respect to attenuating fatigue or enhancing repeated-sprint performance.

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References

1. Harris RC, Marlin DJ, Dunnett M, Snow DH, Hultman E. Muscle buffering capacity and dipeptide content in the thoroughbred horse, greyhound dog and man. Comp Biochem Physiol. 1990;97(2):249–251.
2. Trivedi B, Danforth WH. Effect of pH on the kinetics of frog muscle phosphofructokinase. J Biol Chem. 1966;241(17):4110
3. Fabiato A, Fabiato F. Effects of pH on the myofilaments and the sarcoplasmic reticulum of skinned cells from cardiace and skeletal muscles. J Physiol (Lond). 1978;276(1):233
4. Parkhouse WS, McKenzie DC. Possible contribution of skeletal muscle buffers to enhanced anaerobic performance: a brief review. Med Sci Sports Exerc. 1984;16(4):328–338.
5. Girard O, Brocherie F, Millet GP. Effects of altitude/hypoxia on single- and multiple-sprint performance: a comprehensive review. Sports Med. 2017;47(10):1931–1949.
6. Millet GP, Faiss R, Brocherie F, Girard O. Hypoxic training and team sports: a challenge to traditional methods? Br J Sports Med. 2013;47(Suppl 1):i6.
7. Millet GP, Roels B, Schmitt L, Woorons X, Richalet JP. Combining hypoxic methods for peak performance. Sports Med. 2010;40(1):1–25.
8. Faiss R, Léger B, Vesin J-M, Fournier P-E, Eggel Y, Dériaz O, Millet GP. Significant molecular and systemic adaptations after repeated sprint training in hypoxia. PLoS One. 2013;8(2):e56522.
9. Galvin HM, Cooke K, Sumners DP, Mileva KN, Bowtell JL. Repeated sprint training in normobaric hypoxia. Br J Sports Med. 2013;47(Suppl 1):i74–i79.
10. Girard O, Mendez-Villanueva A, Bishop D. Repeated-sprint ability - Part I: factors contributing to fatigue. Sports Med. 2011;41(8):673–694.
11. Hautier CA, Linossier MT, Belli A, Lacour JR, Arsac LM. Optimal velocity for maximal power production in non-isokinetic cycling is related to muscle fibre type composition. Europ J Appl Physiol. 1996;74(1–2):114–118.
12. McDonough P, Behnke BJ, Padilla DJ, Musch TI, Poole DC. Control of microvascular oxygen pressures in rat muscles comprised of different fibre types. J Physiol (Lond). 2005;563(Pt 3):903–913.
13. Holliss BA, Fulford J, Vanhatalo A, Pedlar CR, Jones AM. Influence of intermittent hypoxic training on muscle energetics and exercise tolerance. J Appl Physiol. 2013;114(5):611–619.
14. Kasai N, Kojima C, Sumi D, Takahashi H, Goto K, Suzuki Y. Impact of 5 days of sprint training in hypoxia on performance and muscle energy substances. Int J Sports Med. 2017;38(13):983–991.
15. Calbet JA, Lundby C. Air to muscle O2 delivery during exercise at altitude. High Alt Med Biol. 2009;10(2):123–134.
16. Faiss R, Girard O, Millet GP. Advancing hypoxic training in team sports: from intermittent hypoxic training to repeated sprint training in hypoxia. Br J Sports Med. 2013;47(Suppl 1):i45–i50. Suppl 1(Suppl 1):
17. Hoppeler H, Vogt M. Muscle tissue adaptations to hypoxia. J Exp Biol. 2001;204(Pt 18):3133–3139.
18. Lundby C, Calbet JAL, Robach P. The response of human skeletal muscle tissue to hypoxia. Cell Mol Life Sci. 2009;66(22):3615–3623.
19. Brocherie F, Girard O, Faiss R, Millet GP. Effects of repeated-sprint training in hypoxia on sea-level performance: a meta-analysis. Sports Med. 2017;47(8):1651–1660.
20. Hoffman JR, Stout JR, Harris RC, Moran DS. β-Alanine supplementation and military performance. Amino Acids. 2015;47(12):2463–2474.
21. Hobson RM, Saunders B, Ball G, Harris RC, Sale C. Effects of beta-alanine supplementation on exercise performance: a meta-analysis. Amino Acids. 2012;43(1):25–37.
22. Saunders B, Sale C, Harris RC, Sunderland C. Effect of sodium bicarbonate and Beta-alanine on repeated sprints during intermittent exercise performed in hypoxia. Int J Sport Nutr Exerc Metab. 2014;24(2):196–205.
23. Wang R, Fukuda DH, Stout JR, et al. Tracking changes in the upper boundary of the heavy-intensity exercise domain: End-test power versus respiratory compensation point. Kinesiology. 2017;49(1):415.
24. Daanen HA, Lamberts RP, Kallen VL, Jin A, Van Meeteren NL. A systematic review on heart-rate recovery to monitor changes in training status in athletes. Int J Sports Physiol Perform. 2012;7(3):251–260.
25. Brocherie F, Girard O, Faiss R, Millet GP. High-intensity intermittent training in hypoxia: a double-blinded, placebo-controlled field study in youth football players. J Strength Cond Res. 2015;29(1):226–237.
26. Hamlin MJ, Olsen PD, Marshall HC, Lizamore CA, Elliot CA. Hypoxic repeat-sprint training improves rugby player's repeated sprint but not endurance performance. Front Physiol. 2017;8:24.
27. Goods PS, Dawson B, Landers GJ, Gore CJ, Peeling P. No additional benefit of repeat-sprint training in Hypoxia than in Normoxia on Sea-Level Repeat-Sprint Ability. J Sports Sci Med. 2015;14(3):681–688.
28. Faiss R, Willis S, Born DP, Sperlich B, Vesin JM, Holmberg HC, et al. Repeated double-poling sprint training in hypoxia by competitive cross-country skiers. Med Sci Sports Exerc. 2015;47(4):809–817.
29. Gatterer H, Philippe M, Menz V, Mosbach F, Faulhaber M, Burtscher M. Shuttle-run sprint training in hypoxia for youth elite soccer players: a pilot study. J Sports Sci Med. 2014;13(4):731–735.
30. Kasai N, Mizuno S, Ishimoto S, Sakamoto E, Maruta M, Goto K. Effect of training in hypoxia on repeated sprint performance in female athletes. SpringerPlus. 2015;4:310

31. Montero D, Lundby C. Repeated sprint training in hypoxia versus normoxia does not improve performance: A double-blind and cross-over study. Int J Sports Physiol Perform. 2017;12(2):161–167.
32. Lundby C, Robach P. Does 'altitude training' increase exercise performance in elite athletes? Exp Physiol. 2016;101(7):783–788.
33. Millet GP, Brocherie F, Faiss R, Girard O. Clarification on altitude training. Exp Physiol. 2017;102(1):130–131.
34. Bishop D, Edge J, Goodman C. Muscle buffer capacity and aerobic fitness are associated with repeated-sprint ability in women. Eur J Appl Physiol. 2004;92(4–5):540–547.
35. Kaikkonen P, Rusko H, Martinmaki K. Post-exercise heart rate variability of endurance athletes after different high-intensity exercise interventions. Scand J Med Sci Sports. 2007;18(4):511–519.
36. Ostojic SM, Markovic G, Calleja-Gonzalez J, Jakovljevic DG, Vucetic V, Stojanovic MD. Ultra short-term heart rate recovery after maximal exercise in continuous versus intermittent endurance athletes. Eur J Appl Physiol. 2010;108(5):1055–1059.
37. Jones AM, Vanhatalo A, Burnley M, Morton RH, Poole DC. Critical power: Implications for determination of VO2max and exercise tolerance. Med Sci Sports Exerc. 2010;42(10):1876–1890.
38. Trexler ET, Smith-Ryan AE, Stout JR, Hoffman JR, Wilborn CD, Sale C, et al. International society of sports nutrition position stand: Beta-Alanine. J Int Soc Sports Nutr. 2015;12:30
39. Abbiss CR, Thompson KG, Lipski M, Meyer T, Skorski S. Difference in pacing between time- and distance-based time trials in trained cyclists. Int J Sports Physiol Perform. 2016;11(8):1018–1023.
40. Saunders B, Elliott-Sale K, Artioli GG. et al. β-alanine supplementation to improve exercise capacity and performance: a systematic review and meta-analysis. Br J Sport Med. 2017;51(8):658–669.
41. Spriet LL, Soderlund K, Bergstrom M, Hultman E. Skeletal muscle glycogenolysis, glycolysis, and pH during electrical stimulation in men. J Appl Physiol. 1987;62(2):616–621.
42. Baguet A, Koppo K, Pottier A, Derave W. Beta-alanine supplementation reduces acidosis but not oxygen uptake response during high-intensity cycling exercise. Eur J Appl Physiol. 2010;108(3):495–503.
43. Bellinger PM, Minahan CL. Additive benefits of β-Alanine supplementation and sprint-interval training. Med Sci Sports Exer. 2016;48(12):2417–2425.
44. Saunders B, Sale C, Harris RC, Sunderland C. Effect of beta-alanine supplementation on repeated sprint performance during the Loughborough Intermittent Shuttle Test. Amino Acids. 2012;43(1):39–47.
45. Tobias G, Benatti FB, de Salles Painelli V, Roschel H, Gualano B, Sale C, et al. Additive effects of beta-alanine and sodium bicarbonate on upper-body intermittent performance. Amino Acids. 2013;45(2):309–317.
46. Dimmer KS, Friedrich B, Lang F, Deitmer JW, Broer S. The low-affinity monocarboxylate transporter MCT4 is adapted to the export of lactate in highly glycolytic cells. Biochem J. 2000;350(1):219–227.
47. Ullah MS, Davies AJ, Halestrap AP. The plasma membrane lactate transporter MCT4, but not MCT1, is up-regulated by hypoxia through a HIF-1alpha-dependent mechanism. J Biol Chem. 2006;281(14):9030–9037.
48. Brocherie F, Millet GP, D'Hulst G, Van Thienen R, Deldicque L, Girard O. Repeated maximal-intensity hypoxic exercise superimposed to hypoxic residence boosts skeletal muscle transcriptional responses in elite team-sport athletes. Acta Physiol. 2017;222(1):e12989. doi:10.1111/apha.12851.
49. Church DD, Hoffman JR, Varanoske AN, Wang R, Baker KM, La Monica MB, et al. Comparison of two β-alanine dosing protocols on muscle carnosine elevations. J Am Coll Nutr. 2017;36(8):608–616.