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PHYSIOLOGICAL AND FUNCTIONAL ADAPTATIONS OF HIGH-INTENSITY INTERVAL TRAINING AT TWO ALTITUDES IN MODERATE-ALTITUDE ENDURANCE RUNNERS: A RANDOMIZED CONTROLLED TRIAL

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Adaptacje fizjologiczne i funkcjonalne treningu interwałowego o wysokiej intensywności na dwóch wysokościach u biegaczy wytrzymałościowych uprawiających sporty wytrzymałościowe na średnich wysokościach: randomizowane badanie kontrolowane

Streszczenie

Wykazano, że trening interwałowy o wysokiej intensywności (HIIT) w warunkach hipoksji zwiększa wydolność sportowców na poziomie morza, ale istnieją ograniczone dowody dotyczące biegaczy na średnich wysokościach. Celem tego badania była analiza 8-tygodniowego treningu HIIT na niskich (~1220 m) i umiarkowanych (~2850 m) wysokościach pod kątem adaptacji fizjologicznych (maksymalna wydolność tlenowa (VO_2max) i prędkość związana z VO_2max (vVO_2max)) oraz funkcjonalnych (czas biegu na 5000 m (5kRT). Czterdziestu dwóch wytrenowanych biegaczy długodystansowych zostało losowo przydzielonych do jednej z trzech grup: HIIT na wysokości 1220 m (HIIT1220m, n=14), HIIT na wysokości 2850 m (HIIT2850 m, n=14) lub grupy kontrolnej na wysokości 2850 m (CG2850 m, n=14). Podczas gdy wszyscy uczestnicy utrzymywali regularny trening

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na wysokości 2850 m, grupy HIIT ukończyły dwie cotygodniowe sesje (4x4-minutowy interwał pracy przy 100% vVO_2max, 3-minutowy odpoczynek przy 70% vVO_2max). Obie interwencje pokazały istotną poprawę w czasie ($p < 0,05$) w vVO_2max, VO_2max i 5kRT, z większymi zyskami w HIIT1220m (+1,2%, +1%, –1,8%) niż w HIIT2850m (+0,6%, +0,8%, –1,4%). Ponadto zaobserwowano silną korelację w HIIT2850m między zmianami w 5kRT i vVO_2max ($r = -0,64$, $p = 0,013$) i VO_2max ($r = 0,74$, $p = 0,002$). Podsumowując, HIIT na małych wysokościach wywołał większą poprawę funkcjonalną niż na umiarkowanych wysokościach. Dlatego sportowcy i trenerzy uprawiający sporty długodystansowe na średnich wysokościach mogą odnieść większe korzyści ze strategicznego zarządzania treningiem HIIT na niższych wysokościach.

Słowa kluczowe: wydajność sportowa, wydolność treningowa wytrzymałościowa, jakość treningu, pobyt na dużych wysokościach, sukces w bieganiu, niedotlenienie.

Abstract

High-intensity interval training (HIIT) under hypoxia has been demonstrated to increase sea-level athletes' performance, but limited evidence exists regarding moderate-altitude runners. This study aimed to examine 8-week HIIT at low (~1,220 m) and moderate (~2,850 m) altitudes on physiological (maximal aerobic capacity (VO_2max) and velocity associated with VO_2max (vVO_2max)) and functional (5,000 m running time (5kRT)) adaptations. Forty-two trained long-distance runners were randomly assigned to one of three groups: HIIT at 1,220 m (HIIT1220m, n=14), HIIT at 2,850 m (HIIT2850m, n=14) or control group at 2,850 m (CG2850m, n=14). While all participants maintained regular training at ~2,850 m, the HIIT groups completed two weekly sessions (4x4-minute work interval at 100% vVO_2max, 3-minute recovery at 70% vVO_2max). Both interventions had significant improvements over time ($p < 0.05$) in vVO_2max, VO_2max, and 5kRT, with greater gains in the HIIT1220m (+1.2%, +1%, –1.8%) than HIIT2850m (+0.6%, +0.8%, –1.4%), respectively. In addition, a strong correlation was observed in the HIIT2850m between changes in 5kRT and vVO_2max ($r=-0.64$, $p=0.013$) and VO_2max ($r=0.74$, $p=0.002$). In conclusion, HIIT at low altitudes induced greater functional improvements than it did at moderate altitudes. Thus, moderate-altitude long-distance athletes and coaches may benefit more when HIIT is strategically managed at lower altitudes.

Key words: sport performance, endurance training capacity, quality training, altitude residence, running success, hypoxia.

Introduction

Training for long-distance running focuses primarily on enhancing endurance, speed, and strength to achieve the shortest possible completion time. While running performance is influenced by a variety of factors, physiological variables, particularly maximum aerobic capacity (VO_2 max) and VO_2 max associated speed (vVO_2 max), hold premium shares (Midgley et al., 2007). These factors play critical roles in sprinting ability and oxygen utilization (Enoksen et al., 2011). In trained athletes, high-altitude and high-intensity interval training (HIIT) is widely employed to optimize physiological and functional adaptations by stimulating neuromuscular and physiological functions (Enoksen et al., 2011).

High-altitude training and exposure results in too low barometric pressure and a reduced fraction of inspired oxygen, which results in a decreased partial pressure of arterial oxygen and leads to a state of hypoxia (Conkin & Wessel, 2008). While altitude is commonly classified as low (500-2000 m), moderate (2000-3000 m), and high (3000-5500 m), significant reductions in VO_2 max start to occur at 500 m in elevation (Bärtsch et al., 2008). As a consequence, training and competitive performance are impaired because of compromised training quality. For example, the lactate threshold and VO_2 max intensity are significantly influenced during training, as demonstrated by a 6–10% reduction in running speed in excellent runners trained at an altitude of 2,100 m (Sharma et al., 2017). In a wider context, running speed is reduced by ~5–15% at high altitudes compared with sea level (Peltonen et al., 2001).

Taking these into account, athletes and coaches, aiming to maximize physiological adaptations, have adopted various strategies to optimize training by combining living and training at different natural and simulated altitudes. The most commonly applied protocols include live high train high (LHTH), live high train low (LHTL), and live low train high (LLTH) methods. Over the past half-century, high-altitude training has played a significant role in competitive success, contributing to approximately 90% of the medals won in middle distance to marathon events (Wilber & Pitsiladis, 2012). However, the underlying rationale behind the protocol was adopted for sea-level athletes on the basis of the success of high-altitude athletes' experience as an alternative means to ascend during the preparation for a specified period to achieve altitude training (Haugen et al., 2022; Khodaee et al., 2016; Wilber, 2007).

These protocols are also used in combination with HIIT, which is a form of speed-endurance training that effectively enhances performance when appropriately incorporated into the already high training volumes of endurance athlete programs (Iaia & Bangsbo, 2010). It involves repeated intense activity performed at or beyond the race pace, interspersed with low-intensity recovery (Atakan et al., 2021; Gibala & Jones, 2013). Various HIIT modalities have been characterized, ranging along a continuum from supermaximal repeated sprint training (lasting <20 sec) and maximal all-out sprint interval training (>20–45 sec) to submaximal long interval HIIT (2–4 min) sessions with intervals of work interspersed with interval recovery (Buchheit & Laursen, 2013; Helgerud et al., 2023). Among these, long interval HIIT has been shown to be effective in improving VO_2 max and running performance (Helgerud et al., 2023). This is due to the training intensity being sustained for longer durations at or around the athletes' VO_2 max (Laursen and Jenkins 2002), which lasts between 20 and 40 minutes of training sessions (Hottenrott et al., 2012).

The efficacy of HIIT in improving performance across different altitude conditions has been well-documented (Camacho-Cardenosa et al., 2018; Stankovic et al., 2023). Several meta-analyses have consistently demonstrated that performing HIIT under hypoxic conditions leads to greater improvements in VO_2 max and running performance than performing HIIT under normoxic conditions does (Atakan et al., 2021; Bonetti & Hopkins, 2009; Chang et al., 2023; Fentaw et al., 2025; Gibala & Jones, 2013; Jacob et al., 2024). In the context of long-distance runners, several findings revealed that, compared with similar training conducted at sea level, HIIT performed under hypoxic conditions leads to greater improvements in VO_2 max and 5 km time (Jung et al., 2020; Park et al., 2022). In contrast, athletes following the LHTL protocol who reside at high altitude while performing HIIT at sea level have demonstrated greater gains than those following the LHTH approach (Levine & Stray-Gundersen, 1997; Stray-Gundersen & Levine, 1999). Despite the generally positive findings from these studies supporting HIIT as an effective strategy, most of the participants were lower-altitude athletes, which may limit the generalizability of the results to higher altitude populations.

This is because, the concept of altitude training for higher altitude native athletes encompasses a broader and more complex reality than what is typically explained in the literature. These athletes not only are temporarily exposed to high altitudes but are also permanently immersed in high-altitude environments. For example, East African distance runners have lived and trained at elevations between 2,000 and 2,500 m in almost all training intensity zones for lifetimes (Haugen et al., 2022). In this context, there is a notable lack of research examining specific HIIT strategies aimed at performance development. In particular, limited research attention has been given to understanding how HIIT performed at low and moderate altitudes responds in athletes who are already adapting to living and training at higher altitudes. This question has practical implications for optimizing training strategies in altitude-native populations. As a result, the current body of evidence is difficult to interpret across all running populations, given the variability in altitude conditions with real-life training and competition. A recent review highlighted that the capacity of moderate-altitude long-distance runners to perform HIIT at different altitudes has not yet been systematically investigated (Fentaw et al., 2025).

In light of these considerations, athletes who reside and train at high altitudes present a distinct population, methodological, and environmental gaps that warrant investigation to optimize training outcomes. To address this gap, the present study aimed to examine the physiological and functional adaptations to HIIT performed at two different altitudes among endurance runners residing at moderate-altitude. More specifically, this study sought to address the following research questions: (1) Does HIIT conducted at low-altitude (~1,220 m) and moderate-altitude (~2,850 m) produce differential effects on VO_2 max and vVO_2 max?, and (2) Does HIIT at a lower altitude would result in superior improvements in functional performance, as measured by Coopers' 12 minute run, and 5,000 m running time?

Based on previous literature, we hypothesized that managing HIIT at lower altitudes would result in greater improvements in vVO_2 max and VO_2 max than HIIT would at the athletes' residence moderate-altitude. In addition, it was hypothesized that considering higher-quality training at low altitudes would improve functional performance.

Materials and methods

Study design

This study was a balanced randomized control trial designed to minimize variations among groups in which athletes were matched to ensure equal distributions of sex, event specialization, and 5,000 m running time (5kRT). The participants were active competitors who lived and trained at moderate altitudes (~2,850 m). They were included in the study if they: 1) were at least three years of training age, 2) were 18 years of chronological age, 3) did not perform systematic training during a transition period, 4) had at least a history of regional competition, 5) trained and competed from 3 km--to-marathon events, 6) were not trained or exposed to low altitudes <1,500 m within the previous three months for more than 48 hours and 7) provided a completed physical activity prescreening questionnaire and informed consent documents. On the other hand, the study excluded participants with recent illnesses or injuries that limit training and racing, such as heat allergies, epistaxis, malaria, fever, gastrointestinal distress, pregnancy, and anaemia. Moreover, those who could not provide informed consent or who were missing more than 20% of the usual training or intervention data were excluded.

Sample size determination

The required sample size was estimated on the basis of the recommended and previously published VO_2 max effect size (0.34) (Cohen, 1992; Levine & Stray-Gundersen, 1997), via a priori-repeated measures ANOVA with a preliminary power analysis (G*Power 3.1.9.7) for repeated measures design with three groups and two measurement points. A total of thirty-nine participants (13 per group) were required to detect the expected effect size with a statistical power of 0.95 and an alpha (α) level of 0.05. To account for an anticipated dropout rate of approximately 10% (4 participants) due to potential missing data (Suresh & Chandrashekara, 2012), additional five participants were recruited to ensure balanced group distributions. This approach results in a total sample size of 48.

Consequently, among 119 moderate-altitude resident long-distance runners from local athletics clubs, seventy-one were excluded for various reasons. Forty-eight (24 females and 24 males) athletes agreed to participate and signed an informed consent form after they were informed about the study's purpose, possible risks, and benefits. Randomization was employed via stratified allocation, where sex, event specialization and 5kRT were considered randomly and equally assigned to 16 participants (8 males and 8 females); either the HIIT group at moderate altitude (HIIT2850m), the HIIT group at low altitude (HIIT1220m), or the control group at moderate altitude (CG2850m). To ensure unbiased allocation, the second author was determined in sequence and was situated outside during recruitment, and stratification and coding were performed by the first and third authors. Among the included participants, six (two in each group) dropped out of the study for personal reasons. The final analysis included 14 athletes in each group, distributed as follows: HIIT2850m (n = 14), HIIT1220m (n = 14), and CG2850m (n = 14), as shown in Figure 1. The participants baseline characteristics prior to the intervention are presented in Table 1.

Table 1
Anthropometric, training, and performance characteristics of the participants before the HIIT intervention at low and moderate altitudes

Variable	All subjects	Intervention			p value (η_p^2)
		HIIT2850m	HIIT1220m	CG2850m	
Number of participants	42	14	14	14	
Sex (male/female)	23/19	7/7	8/6	8/6	
Chronological age (yrs.)	22.2±4.3	22.2±5	22.6±4.6	21.7±3.4	.86 (.008)
Training age in running (yrs.)	6.2±2.3	6.3±2.6	6.4±2.6	5.9±1.7	.87 (.007)
Competition experience (yrs.)	4.8±1.8	4.9±2.2	4.9±1.7	4.4±1.6	.72 (.02)
Training frequency (days·wk^{-1})	6.8±1.3	6.6±1	6.8±1.2	7.1±1.6	.59 (.03)
Height (m)	1.64±0.07	1.63±0.08	1.65±0.07	1.63±0.06	.81 (.011)
Body mass (kg)	49.5±5.3	49.7±5.4	49.9±6	48.8±4.8	.84 (.009)
Body mass index (kg/m^2)	18.4±1.2	18.7±1.2	18.4±1.1	18.3±1.3	.67 (.02)
5000 m race time (min)	18±1.7	18.2±2.1	17.9±1.2	18±1.7	.9 (.005)
VO_2 max (mL/kg/min)	63.2±7.3	62.8±7.6	63.4±7.6	63.3±7.2	.97 (.002)
100% intensity (m·s^{-1})	—	5.12±0.34	5.22±0.42	—	.4 (.022)

The values are the means ± standard deviation (SDs). No significant differences were observed among groups in any variable. *p* values and effect sizes (η_p^2) refer to group comparisons prior to the intervention.

Abbreviations: HIIT2850m, high-intensity interval training group at moderate altitude; HIIT1220m, high-intensity interval training group at low altitude; CG2850m, control group at moderate altitude; p value, probability value; η_p^2, partial eta-squared; VO_2 max,: maximum aerobic capacity; mL/kg/min, milliliters of oxygen used up in a minute per kilogram of body weight; m·s^{-1}, meter per second; yrs., years; wk^{-1}, training sessions per week.

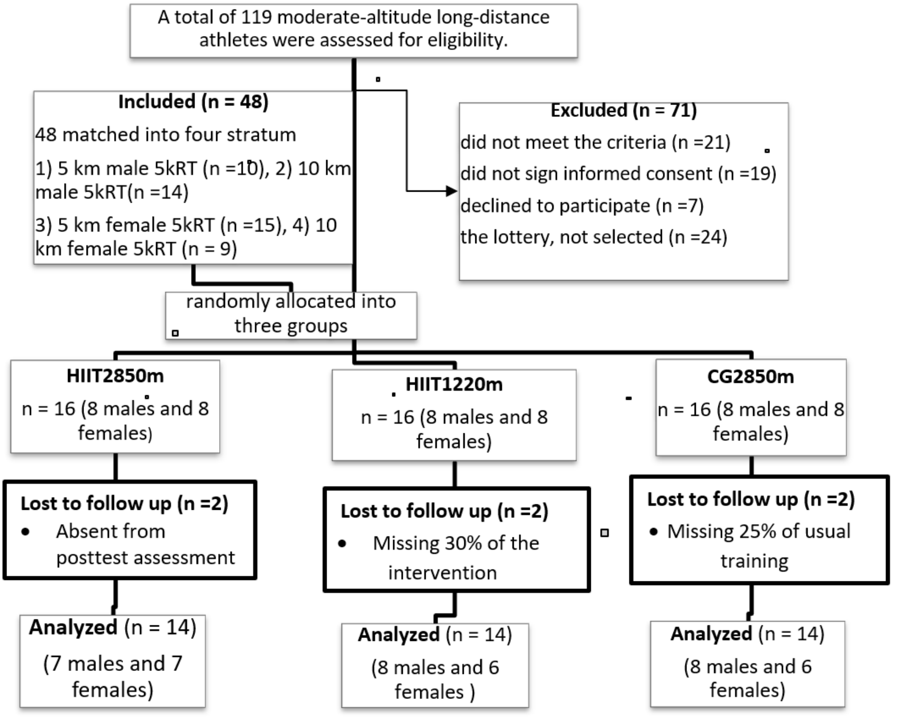

Figure 1
Flow of participant recruitment, eligibility assessment, randomization, and final analysis. Abbreviations: 5kRT, 5, 000 m running time; HIIT2850m, high-intensity interval training group at 2,850 m; HIIT1220m, high-intensity interval training group at 1,220 m; CG2850m: a control group living at 2,850 m.

The participants were engaged in regular long-distance running and were classified as trained runners. The experimental procedures were submitted, and the Sport Academy ethical committee at Bahir Dar University approved of the study [Approval Number: IRERC 06/2024, Bahir Dar, Ethiopia]. The study procedures were performed according to the ethical standards outlined by the Helsinki Declaration of 1975.

High-intensity interval training protocol

The intervention was applied for eight weeks at 2,850 m (Debark) and 1,220 m (Zarima) to the HIIT2850m and HIIT1220m groups, respectively. Training was provided on a 400 m track for two nonconsecutive sessions per week (Monday and Thursday) to allow sufficient recovery. In contrast, CG2850m did not participate in any additional training program but maintained their usual running with the other groups at 2,850 m. The HIIT sessions consisted of four phases as previously described by Helgerud et al., (2007): a) warm-up of a ten-minute period at 70% vVO_2 max consisting of continuous jogging followed by dynamic stretching along with jogging; b) main interval running for 25 min, which consisted of four 4-min running intervals, each separated by 3 min of active recovery at 70% vVO_2 max; and c) five-minute cooling down at 50% vVO_2 max. Each session lasted approximately 40 minutes. At each altitude training site, the number of intervals, interval duration, and intensity during work and rest intervals remained constant throughout the intervention for both HIIT groups to ensure reliable training stimuli. However, the intensity was determined on the basis of each participant's vVO_2 max value via a 5-minute maximal aerobic speed test taken at intervention venues, in which participants were grouped based on the equivalent vVO_2 max performance for the intervention. In each interval run, in addition to a verbal instruction, a whistle signal was also blown to alternatively utilize the 100% and 70% vVO_2 max performance to complete efficiently. Accordingly, immediately after each interval, training intensity was continuously monitored by two experienced coaches and two sports training research experts focusing on vVO_2 max, running pace, and the Borg scale (6–20), following the intensity measures adopted by Ciolac et al. (2015).

Procedures

The participants were informed about the study's aim, methodology, and procedures. Prior to testing, the procedures were thoroughly explained to the participants to ensure familiarization. The VO_2 max, vVO_2 max, and 5kRT measurements were preceded by a standardized warm-up, which consisted of 12 minutes of jogging, and 8 minutes of dynamic movements for the upper and lower extremities combined with 40 meters of back-and-forth jogging. The participants with similar performances were grouped to run together for motivation and were encouraged to perform maximally. Finally, the athletes performed the tests accordingly, as the assessors told them to perform measurements before and after eight weeks of intervention.

The participants performed the usual training preparation for cross-country competition at approximately 2,850 m (Debark, Ethiopia). While the HIIT2850m group was trained at their usual residence in Debark for eight weeks, the HIIT1220m group participants was transported 38 km downhill by car to a low-altitude location (approximately 1,220 m) for their HIIT sessions. These low altitude HIIT sessions were conducted at the foothills of Lima-Limo and Semein Mountains National Park at Zarima, Ethiopia during the specific preparation training phase. All testing and training sessions took place in the morning, between 8:00 and 10:00 a.m., on a 400-m track, from September 26 to November 20, 2024.

All tests were conducted at 2,850 m training venue separated by at least 48 hours after each visit to allow sufficient recovery at a properly measured 400 m round outdoor field track. The participants were also encouraged to maintain their usual nutrition and hydration habits, perform the same warm-ups, rest throughout the study, and be vigorously encouraged during testing. In addition, the participants were instructed to abstain from stimulants or alcoholic beverages one day before the test. Before each measurement, all the participants confirmed that they obtained adequate rest and recovery and abstained from exhausting training for at least two days. The participants performed testing at the same time of day under similar environmental conditions.

Measurements

Pre-and post-test primary outcomes

Maximal aerobic capacity

Despite the laboratory treadmill test being the gold standard for measuring VO_2 max, Cooper's 12-minute running test is simple and cost-effective to administer. It is the best predictor of an athlete's VO_2 max (r= 0.9) as described elsewhere (Bandyopadhyay, 2015). The relative VO_2 max (mL/kg/min, milliliters of oxygen used up in a minute per kilogram of body weight) was estimated with the help of Cooper's 12-minute run test. In particular, this test has excellent accuracy and reliability in predicting the VO_2 max of endurance runners (Alvero-Cruz et al., 2017).

Following the warming-up, the test was conducted at a properly measured 400 m outdoor round track marked every 10 m. Hence, athletes ran in 5kRT matched groups as a source of motivation for twelve minutes as long as possible to record a greater possible distance to cover along with other athletes. The estimated VO_2 max (mL/kg/min) value was obtained from Cooper's twelve-minute test (D12 km) in kilometers. Accordingly, it was calculated via Bandyopadhyay's regression equation for predicting the VO_2 max of males (equation (eq.) (1), r=0.9) and females (equation (2), r=0.9), respectively:

Eq. 1. VO_2 max (mL/kg/min) = (22.351 × D12 km)-11.288)

Eq. 2. VO_2 max (mL/kg/min) = (19.55 × D12 km)-2.39)

Minimum running velocity at VO_2 max

The VO_2 max velocity (vVO_2 max) is the maximal aerobic speed (MAS) (Renoux et al., 2000), which is the point at which VO_2 max starts to occur and helps to determine athletes' performance. While the vVO_2 max laboratory measure is the gold standard for determining the vVO_2 max, its cost, complexity, and impracticality have led to the development of several field measures, such as the multistage Montreal Beep, set time trial, and set distance trial (Baker & Heaney, 2015). However, the time set (5-minute) trial is easy, quick, and highly correlated with the laboratory measure of vVO_2 max (r= 0.94) (Berthon et al., 1997;

Chamoux et al., 1996), in which athletes perform maximal efforts in the allotted time to cover more distance as fast as possible.

Meanwhile, following the warm-up, the athletes were instructed to run 5-minute time trials as fast as possible to cover more distance around a marked 400 m running track. In each group, athletes of similar 5kRT and sex ran together and were encouraged to cover more distance and maintain higher paces in the allotted time. Subsequently, while counting down the last 10 seconds in the given time (10--1), the athletes immediately got stationary at the last count. Hence, the distance covered in meters over five minutes was recorded. Accordingly, the vVO_2 max is determined by dividing the distance covered in meters by the given time in seconds.

5000 M RUNNING TIME (5KRT)

The 5kRT test was initiated after adequate warm-up exercises. Athletes were instructed to achieve the best time possible in the trial in which they ran alongside others. The start was given as usual in the competition at the start line. Wearing watches during the run was not allowed, while the laps and times were recorded and put down for each 400 m split by the runners' coach. The total time to complete the 5kRT was recorded at the closest of 0.01 s as the athletes crossed the finish line. Three experienced timers, two of whom were the athletes' coaches and one assessor, provided the mean values for analysis.

SECONDARY OUTCOME MEASURES

ANTHROPOMETRIC CHARACTERISTICS

The participants' height and body mass were measured simultaneously via a height-rod–equipped stadiometer with an integrated digital scale (model: SKU, KC-3001), accurate to the nearest 0.1 cm and 0.1 kg. The measurements were taken with the participants wearing light clothing standing barefoot in an upright position, with heels together and the head aligned in the Frankfort plane. Each measurement was repeated under consistent conditions, and the mean value was recorded to ensure reliability. The participants body mass index (BMI) value was subsequently calculated as body mass (kg) divided by height squared (m^2), using the formula BMI = body mass/height^2.

TRAINING AND PERFORMANCE CHARACTERISTICS

The participants completed a questionnaire survey about their general training and performance history.

COVERED DISTANCE AND TRANSFORMED SPEED

The measured covered distance during the five-minute MAS and Cooper twelve-minute run tests and its transformed speed in meters per second were used in the analysis. This helps reveal the influence of the training intervention on speed and endurance performance via a holistic approach.

Statistical analysis

The data are presented as the means and standard deviations (SDs) in the text and tables. To ensure that, the participants' anthropometric, training, and performance levels among groups were compared via one-way analysis of variance (ANOVA). In addition, we used independent t tests to compare 100% MAS training interventions, and paired t tests to assess changes over time for practical significance. These effect sizes, expressed as Cohen's d, are classified as small (0.2–0.4), moderate (0.5–0.7), or large (≥0.8) (Cohen, 1988). All the statistical analyses were performed via IBM SPSS statistics version 27.0.1, with a significance level set at $p \leq 0.05$. The Shapiro–Wilk and Levene tests confirmed the data normality and homogeneity of variances ($p > 0.05$), respectively. Consequently, two-way repeated measures ANOVA was used to identify the effects of the group (HIIT2850m, HIIT1220m, CG2850m) and time (pretest and posttest) conditions. Where appropriate, Bonferroni post hoc analysis was performed to determine the source of the difference when significant differences in group or interaction were observed. The partial eta-square (η_p^2) was calculated as an effect size measure for all analyses and interpreted as small (0.01–0.06), moderate (0.06–0.14), or large (>0.14) effects (Cohen, 2013). The potential relationship between changes in VO_2 max and vVO_2 max scores with a 5,000 m running time was determined via Pearson correlation.

Results

Baseline characteristics of the subjects

The anthropometric, training, and performance characteristics of the three groups examined at baseline are depicted in Table 1. There were no significant differences ($p>0.05$) in any of the baseline anthropometric, training, or performance characteristics among the groups. Forty-two athletes completed the study, whereas six athletes (two in each group) dropped out for non-intervention reasons (2-absent from assessment, 2-missing more than 25% of the usual training and 2-missing 30% of the intervention), and their data were excluded from the analysis. Hence, a similar profile at baseline and training intensity ensures that the observed changes resulted from the intervention rather than prior differences. On the other hand, no significant differences were found among the exercise intensities, explained as % vVO_2 max over the intervention. Hence, the total training load (volume and intensity) of the two experimental groups was similar over the intervention period.

Minimum running velocity at VO_2 max

A summary of the physiological variables measured before and after the HIIT intervention is presented in Table 2 and Figure 2. Significant differences were found for the main effect of time ($p<0.001$; $\eta_p^2=0.3$) and the group × time interaction ($p=0.02$; $\eta_p^2=0.19$) effects for vVO_2 max after training. However, the post hoc analyses revealed no significant differences in the vVO_2 max mean difference between the groups. The mean changes in vVO_2 max were 0.04±0.05, 0.6% vs 0.06±0.07, and 1.2% in the HIIT2850m and HIIT1220m intervention groups, respectively, with 0.004±0.02 and no changes in the control group. However, there was no significant main effect of group ($p=0.98$; $\eta_p^2=0.001$). In addition, the distance covered within five minutes of the MAS test increased in both intervention groups, with higher values observed in the HIIT1220m group.

Maximum aerobic capacity

Repeated-measures ANOVA demonstrated that the VO_2 max (mL/kg/min) significantly increased to the mean ± SD: 0.52±0.5 and 0.6±0.5 in the HIIT2850m and HIIT1220m groups, respectively, after HIIT at the two altitudes. This finding revealed that the VO_2 max significantly improved, and these increases were greater in the HIIT2850m (0.8%) and HIIT1220m (1%) groups than in the CG2850m (0.2%) group after the intervention, with no significant main effect of group ($p=0.97$, $\eta_p^2=0.002$) as shown in Table 2. Post hoc analyses revealed that the VO_2 max was not significantly different between the groups. However, HIIT at 1,220 m resulted in a significantly greater increase in the mean change in the VO_2 max (0.6±0.5; $p<0.001$) than HIIT at 2,850 m (0.5±0.5; $p<0.001$) and CG2850m (0.13±0.3, $p=0.16$) did.

In addition, the distance covered within the twelve-minute Cooper test increased in both intervention groups. However, the speed improved more in the HIIT1220m group than in the HIIT2850m group. The improved VO_2 max assisted in covering more distances in the Cooper run test at individual intensity, but it was different in the control groups. The VO_2 max mean difference within the group was significantly greater in the lower-altitude training group than in the moderate-altitude training group after HIIT, with no baseline difference. The Cooper 12-minute run covered a distance that increased in both intervention groups, whereas in the HIIT1220m group, there was a greater extent of improvement. The covered distance in twelve minutes of running and its speed in $m \cdot s^{-1}$ occurred at the same percentage change, which was quite similar to the VO_2 max values between the intervention groups.

Table 2

Changes in physiological and functional performance measured before and after eight weeks of HIIT at low (HIIT1220m) and moderate (HIIT2850m) altitudes

Variable	Intervention									Effect p value (η_p^2)		
	HIIT2850m (n=14)			HIIT1220m (n=14)			CG2850m (n=14)			Group	Time	Interaction
	pre	post	Δ, p value, ES	pre	post	Δ, p value, ES	pre	post	Δ, p value, ES			
5-min. Distance (m)	1525.5±99.7	1535.9±95.4	10.4±13.4, 0.01*, 0.8	1527.6±91.7	1545.3±92.3	17.7±20.2, 0.006*, 0.9	1535.4±94.5	1536.6±96.6	1.1±5.7, 0.47, 0.2	0.98 (0.001)	<0.001 (0.3)	0.02 (0.19)
v VO_2 max ($m·s^{-1}$)	5.09±0.33	5.12±0.32	0.04±0.05, 0.01*, 0.8	5.09±0.31	5.15±.31	0.06±0.07, 0.006, 0.9	5.12±.32	5.12±0.32	0.004±0.02, 0.47, 0.2	0.98 (0.001)	<0.001(0.3)	0.02 (0.19)
Cooper 12-min distance (m)	3302.6±348.7	3327.4±355.2	24.8±22.3, 0.001*, 1.1	3332.1±351.8	3360.4±346.5	28.4±25.1, <0.001*, 1.1	3326.7±332.9	3332.4±332.6	5.7±14.5, 0.16, 0.4	0.97 (0.001)	<0.001(0.5)	0.02 (0.19)
Cooper 12-min speed ($m·s^{-1}$)	4.6±0.48	4.6±0.49	0.03±0.03, 0.001*, 1.1	4.6±0.49	4.7±0.48	0.04±0.04, <0.001*, 1.1	4.6±0.46	4.6±0.46	0.01±0.02, 0.096, 0.4	0.97 (0.001)	<0.001(0.5)	0.02 (0.19)
VO_2 max (mL/km/min)	62.8±7.6	63.3±7.7	0.52±0.47, 0.001*, 1.1	63.4±7.6	64±7.5	0.6±0.52, <0.001*, 1.1	63.3±7.2	63.4±7.2	0.13±0.31, 0.16, 0.4	0.97 (0.002)	<0.001(0.5)	0.02 (0.19)
5kRT (min.)	18.2±2.2	17.9±2	-0.3±0.4, 0.03*, -0.7	17.9±1.2	17.6±1.2	-0.34±0.4, 0.007*, -0.9	17.99±1.7	17.89±1.8	-0.1±0.4, 0.33, -0.3	0.98 (0.001)	<0.001(0.3)	0.3 (0.07)
5kRT speed ($m·s^{-1}$)	4.64±0.56	4.7±0.53	0.06±0.1, 0.04*, 0.6	4.7±0.3	4.8±0.3	0.09±0.1, 0.008*, 0.8	4.7±0.44	4.7±0.47	0.03±0.1, 0.29, 0.3	0.97 (0.002)	<0.001(0.3)	0.34 (0.05)

The values are means ± standard deviations. Δ represents the mean difference between pretest and post-intervention values, with corresponding *p* values and effect sizes (ES). $p < 0.05$ indicates a significant change over time. Group, time, and interaction effects are reported with *p* values and partial eta-squared (η_p^2).* The across-time mean difference is significant at 0.05.

Abbreviations: HIIT2850m, high-intensity interval training group at moderate altitude; HIIT1220m, high-intensity interval training group at low altitude; CG2850m, control group at moderate altitude; p value, probability value; η_p^2, partial eta-squared; Δ, the mean difference; ES, effect size; VO_2 max, maximal aerobic capacity; vVO_2 max, velocity at maximum aerobic capacity; $m·s^{-1}$, meters per second; mL/km/min, milliliters of oxygen used up in a minute per kilogram of body weight; 5kRT, 5000 m running time; pre, before an 8-week intervention; post, after an 8-week intervention.

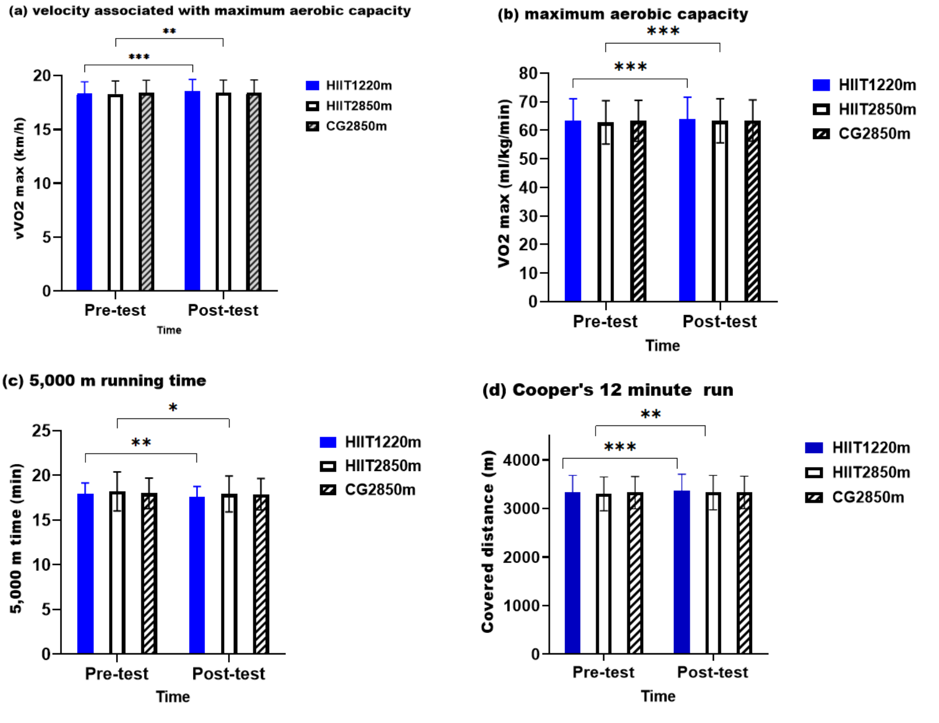

Figure 2
Physiological and functional variables before and after high-intensity interval training (HIIT) at two different altitudes. The panels illustrate (a) running velocity at VO_2max (vVO_2 max, km·h^{-1}), (b) maximal oxygen uptake (VO_2 max, mL·kg^{-1}·min^{-1}), (c) 5 km running time (5kRT, min), and (d) distance covered during the 12-minute Cooper run test. The data are presented as mean ± standard deviation (SDs). Significance levels are denoted by asterisks: * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$.

5,000 m running performance

The 5kRT performance after intervention training significantly improved over time, as indicated by a significant main effect of time ($p<0.001$, $\eta_p^2=0.34$). In contrast, the change scores of the HIIT2850m and HIIT1220m groups improved compared with those of the CG2850m group (shown in Table 2). However, there was a significant increase in the mean change in the HIIT2850m (Δ=-0.3±0.4, p=0.03) and HIIT1220m (Δ=-0.34±0.4, p=0.007) groups after the intervention compared with the CG2850m group (Δ=-0.1±0.4, p=0.33). However, the magnitude of improvement was greater in the HIIT1220m group (1.8%) than in the HIIT2850m group (1.4%). The post hoc analyses indicated no significant differences in running time between the groups. Nevertheless, it was significantly greater in the lower-altitude training group than in the moderate-altitude HIIT group. The running speed was the same as the percentage change in the

5kRT between the groups. Despite significant improvements in 5kRT in both groups following HIIT, the HIIT1220m group performed better. The speed to cover the running race increased in both groups, similar to the 5kRT.

Physiological and functional performance correlations

A strong negative association was found between 5kRT and vVO_2 max ($r=-0.64$, $p=0.013$) and positive association between 5kRT and VO_2 max ($r=0.74$, $p=0.002$) in the HIIT2850m group following training. However, weak associations were observed between 5kRT and vVO_2 max ($r=0.31$, $p=0.286$) and VO_2 max ($r=-0.07$, $p=0.809$) in the HIIT1220m group after training. These findings suggest that quality training at moderate altitudes has a positive effect on inducing changes in physiological parameters compared with training at low altitudes. However, weak associations were found in the control group (VO_2 max: $r=-0.16$, $p=0.58$; vVO_2 max: $r=0.08$, $p=0.776$).

Discussion

In this study, we examined the effects of manipulating HIIT at two different natural altitudes on selected physiological (vVO_2 max and VO_2 max) and functional (5,000 m race performance, maximal aerobic speed, and Coopers' 12-minute run) adaptations in moderate-altitude resident long-distance athletes. The main observation of this study is that high-intensity training performed at low altitude leads to greater improvements in 5,000 m running time compared to training at moderate altitude, resulting in enhanced physiological adaptations among moderate-altitude endurance runners.

Interestingly, compared with HIIT2850m (-0.3 ± 0.4, -1.4%) and CG2850m (-0.1 ± 0.4, -0.6%), HIIT at 1,220 m elicited a significantly greater performance improvement of 5,000 m time by (-0.34 ± 0.4, -1.8%). Moreover, vVO_2 max and VO_2 max substantial changed within the HIIT1220m and HIIT2850m groups compared with the CG2850m group. However, vVO_2 max and VO_2 max substantially differed between the HIIT1220m and HIIT2850m groups. These observed results indicate that lower-altitude environments most likely enable athletes to maintain high-intensity training at the VO_2 max training velocity and improved pacing adaptations that help improve the economy of running, which enables improvements in the vVO_2 max, VO_2 max and 5,000 m running performance. HIIT at high altitudes requires special caution in monitoring intensity, even for high-altitude residential athletes, to elicit induced adaptations.

Although our findings do not necessarily challenge the existing knowledge on high-intensity training at high altitudes, our study sought to test the hypothesis: What are the physiological and functional benefits of performing high-intensity training at high versus low altitudes for moderate-altitude athletes? As altitude increases, the difficulty of performing high-intensity training prevails for moderate-altitude athletes, similar to sea level athletes. Hence, the possible improvement mechanisms following HIIT at two different altitudes are related to the efficiency of HIIT loads performed at the individual maximal potential. At baseline, there were no differences among the groups, suggesting that potential differences at baseline did not influence the results. The variables were measured at moderate altitudes to create similar conditions and decrease substantial variance.

While HIIT provides a powerful spur for cardiovascular and central adaptations (Gibala & Jones, 2013), in our study, some differences in HIIT load between the intervention groups were considered to occur due to the influence of altitude variation. Nevertheless, no significant difference was found in exercise intensity, explained as % vVO_2 max, across the intervention groups. The interval running speed differed between low and moderate altitudes, with a 3.33% increase in speed observed in the low-altitude training groups. Consequently, the HIIT1220m group trained slightly faster than did the moderate-altitude training group. Notably, the physiological stress experienced during high-altitude running is considered a training load. The total training load, duration, and frequency were comparable between the two experimental groups over the intervention period. These findings support the conclusion that the training interventions were similar across the study period.

Hence, the training intervention was performed individually to tailor the maximal aerobic speed in an environmentally determined program in which similar protocols were implemented. This finding indicates that vVO_2 max values were relatively similar for all participants across the HIIT sessions. In addition, the total HIIT duration was similar for both intervention groups. As such, significant VO_2 max and aerobic performance adaptations are observed following HIIT at 100% vVO_2 max in endurance athletes (Gibala & McGee, 2008). In particular, competitive runners benefit from this type of training (García-Pinillos et al., 2017).

More specifically, studies have been conducted in the case of lower-altitude athletes using HIIT at simulated and natural altitudes for middle and long-distance runners. However, athletes residing at high altitudes and sea levels have similar VO_2 max values; the only difference was the low cost of running found in high-altitude athletes (Saltin et al., 1995). In addition, sea-level athletes show a decline in performance at high altitudes, whereas altitude athletes have better physiological and recovery adaptations (Aughey et al., 2013). Acute and chronic altitude exposure influences the actual performance of low- and high-altitude natives differently, which might give high-elevation natives a competitive advantage at altitudes above 1,500 m (Mateo-March et al., 2022). Hypoxic training has been shown to enhance endurance performance by improving metabolic function and capillary characteristics (Suzuki, 2022).

The findings of this study are congruent with the previous results of Levine and Stray-Gunderson (1997), who demonstrated a 5% VO_2 max improvement in the LHTL and LHTH groups, who received high-intensity training at sea level and high altitude, respectively. However, the LLTL group yielded no improvements. Nakamoto et al., (2016) also reported a significant improvement in VO_2 max following HIIT under hypoxia, whereas the normoxic group failed to show differences. In addition, other studies also demonstrated that VO_2 max improvements following HIIT under hypoxia and normoxia were apparent (Jung et al., 2020; Park et al., 2022) and that there were no improvements in VO_2 max under either condition (Neya et al., 2007).

Moreover, while most previous studies employed simulated altitudes conditions, Levine and Stray-Gundersen (1997) uniquely examined sea-level endurance athletes at natural altitudes. In contrast, the present study involved moderate-altitude long-distance athletes who trained in their native environment. This training protocol is therefore considered essential for promoting both physiological and functional adaptations.

Although running performance is influenced by several factors, such as age, fitness level, and the intensity and duration of the intervention, the VO_2 max improved from 4–46% (Burgomaster et al., 2008; Helgerud et al., 2007). In previous studies, the VO_2 max changes following HIIT under hypoxia and normoxia in lower altitude distance running athletes were 4–13% and 1–5%, respectively (Jung et al., 2020; Levine & Stray-Gundersen, 1997; Nakamoto et al., 2016; Park et al., 2022). Furthermore, a 3% improvement in VO_2 max was observed (Stray-Gundersen et al., 2001). In our study, however, 0.8% and 1% VO_2 max improvements were observed in the moderate- and low-altitude HIIT groups, respectively. The underlying mechanisms of these changes were not assessed, these findings indicate that such mechanistic gains may be mediated by improved mitochondrial biogenesis, increased capillary density, increased enzymatic activity, neuromuscular adaptations, or hormonal responses to greater hormones and improvements following HIIT (Mølmen et al., 2025). Similarly, Geiser et al. (2001) reported that the VO_2 max increases from 8.5--11.1% and 2.9--7.2% in response to normoxia and hypoxia, respectively, in response to hypoxic training. Aerobic capacity adaptations decline after altitude training but peak within 1–3 weeks (Chapman et al., 2014).

Another finding of this study is that the vVO_2 max improved in both intervention groups. The improvement in vVO_2 max may have been attributed to the training load being prescribed according to the maximal aerobic speed, which performs similar relatively high-intensity training independently to help maintain and improve pace adaptations. The maximal aerobic capacity improved similarly in both training groups. This may improve body oxygen utilization and delivery during high-intensity training. This occurred because low-altitude groups tend to have greater potential for oxygen access than moderate-altitude groups do. The training protocol of this study, such as the intensity, frequency, and duration, is almost comparable with those of the studies conducted by Park et al., (2022) and Jung et al., (2020). Most importantly, Helgerud et al. (2007) designed a similar HIIT protocol, except for the altitude conditions added in our study. The individual responses and the HIIT protocol applied during the study significantly influenced vVO2 max adaptations.

Physiological parameters play crucial roles in running performance improvement. Hence, the 5,000 m running performance improved after HIIT at low and moderate altitudes. We found that the time to complete the running time decreased, which is an improvement in performance following HIIT at both low and moderate altitude. Similarly, Levine and Stray-Gundersen, (1997) reported a significant improvement in the 5,000 m running performance of the LHTL group with a 13.4±10 second decrease in running time. In contrast, the LHTH and LLTL groups presented longer (increased) running times. In addition, Stray-Gundersen et al., (2001) reported a 1.1% improvement in a 3 km trial following the LHTL approach. In contrast, Jung et al. (2020) and Park et al. (2022) reported that 3 km running time has no significant interaction effect but is significant across time in both groups.

Hence, the 5,000 m performance improvement is inversely associated with vVO_2 max and VO_2 max, which are good predictors of running performance, as expected. In some cases, without the VO_2 max change, there is an increase in the running performance of athletes (Jones, 1998). These findings indicate that moderate-altitude long-distance runners may benefit more from low-altitude high-intensity training. This may be the case for athletes with speed problems who pursue time improvement. In particular, high-altitude athletes struggle to manage high-intensity training at high altitudes. This limitation may lead to a corresponding performance plateau and thus may require a more advanced training approach for possible performance adaptations.

In general, both the physiological and running performance improved in both intervention groups, with the lower-altitude HIIT group advancing more than the other groups. These findings indicate that speed training at lower altitudes could provide substantial access to oxygen to help individuals perform at the highest potential. This highlights the importance of training intensity monitoring at different altitudes, which contributes to running velocity and oxygen utilization for improved running performance. The significant improvement in 5,000 m running performance under both experimental conditions indicates that physiological variables contribute to potential running efficiency. This training is widely recognized for its ability to yield benefits in a short time individually and in combination with hypoxia. In particular, HIIT is relevant for endurance sports in already fit individuals (Larson and Jenkins, 2002).

These findings highlight the significant physiological and functional enhancement following HIIT at lower altitudes for endurance runners. This was also demonstrated in a crossover study on horses, where HIIT under hypoxic conditions improved training performance and VO_2 max (Mukai et al., 2020). In fact, running performance influencing factors such as physiological (Denadai & Greco, 2022), morphological (Knechtle et al., 2015), environmental and psychological (Ogueta-Alday & Garcia-Lopez, 2016) ones are prevalent, our findings support the premise that HIIT at low and moderate altitudes effectively improves running performance.

Previous findings suggest that incorporating HIIT under hypoxia is an efficient strategy that can significantly improve key physiological variables compared with HIIT under normoxia (Fentaw et al., 2025). In addition, living at high altitudes and HIIT at lower altitudes significantly improve athletic performance compared with sea-level living and training (Levine & Stray-Gundersen, 1997). These results agree with our findings despite methodological and population issues. The nature of HIIT is well known to utilize speed intervals that maintain training at the given intensity and duration. This shows that training at lower altitudes allows for greater training intensity due to reduced physiological stress in comparison with higher altitudes, which may have contributed to increased functional adaptations. However, the degree of improvement did not differed between the training groups, indicating comparable progress.

Consequently, the lower altitude HIIT group rendered greater vVO_2 max, VO_2 max and running performance than the moderate altitude HIIT group did. These improvements following lower altitude HIIT may suggest that these HIIT programs elicited greater impacts and stress on physiological factors. Nevertheless, our study participants were moderate-altitude resident distance runners, given that HIIT interventions were provided at their residences and brought to lower altitudes for high-intensity training for the other group. Such training taxes the physiological factors to a greater degree, suggesting the importance of providing HIIT at lower altitudes for moderate-altitude athletes.

This study also revealed that 5,000 m running time associations with VO_2 max and vVO_2 max are similar to the findings of Levine and Stray-Gundersen, (1997), and Neya et al. (2016), who reported a negative correlation between 5 km running performance and VO_2 max in the LHTL group ($r=0.65$, $p<0.00001$). However, the participants were sea-level athletes who were exposed to hypoxia, which led to acute physiological stress. In contrast to these studies, we included moderate-altitude endurance runners. Levine and Stray-Gundersen (1997) reported that a 5% increase in VO_2 max leads to a 13.4±10 s improvement at 5 km. In this study, 5,000 m time was significantly correlated with the VO_2

max (r =-0.7, p = 0.002) in the HIIT2850m group, accounting for 1.4% of the variance in 5 km performance. The effect of HIIT on athletic performance quality has been confirmed to be positive and significantly correlated with changes in performance. These changes may exist because, compared with HIIT at moderate altitudes, HIIT is best performed by moderate-altitude distance runners at lower altitudes. These findings suggest that maintaining HIIT at lower altitudes for moderate-altitude athletes is an effective approach for optimizing performance.

Limitations and Future Considerations

This study highlights the necessity of HIIT at low altitudes for high-altitude long-distance running athletes to achieve the best possible time goals. However, experimenting with two different altitudes is demanding because of the difficulty in terms of logistics and managing and controlling other psychological and physiological confounders during the intervention. Consequently, some methodological, population and logistical issues must be underscored. The time spent during transportation from/to lower altitudes may have influenced the results. In particular, the effects of nutritional and recovery time complications during transportation to/from residences and training sites were not evaluated. However, the participants were encouraged to maintain their usual habits as much as possible, and we tried to provide food and water immediately after the intervention sessions to minimize the influences associated with them. Hence, convenient lower-altitude residences minimize the influence, which helps to efficiently perform HIIT after full recovery, which we recommend for future studies. In addition, simulated sea levels may be utilized at high altitudes, which may have benefits and should be considered. Blinding was not performed on either the participants or the researchers in the experimental conditions. However, we encouraged participants during training and testing and informed them about the purpose and procedures of the study to mitigate these limitations.

The optimal training at low altitudes and the immediate effect and durability of the obtained benefits warrant future study. We sought results as a group; however, training, competition experience and performance levels may create intersubject variability in improvements. Therefore, determining the dose–response relationships of individuals is an area for further research.

Although the study examined some selected physiological changes through an indirect means of value estimation which are reliable and valid, we acknowledge that they may not have been sensitive enough to detect changes. Therefore, more rigorous research is needed that utilizes direct laboratory tools. In summary, these limitations do not mean that our results are in trouble; instead, we refer to the existing possibilities that may affect the findings. Hence, future studies should aim to create more favourable conditions that could yield more reliable and optimal results.

Conclusion

This study demonstrated that eight weeks of high-intensity interval training led to significant improvements in the physiological and functional parameters of endurance athletes, regardless of the training site, compared with the control group. Consistent with our hypothesis, HIIT performed at lower altitudes produced greater 5,000 m time improvements than HIIT conducted at moderate altitudes, indicating superior functional adaptation. These findings confirm that proper caution should be taken during HIIT at high altitudes, which influences the magnitude of induced gains. In particular, understanding the influence of high altitudes on individual athlete physiological responses is necessary for designing and monitoring training intensity plans. Planning HIIT at lower altitudes for moderate-altitude resident athletes may serve as an effective strategy to optimize aerobic capacity and endurance performance, which could lead to potential recommendations for long-distance athletes and coaches.

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Statement of Ethics

This study was conducted in accordance with the World Medical Association Declaration of Helsinki. The study protocol was reviewed and approved by the Sport Academy ethical committee at Bahir Dar University (APPROVAL NUMBER; IRERC 06/2024, Bahir Dar, Ethiopia). All participants provided written informed consent to participate in this study.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interests with respect to the research, authorship, and/or publication of the article *Physiological and functional adaptations of high-intensity interval training at two altitudes in moderate-altitude endurance runners: a randomized controlled trial.*

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AUTHORS' CONTRIBUTIONS

Sisay Fentaw: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing - Original Draft, Review and Editing, Visualization, Funding acquisition.
Tefera Tadesse: Methodology, Software, Validation, Investigation, Writing - Review & Editing, Visualization, Supervision, Project administration.
Zerihun Birhanu: Methodology, Investigation, Validation, Writing - Review and Editing, Visualization, Supervision, Project administration. All authors approved the final version of the manuscript.

References

Alvero-Cruz, J. R., García, M. A. G., & Carnero, E. A. (2017). Reliability and accuracy of Cooper's test in male long distance runners. *Revista Portuguesa De Pneumologia*, *10*, 60–63, https://doi.org/10.1016/j.ramd.2016.1003.1001.

Atakan, M. M., Li, Y., Koşar, Ş. N., Turnagöl, H. H., & Yan, X. (2021). Evidence-Based Effects of High-Intensity Interval Training on Exercise Capacity and Health: A Review with Historical Perspective. *International Journal of Environmental Research and Public Health*, *18*(13), 7201, https://doi.org/10.3390/ijerph18137201.

Aughey, R. J., Hammond, K., Varley, M. C., Schmidt, W. F., Bourdon, P. C., Buchheit, M., Simpson, B., Garvican-Lewis, L. A., Kley, M., Soria, R., Sargent, C., Roach, G. D., Claros, J. C. J., Wachsmuth, N., & Gore, C. J. (2013). Soccer activity profile of altitude versus sea-level natives during acclimatisation to 3600 m (ISA3600). *British Journal of Sports Medicine*, *47*(Suppl 1), i107–i113, https://doi.org/10.1136/bjsports-2013-092776.

Baker, D., & Heaney, N. (2015). Review of the literature normative data for maximal aerobic speed for field sport athletes: a brief review. *Journal of Australia strength and condition*, *23*(7), 60–67.

Bärtsch, P., Saltin, B., & Dvorak, J. (2008). Consensus statement on playing football at different altitude. *Scandinavian journal of medicine & science in sports*, *18*, 96–99, https://doi.org/10.1111/j.1600-0838.2008.00837.x.

Berthon, P., Fellmann, N., Bedu, M., Beaune, B., Dabonneville, M., Coudert, J., & Chamoux, A. (1997). A 5-min running field test as a measurement of maximal aerobic velocity. *European Journal of Applied Physiology and Occupational Physiology*, *75*(3), 233–238, https://doi.org/10.1007/s004210050153.

Bonetti, D. L., & Hopkins, W. G. (2009). Sea-level exercise performance following adaptation to hypoxia: a meta-analysis. *Sports Medicine*, *39*(2), 107–127, https://doi.org/10.2165/00007256-200939020-00002.

Buchheit, M., & Laursen, P. B. (2013). High-intensity interval training, solutions to the programming puzzle: Part I: cardiopulmonary emphasis. *Sports Medicine*, *43*(5), 313–338, https://doi.org/https://doi.org/10.1007/s40279-013-0029-x.

Burgomaster, K. A., Howarth, K. R., Phillips, S. M., Rakobowchuk, M., Macdonald, M. J., McGee, S. L., & Gibala, M. J. (2008). Similar metabolic adaptations during exercise after low volume sprint interval and traditional endurance training in humans. *The journal of physiology*, *586*(1), 151–160, https://doi.org/10.1113/jphysiol.2007.142109.

Camacho-Cardenosa, A., Camacho-Cardenosa, M., Burtscher, M., Martínez-Guardado, I., Timon, R., Brazo-Sayavera, J., & Olcina, G. (2018). High-intensity interval training in normobaric hypoxia leads to greater body fat loss in overweight/obese women than high-intensity interval training in normoxia. *Frontiers in Physiology*, *9*, 60, https://doi.org/10.3389/fphys.2018.00060.

Chamoux, A., Berthon, P., & Laubignat, J. F. (1996). Determination of maximum aerobic velocity by a five minute test with reference to running world records. A theoretical approach. Archives of physiology and biochemistry, *104*(2), 207–211, https://doi.org/10.1076/apab.104.2.207.12877.

Chang, W.-Y., Wu, K.-C., Yang, A.-L., & Chen, Y.-L. (2023). Simulated Altitude Training and Sport Performance: Protocols and Physiological Effects. *Applied Sciences*, *13*(20), 11381, https://doi.org/10.3390/app132011381.

Chapman, R. F., Laymon Stickford, A. S., Lundby, C., & Levine, B. D. (2014). Timing of return from altitude training for optimal sea level performance. *Journal of Applied Physiology* (*1985*), *116*(7), 837–843, https://doi.org/10.1152/japplphysiol.00663.2013.

Ciolac, E. G., Mantuani, S. S., Neiva, C. M., Verardi, C., Pessôa-Filho, D. M., & Pimenta, L. (2015). Rating of perceived exertion as a tool for prescribing and self regulating interval training: a pilot study. *Biology of Sport*, *32*(2), 103–108, https://doi.org/10.5604/20831862.1134312.

Cohen, J. (1992). Statistical Power Analysis. *Current Directions in Psychological Science*, *1*(3), 98–101, https://doi.org/10.1111/1467-8721.ep10768783.

Cohen, J. (2013). *Statistical power analysis for the behavioral sciences*. Cambridge: Academic press, https://doi.org/10.4324/9780203771587.

Conkin, J., & Wessel, J. H., 3rd. (2008). Critique of the equivalent air altitude model. *Aviation, space, and environmental medicine*, *79*(10), 975–982, https://doi.org/10.3357/asem.2331.2008.

Denadai, B. S., & Greco, C. C. (2022). Could middle- and long-distance running performance of well-trained athletes be best predicted by the same aerobic parameters? *Current research in physiology*, *5*, 265–269, https://doi.org/10.1016/j.crphys.2022.06.006.

Enoksen, E., Shalfawi, S. A. I., & Tønnessen, E. (2011). The Effect of High- vs. Low-Intensity Training on Aerobic Capacity in Well-Trained Male Middle-Distance Runners. *The Journal of Strength & Conditioning Research*, *25*(3), 812–818, https://doi.org/10.1519/JSC.0b013e3181cc2291.

Fentaw, S., Tadesse, T., & Birhanu, Z. (2025). Methodological and aerobic capacity adaptations of high-intensity interval training at different altitudes in distance runners: A comprehensive meta-analysis. *Physiological Reports*, *13*(9), https://doi.org/10.14814/phy2.70349.

García-Pinillos, F., Soto-Hermoso, V. M., & Latorre-Román, P. A. (2017). How does high-intensity intermittent training affect recreational endurance runners? Acute and chronic adaptations: A systematic review. *Journal of Sport and Health Science*, *6*(1), 54–67, https://doi.org/10.1016/j.jshs.2016.08.010.

Gibala, M. J., & Jones, A. M. (2013). Physiological and performance adaptations to high-intensity interval training. *Nestle Nutrition Institution workshop series*, *76*, 51–60, https://doi.org/10.1159/000350256.

Gibala, M. J., & McGee, S. L. (2008). Metabolic adaptations to short-term high-intensity interval training: a little pain for a lot of gain? *Exercise and Sport Sciences Reviews*, *36*(2), 58–63, https://doi.org/10.1097/JES.0b013e318168ec1f.

Haugen, T., Sandbakk, Ø., Seiler, S., & Tønnessen, E. (2022). The Training Characteristics of World-Class Distance Runners: An Integration of Scientific Literature and Results-Proven Practice. *Sports Medicine - Open*, *8*(1), https://doi.org/10.1186/s40798-022-00438-7.

Helgerud, J., Hov, H., Mehus, H., Balto, B., Boye, A., Finsås, L., Hoff, J., & Wang, E. (2023). Aerobic high-intensity intervals improve V̇O2max more than supramaximal sprint intervals in females, similar to males. *Scandinavian journal of medicine & science in sports*, *33*(11), 2193–2207, https://doi.org/10.1111/sms.14470.

Helgerud, J., Høydal, K., Wang, E., Karlsen, T., Berg, P., Bjerkaas, M., Simonsen, T., Helgesen, C., Hjorth, N., & Bach, R. (2007). Aerobic high-intensity intervals improve VO2max more than moderate training. *Medicine & Science in Sports & Exercise*, *39*(4), 665–671, https://doi.org/10.1249/mss.0b013e3180304570.

Hottenrott, K., Ludyga, S., & Schulze, S. (2012). Effects of high intensity training and continuous endurance training on aerobic capacity and body composition in recreationally active runners. *Journal of sports science & medicine*, *11*(3), 483.

Iaia, F., & Bangsbo, J. (2010). Speed endurance training is a powerful stimulus for physiological adaptations and performance improvements of athletes. *Scandinavian journal of medicine & science in sports*, *20*, 11–23, https://doi.org/10.1111/j.1600-0838.2010.01193.x.

Jacob, E., Moura, A., & Avery, A. (2024). A Systematic Review of Physical Activity and Nutritional Interventions for The Management of Normal Weight and Overweight Obesity. *Nutrition, Metabolism and Cardiovascular Diseases*, https://doi.org/10.1016/j.numecd.2024.08.001.

Jones, A. M. (1998). A five year physiological case study of an Olympic runner. *British Journal of Sports Medicine*, *32*(1), 39–43, https://doi.org/10.1136/bjsm.32.1.39.

Jung, W. S., Kim, S. W., & Park, H. Y. (2020). Interval Hypoxic Training Enhances Athletic Performance and Does Not Adversely Affect Immune Function in Middle- and Long-Distance Runners. *International Journal of Environmental Research and Public Health*, *17*(6), https://doi.org/10.3390/ijerph17061934.

Khodaee, M., Grothe, H. L., Seyfert, J. H., & VanBaak, K. (2016). Athletes at high altitude. *Sports Health*, *8*(2), 126–132, https://doi.org/10.1177/1941738116630948.

Knechtle, B., Stiefel, M., Rosemann, T., Rüst, C., & Zingg, M. (2015). Laufsport und der Zusammenhang zwischen Training und Körperbau: Running and the association with anthropometric and training characteristics. *Therapeutische Umschau*, *72*, 343–355, https://doi.org/10.1024/0040-5930/a000685.

Levine, B. D., & Stray-Gundersen, J. (1997). "Living high-training low": effect of moderate-altitude acclimatization with low-altitude training on performance. *Journal of Applied Physiology* (*1985*), *83*(1), 102–112, https://doi.org/10.1152/jappl.1997.83.1.102.

Mateo-March, M., Muriel, X., Valenzuela, P. L., Gandia-Soriano, A., Zabala, M., Barranco-Gil, D., Pallarés, J. G., & Lucia, A. (2022). Altitude and Endurance Performance in Altitude Natives versus Lowlanders: Insights from Professional Cycling. *Medicine & Science in Sports & Exercise*, *54*(7), 1218–1224, https://doi.org/10.1249/mss.0000000000002890.

Midgley, A. W., McNaughton, L. R., & Jones, A. M. (2007). Training to enhance the physiological determinants of long-distance running performance: can valid recommendations be given to runners and coaches based on current scientific knowledge? *Sports Medicine*, *37*(10), 857–880, https://doi.org/10.2165/00007256-200737100-00003.

Mølmen, K. S., Almquist, N. W., & Skattebo, Ø. (2025). Effects of Exercise Training on Mitochondrial and Capillary Growth in Human Skeletal Muscle: A Systematic Review and Meta-Regression. *Sports Medicine*, *55*(1), 115–144, https://doi.org/10.1007/s40279-024-02120-2.

Mukai, K., Ohmura, H., Matsui, A., Aida, H., Takahashi, T., & Jones, J. H. (2020). High-intensity training in normobaric hypoxia enhances exercise performance and aerobic capacity in Thoroughbred horses: A randomized crossover study. *Physiological Reports*, *8*(10), e14442, https://doi.org/10.14814/phy2.14442.

Nakamoto, F. P., Ivamoto, R. K., Andrade Mdos, S., de Lira, C. A., Silva, B. M., & da Silva, A. C. (2016). Effect of Intermittent Hypoxic Training Followed by Intermittent Hypoxic Exposure on Aerobic Capacity of Long Distance Runners. *The Journal of Strength & Conditioning Research*, *30*(6), 1708–1720, https://doi.org/10.1519/jsc.0000000000001258.

Neya, M., Enoki, T., Kumai, Y., Sugoh, T., & Kawahara, T. (2007). The effects of nightly normobaric hypoxia and high intensity training under intermittent normobaric hypoxia on running economy and hemoglobin mass. *Journal of Applied Physiology* (*1985*), *103*(3), 828–834, https://doi.org/10.1152/japplphysiol.00265.2007.

Ogueta-Alday, A., & Garcia-Lopez, J. (2016). Factores que afectan al rendimiento en carreras de fondo. [Factors affecting long-distance running performance]. RICYDE. *Revista internacional de ciencias del deporte*, *12*, 278–308, https://doi.org/10.5232/ricyde2016.04505.

Park, H. Y., Jung, W. S., Kim, S. W., Kim, J., & Lim, K. (2022). Effects of Interval Training Under Hypoxia on Hematological Parameters, Hemodynamic Function, and Endurance Exercise Performance in Amateur Female Runners in Korea. *Frontiers in Physiology*, *13*, 919008, https://doi.org/10.3389/fphys.2022.919008.

Peltonen, J. E., Tikkanen, H. O., & Rusko, H. K. (2001). Cardiorespiratory responses to exercise in acute hypoxia, hyperoxia and normoxia. *European Journal of Applied Physiology*, *85*(1-2), 82–88, https://doi.org/10.1007/s004210100411.

Renoux, J. C., Petit, B., Billat, V., & Koralsztein, J. P. (2000). Calculation of times to exhaustion at 100 and 120% maximal aerobic speed. *Ergonomics*, *43*(2), 160–166, https://doi.org/10.1080/001401300184530.

Saltin, B., Kim, C. K., Terrados, N., Larsen, H., Svedenhag, J., & Rolf, C. J. (1995). Morphology, enzyme activities and buffer capacity in leg muscles of Kenyan and Scandinavian runners. *Scandinavian journal of medicine & science in sports*, *5*(4), 222–230, https://doi.org/10.1111/j.1600-0838.1995.tb00038.x.

Sharma, A. P., Saunders, P. U., Garvican-Lewis, L. A., Clark, B., Stanley, J., Robertson, E. Y., & Thompson, K. G. (2017). The effect of training at 2100-m altitude on running speed and session rating of perceived exertion at different intensities in elite middle-distance runners. *International Journal of Sports Physiology and Performance*, *12*(s2), S2–147–S142–152, https://doi.org/10.1123/ijspp.2016-0402.

Stankovic, M., Djordjevic, D., Trajkovic, N., & Milanovic, Z. (2023). Effects of High-Intensity Interval Training (HIIT) on Physical Performance in Female Team Sports: A Systematic Review. *Sports Medicine - Open*, *9*(1), 78, https://doi.org/10.1186/s40798-023-00623-2.

Stray-Gundersen, J., Chapman, R. F., & Levine, B. D. (2001). "Living high-training low" altitude training improves sea level performance in male and female elite runners. *Journal of Applied Physiology* (*1985*), *91*(3), 1113–1120, https://doi.org/10.1152/jappl.2001.91.3.1113.

Stray-Gundersen, J., & Levine, B. D. (1999). “Living high and training low” can improve sea level performance in endurance athletes. *British Journal of Sports Medicine*, *33*(3), 150–151, https://doi.org/10.1136/bjsm.33.3.150.

Suresh, K., & Chandrashekara, S. (2012). Sample size estimation and power analysis for clinical research studies. *Journal of Human Reproductive Sciences*, *5*(1), 7–13, https://doi.org/10.4103/0974-1208.97779.

Suzuki, J. (2022). Endurance exercise under short-duration intermittent hypoxia promotes endurance performance via improving muscle metabolic properties in mice. *Physiological Reports*, *10*(23), e15534, https://doi.org/10.14814/phy2.15534.

Wilber, R. L. (2007). Application of altitude/hypoxic training by elite athletes. *Medicine & Science in Sports & Exercise*, *39*(9), 1610–1624, https://doi.org/10.1249/mss.0b013e3180de49e6.

Wilber, R. L., & Pitsiladis, Y. P. (2012). Kenyan and Ethiopian distance runners: what makes them so good? *International Journal of Sports Physiology and Performance*, *7*(2), 92–102, https://doi.org/10.1123/ijspp.7.2.92.