

Physiological and hematological responses to high-intensity speed training among ethiopian middle- and long-distance runners

NIGATU WORKU¹, ASCHENAKI TADDESE², ZERU BEKELE TOLA³

^{1,2,3}Department of Sport Science, Addis Ababa University ADDIS ABABA, ETHIOPIA

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Abstract

Problem Statement: Aerobic capacity, particularly maximal oxygen uptake ($\text{VO}_{2\text{max}}$), is a key determinant of performance in elite middle- and long-distance runners. Although high-intensity training (HIT) is widely recognized as effective, its concurrent effects on both physiological and hematological parameters in elite athletes training at altitude remain insufficiently understood, limiting the optimization of performance adaptations. **Purpose:** This study aimed to investigate the effects of a six-week high-intensity speed training (HIST) intervention on key physiological and hematological parameters relevant to performance in elite Ethiopian middle- and long-distance runners training at moderate altitude. **Approach:** A quasi-experimental design was used involving 21 elite male Ethiopian runners. The intervention consisted of a six-week speed training program performed at moderate altitude (2100–3500 m), with three high-intensity interval training (HIIT) sessions per week. Physiological parameters ($\text{VO}_{2\text{max}}$, 5000 m performance, 400 m speed, and resting heart rate (RHR)) and hematological parameters (red blood cell (RBC) count, hemoglobin (HGB), hematocrit (HCT), and white blood cell (WBC) count) were assessed before and after the intervention. **Results:** Significant post-intervention improvements were observed across all measured variables. $\text{VO}_{2\text{max}}$ increased by 3.2% ($p < 0.000001$), 5000 m performance time decreased by 22.2 s ($p < 0.000001$), and 400 m sprint time improved by 2.3 s ($p < 0.0001$). RHR decreased by 5.2% ($p < 0.0001$). Hematological parameters also demonstrated significant increases, including RBC count (+8.1%), HGB concentration (+6.7%), and HCT (+5.9%) (all $p < 0.001$). Regression analysis identified $\text{VO}_{2\text{max}}$, RHR, and 400 m sprint time as significant predictors of 5000 m performance, explaining approximately 68% of the variance ($R^2 \approx 0.68$). **Conclusions:** A six-week HIST program performed at altitude produced significant improvements in both aerobic and anaerobic performance in elite Ethiopian middle- and long-distance runners. These performance gains were accompanied by favorable hematological adaptations, indicative of enhanced oxygen-carrying capacity and cardiovascular efficiency. Collectively, these findings support the inclusion of HIST as an effective complementary modality for elite endurance athletes training at altitude.

Keywords: speed training, altitude training, aerobic power, oxygen transport, elite runners, hematological adaptations

Introduction

Aerobic capacity is a fundamental determinant of performance in middle- and long-distance runners, with maximal oxygen uptake ($\text{VO}_{2\text{max}}$) serving as a sensitive indicator of performance differences at the elite level (Joyner & Coyle, 2008). In addition to aerobic fitness, anaerobic factors—particularly running speed and anaerobic capacity—play a critical role in enabling rapid force production during running (Slawinski et al., 2010). Accordingly, endurance performance is influenced by the interaction of several well-established determinants, including $\text{VO}_{2\text{max}}$, endurance capacity, anaerobic fitness, and movement efficiency (Hawley & Myburgh, 2020).

To optimize physiological adaptations in endurance athletes, training programs commonly combine high-volume, low-intensity exercise with low-volume, high-intensity protocols (Laursen, 2010; Seiler & Tønnessen, 2009). Although high-intensity training (HIT) represents a relatively small proportion of overall training volume, it is essential for the performance development of elite endurance athletes (Stöggl & Sperlich, 2015). High-intensity interval training (HIIT), one of the most widely used high-intensity strategies, is characterized by alternating bouts of intense exercise and recovery periods (Laursen, 2010). However, the existence of multiple HIIT formats—including submaximal, $\text{VO}_{2\text{max}}$ -targeted, and supramaximal protocols—makes it challenging to identify the optimal training stimulus. Notably, submaximal HIIT has been shown to improve endurance performance in trained runners and cyclists (Rønnestad et al., 2014; Seiler & Tønnessen, 2009). HIT is typically defined by brief- to moderate-duration intervals performed at intensities exceeding the anaerobic threshold, interspersed with short periods of low-intensity exercise or rest to allow partial recovery (Buchheit & Laursen, 2013). In contrast, sprint interval training (SIT) has been shown to elicit substantial improvements in aerobic power and endurance performance (Hazell et al., 2010; Macpherson et al., 2011). More

recently, findings by Jones et al. (2024) further support the effectiveness of SIT, demonstrating superior gains in VO_2max and time-trial performance in elite runners compared with traditional moderate-intensity training.

Speed training has been demonstrated to improve physiological parameters in both middle- and long-distance runners (Mujika & Padilla, 2001). However, it may also pose certain risks, such as immune suppression and an increased susceptibility to illness. Hematological responses to anaerobic exercise are dynamic; research indicates initial increases in hematocrit (HCT), hemoglobin (HGB), and white blood cell (WBC) counts, followed by reductions in 24 h. Moreover, prolonged intensive training has been associated with lower hematological values compared with non-athletic populations. In contrast, HIIT has been related to increases in RBC volume, which may increase oxygen transport and utilization (Gore & Hopkins, 2005).

Metabolites such as urea, creatinine, ketone bodies, and other nitrogenous compounds detectable in urine provide valuable insight into metabolic responses to exercise (Daskalaki & Gika, 2017; Lewis & Gerszten, 2014). During physical activity, the body generates metabolites including lactate, pyruvate, alanine, and hypoxanthine (Wasserman, 2009). Elevated urea levels in urine may reflect increased muscle protein metabolism and gluconeogenesis, with potential implications for performance. Ketone bodies serve as alternative energy substrates when glucose availability is limited (Phinney & Volek, 2012; Volek & Phinney, 2012).

Monitoring exercise-related metabolites such as creatine, ketone bodies, nitrogenous compounds, and phosphate is essential for optimizing training regimens. Intense exercise leads to the accumulation of hydrogen ions, resulting in a reduction in intramuscular pH and the onset of fatigue, which impairs muscle function. Phosphate, a key component of energy production, becomes depleted during prolonged exercise, thereby influencing cellular metabolism. Therefore, urinary phosphate excretion may serve as an indicator of exercise intensity and energy expenditure. Overall, the analysis of urinary metabolites provides a non-invasive approach to evaluating athlete performance and physiological homeostasis. HIIT has been shown to improve VO_2max , lactate threshold, and running economy in endurance athletes (Helgerud et al., 2007; Laursen, 2010). Both submaximal and supramaximal HIIT protocols enhance endurance performance (Rønnestad et al., 2014; Seiler & Tønnessen, 2009), whereas speed training specifically improves anaerobic capacity and running economy (Mujika & Padilla, 2001). These physiological adaptations are associated with increases in RBC volume and improved efficiency of oxygen transport (Gore & Hopkins, 2005). Despite these findings, the interaction between speed training, hematological adaptations, and metabolic responses remains insufficiently explored, particularly among elite athletes. Therefore, this study aims to examine these relationships through a six-week speed training intervention in Ethiopian elite middle- and long-distance runners—athletes renowned for their sustained global dominance in distance running. The primary objective is to evaluate the effects of speed training on key physiological and hematological parameters relevant to endurance performance.

Materials and Methods

Participants

The study was performed in the Addis Ababa region of Ethiopia and involved elite male athletes from the Jeani Demadona Management-affiliated Adidas track team. The participants specialized in middle- and long-distance events ranging from 1500 to 10,000 m and routinely trained in high-altitude environments (2,100–3,500 m) in and around Addis Ababa, including Intoto, Sululta, and Kenenisa training tracks. Purposive and convenience sampling methods were used to recruit 21 elite male athletes who represent Ethiopia in international competitions. The study protocol was approved by the Research Ethics Committee of the Addis Ababa University College of Natural Sciences. All participants provided written informed consent in accordance with the Declaration of Helsinki. Prior to enrollment, each athlete completed a health-screening questionnaire and underwent basic medical assessments, including measurements of blood pressure, heart rate, body weight, and body mass index (BMI).

Training Protocol

The speed training program was designed to complement the athletes' weekly training regimen. Each session began with a 5 km warm-up and 20 min of dynamic mobilization, followed by either long intervals (1,000–1,600 m) at 95%–100% VO_2max or short intervals (200–800 m) at 105%–110% VO_2max . The speed training component accounted for approximately 6% of the weekly training volume and concluded with a 3 km cool-down and 10 min of static stretching. The weekly program included three primary interval sessions, three morning easy runs, four afternoon easy runs, and one rest day, totaling 120 km per week. Easy run sessions consisted of 13 km morning runs with 5 × 150–200 m run-outs and 6 km afternoon recovery runs. Interval workouts were progressively adjusted over the six-week period, with variations in distance and intensity, as detailed in Table 1.

Table 1: Training protocol progression

Week	Long Intervals (95-100% VO_2max)	Short Intervals (105-110% VO_2max)
1	3 x 1000m (2 min rest)	6 x 200m (1 min rest)
2	3 x 1200m (2.5 min rest)	8 x 200m (1 min rest)
3	2 x 1600m (3 min rest)	6 x 400m (1.5 min rest)
4	3 x 1200m (2.5 min rest)	8 x 400m (1.5 min rest)
5	2 x 1600m (3 min rest)	6 x 800m (2 min rest)
6	3 x 1000m (2 min rest)	8 x 800m (2 min rest)

Procedure

Participants underwent all measurements and testing in a controlled environment over the course of a single week. They were instructed to refrain from strenuous exercise the day prior to testing and to arrive well-rested and adequately hydrated. Anthropometric parameters and aerobic fitness were assessed 24 h before the motor tests. To ensure reliability, each motor test was performed twice. Prior to the initial testing session, participants attended a familiarization session to learn the proper execution of each exercise. Furthermore, identical equipment was used for both pre- and post-program assessments to maintain consistency.

Physiological Parameters

VO₂max: Estimated during event-specific time trials on a 400 m track using Garmin Forerunner watches (model 235 or above; Garmin Ltd., Olathe, KS, USA). Athletes' age, height, weight, and resting heart rate (RHR) were entered into the devices to enhance the accuracy of the estimation.

Racing Performance: Event-specific time trials were performed both before and after the intervention on a standard 400 m track. Additionally, race times from nationally or internationally approved competitions during the intervention period were recorded.

Speed Test: Maximum speed was assessed using a 400 m sprint test, performed at least 24 h after any vigorous activity. A standard 400 m track and a stopwatch were used to record performance.

Resting Heart Rate (RHR): Measured before the time trials and speed assessments. Athletes remained supine in bed before measurement, and heart rate was recorded over a 15-s period, then multiplied and converted to beats per minute (bpm) for accuracy.

Hematological Parameters

Complete Blood Chemistry: Blood samples (10 mL) were collected from the antecubital vein 48 h after training, following a 12-h overnight fast, in the early morning before any physical activity or breakfast. Samples were obtained both before and after the intervention to measure red blood cell (RBC) count, white blood cell (WBC) count, HGB, HCT, iron, calcium, and creatinine levels. Analyses were performed by experienced laboratory professionals at the Ethiopian Youth and Sport Institute using standardized procedures.

Statistical analysis

All statistical analyses were performed using R (Version 4.3.1; R Foundation for Statistical Computing, Vienna, Austria) and Python (Version 3.11.5; Python Software Foundation, Wilmington, DE, USA), with a significance threshold set at $\alpha = 0.05$. Data were initially evaluated for normality using the Shapiro–Wilk test and for homogeneity of variance using Levene's test. Variables that violated the assumption of normality were log-transformed when appropriate; otherwise, non-parametric tests were applied. Descriptive statistics are reported as mean $\pm$ standard deviation (SD) for normally distributed variables and as median [interquartile range, IQR] for non-normally distributed variables. Longitudinal changes in physiological, performance, and hematological parameters across the training phases (pre-, mid-, and post-training) were subsequently assessed. Paired t-tests were used to compare means between two time points (pre- vs. mid-training, mid- vs. post-training, and pre- vs. post-training) for parametric data. For paired data that were not normally distributed, the Wilcoxon signed-rank test was applied. To examine the effect of time (training phase) on 12-min running distance and 5000 m performance, a one-way repeated-measures analysis of variance (ANOVA) was performed. Sphericity was evaluated using Mauchly's test, and when violated ($\epsilon < 0.75$), the Greenhouse–Geisser correction was applied to adjust the degrees of freedom. Significant main effects of time were further analyzed through post-hoc pairwise comparisons with Bonferroni adjustment to control the family-wise error rate. Additionally, ordinary least squares (OLS) regression was used to model baseline 5000 m performance.

The predictor variables included baseline body weight, RHR, 12-min running distance, VO₂max, and 400 m sprint time. Multicollinearity among predictors was assessed using the variance inflation factor (VIF), with values below 2.0 indicating no problematic collinearity. The overall fit of the regression model was evaluated using the coefficient of determination (R^2) and the root mean squared error (RMSE). To examine the multivariate relationships between post-training 400 m sprint times (response variable) and a set of post-training physiological predictors (VO₂max, RHR, 12-min running distance, and body weight), redundancy analysis (RDA) was performed. The significance of the RDA model and its individual constrained axes was assessed using permutation tests with 999 iterations. Standardized coefficients (β) and their 95% confidence intervals (CI) were reported to indicate the unique contribution and precision of each physiological predictor in explaining variance in 400 m sprint time, while controlling for the effects of other predictors. Bivariate associations between baseline 5000 m performance and key baseline physiological and performance metrics were quantified using Pearson's correlation coefficient (r). To illustrate patterns of correlations across multiple variables, a correlation matrix was generated and visualized as a heatmap. Hierarchical clustering, based on Euclidean distance and Ward's method, was applied to the correlation matrix to group variables with similar correlation profiles. Effect sizes were calculated for all primary inferential analyses to quantify the magnitude of observed effects. Cohen's d was calculated for paired t-tests, and partial eta-squared (η^2) was reported for repeated-measures ANOVA. Bias-corrected 95% confidence intervals for hematological parameters were generated using a bootstrap resampling approach with 10,000 iterations. Potentially influential outliers in the OLS regression models were identified using Cook's distance. The generalizability and robustness of the OLS model for predicting baseline 5000 m performance were assessed using leave-one-out cross-validation (LOOCV).

Results

The participants had a mean age of 24.24 ± 1.73 years and a mean height of 174.76 ± 4.76 cm. Baseline body weight was 57.05 ± 2.62 kg. Height remained unchanged during the study, whereas body weight showed a statistically significant reduction at the mid-training assessment compared with baseline ($p = 0.0389$), followed by stabilization between the mid- and post-training assessments. Key physiological and hematological changes are summarized in Table 2.

Table 2: Physiological and hematological parameters before and after training

Parameter	Baseline (Mean $\pm$ SD)	Post-Training (Mean $\pm$ SD)	p-value
Body Weight (kg)	57.05 ± 2.62	56.45 ± 2.55	0.0389
Resting Heart Rate (bpm)	54.48 ± 3.74	51.62 ± 3.14	< 0.0001
VO ₂ max (mL·kg ⁻¹ ·min ⁻¹)	78.47 ± 2.01	80.97 ± 2.02	< 0.000001
400m Sprint Time (s)	52.1 ± 1.2	49.8 ± 1.1	< 0.0001
5000m Performance (s)	900.5 ± 15.3	878.3 ± 14.9	< 0.000001
RBC Count ($\times 10^{12}$ cells/L)	5.01 ± 0.21	5.42 ± 0.23	< 0.001
Hemoglobin (g/dL)	15.1 ± 0.8	16.1 ± 0.9	< 0.001
Hematocrit (%)	45.3 ± 2.1	48.0 ± 2.2	< 0.001
WBC Count ($\times 10^9$ cells/L)	7.5 ± 1.0	7.4 ± 1.1	0.75

The training intervention resulted in significant improvements in several physiological and performance parameters. RHR decreased progressively from a baseline mean of 54.48 ± 3.74 bpm to 51.62 ± 3.14 bpm post-training, indicating enhanced cardiovascular efficiency. VO₂max demonstrated a time-dependent response to the intervention, increasing from 78.47 ± 2.01 mL·kg⁻¹·min⁻¹ at baseline to a mid-intervention peak of 82.33 ± 2.01 mL·kg⁻¹·min⁻¹ ($p < 0.000001$ vs. baseline), followed by a slight decline to 80.97 ± 2.02 mL·kg⁻¹·min⁻¹ post-training ($p < 0.000001$ vs. baseline; $p = 0.000001$ vs. mid-training), as shown in Fig. 1. This pattern suggests an initial rapid adaptation to training, followed by a plateau or slight regression as athletes approached their physiological limits. The 400 m sprint time improved significantly, decreasing from 52.1 ± 1.2 s at baseline to 49.8 ± 1.1 s post-training ($p < 0.0001$), reflecting enhanced anaerobic capacity and speed. Similarly, 5000 m performance improved from 900.5 ± 15.3 s at baseline to 878.3 ± 14.9 s post-training ($p < 0.000001$), indicating enhanced endurance performance, as shown in Fig. 1.

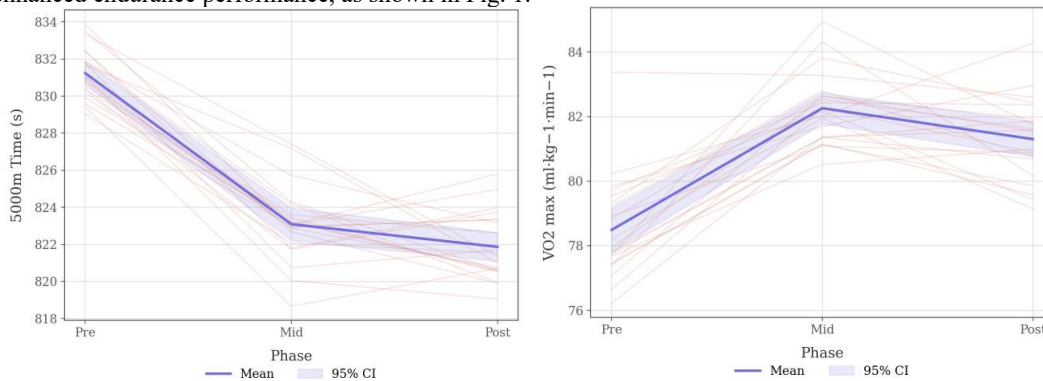


Figure 1: Longitudinal changes in performance metrics across pre-training (baseline), mid-training (week 3), and post-training (week 6) phases. The left panel shows 5000 m performance time (s), while the right panel shows VO₂max (mL·kg⁻¹·min⁻¹). Purple lines represent the mean, and shaded areas indicate the 95% confidence interval.

Hematological parameters showed significant positive adaptations in response to the training intervention. RBC count increased from $5.01 \pm 0.21 \times 10^{12}$ cells/L at baseline to $5.42 \pm 0.23 \times 10^{12}$ cells/L post-training ($p < 0.001$). HGB levels increased from 15.1 ± 0.8 g/dL to 16.1 ± 0.9 g/dL ($p < 0.001$), and HCT increased from $45.3\% \pm 2.1\%$ to $48.0\% \pm 2.2\%$ ($p < 0.001$), reflecting an enhanced oxygen-carrying capacity of the blood—a critical adaptation for endurance performance at altitude. WBC count remained stable during the intervention, indicating no significant immune suppression (Table 2).

The correlation analysis identified several significant relationships between physiological variables and 5000 m running performance, as shown in Fig. 2. RHR exhibited the strongest positive correlation ($r = 0.510$, $p < 0.001$), indicating that athletes with higher RHR tended to record slower 5000 m times. Similarly, 400 m sprint time showed a strong positive correlation ($r = 0.466$, $p < 0.001$), suggesting that slower sprint performance was associated with slower distance running times. In contrast, VO₂max demonstrated a strong negative correlation ($r = -0.427$, $p < 0.001$), confirming that higher aerobic capacity predicts faster 5000 m performance. A moderate negative correlation was also observed for 12-min distance ($r = -0.315$, $p < 0.05$), indicating that covering a greater distance in this test was related to faster 5000 m times. However, body weight showed only a weak, non-significant correlation ($r = 0.081$, $p > 0.05$), suggesting it has minimal influence on 5000 m performance among the variables measured.

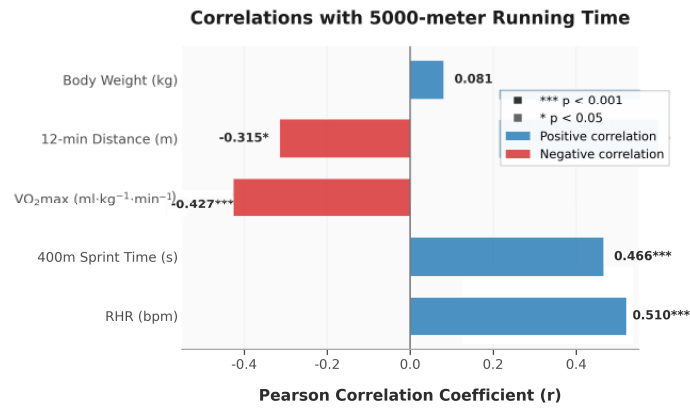


Figure 2: Pearson correlation coefficients between baseline 5000 m performance and selected variables. Regression analysis indicated that VO₂max, RHR, and 400 m sprint time were significant predictors of 5000 m performance ($R^2 \approx 0.68$), highlighting the combined influence of aerobic and anaerobic factors on endurance race outcomes (Fig. 3). LOOCV confirmed the robustness and generalizability of the OLS model in predicting baseline 5000 m performance.

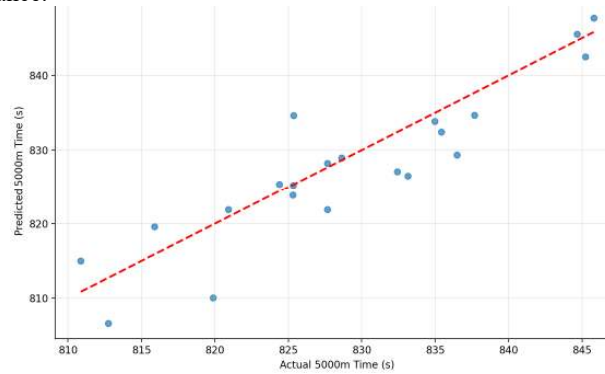


Figure 3: Ordinary least squares (OLS) regression model predicting baseline 5000 m performance. The scatter plot shows the relationship between observed and model-predicted times ($R^2 = 0.68$). Predictor variables include body weight, RHR, 12-min distance, VO₂max, and 400 m sprint time.

RDA further examined the relationships between post-training physiological predictors and performance times, as shown in Fig. 4. The results identified distinct physiological determinants for 5000 and 400 m sprint performance. For a 5000 m time, VO₂max emerged as the strongest negative predictor (coefficient = -0.42), indicating that higher aerobic capacity substantially contributes to faster distance running. In contrast, RHR displayed the strongest positive coefficient (0.38), suggesting that elevated RHR is associated with slower 5000 m performance. Body weight showed a moderate positive relationship (0.25) with 5000 m times, suggesting that greater body mass contributes to slower distance running. For 400 m sprint performance, the 12-min distance demonstrated the strongest negative association (-0.36), indicating that superior endurance capacity predicts faster sprint times. VO₂max exhibited a weaker negative relationship with sprint performance (-0.19) compared to its effect on distance running. RHR consistently showed a positive association with slower sprint times (0.31), whereas body weight had minimal influence on sprint performance (0.08). Overall, the RDA models explained 47% of the variance in 5000 m times and 38% of the variance in 400 m sprint times, confirming these physiological factors as significant determinants of running performance across different distances.

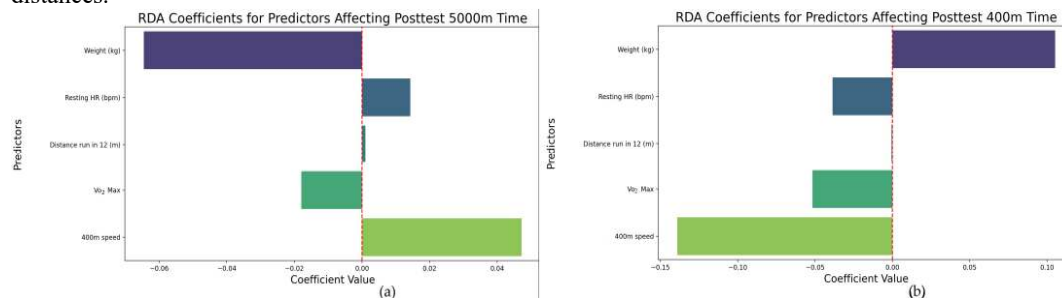


Figure 4: Redundancy analysis (RDA) of post-training performance predictors. The charts show standardized coefficients for predictors of 5000-meter time (a) and 400-meter sprint time (b). For both charts, positive coefficient values indicate a factor that contributes to slower performance times, while negative values indicate a factor that contributes to faster performance times.

Discussion

This study examined the effects of a six-week high-intensity speed training (HIST) intervention on physiological and hematological parameters in elite Ethiopian middle- and long-distance runners training at altitude. The findings demonstrate significant improvements in both aerobic and anaerobic performance, accompanied by favorable hematological adaptations, highlighting the effectiveness of speed training as a complementary strategy for elite endurance athletes in high-altitude environments.

The observed increase in $\text{VO}_{2\text{max}}$ (+3.2%) aligns with previous research demonstrating the effectiveness of HIT in improving aerobic capacity (Helgerud et al., 2007; Laursen, 2010). The initial rapid increase in $\text{VO}_{2\text{max}}$, followed by a slight post-training decline, may reflect a plateau effect as athletes approach their physiological ceiling or indicate a need for varied training stimuli to drive further adaptations. This pattern is consistent with the principle of diminishing returns in highly trained individuals, where incremental gains become increasingly difficult to achieve. Significant improvements in 400 m sprint time (−2.3 s) and 5000 m performance (−22.2 s) highlight the dual benefits of speed training, enhancing both anaerobic power and endurance. Such adaptations are particularly valuable for middle- and long-distance runners, for whom a strong finishing sprint and sustained speed are critical for competitive success.

The observed positive hematological adaptations, including increases in RBC count (+8.1%), HGB (+6.7%), and HCT (+5.9%), are particularly noteworthy. These changes reflect an enhanced oxygen-carrying capacity, a critical adaptation for athletes training and competing at altitude (Gore & Hopkins, 2005). While altitude exposure is known to stimulate erythropoiesis, our findings suggest that HIST further augments this process, contributing to a more efficient oxygen transport system (Gonzales & Patel, 2024). The stability of WBC count during the intervention indicates that the training load was well-managed and did not induce significant immune suppression, a common concern with intensive training programs (Mylona et al., 2022).

The regression analysis, which identified $\text{VO}_{2\text{max}}$, RHR, and 400 m sprint time as significant predictors of 5000 m performance ($R^2 \approx 0.68$), underscores the multifactorial nature of endurance performance. While aerobic capacity ($\text{VO}_{2\text{max}}$) remains a key determinant, anaerobic capabilities (400 m sprint time) and cardiovascular efficiency (RHR) also contribute substantially to race outcomes. The robustness of the OLS model, confirmed through LOOCV, indicates that these findings are likely generalizable to similar elite athlete populations (Casado et al., 2022; Pugliese et al., 2023).

While this study provides valuable insights, several limitations should be noted. The relatively small sample size ($n = 21$) and the focus on male elite Ethiopian runners may restrict the generalizability of the findings to other populations or to female athletes. Future research could examine the long-term effects of such training interventions, explore the underlying molecular mechanisms driving these adaptations (Keir et al., 2021), and determine the optimal periodization of speed training in a comprehensive annual training plan (Rønnestad & Mujika, 2020). Additionally, including a control group performing traditional endurance training would allow for a more direct comparison of the specific benefits of speed training (Belmonte et al., 2020; Worku Angasu et al., 2025).

Conclusions

This study provides compelling evidence that a six-week HIST program at moderate altitude (2100–3500 m) elicits significant, concurrent improvements in aerobic, anaerobic, and hematological parameters in elite Ethiopian middle- and long-distance runners. Key findings include a 3.2% increase in $\text{VO}_{2\text{max}}$ ($p < 0.000001$), a 2.3-s reduction in 400 m sprint time ($p < 0.0001$), enhanced oxygen-carrying capacity (RBC +8.1%, HGB +6.7%, HCT +5.9%; all $p < 0.001$), and improved endurance performance (5000 m time reduced by 22.2 s, $p < 0.000001$). These results challenge conventional training paradigms by demonstrating that relatively brief, high-intensity efforts can simultaneously enhance both aerobic and anaerobic systems in elite athletes. Temporal adaptation patterns showed that endurance gains plateaued after three weeks, whereas speed and cardiovascular efficiency—reflected in a 5.2% reduction in RHR—continued to improve linearly throughout the intervention, offering valuable insights for optimizing training periodization.

The theoretical significance of this study lies in advancing our understanding of the timelines of physiological adaptation and the synergistic effects of HIT under hypoxic conditions. Multivariate analyses identified $\text{VO}_{2\text{max}}$, RHR, and 400 m sprint time as significant predictors of 5000 m performance ($R^2 \approx 0.68$), highlighting the integrated nature of physiological determinants in elite endurance running. This holistic perspective moves beyond focusing on isolated parameters, supporting a more comprehensive approach to athlete development. Additionally, the study advances altitude training science by showing that moderate altitude can be effectively used to enhance both endurance and speed when paired with appropriate high-intensity stimuli, thereby broadening the practical applications of altitude training beyond conventional strategies.

Practically, these findings provide an efficient, evidence-based framework for coaches and athletes. Incorporating HIST, accounting for only 6% of weekly volume, into altitude training regimens offers a potent performance stimulus without excessive load, thereby minimizing the risk of overtraining and injury. The observed differential adaptation patterns inform periodization strategies, suggesting initial 3-week blocks targeting endurance and hematological gains, followed by extended HIST phases to maximize speed and cardiovascular improvements. Furthermore, the strong correlation between accessible field tests—such as the

400 m sprint and RHR—and competitive performance supports their use as practical monitoring tools, particularly in resource-limited settings. Future research should address current limitations by incorporating direct measures of HGB mass and plasma volume, investigating underlying molecular mechanisms, and validating these findings across diverse populations and competitive seasons. Ultimately, this work bridges laboratory and field applications, providing a credible framework for optimizing elite endurance performance through integrated, time-efficient training strategies. By linking performance metrics with systemic physiological responses, it advances evidence-based approaches for enhancing altitude training in elite endurance athletes.

Declarations

Ethical Approval and Informed Consent All experimental work involving human participants conformed to the requirements stipulated in the Declaration of Helsinki. The study protocol was reviewed and approved by the Addis Ababa University College of Natural Sciences research ethics committee (No. DSS/CNS/AAU/04/05/2023). All participating athletes provided written informed consent prior to their inclusion in the study.

Conflict of Interest The authors declare that they have no conflict of interest.

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Data Availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

The Use of Generative AI statement

In the preparation of this work, the authors utilized Julius (<https://julius.ai>) for data analysis and visualization, including generating code, creating exploratory visualizations, and drafting initial descriptions of results, and employed ChatGPT-4 (OpenAI) for writing assistance, which involved drafting and refining text, enhancing clarity, and suggesting improved wording. Subsequent to using these generative AI tools, the authors thoroughly reviewed, verified, and meticulously edited all outputs to correct any errors and ensure the accuracy and integrity of the content, and the authors assumes full responsibility for the final publication.

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