

Article

Sex- and Age-Specific Trajectories of Hemoglobin and Aerobic Power in Competitive Youth Athletes

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Abstract

Maximal aerobic power ($\dot{V}O_{2peak}$) in youth depends on hemoglobin (Hb)—mediated oxygen transport. While sex- and age-specific patterns are established in untrained cohorts, further research is needed in competitive adolescent athletes. We studied 124 young athletes matched by age and sex (62 boys, 62 girls; 10–16 years). Hb was measured from fasting blood samples, and $\dot{V}O_{2peak}$ was determined via cardiopulmonary exercise testing (CPET). Boys showed higher Hb than girls (14.43 ± 0.85 g/dL vs. 13.6 ± 0.74 g/dL; $p < 0.001$) and a significant age-related increase ($B = 0.29$, $p < 0.001$), whereas girls remained stable. $\dot{V}O_{2peak}$ was also higher in boys (50.03 ± 6.18 mL/min/kg, $p < 0.001$). Regression analysis identified Hb as a strong predictor of $\dot{V}O_{2peak}$ ($\beta = 0.40$, $p < 0.001$). These findings demonstrate that classical developmental Hb trajectories persist in highly trained youth and confirm Hb as a key determinant of aerobic power. Monitoring hematological status, particularly in female athletes, is essential for optimizing performance and development.

Keywords: youth athletes; hemoglobin; oxygen transport power; $\dot{V}O_{2peak}$; exercise; sex differences; cardiorespiratory fitness; erythropoiesis



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1. Introduction

Maximal aerobic power ($\dot{V}O_{2peak}$) in youth is fundamentally constrained by the blood's oxygen-carrying capacity. Hemoglobin (Hb) within circulating erythrocytes is central to this process, as it determines the maximal arteriovenous oxygen difference and thereby sets the ceiling for systemic oxygen delivery [1,2]. Even small changes in total hemoglobin mass (Hbmass) substantially affect aerobic power. In adults, an increase of ~1 g Hbmass raises $\dot{V}O_{2peak}$ by approximately 4 mL/min [3]. In children and adolescents, the same physiological principles apply, but growth and puberty introduce additional complexity, particularly through sex-specific hormonal regulation and iron metabolism.

Before puberty, boys and girls display comparable hematological profiles, with hemoglobin increasing gradually and similarly in both sexes during childhood. With the onset of puberty, trajectories diverge [4]. Rising testosterone in boys stimulates erythropoiesis by enhancing erythropoietin (EPO) activity and suppressing hepcidin, thereby increasing iron availability. These androgen effects account for roughly two-thirds of the pubertal gain in Hbmass and contribute to an ~11% increase in hemoglobin concentration compared to prepubertal levels [5,6]. By late adolescence, boys typically exhibit hemoglobin concentrations 1–2 g/dL higher than girls [4]. In girls, the increase in hemoglobin after menarche is often limited because menstrual blood loss and elevated iron requirements

restrict iron bioavailability. In combination with hormonal influences, these factors may result in hemoglobin levels remaining stable or slightly declining after menarche [7,8]. Cohort and athletic data support this pattern: Hbmass rises markedly in both sexes during puberty (~95% in boys, ~33% in girls), but only boys show a significant increase in concentration [5]. These sex-specific differences persist into adulthood, where women maintain hemoglobin levels about 10–12% lower than men, which contributes to their $\dot{V}O_2$ peak averaging 70–75% of male values [9,10].

Puberty also alters how training influences aerobic performance. In boys, testosterone-driven gains in muscle mass, cardiac size and hemoglobin amplify $\dot{V}O_2$ peak improvements [11,12]. Girls, by contrast, exhibit limited hematological adaptation and their performance gains rely more on metabolic and training-driven mechanisms [13]. Evidence indicates that training before puberty exerts little effect on Hbmass or $\dot{V}O_2$ peak [14]. After puberty however, endurance-trained adolescents demonstrate moderately higher Hbmass and up to markedly higher $\dot{V}O_2$ peak than untrained peers, with a substantial proportion of this advantage explained by enhanced oxygen-carrying capacity [14]. Across studies, even modest increases in Hbmass translate into meaningful $\dot{V}O_2$ peak improvements, whereas iron deficiency, which is more common among female athletes, blunts these adaptations [15,16]. Collectively, these findings underscore hemoglobin as a central determinant of aerobic performance during adolescence, shaped by the interplay of growth, sex hormones, and training.

Despite its importance, the joint effect of age and sex on hemoglobin and its implications for aerobic fitness remain insufficiently studied in young competitive athletes. Much of the existing evidence derives from adults or mixed-age cohorts, and few investigations have directly linked hemoglobin development with $\dot{V}O_2$ peak during the pubertal transition.

To address this gap, this study aimed to determine the influence of age and sex on hemoglobin development and to assess the relationship between hemoglobin and aerobic power ($\dot{V}O_2$ peak) in a balanced, age- and sex-matched cohort of adolescent athletes.

2. Materials and Methods

2.1. Study Design

This cross-sectional analysis draws on baseline data from the first year of the MuCAYAplus study (Munich Cardiovascular Adaptations in Young Athletes Plus) [17], a prospective single-center cohort conducted at the Institute of Preventive Pediatrics at the Technical University of Munich (TUM). The three-year project investigates cardiovascular and systemic adaptations to physical activity in youth athletes. All clinical and laboratory assessments were performed on site, with data for the present analysis collected between November 2023 and November 2024. A detailed study protocol has been published previously, outlining participant recruitment, explicit inclusion/exclusion criteria, and comprehensive methodological procedures [17].

2.2. Participants

Participants were children and adolescents aged 10–16 years who were presented for sports medical examination at the Institute's outpatient clinic. Inclusion criteria comprised regular engagement in a primary sport, club membership, competitive participation, and a minimum training volume of three hours per week. Testing was conducted at least 12 h after the last intensive exercise session. Exclusion criteria were acute infection, injury, chronic disease, or missing consent. Annual follow-up over three years was required for study enrollment.

2.3. Blood Sampling

Fasting venous blood samples were obtained from all participants in the morning under standardized conditions, processed, and analyzed at an external accredited laboratory (SYNLAB MVZ Labor, Munich, Germany), including an extensive panel for comprehensive evaluation of hematological and biochemical parameters. For the present study, only hemoglobin concentration was investigated, which was determined photometrically from EDTA-anticoagulated whole blood using standard laboratory procedures. Further information on the extended hematological and biochemical panel and laboratory procedures is available elsewhere [17].

2.4. Cardiopulmonary Fitness

Cardiopulmonary exercise testing (CPET) was performed on a cycle ergometer (Corival, Lode B.V., Groningen, Netherlands) using a modified Godfrey ramp protocol [18]. Gas sensor calibration was performed every two weeks according to the manufacturer's protocol. After a 2 min seated rest, exercise commenced at 50% of body mass ($1 \text{ W} \times 50\%$ body mass), with ramp increments individually adjusted to elicit exhaustion within 8–12 min [19]. Maximal effort was defined as a respiratory exchange ratio ($\text{RER} \geq 1.10$). Primary objective criterion for test cessation was $\text{RER} \geq 1.10$; however, maximal effort was adjudicated using a composite of indices, including peak heart rate ($\text{HR} \geq 95\%$ of age-predicted or ≥ 195 beats/min) and accepted subjective signs of exhaustion (e.g., inability to maintain cadence despite strong encouragement). Gas exchange was measured breath-by-breath (MetaMax 3B, Cortex Biophysik, Leipzig, Germany). To ensure comparability, performance was normalized to body mass and expressed as relative peak oxygen uptake ($\dot{V}\text{O}_{2\text{peak}}$, mL/min/kg). Continuous 12-lead ECG monitoring was applied, blood pressure was measured every 2 min, and oxygen saturation was measured intermittently via pulse oximetry. After exhaustion, a 5 min supervised recovery was conducted.

2.5. Physical Activity Questionnaire (MoMo-PAQ)

Physical activity (PA) was assessed using the validated “Motorik-Modul”—Physical Activity Questionnaire (MoMo-PAQ) [20,21]. The instrument captures PA in organized sports and daily life, including training history, years of experience, primary discipline, weekly training hours, and competition participation. To standardize training loads across disciplines, weekly metabolic equivalent hours (MET-h/week) were calculated, incorporating both activity duration and intensity for the primary sport and additional non-club activities.

2.6. Statistical Analysis

Statistical analyses were performed using SPSS v29.0.2.0 (IBM Corp., Chicago, IL, USA), with significance set at $p < 0.05$. Continuous variables are reported as mean $\pm$ standard deviation (SD), and categorical data as frequencies and percentages. Normality was verified using the Shapiro–Wilk test. Between-group differences (boys vs. girls) were analyzed using independent-samples t -tests. Associations between continuous variables were examined using Pearson's and Spearman's correlation coefficients. To assess the relationship between age, sex, and Hb concentration—multiple linear regression analyses were conducted, including age, sex and the age $\times$ sex interaction term as predictors. Simple slopes analyses were performed to visualize interaction effects. The association between Hb concentration and aerobic power ($\dot{V}\text{O}_{2\text{peak}}$) was analyzed using simple and multiple linear regression models. In the multiple model, sex and the Hb $\times$ sex interaction was included to test for sex-specific effects. Model assumptions (lin-

earity, homoscedasticity, independence, and normal distribution of residuals) were verified graphically and statistically.

2.7. Ethical Approval

The study protocol was approved by the Ethics Committee of the Technical University of Munich (approval number: 516547656). Prior to enrollment, all participants and their legal guardians received written and verbal information about the study. Written informed consent was obtained from both participants and guardians in accordance with age-appropriate ethical standards.

3. Results

3.1. Study Population

The overall study population is $n = 124$ adolescent athletes (62 girls, 62 boys) with a mean age of 13.26 ± 1.65 [9.93; 15.92] years; mean height: 162.35 ± 11.83 [134.80; 192.10] cm; mean weight: 49.53 ± 11.87 [26.50; 81.00] kg; mean BMI: 18.50 ± 2.41 [13.58; 28.63] kg/m²; and mean weekly physical activity: 86.72 ± 49.96 [7.50; 247.47] MET-h/week. The cohort was precisely age- and sex-matched (mean age difference— 0.02 ± 0.05 [−0.19; 0.08] years per pair). Descriptive statistics are summarized in Table 1.

Table 1. Demographics and descriptive results of participants (overall and by sex).

Parameter	n	Overall	n	Boys	n	Girls	<i>p</i>
Age (years)	124	13.26 ± 1.65 [9.93; 15.92]	62	13.27 ± 1.65 [9.97; 15.92]	62	13.25 ± 1.65 [9.93; 15.92]	0.956
BMI (kg/m ²)	124	18.50 ± 2.41 [13.58; 28.63]	62	18.28 ± 2.17 [13.58; 22.99]	62	18.72 ± 2.62 [13.93; 28.63]	0.311
$\dot{V}O_{2peak}$ (mL/min/kg)	124	46.98 ± 6.89 [31.62; 65.19]	62	50.03 ± 6.18 [35.44; 65.19]	62	43.98 ± 6.25 [31.62; 60.09]	<0.001 *
VT2 (mL/min/kg)	105	42.97 ± 6.82 [27.10; 60.00]	51	46.53 ± 5.77 [35.85; 60.00]	54	39.61 ± 6.01 [27.10; 56.65]	<0.001 *
VT2/ $\dot{V}O_{2peak}$ (%)	105	90.11 ± 5.82 [68.04; 99.40]	51	91.37 ± 4.98 [79.60; 99.40]	54	88.91 ± 6.32 [68.04; 98.33]	0.030 *
HR _{peak} (absolute)	124	187.66 ± 9.58 [165; 211]	62	188.48 ± 10.39 [165; 211]	62	186.85 ± 8.71 [166; 209]	0.351
RER _{peak} (absolute)	124	1.13 ± 0.00 [0.98; 1.25]	62	1.12 ± 0.05 [0.98; 1.21]	62	1.13 ± 0.05 [1.00; 1.25]	0.370
Workload (watts)	124	205.97 ± 62.15 [91; 368]	62	216.7 ± 195.39 [109; 368]	62	195.39 ± 50.22 [91; 303]	0.058
Hb (g/dL)	124	14.03 ± 0.90 [11.8; 17.2]	62	14.43 ± 0.85 [12.9; 17.2]	62	13.6 ± 0.74 [11.8; 15.7]	<0.001 *

*, statistically significant ($p < 0.05$); kg, kilograms; m, meters; BMI, body-mass-index; mL, milliliters; min, minute; HR, heartrate; RER, Respiratory Exchange Ratio; Hb, hemoglobin.

3.2. Hemoglobin Concentration and Age

Mean Hb concentration was 14.43 ± 0.85 g/dL in boys ($n = 62$) and 13.6 ± 0.74 g/dL in girls ($n = 47$), with significantly higher values in boys ($p < 0.001$). Across the total sample, Hb correlated positively with age ($R = 0.246$, $n = 97$, $p = 0.015$ *). Stratified analyses indicated a strong positive correlation in boys ($R = 0.561$, $n = 50$, $p < 0.001$ *), whereas in girls, the relationship was negative, though not statistically significant ($R = -0.156$, $n = 47$, $p = 0.294$). Comparable results were obtained using Spearman's rank correlations (overall: $R = 0.217$, $n = 97$, $p = 0.033$ *; boys: $R = 0.576$, $n = 50$, $p < 0.001$ *; girls: $R = -0.167$, $n = 47$, $p = 0.263$). Multiple linear regression confirmed significant main effects of age ($B = 0.29$,

SE = 0.06, $p < 0.001$), sex ($B = 4.04$, SE = 1.23, $p = 0.001$), as well as a significant age $\times$ sex interaction ($B = -0.37$, SE = 0.09, $p < 0.001$).

The overall model was significant, $F(3, 93) = 17.90$, $p < 0.001$, explaining 36.6% of the variance in Hb ($R^2 = 0.37$, adj. $R^2 = 0.35$). Simple slopes analyses revealed that in boys, Hb increased significantly with age ($B = 0.29$, $p < 0.001$), whereas in girls, Hb showed a slight, nonsignificant decline with increasing age ($B = -0.07$, $p = 0.29$). This pattern indicates that the relationship between age and Hb concentration differs by sex: boys start at lower Hb values but show an age-related increase, while girls start higher but remain stable or slightly decline with age (see Figure 1).

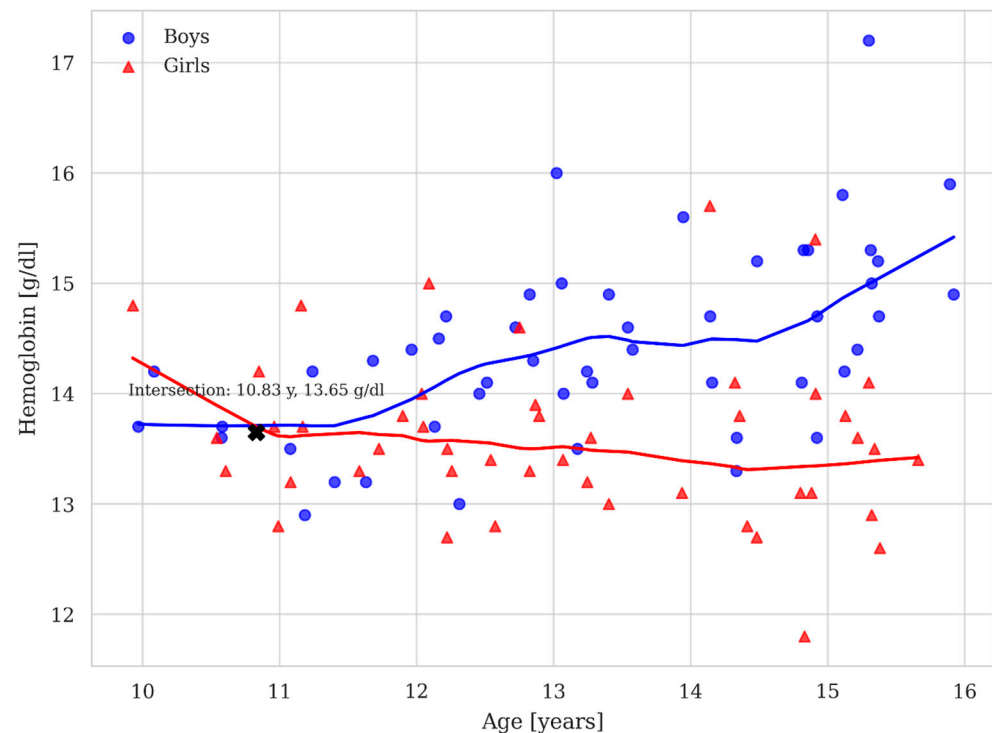


Figure 1. Relationship between hemoglobin concentration (Hb) and age by biological sex; Intersection at age 10.83 years, Hb 13.65 g/dL; blue, boys; red, girls. Bold x marks the intersection point of the curves.

3.3. Aerobic Power

Relative peak oxygen uptake ($\dot{V}O_{2peak}$) for the total cohort was 46.98 ± 6.89 mL/min/kg ($n = 123$). Boys achieved a mean $\dot{V}O_{2peak}$ of 50.03 ± 6.18 mL/min/kg ($n = 61$), which was significantly higher than girls (43.98 ± 6.25 mL/min/kg, $n = 62$; $p < 0.001$).

A simple linear regression revealed a significant positive association between Hb and $\dot{V}O_{2peak}$, $F(1, 95) = 17.72$, $p < 0.001$, explaining 15.7% of the variance in Hb ($R^2 = 0.16$). $\dot{V}O_{2peak}$ was a significant positive predictor of Hb ($B = 0.052$, SE = 0.012, $\beta = 0.40$, $p < 0.001$), indicating that higher $\dot{V}O_{2peak}$ values were associated with higher hemoglobin concentrations.

The multiple regression model tested the effects of Hb, sex, and their interaction on $\dot{V}O_{2peak}$. The model was significant, $F(3, 93) = 11.79$, $p < 0.001$, explaining 27.5% of the variance in $\dot{V}O_{2peak}$ ($R^2 = 0.28$). Hb was a significant positive predictor of $\dot{V}O_{2peak}$ ($B = 2.00$, SE = 0.99, $\beta = 0.26$, $p = 0.046$), indicating that higher hemoglobin concentrations were associated with higher $\dot{V}O_{2peak}$. Neither sex ($B = 6.02$, $p = 0.779$) nor the Hb $\times$ sex interaction ($B = -0.81$, $p = 0.600$) was significant, suggesting that the positive association between Hb concentration and $\dot{V}O_{2peak}$ was comparable across boys and girls. The regression slope for Hb ($B = 2.00$) indicates that, on average, $\dot{V}O_{2peak}$ increases by approximately

2 mL/kg/min for each 1 g/dL increase in hemoglobin concentration. The strength of the association between Hb concentration and $\dot{V}O_{2\text{peak}}$ did not differ significantly between sexes (see Figure 2). Simple linear regression showed that Hb concentration significantly predicted $\dot{V}O_{2\text{peak}}$ in males ($F(1, 48) = 4.51, p = 0.039, R^2 = 0.09$), with $\dot{V}O_{2\text{peak}}$ increasing by 1.99 mL/kg/min for each 1 g/dL increase in hemoglobin. For females, the model was not significant ($F(1, 45) = 0.94, p = 0.337, R^2 = 0.02$), although $\dot{V}O_{2\text{peak}}$ increased by 1.19 mL/kg/min per 1 g/dL increase in hemoglobin.

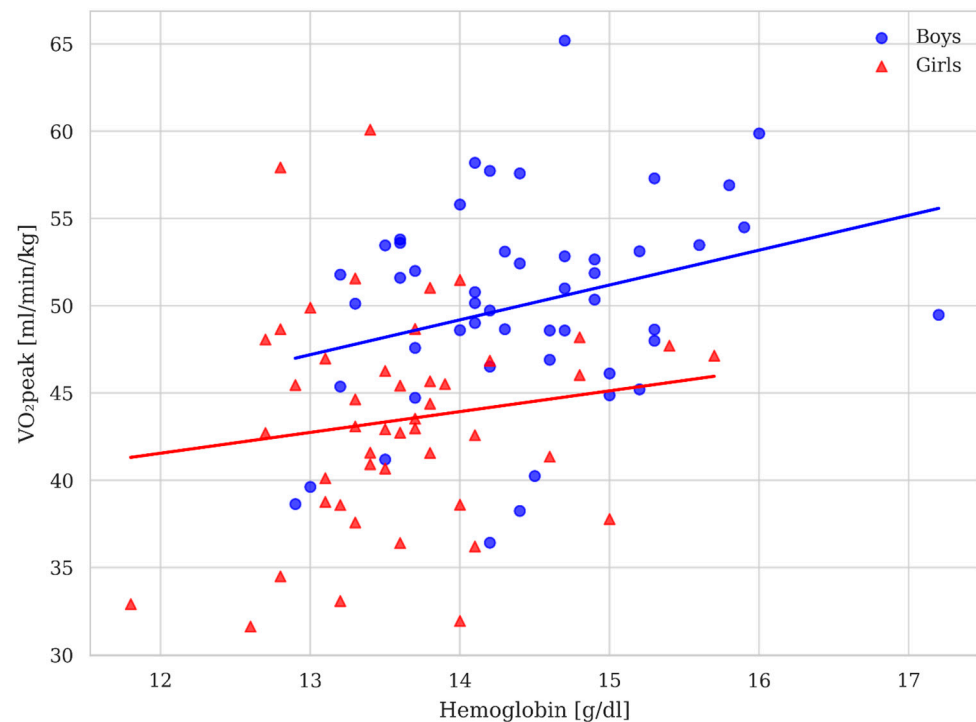


Figure 2. Relationship between $\dot{V}O_{2\text{peak}}$ and hemoglobin concentration by biological sex; blue, boys; red, girls.

4. Discussion

This study provides new insights into the hematological and aerobic characteristics of highly trained adolescent athletes, a population that has been largely understudied compared with untrained or mixed cohorts. In a balanced sample of 62 sex- and age-matched youth athletes, we observed pronounced sex- and age-specific differences in hemoglobin concentration and aerobic power. Boys displayed significantly higher hemoglobin levels than girls, with values increasing across age, while girls exhibited stable or slightly declining hemoglobin concentrations. Boys also demonstrated higher relative $\dot{V}O_{2\text{peak}}$ values, yet the positive association between hemoglobin and $\dot{V}O_{2\text{peak}}$ was comparable across sexes. These findings emphasize that, even in a cohort with high training exposure, sex-specific pubertal development remains the primary driver of hematological trajectories, whereas hemoglobin concentration emerges as a robust predictor of aerobic performance regardless of sex.

The sex divergence in hemoglobin concentration observed here is consistent with established developmental physiology. Before puberty, hematological parameters are largely comparable in boys and girls. With pubertal onset, however, this parallel trajectory diverges as testosterone stimulates erythropoiesis through increased EPO signaling and reduced hepcidin activity, resulting in significant gains in hemoglobin mass and concentration in boys [6,14]. From this point onward, the hemoglobin trajectories of boys and girls diverge in a widening, bracket-like pattern with age, indicating that no parallel course is re-

established during adolescence and underscoring the dominant influence of sex hormones on erythropoietic development. Girls' hemoglobin values typically remain unchanged or decline slightly after menarche, a pattern attributed to menstrual blood loss, increased iron requirements, and the modulatory role of estrogen in iron metabolism [7,8,22]. By late adolescence, boys exceed girls approximately by 1–2 g/dL in hemoglobin concentration, a difference that persists into adulthood as both sexes thereafter follow roughly parallel trajectories again on distinct absolute levels [4,14]. Our results mirror these patterns in a high-performance context, supporting the interpretation that endocrine regulation governs hematological development during adolescence.

Importantly, the association between hemoglobin and aerobic power persisted in this highly trained sample. Each unit increase in hemoglobin was associated with a meaningful rise in $\dot{V}O_{2\text{peak}}$, underscoring the central role of oxygen-carrying capacity in limiting endurance performance. Prior adult studies have established that each gram of Hbmass yields ~4.0 mL/min higher $\dot{V}O_{2\text{peak}}$ [3]. Our findings demonstrate that this relationship is similar in youth athletes, with proportional benefits in both sexes. Thus, hemoglobin concentration can be considered a fundamental determinant of aerobic power across developmental stages, in the context of high-volume, systematic training.

The specificity of the present cohort provides important novelty. While most existing pediatric data derive from untrained populations, our study demonstrates that the classical sex- and age-related patterns in Hb and $\dot{V}O_{2\text{peak}}$ are preserved in young athletes who already engage in high weekly training volumes. The observed bracket-like divergence in hemoglobin trajectories further highlights that maturational, hormone-driven mechanisms dominate over training-induced adaptations throughout adolescence, supporting earlier conclusions that training alone does not override maturational trajectories but rather interacts with them [14,23]. In boys, training coincides with androgen-driven increases in Hb, while in girls, high training loads may not prevent Hb stabilization or decline if iron availability is compromised. This has direct relevance for pediatric sports medicine, where monitoring of hematological status, particularly in young female athletes, should be considered integral to training surveillance.

Limitations and Future Directions

Several limitations should be acknowledged. First, the cross-sectional design precludes causal inference and prevents tracking of individual developmental trajectories across puberty. Second, pubertal maturation was not directly assessed (via Tanner staging or hormonal profiling), and chronological age alone may not fully capture biological development. Third, we measured Hb concentration but not total Hbmass or blood volume, which are more accurate indicators of oxygen-carrying capacity. Because Hb concentration reflects hemoglobin per unit volume and is sensitive to acute plasma-volume fluctuations (e.g., hydration, posture, short-term training or environmental effects), our estimates of the association with aerobic performance may be partially influenced by volume status and could differ in magnitude or precision had Hbmass been assessed. Fourth, iron status (ferritin, transferrin saturation, hepcidin) was not determined. This is critical, as iron deficiency is highly prevalent in adolescent female athletes and directly influences Hb levels and aerobic performance. Moreover, HB may vary with menstrual-cycle-related changes in plasma volume and iron status. As the cycle phase was not assessed in our cohort, residual confounding is possible. Future studies should time assessments to the cycle phase and/or adjust for menstrual status. Fifth, the sample consisted exclusively of competitive athletes with substantial training loads, limiting generalizability to untrained youth. Finally, participants represented a heterogeneous range of sport disciplines, and sport-specific effects on hematological adaptation were not explored. Residual confounding

could therefore apply in our cohort due to differences in training characteristics, which have been linked to hematological profiles in endurance athletes [24].

Future research should address these limitations by adopting longitudinal designs that follow athletes from pre-trough late puberty, thereby capturing developmental trajectories of Hb and $\dot{V}O_2$ peak across critical maturational stages. Such studies should incorporate direct assessment of Hbmass and blood volume to provide more accurate estimates of oxygen-carrying capacity than concentration measures alone. The integration of iron biomarkers and hormonal assays is essential to account for nutritional and endocrine influences on hematological development. Ultimately, the combined assessment of Hb, iron status and key maturational hormones may not only elucidate physiological mechanisms but could also enable indirect evaluation of an athlete's iron balance and maturational stage in the future. In addition, sport-specific analyses are warranted to determine whether endurance training exerts distinct effects on hematological parameters compared with mixed-discipline sports. Finally, future work should aim to define training thresholds and developmental windows during which exercise most effectively interacts with growth and maturation to enhance hemoglobin levels and aerobic performance.

5. Conclusions

This study demonstrates that hemoglobin concentration is a central determinant of aerobic performance in adolescent athletes, even with a cohort characterized by high and consistent training loads. Boys showed age-related increases in Hb and $\dot{V}O_2$ peak, whereas girls exhibited stable or slightly declining Hb concentrations. Crucially, Hb was a significant predictor of $\dot{V}O_2$ peak in both sexes, with comparable slopes, underscoring its universal role in limiting aerobic performance. These findings extend current knowledge by confirming that sex-specific pubertal trajectories of Hb are preserved in highly trained youth, highlighting the importance of integrating hematological monitoring into athlete development programs. Future longitudinal, mechanistically focused studies are needed to clarify how growth, sex hormones, iron metabolism, and training interact to shape aerobic power during adolescence.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the TUM Ethics Committee of the Technical University of Munich (protocol code: 2023-426-S-DFG-SB; date of approval: 13 October 2023).

Informed Consent Statement: All participants were provided with a written document containing detailed study information, along with verbal explanations. Depending on the participants' age, written informed consent was obtained from both the participants themselves and their legal guardians.

Data Availability Statement: The datasets presented in this article are not readily available due to privacy and ethical restrictions. Requests to access the datasets should be directed to the corresponding author.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

$\dot{V}O_{2peak}$	peak oxygen uptake
Hb	hemoglobin
Hbmass	hemoglobin mass
EPO	erythropoietin
MuCAYA	Munich Cardiovascular Adaptations in Young Athletes
CPET	cardiopulmonary exercise testing
RER	respiratory exchange ratio
ECG	electrocardiogram
PA	physical activity
MoMo-PAQ	Motorik-Modul-Physical Activity Questionnaire
MET-h	metabolic equivalent of training hours

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