International Journal of Sports Physiology and Performance, (Ahead of Print)
https://doi.org/10.1123/ijspp.2023-0205
 First Published Online: July 17, 2024

Predicting future athletic performance in young female road cyclists based on aerobic fitness and hematological variables

Original Investigation

Dariusz Sitkowski, Jadwiga Malczewska-Lenczowska, Ryszard Zdanowicz, Michał Starczewski, Andrzej Pokrywka, Piotr Żmijewski, Raphael Faiss

Dariusz Sitkowski, *Department of Physiology, Institute of Sport – National Research Institute, Warsaw, Poland*

Jadwiga Malczewska-Lenczowska, *Department of Physiology Nutrition and Dietetics, Institute of Sport – National Research Institute, Warsaw, Poland*

Ryszard Zdanowicz, *Department of Physiology, Institute of Sport – National Research Institute, Warsaw, Poland*

Michał Starczewski – *Department of Physiotherapy Fundamentals*, *Faculty of Rehabilitation, University of Physical Education, Warsaw, Poland*

Andrzej Pokrywka – *Department of Biochemistry and Pharmacogenomics, Faculty of Pharmacy, Medical University of Warsaw, Warsaw, Poland*

Piotr Żmijewski – *Department of Biomedical Sciences, Faculty of Physical Education, University of Physical Education, Warsaw, Poland*

Raphael Faiss – *Institute of Sport Sciences, University of Lausanne, Switzerland*

Corresponding author – Raphael Faiss,
e-mail: raphael.faiss@unil.ch

Running head – Predicting future cycling performance

Abstract word count - 250
Text-only word count - 3215
Number of figures and tables – 2 figures and 3 tables

International Journal of Sports Physiology and Performance, (Ahead of Print)
https://doi.org/10.1123/ijspp.2023-0205
 First Published Online: July 17, 2024

Abstract

Purpose: This study aimed to determine whether the initial levels of aerobic fitness and hematological variables in young female road cyclists are related to their athletic performance development during their careers. Methods: Results of graded exercise tests (GXT) on a cycle ergometer and total hemoglobin mass (tHb-mass) measurements were analyzed in thirty-four female road cyclists (aged 18.6 [1.9] years). Among them, two groups were distinguished based on their competitive performance (*Union Cycliste Internationale* [UCI] world ranking) over the following eight years. Areas under the curve (AUC) in receiver operating characteristic (ROC) curves were calculated as indicators of elite performance prediction. Results: Initial GXT variables (peak power, peak oxygen uptake, and power at 4 mmol/L blood lactate) were not significantly different in elite (n = 13) vs. non-elite (n = 21) riders. In contrast, elite riders had higher tHb-mass expressed either in absolute (664 [75] vs. 596 [59] g, $P = .006$) or normalized to body mass (11.2 [0.8] vs. 10.3 [0.7] g/kg, $P = .001$) and fat-free mass (14.4 [0.9] vs. 13.1 [0.9] g/kg, $P < .001$). Also, absolute and relative erythrocyte volume were significantly higher in elite subjects (P values ranged from < .001 to .006). Of all the variables analyzed, the relative tHb-mass had the highest predictive ability to reach the elite level (AUC ranged from .82 to .85). Conclusions: Measurement of tHb-mass can be a helpful tool in talent detection to identify young female road cyclists with the potential to reach the elite level in the future.

Keywords: endurance athletes, talent identification, graded exercise test, total hemoglobin mass, intravascular volumes

International Journal of Sports Physiology and Performance, (Ahead of Print)
https://doi.org/10.1123/ijspp.2023-0205
 First Published Online: July 17, 2024

Introduction

Measurements of maximal and peak oxygen uptake, peak power output, and power at the lactate threshold, taken during incremental exercise testing in the laboratory, are considered valid determinants of performance in road cycling.[1–3] Physiological assets, evaluated in the junior age category, may determine a cyclists' adaptive potential and thus, their ability to reach an elite level in their career development.[4] Accordingly, measures of aerobic fitness have been used for talent detection to predict the professional careers of young riders, but with divergent results.[5,6]

It is well-documented that high-level endurance athletes exhibit a higher total hemoglobin mass (tHb-mass) than untrained individuals, non-endurance athletes, or when compared to less successful counterparts.[7,8] This seems reasonable since more hemoglobin is directly related to improvements in oxygen transport capacity in the blood.[7] Buffering capacity in blood, and nitric oxide released from red blood cells, may also facilitate higher tHb-mass leading to enhanced vascular reactivity and improved blood flow in working muscles.[9] Overall, hemoglobin definitely plays a crucial role in endurance exercise performance, which is mainly limited by oxygen supply to working muscles in trained individuals.[10] Measuring tHb-mass in novice athletes was therefore suggested as a valuable tool for identifying talent in road cycling[11] while evidence to date is scarce. Nevertheless, the results of a recent longitudinal study on male cross-country skiers and triathletes from age 16 to 19 years suggested that tHb-mass is a good predictor of national team membership later in their career.[12] In contrast to hemoglobin concentration ([Hb]), tHb-mass is not affected by changes in plasma volume, therefore reflecting the hematological status of athletes much better than [Hb]. Interestingly, during puberty, the additive effect of endurance training on tHb-mass was observed only in boys, while no changes were found in girls at the same time.[13] Development of tHb-mass in late adolescence in boys was reported as comparably small, and not influenced by endurance training, supporting the fact that tHb-mass at the age of 16 years may represent an important determinant for tHb-mass as adults, and possibly for attaining high-level endurance performance.[14] Besides, only minor variations in tHb-mass (3% in average) were reported in elite female cyclists during a competitive season.[15] tHb-mass in competitive endurance athletes was also reported to be stable (individual oscillation <6%) throughout the training year, despite important (~25%) fluctuations in training volume.[16] Furthermore, no increase in relative tHb-mass was observed during one year of training in novice male and female cyclists

International Journal of Sports Physiology and Performance, (Ahead of Print)
https://doi.org/10.1123/ijspp.2023-0205
 First Published Online: July 17, 2024

aged 11-15 years.[11] Nevertheless, tHb-mass increased by 6.0% after endurance training in previously untrained individuals,[10] and 6.5% in athletes with altitude training.[7] Taken together, these findings show that tHb-mass is relatively stable and only slightly affected by age and training, in contrast to indices of exercise capacity.[17] Thus, we hypothesize that there is a genetic predisposition of high tHb-mass in elite athletes.[7] On the other hand, some adult individuals with no history of training may have a tHb-mass comparable to endurance athletes,[18] confirming tHb-mass depends more on the presence of genetic characteristics rather than training. While genetic testing could theoretically be included for talent identification purposes in road cycling,[19] single nucleotide polymorphisms linked to tHb-mass has so far only been reported in male road cyclists, but not in women.[20]

Finally, recent scientific focus has been placed on women's cycling with an extensive description of physical requirements for elite performers. However, scarce literature has described those physiological factors underlying athletic performance in elite female cyclists. This study aimed to determine whether the initial levels of aerobic fitness and hematological variables in young female road cyclists are related to athletic performance development during their sporting careers. We hypothesized that the initial level of tHb-mass (measured at a junior age) has some predictive value in determining elite status at a senior level.

Methods

Subjects

Thirty-seven female road cyclists (mean ± SD: age 18.6 ± 2.1 years, body height 168 ± 5 cm, body mass 58.0 ± 5.5 kg, body fat 21.5 ± 3.0%, fat-free mass 45.4 ± 3.4 kg, and training experience 6.1 ± 2.6 years) participated in this study. None of them was born or lived at altitudes above 700 m. While athletes were subject to anti-doping tests in- or out-of-competition, none of them returned any adverse analytical finding nor were sanctioned for any anti-doping rule violation.

This study was approved by the local Committee of Ethics (KEBN-22-75-DS) and performed in accordance with the Declaration of Helsinki and its later amendments. All subjects, and parents or legal guardians in the case of those under 18 years of age, provided an informed written consent before taking part in the study.

Design

For this retrospective study, we used laboratory tests results collected from athletes who participated in a Polish national talent identification program in 2013 and 2014. Over the following eight years, their performances were retrieved from the

International Journal of Sports Physiology and Performance, (Ahead of Print)
https://doi.org/10.1123/ijspp.2023-0205
 First Published Online: July 17, 2024

Union Cycliste Internationale (UCI) as points scored in the world ranking in the women's elite category (www.uci.org). Any athlete who stopped training or competing in road cycling within three years after initial testing was excluded from the analysis. Three athletes stopped competing in road cycling within 3 years after the initial tests and were therefore excluded from the analysis. A period of eight years was considered sufficient to reach the elite level in professional cycling, which was defined as reaching a ranking among the top 400 in the UCI ranking. Moreover, after this period, the age of the athletes who took part in our study was similar to the age (27.8 ± 3.9 years) of the top 10 female road cyclists in the 2014 UCI ranking.

Methodology

The athletes spent the night before performing tests in a dormitory located in the laboratory building. The next day they underwent a sequence of tests after a standardized breakfast (in the order listed below): blood sampling, anthropometric measurements, medical examination, graded exercise test, and measurements of total hemoglobin mass and intravascular volumes.

Blood sampling

Between 7.30 and 8.00 a.m., and after 15-min rest in a sitting position, 10 ml blood samples (Vacuette EDTA K2 tubes, Greiner Bio-One, Austria) were collected by trained phlebotomists from an antecubital vein to perform a complete blood count (Advia 120, Bayer, Germany).

Anthropometric measurements

Body height, body mass (BM), and skinfold thicknesses at four sites: biceps, triceps, subscapular, and supra-iliac, were measured after urination. BM was measured with an accuracy of 50 g using an electronic scale (Dolphin, CAS Corp., South Korea); the athletes wore only underwear for this measurement. The percent of body fat and fat-free mass (FFM) were calculated based on skinfold thickness measurements.[21]

Medical examination

All athletes had current medical certificates confirming their ability to practice competitive sports and reported no health problems on the day of the tests and the preceding 2 weeks. Nevertheless, they underwent (at least 75 minutes after breakfast) a medical examination that included a medical history, electrocardiography, auscultation of the heart and lungs, and blood pressure measurement.

Graded exercise test

A graded exercise test (GXT) was performed on a personal bicycle frame mounted on a cycle ergometer (Cyclus2,

International Journal of Sports Physiology and Performance, (Ahead of Print)
https://doi.org/10.1123/ijspp.2023-0205
 First Published Online: July 17, 2024

Avantronic, Germany). The initial load was 1.5 W/kg body mass and thereafter increased every 3 min by 0.65 W/kg until volitional exhaustion (or cycling cadence <70 rpm). Peak power (Ppeak) was calculated as Pcompl + Pincr x (*t*/180); where Pcompl was power at the last fully completed step, Pincr was power increase, and *t* was a time in seconds completed at the final step.[10] During the GXT, oxygen uptake (VO_2) was recorded breath-by-breath at 15-s sampling intervals (MetaMax 3B analyzer; Cortex, Germany). The average value of the two highest consecutive 15-s VO_2 values was taken as VO_2peak. Within the last 15 s of every load increment, capillary blood (20 µl) was collected from fingertips for assessing lactate concentration ([La]) using a dedicated analyzer (Super GL2, Dr. Müller, Germany). Power corresponding to a [La] of 4 mmol/l (PAT4) was determined.

Total hemoglobin mass and intravascular volumes

At least two hours after the exercise test and after the athletes were instructed in detail on how to perform the required rebreathing procedure, total hemoglobin mass (tHb-mass) and intravascular volumes (erythrocyte volume [EV], plasma volume [PV], and blood volume [BV]) were determined using an optimized carbon monoxide rebreathing method well-described elsewhere.[22] The administered gas mixture consisted of 99.97% chemically pure CO (0.8 ml/kg BM) and 99.5% O_2 (3 l bag). A CO sensor (Pac 7000, Dräger, Germany) was used to check potential leaks in exhaled air before and after the test. Blood (~105 µl) was sampled from the hyperemized (Finalgon, Boehringer Ingelheim, Germany) earlobe in the following order: just before the test (4 samples), and in the 6th (2 samples) and 8th minutes (3 samples) from the beginning of inhalation of the gas mixture (lasting 2 min). The samples served to determine the percentage value of carboxyhemoglobin (HbCO%) using a CO oximeter (ABL 80 Flex, Radiometer, Denmark). A dedicated software (Blood Volume Measurements: SpiCO; Blood tec, Bayreuth, Germany) allowed to calculate tHb-mass and intravascular volumes. All measurements were performed by the same experienced laboratory technicians. A typical error of 2.5% for tHb-mass was determined for the measurement during this study based on duplicate measurements in 11 athletes participating in this study.

Statistical Analysis

Descriptive data are presented as arithmetic means ± SD. The normality of the data distribution and the homogeneity of variance were examined by the Shapiro-Wilk and Levene's tests, respectively. Differences between mean values in the groups were tested using the Student's t-test or Mann-Whitney U test, where appropriate. Receiver operating characteristic (ROC) curve analysis with the area under ROC curve (AUC)

International Journal of Sports Physiology and Performance, (Ahead of Print)
https://doi.org/10.1123/ijspp.2023-0205
 First Published Online: July 17, 2024

determination (DeLong's method) was used to evaluate the predictive value of GXT and hematological variables. The following ranges of AUC were used to describe the goodness of discrimination: = .5 – no discrimination, > .5 < .7 – poor discrimination, ≥ .7 < .8 – acceptable discrimination, ≥ .8 < .9 excellent discrimination, ≥ .9 outstanding discrimination.[23] The Youden index was adopted to set the cut-off points. Additionally, Pearson's correlation coefficients were used to determine associations between selected variables. PQStat statistical software ver. 1.8.4 (PQStat Software Company, Poznan, Poland) and JASP ver. 0.17.1 (University of Amsterdam, Netherlands) were employed. In all analyses, the level of significance was set at $P < .05$.

Results

Over the course of the eight-years of systematic training following the initial tests, 13 women out of the 34 riders (38%) reached the elite level (EL), ranking between 5th and 400th, whereas 21 (62%) were not ranked in the UCI classification, and were included in the non-elite group (NEL).

No significant differences were observed between the groups for anthropometric or training variables (Table 1).

Table 1 somewhere here

From the initial GXT results, no between-group difference was observed for any of the variables. The analysis of hematological variables indicated that EL had significantly higher tHb-mass and EV (both in absolute values and per kg of BM or FFM) than NEL as illustrated in Table 2. Nevertheless, none of the variables was significantly correlated with the UCI ranking in the EL group ($r < .364$, $P > .222$).

Table 2 somewhere here
Figure 1 somewhere here

All GXT variables had poor discriminatory ability (AUC ranged from .61 to.69). Among hematological variables, tHb-mass and EV normalized to kg BM and FFM had an excellent discriminatory ability with AUC ranging from .81 to .85 (Table 3).

Table 3 somewhere here

No significant difference was found between the AUC of tHb-mass/BM and tHb-mass/FFM ($P = .448$). In addition, sensitivity and specificity did not differ substantially between variables (i.e., .92 and .67, respectively).

International Journal of Sports Physiology and Performance, (Ahead of Print)
https://doi.org/10.1123/ijspp.2023-0205
 First Published Online: July 17, 2024

Figure 2 somewhere here

Discussion

In the present study, we investigated whether initial levels of aerobic fitness and hematological status among young female road cyclists were related to athletic performance development in the following 8 years. The most important finding is that selected hematological variables (i.e., total hemoglobin mass [tHb-mass] and erythrocyte volume [EV]) were able to discriminate between those riders who later reached an elite level from those who did not achieve the same developmental level.

tHb-mass and EV, normalized to BM and FFM, demonstrated the highest predictive ability in terms of future athletic development (see Table 3). Such findings confirm earlier published work[11,12,14] that tHb-mass in young endurance-trained athletes, including cyclists, may be an important predictor of athletic performance trajectories, and its measurement may provide a valuable tool for talent identification or training potential. Furthermore, EV was found to be a robust predictor of attaining elite level status. However, EV being calculated from tHb-mass, [Hb], and hematocrit, contains a greater measurement uncertainty compared to the more accurate measurement of tHb-mass.[24]

The GXT variables did not differ between the EL and NEL cyclists (see Table 2) and thus, were unable to discriminate career development in our study cohort. Furthermore, when evaluating the predictive ability of GXT variables (Table 3), Ppeak or PAT4 were not better predictors of future athletic performance compared to VO_2peak. The poor discriminatory ability of the GXT variables may, at least in part, be due to individual variation in training content between riders, despite all being well-trained during the period of testing. Seasonal variation in performance during incremental testing on a cycle ergometer was reported in male cyclists,[17] but no such variation in GXT variables was observed in young girls (aged 13–16) involved in mountain biking.[25] Nevertheless, our results confirmed the AUC values for VO_2peak/BM (.69) reported by other authors, who examined the usefulness of using aerobic fitness indices for predicting the professional career of young male cyclists.[5]

Research on the physiological determinants underpinning athletic performance in women's road cycling is scarce. However, a study on female riders, who represented a wide range of athletic abilities, found that relative VO_2max determined on a cycle ergometer may account for as much as 82% of performance in multi-day road racing[3]. Conversely, VO_2peak emerged as a poor predictor of a successful professional career in a more homogenous group of young male cyclists[5]. Although a high

International Journal of Sports Physiology and Performance, (Ahead of Print)
https://doi.org/10.1123/ijspp.2023-0205
 First Published Online: July 17, 2024

VO_2max would seem a prerequisite for competing at a high level in road cycling, actual endurance performance can vary among individuals with similar levels of VO_2max.[26] Another study on trained female cyclists reported that power at blood lactate transition thresholds and peak aerobic power during incremental exercise testing are better predictors of endurance performance than VO_2peak[2]. In addition, a study on 18-year-old male road cyclists[6] showed that power at the final minute of a ramp cycle ergometer test, but not VO_2max, was able to distinguish between cyclists who later became World Tour riders and those who did not.

Taken together with the current results, we suggest that tHb-mass offers an important indicator of long-term aerobic potential among young female cyclists. Changes in tHb-mass during childhood and adolescence, as reported in the literature, show that relative tHb-mass increases around (and after) puberty in males, while tHb-mass is largely unchanged in females, even those undergoing regular endurance training.[13,14,27] This sex difference in tHb-mass trajectories with pubertal onset could be explained by a marked increase in testosterone levels in boys, being a strong stimulator of erythropoiesis, besides the concomitant positive changes in fat free mass among boys.[28] Some authors, however, failed to find a direct effect of testosterone on erythropoiesis during adolescence.[27]

Although the studied cohort was homogeneous in terms of body composition, the predictive ability of the tHb-mass/FFM (AUC = .85) appears to be slightly greater than that observed for the tHb-mass/BM (AUC = .82) (Table 3). Still, the ROC curve comparison showed that this difference is negligible (Fig. 2). In addition, the determination of FFM may be associated with some measurement error, hence the tHb-mass/FFM does not appear to be a more useful indicator than tHb-mass/BM in female road cyclists, who themselves are generally characterized by having a low degree of fat mass.

The current findings suggest a higher initial tHb-mass amongst those young female road cyclists who also achieved elite status later in their careers. Determining an absolute threshold (for tHb-mass) to become an elite women cyclist does, however, remain difficult. A value of 10.3 g of tHb-mass/BM was considered a target for identifying talent in female riders, based on a linear regression in novice cyclists aged 11–15.[11] Our results suggest 10.6 g/kg as a possible threshold to reach the elite level, with the cut-off point obtained from the ROC curve analysis and the Youden index (Table 3). Interestingly, the average tHb-mass/BM in the EL group was 11.2 ± 0.8 g/kg (Table 2), which is consistent with other data on highly-trained female cyclists (11.1 ± 0.6 g/kg),[29] but lower than world-class female cyclists from the Australian National Team (12.3 ± 0.9 g/kg).[15] Overall,

International Journal of Sports Physiology and Performance, (Ahead of Print)
https://doi.org/10.1123/ijspp.2023-0205
 First Published Online: July 17, 2024

competitive performance in elite female cyclists does appear to be related to their relative tHb-mass.[8]

According to a published classification framework, road cyclists ranked in the top 200 in the UCI ranking could be classified as world-class.[30] Our EL group consisted of riders ranked from 5th to 400th. We therefore recalculated the cut-off point for tHb-mass/BM considering only those riders who were ranked up to 200th (n = 7). The cut-off value remained almost unchanged (10.7 g/kg), while the mean value of the tHb-mass/BM was still the same (11.2 ± 1.0 g/kg) as those athletes ranked up to 400th. Combined with the lack of correlation between tHb-mass and UCI ranking position in the EL group, it appears that a high tHb-mass remains a strong candidate for reaching the elite level in women's road cycling, while other performance determinants need to be tested to explain better rankings in elite riders (i.e., those with a high tHb-mass).

The study undertaken does have inherent limitations. For example, the criterion used to define elite status, the small number of participants tested, and cross-sectional design (during initial testing), may all introduce bias our prediction models. On the other hand, we speculate that some physiological assets (e.g., a high tHb-mass) may have robust predictive power for future performance in this sporting discipline, where aerobic capacity is paramount, while also potentially influencing other factors (e.g. sprint, technical and tactical abilities, aerodynamics, and coping with stressful conditions) that were not considered herein. The role of a rider within a team adds to these complexities. Some cyclists with a favorable physiological predisposition may sacrifice their own rankings in order to support stronger riders within a team.

Practical applications

Aerobic capacity, which is fundamental to performance in road cycling, is strongly related to hematological variables. Both are genetically determined, but while the former can change significantly under the influence of systematic training, the latter can change only moderately, reflecting innate potential better than aerobic capacity indices. Therefore, measurement of tHb-mass can be a helpful tool to identify young female road cyclists with the potential to reach the elite level. As the use of junior sports performance for selection purposes has been strongly questioned recently,[31] this information may be of prime importance in talent identification for sporting federations, teams, and coaches.

Conclusions

Hematological variables (i.e., total hemoglobin mass [tHb-mass] and erythrocyte volume) measured at junior age allowed to distinguish female road cyclists who reached the elite level in the

International Journal of Sports Physiology and Performance, (Ahead of Print)
https://doi.org/10.1123/ijspp.2023-0205
 First Published Online: July 17, 2024

following 8 years from those who did not achieve the same performance level. However, initial fitness and performance in a graded exercise test were poor predictors of reaching future elite performance level. Overall, the relative tHb-mass at a young age represented the most robust predictor of future elite performance in women's road cycling.

Acknowledgments
The authors of this article wish to thank Mr. Andrzej Piątek – the former Sports Director of the Polish Cycling Federation, for his help in organizing this research, Mrs. Beata Szczepańska M.Sc. for assessing the cyclists' body composition, and Dr. Blair Crewther for valuable feedback when preparing this manuscript.

References

1. Faria EW, Parker DL, Faria IE. The science of cycling: physiology and training - part 1. *Sports Med*. 2005;35(4):285-312. doi:10.2165/00007256-200535040-00002

2. Bishop D, Jenkins DG, Mackinnon LT. The relationship between plasma lactate parameters, Wpeak and 1-h cycling performance in women. *Med Sci Sports Exerc*. 1998;30(8):1270-1275.

3. Pfeiffer R, Harder B, Landis D, Barber D, Harper K. Correlating indices of aerobic capacity with performance in elite women road cyclists. *J Strength Cond Res*. 1993;7(4):201-205.

4. Schumacher YO, Mroz R, Mueller P, Schmid A, Ruecker G. Success in elite cycling: A prospective and retrospective analysis of race results. *J Sports Sci*. 2006;24(11):1149-1156. doi:10.1080/02640410500457299

5. Menaspà P, Sassi A, Impellizzeri FM. Aerobic fitness variables do not predict the professional career of young cyclists. *Med Sci Sports Exerc*. 2010;42(4):805-812. doi:10.1249/MSS.0b013e3181ba99bc

6. Svendsen IS, Tønnesen E, Tjelta LI, Ørn S. Training, Performance, and Physiological Predictors of a Successful Elite Senior Career in Junior Competitive Road Cyclists. *Int J Sports Physiol Perform*. Published online November 2018:1-6. doi:10.1123/ijspp.2017-0824

International Journal of Sports Physiology and Performance, (Ahead of Print)
https://doi.org/10.1123/ijspp.2023-0205
 First Published Online: July 17, 2024

7. Schmidt W, Prommer N. Effects of various training modalities on blood volume. *Scand J Med Sci Sports*. 2008;18 Suppl 1:57-69. doi:10.1111/j.1600-0838.2008.00833.x

8. Zelenkova IE, Zotkin S V, Korneev P V, Koprov S V, Grushin AA. Relationship between total hemoglobin mass and competitive performance in endurance athletes. *J Sports Med Phys Fitness*. 2019;59(3):352-356. doi:10.23736/S0022-4707.18.07865-9

9. Mairbaurl H. Red blood cells in sports: effects of exercise and training on oxygen supply by red blood cells. *Front Physiol*. 2013;4:332. doi:10.3389/fphys.2013.00332

10. Montero D, Cathomen A, Jacobs RA, et al. Haematological rather than skeletal muscle adaptations contribute to the increase in peak oxygen uptake induced by moderate endurance training. *J Physiol*. 2015;593(20):4677-4688. doi:10.1113/JP270250

11. Eastwood A, Bourdon PC, Withers RT, Gore CJ. Longitudinal changes in haemoglobin mass and VO(2max) in adolescents. *Eur J Appl Physiol*. 2009;105(5):715-721. doi:10.1007/s00421-008-0953-x

12. Wehrlin JP, Steiner T. Is Hemoglobin Mass at Age 16 a Predictor for National Team Membership at Age 25 in Cross-Country Skiers and Triathletes? *Front Sport Act living*. 2021;3:580486. doi:10.3389/fspor.2021.580486

13. Mancera-Soto EM, Ramos-Caballero DM, Rojas J JA, et al. Hemoglobin Mass, Blood Volume and VO(2)max of Trained and Untrained Children and Adolescents Living at Different Altitudes. *Front Physiol*. 2022;13:892247. doi:10.3389/fphys.2022.892247

14. Steiner T, Maier T, Wehrlin JP. Effect of Endurance Training on Hemoglobin Mass and V˙O2max in Male Adolescent Athletes. *Med Sci Sports Exerc*. 2019;51(5):912-919. doi:10.1249/MSS.0000000000001867

15. Garvican LA, Martin DT, McDonald W, Gore CJ. Seasonal variation of haemoglobin mass in internationally competitive female road cyclists. *Eur J Appl Physiol*. 2010;109(2):221-231. doi:10.1007/s00421-009-1349-2

16. Prommer N, Sottas P-E, Schoch C, Schumacher YO, Schmidt W. Total hemoglobin mass - a new parameter to

https://doi.org/10.1123/ijspp.2023-0205
 First Published Online: July 17, 2024

detect blood doping? *Med Sci Sports Exerc*. 2008;40(12):2112-2118. doi:10.1249/MSS.0b013e3181820942

17. Zapico AG, Calderon FJ, Benito PJ, et al. Evolution of physiological and haematological parameters with training load in elite male road cyclists: a longitudinal study. *J Sports Med Phys Fitness*. 2007;47(2):191-196.

18. Martino M, Gledhill N, Jamnik V. High VO2max with no history of training is primarily due to high blood volume. *Med Sci Sports Exerc*. 2002;34(6):966-971. doi:10.1097/00005768-200206000-00010

19. Jacob Y, Spiteri T, Hart NH, Anderton RS. The Potential Role of Genetic Markers in Talent Identification and Athlete Assessment in Elite Sport. *Sport (Basel, Switzerland)*. 2018;6(3). doi:10.3390/sports6030088

20. Malczewska-Lenczowska J, Orysiak J, Majorczyk E, Sitkowski D, Starczewski M, Żmijewski P. HIF-1α and NFIA-AS2 Polymorphisms as Potential Determinants of Total Hemoglobin Mass in Endurance Athletes. *J strength Cond Res*. 2022;36(6):1596-1604. doi:10.1519/JSC.0000000000003686

21. Durnin J V, Womersley J. Body fat assessed from total body density and its estimation from skinfold thickness: measurements on 481 men and women aged from 16 to 72 years. *Br J Nutr*. 1974;32(1):77-97. doi:10.1079/bjn19740060

22. Schmidt W, Prommer N. The optimised CO-rebreathing method: a new tool to determine total haemoglobin mass routinely. *Eur J Appl Physiol*. 2005;95(5-6):486-495. doi:10.1007/s00421-005-0050-3

23. Hosmer D, Lemeshow S, Sturdivant R. *Applied Logistic Regression*. 3rd ed. John Wiley & Sons; 2013.

24. Gore CJ, Hopkins WG, Burge CM. Errors of measurement for blood volume parameters: a meta-analysis. *J Appl Physiol*. 2005;99(5):1745-1758. doi:10.1152/japplphysiol.00505.2005

25. Fornasiero A, Savoldelli A, Modena R, Boccia G, Pellegrini B, Schena F. Physiological and anthropometric characteristics of top-level youth cross-country cyclists. *J Sports Sci*. 2018;36(8):901-906. doi:10.1080/02640414.2017.1346271

26. Coyle EF, Coggan AR, Hopper MK, Walters TJ. Determinants of endurance in well-trained cyclists. *J*

International Journal of Sports Physiology and Performance, (Ahead of Print)
https://doi.org/10.1123/ijspp.2023-0205
 First Published Online: July 17, 2024

Appl Physiol. 1988;64(6):2622-2630. doi:10.1152/jappl.1988.64.6.2622

27. Landgraff HW, Hallén J. Longitudinal Training-related Hematological Changes in Boys and Girls from Ages 12 to 15 yr. *Med Sci Sports Exerc*. 2020;52(9):1940-1947. doi:10.1249/MSS.0000000000002338

28. Hero M, Wickman S, Hanhijärvi R, Siimes MA, Dunkel L. Pubertal upregulation of erythropoiesis in boys is determined primarily by androgen. *J Pediatr*. 2005;146(2):245-252. doi:10.1016/j.jpeds.2004.09.002

29. Garvican LA, Pottgiesser T, Martin DT, Schumacher YO, Barras M, Gore CJ. The contribution of haemoglobin mass to increases in cycling performance induced by simulated LHTL. *Eur J Appl Physiol*. 2011;111(6):1089-1101. doi:10.1007/s00421-010-1732-z

30. Jeukendrup AE, Craig NP, Hawley JA. The bioenergetics of World Class Cycling. *J Sci Med Sport*. 2000;3(4):414-433. doi:10.1016/s1440-2440(00)80008-0

31. Barth M, Güllich A, Macnamara BN, Hambrick DZ. Quantifying the Extent to Which Junior Performance Predicts Senior Performance in Olympic Sports: A Systematic Review and Meta-analysis. *Sports Med*. 2024;54(1):95-104. doi:10.1007/s40279-023-01906-0