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Cardiorespiratory Fitness Indicators in Young Athletes: Analysis for Personalized Training Programs

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Abstract: *This study investigates the cardiorespiratory indicators of junior athletes (16–18 years old) with a focus on aerobic (AT) and anaerobic (AnT) thresholds, maximal oxygen uptake (VO_2max), power output, and their relationship with anthropometric parameters. Testing was conducted on 26 triathletes who are candidates for Master of Sport (13 males and 13 females) using a Wattbike ergometer, a Cosmed gas analyzer, and a Polar heart rate monitor. Significant individual and gender differences in functional capabilities were observed. The mean VO_2max values were 68.7±7.2 ml/min/kg for males and 55.1±8.4 ml/min/kg for females ($p < 0.001$), indicating differences in oxygen potential and aerobic power between the groups. The anaerobic threshold was reached at 84.3±6.1% of VO_2max on average, demonstrating high lactate tolerance and efficient use of aerobic and anaerobic energy systems. The power-to-weight ratio (W/kg) was higher in athletes with lower BMI, with values such as 6.0 W/kg at a BMI of 20.8 and 4.9 W/kg at a BMI of 15.9.*
The results highlight the necessity of personalized training programs based on threshold values and anthropometric characteristics. Athletes with low AT/MAX% (<70%) should focus on aerobic endurance development, while those with critically low BMI (<18.5) require adjustments in nutrition and workload to prevent metabolic disorders. This study also proposes a methodology for integrating objective testing data into training programs to optimize young triathletes' preparation. The findings have practical implications for coaches and sports physiologists working in endurance sports.
Keywords: *cardiorespiratory testing, aerobic threshold, anaerobic threshold, VO_2max, personalized training.*

Introduction

Modern sports science places significant emphasis on studying cardiorespiratory indicators as key markers of athletes' physical fitness, particularly in endurance sports like triathlon (Joyner & Coyle, 2008). The individualization of training programs based on objective physiological data has become a primary trend in junior athlete preparation, supported by an increasing number of studies focused on optimizing aerobic and anaerobic thresholds (Buchheit & Laursen, 2013). Maximal oxygen uptake (VO_2max) remains the "gold standard" for assessing aerobic capacity, yet its interpretation requires consideration of age, sex, and anthropometric factors (Bassett & Howley, 2000).

In young athletes, the development of cardiorespiratory endurance involves unique physiological and metabolic adaptations driven by pubertal changes (Armstrong & McManus, 2011). Recent research indicates that the anaerobic threshold (AnT) in juniors occurs at higher VO_2max levels compared to adults, underscoring the need for age-specific training adaptations (Wernhart et al., 2021). However, the relationship between body mass, BMI, and relative power output (W/kg) remains insufficiently studied, especially concerning gender differences (Stöggl & Sperlich, 2015). For instance, female triathletes exhibit lower VO_2max compared to males, partly due to differences in body composition and hormonal profile (Heiestad et al., 2022).

Advanced technologies, such as gas analysis and cycle ergometry, allow precise determination of threshold values, yet their integration into training programs requires methodological standardization (Burnley & Jones, 2022). The use of the respiratory exchange ratio (RER) to identify AnT demonstrates high correlation with lactate measurements but has limited applicability in field settings (Meyer & Timmons, 2021). Additionally, the impact of low BMI on aerobic performance remains debated: some researchers highlight its advantages for relative power output (Singh et al., 2023), while others emphasize the risk of reduced absolute VO_2max (Zhou et al., 2022). For example, female athletes with BMI <18.5 are at increased risk of overtraining and metabolic imbalances (Mountjoy et al., 2023).

Despite progress in sports physiology, there is a lack of studies comprehensively analyzing the relationship between cardiorespiratory indicators, anthropometric data, and training adaptations in juniors (Lucia et al., 2023). Most research focuses on adult athletes, neglecting the characteristics of developing bodies (Biddle & Asare, 2011).

Moreover, standardized protocols for personalizing training loads based on threshold values are missing, limiting their practical application (Laursen & Buchheit, 2013). For example, recommendations on training intensity for improving AnT are often derived from adult data, which may be irrelevant for juniors (Esteve-Lanao et al., 2022).

Another challenge is the integration of recovery and nutrition data into training programs. Nutritional strategies, such as carbohydrate periodization, can influence energy efficiency (Burke et al., 2023), yet their role in junior triathlon remains understudied (Baker & Francis, 2004). Additionally, psychological factors, including motivation and stress resilience, play a crucial role in training adaptation but are rarely incorporated into physiological models (Saw et al., 2022).

The aim of this study is to analyze the cardiorespiratory thresholds (AT, AnT), VO_2max, power output, and their relationship with BMI in junior triathletes aged 16–18. Testing was conducted on 26 athletes using a Wattbike ergometer and Cosmed gas analyzer. Special attention is given to developing recommendations for individualized training programs based on physiological and anthropometric findings. The study aims to fill gaps in existing knowledge and provide practical tools for coaches and sports physiologists working with juniors in endurance sports.

Materials and Methods

This study involved 26 junior triathletes (13 males and 13 females) aged 16–18, all candidates for Master of Sport and actively competing. Inclusion criteria included the absence of injuries or chronic diseases and signed informed consent from athletes and legal representatives. The study was approved by the Ethics Committee of Moscow City University (Protocol No. 01/2025) and conducted following the Helsinki Declaration.

Cardiorespiratory indicators were assessed using a Wattbike Pro ergometer (Wattbike Ltd, UK), with stepwise load increments of 30 W for males and 25 W for females. Each stage lasted 2 minutes until reaching test termination criteria: voluntary exhaustion, a 10% drop in power for 30 seconds, or heart rate ≥95% of age-predicted maximum (calculated as $208 - 0.7 \times \text{age}$). Gas exchange parameters, including oxygen uptake (VO_2), carbon dioxide output (VCO_2), and respiratory exchange ratio (RER), were recorded using a Cosmed K5 gas analyzer (Cosmed, Italy) at a sampling rate of 1 Hz. Equipment calibration was performed before each test using standard gas mixtures (16% O_2, 5% CO_2) and ambient air. Heart rate was monitored with a Polar H10 sensor (Polar Electro Oy, Finland) synchronized with Wattbike and Cosmed software.

Aerobic threshold (AT) was identified by the onset of a sustained increase in ventilation (VE/VO_2) without a concurrent rise in VE/VCO_2, blood lactate concentration ≥2 mmol/L, and an RER of ~0.85, measured with a Lactate Scout+ analyzer (EKF Diagnostics, Germany). Anaerobic threshold (AnT) was determined by an RER ≥1.0 and a sharp lactate rise (>4 mmol/L). VO_2max was calculated as the average VO_2 over the last 30 seconds of the test, while relative power output (W/kg) was defined as the ratio of peak power to body mass.

Data analysis was conducted in SPSS 29.0 (IBM, USA). Group comparisons were performed using Student's t-test, and correlation analysis was carried out using Pearson's method with a significance level of $p < 0.05$. All tests were conducted under standardized conditions: temperature 21±1°C, humidity 50±5%. A medical professional supervised all testing sessions**.**

Results

Analysis of Cardiorespiratory Indicators. The study analyzed the cardiorespiratory parameters of young triathletes, including maximal oxygen uptake (VO_2max), aerobic threshold (AT), anaerobic threshold (AnT), and power output expressed in watts per kilogram of body mass (W/kg).

Sample Characteristics. The study included 26 athletes (13 males and 13 females) aged 16–18 years. The mean anthropometric characteristics differed between the groups: males exhibited significantly greater body mass and height ($p<0.001$), while BMI differences were not statistically significant ($p=0.12$).

Table 1. *Anthropometric Characteristics of Participants (M±SD)*

Parameter	Males (n=13)	Females (n=13)	p-value
Age (years)	17.1 ± 0.7	16.9 ± 0.6	0.58
Body mass (kg)	64.8 ± 5.9	55.4 ± 4.8	<0.001
Height (cm)	175.2 ± 6.1	165.5 ± 5.7	<0.001
BMI (kg/m²)	21.1 ± 1.4	20.2 ± 1.6	0.12

Cardiorespiratory Parameters. Maximal oxygen uptake (VO_2max) was significantly higher in males (68.7 ± 7.2 ml/min/kg) compared to females (55.1 ± 8.4 ml/min/kg, $p<0.001$). This difference reflects higher aerobic endurance in males, likely due to a combination of factors, including greater skeletal muscle mass, higher hemoglobin levels, and other physiological characteristics.

Aerobic threshold (AT), expressed as a percentage of VO_2max, was similar between the groups (62.5 ± 5.3% in males vs. 65.2 ± 4.7% in females, $p=0.15$), indicating comparable initial metabolic transition mechanisms. However, the anaerobic threshold (AnT) was significantly higher in males (84.3 ± 6.1% of VO_2max) than in females (79.5 ± 5.8% of VO_2max, $p=0.03$), suggesting greater lactate tolerance in males.

Table 2. *Cardiorespiratory Parameters (M±SD)*

Parameter	Males (n=13)	Females (n=13)	p-value
VO_2max (ml/min/kg)	68.7 ± 7.2	55.1 ± 8.4	<0.001
Aerobic threshold (AT) %VO_2max	62.5 ± 5.3	65.2 ± 4.7	0.15
Anaerobic threshold (AnT) %VO_2max	84.3 ± 6.1	79.5 ± 5.8	0.03

Power Output. The average relative power output (W/kg) recorded in the cycle ergometer test showed significant individual differences associated with BMI. For example, an athlete with a BMI of 20.8 kg/m² achieved 6.0 W/kg, whereas a triathlete with a BMI of 15.9 kg/m² recorded a power output of 4.9 W/kg. The analysis indicates a trend where lower BMI correlates with higher relative power output; however, critically low BMI values (<18.5) may pose risks of impaired aerobic performance.

Discussion

The obtained results demonstrate significant gender differences in the cardiorespiratory characteristics of young triathletes, aligning with previous research in sports physiology (Bassett & Howley, 2000; Lucia et al., 2023). Specifically, it was confirmed that VO_2max is significantly higher in males compared to females, which can be explained by greater skeletal muscle mass, higher hemoglobin concentration, and improved oxygen transport capacity (Heiestad et al., 2022).

Aerobic threshold (AT) as a percentage of VO_2max did not show significant differences between groups, indicating similar aerobic energy supply mechanisms. However, the anaerobic threshold (AnT) was significantly higher in males (84.3 ± 6.1% vs. 79.5 ± 5.8%, $p=0.03$), which is consistent with studies by Hawley & Leckey (2015), confirming greater lactate tolerance and the ability to process lactate more efficiently in males.

Athletes with lower BMI demonstrated relatively high power output (W/kg); however, critically low BMI values (<18.5) associated with insufficient muscle mass may lead to reduced absolute aerobic performance and an increased risk of catabolic states. This is supported by studies (Mountjoy et al., 2014) indicating a high risk of metabolic disorders in female athletes with low BMI. This aspect requires particular attention in training and nutritional planning.

Gender differences in physiological adaptations should also be considered when designing training programs. Males exhibit greater mitochondrial density, a more developed capillary network, and higher levels of aerobic enzymes, whereas females rely more on lipid oxidation for energy metabolism. For example, studies (Seiler & Tønnessen, 2022) indicate that males demonstrate greater resilience to high-intensity training, whereas in females, endocrine regulation of metabolism, including estrogen levels, plays a crucial role in substrate utilization and lactate clearance capacity.

Furthermore, differentiation in training approaches in triathlon remains an essential aspect, given the specificity of each discipline. For instance, aerobic mechanisms dominate in swimming for both groups, whereas in cycling and running, males show greater resistance to lactate accumulation (Morrison & Newell, 2023).

Thus, the results of this study confirm the necessity of individualizing training programs based on sex, cardiorespiratory thresholds, and anthropometric characteristics. Future research should focus on longitudinal studies of adaptations, including the assessment of physiological parameter dynamics throughout long-term athletic training.

Conclusion

This study identified significant gender differences in the cardiorespiratory parameters of young triathletes. Males demonstrated significantly higher VO_2max and anaerobic threshold (AnT), whereas the aerobic threshold (AT) was similar between groups. Analysis of the relationship between BMI and power output showed that athletes with lower BMI exhibited higher relative power, yet critically low values (<18.5) may lead to reduced absolute aerobic performance and an increased risk of metabolic disorders.

The findings emphasize the necessity of individualizing training programs based on sex, cardiorespiratory thresholds, and anthropometric characteristics. Specifically:

- Males with low AnT (<80% VO_2max) are recommended to increase moderate-intensity training to enhance lactate tolerance.
- Females with low BMI (<18.5) require nutritional adjustments and recovery strategies to prevent declines in aerobic performance.
- Optimization of training loads based on objective physiological data enhances the effectiveness of young triathlete preparation.

The main limitations of this study include the relatively small sample size and the lack of longitudinal monitoring. Future research should focus on tracking physiological adaptations over time, including changes in aerobic and anaerobic thresholds, mitochondrial biogenesis, and the impact of training periodization on young athletes' cardiorespiratory parameters.

Conflict of interest
The authors state no conflict of interest.

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