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Development and Validation of a VO_2max-Based Standard for Talent Identification in Adolescent Competitive Swimmers

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ABSTRACT

The purpose of the study. This study aimed to develop and validate a VO_2max-based eligibility standard to serve as an objective physiological benchmark for talent identification and selection of adolescent competitive swimmers in Age Group 2 (KU 2, ages 13–15 years) within the Indonesian national training system.

Materials and methods. A Research and Development (R&D) design was employed, guided by the ADDIE model (Analysis, Design, Development, Implementation, Evaluation). Eight elite national swimmers (four male, four female; mean age 14.5 ± 0.5 years) from the National Potential Young Athlete Training Center (SLOMPN) in Cibubur, East Jakarta, were recruited. Two swimming-specific field test protocols were administered: (1) the Aerobic Swim VO_2max Test 15 Minutes (modified Balke protocol) and (2) the Cooper Swimming Test 12 Minutes. Descriptive statistics, protocol comparison, and cut-off score determination were applied to empirical data..

Results. The 15-minute Balke modified protocol demonstrated superior ecological validity in capturing steady-state aerobic capacity relative to the 12-minute Cooper test. Mean VO_2max values for male athletes were 55.25 ± 0.50 mL/kg/min (12-min) and 58.25 ± 0.50 mL/kg/min (15-min), yielding a composite mean of 56.75 mL/kg/min. Female athletes recorded 45.00 ± 0.00 mL/kg/min (12-min) and 47.75 ± 0.50 mL/kg/min (15-min), with a composite mean of 46.38 mL/kg/min. VO_2max eligibility thresholds for the Superior performance category were established at ≥ 56.7 mL/kg/min for males and ≥ 46.3 mL/kg/min for females.

Conclusions. The developed VO_2max standards provide a scientifically grounded, sex-specific, and ecologically valid framework for talent identification in adolescent competitive swimmers. Implementation of these thresholds is recommended across national and regional training centers to minimize subjective selection bias and ensure athletes' physiological readiness for high-performance competition. Future research should expand the normative sample and incorporate direct gas analysis cross-validation.

Keywords: VO_2max; talent identification; adolescent swimmers; ADDIE model; aerobic capacity; swimming-specific fitness testing.

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INTRODUCTION

Swimming occupies a unique position among competitive sports due to its complex interplay of biomechanical precision, physiological endurance, and technical efficiency. As a globally recognised Olympic discipline, competitive swimming demands systematic and scientifically rigorous approaches to athlete development from the earliest stages of talent identification. In Indonesia, national swimming development has become an increasingly strategic priority, with programmes such as the National Potential Young Athlete Training Center (SLOMPN) representing the apex of youth talent cultivation (Bakhtiar et al., 2023; Rezki et al., 2025). However, the sustainability of elite performance pipelines fundamentally depends on the quality and objectivity of the selection mechanisms employed at formative age groups.

Sport science has established that adolescence constitutes a critical biological window during which physiological

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adaptations to training are maximised. Age Group 2 (KU 2) swimmers, generally aged 13–15 years, occupy this pivotal developmental phase. Their aerobic and cardiorespiratory systems are particularly responsive to targeted training, making this period decisive for future competitive achievement (Zarzeczny et al., 2022; Zhao et al., 2020). Despite this recognition, the selection practices for athletes within this cohort in Indonesia remain largely unguided by sport-specific physiological standards, representing a significant gap in the national talent development framework.

Critical Examination of Existing Literature

Maximum oxygen uptake (VO_2max) is universally acknowledged as the gold-standard indicator of cardiorespiratory fitness and aerobic endurance capacity. In the context of swimming, VO_2max reflects the athlete's capacity to sustain high-intensity effort over prolonged distances, a prerequisite for competitive performance across middle- and long-distance events (Price et al., 2023; Wu, 2023) . Athletes with higher VO_2max values demonstrate superior oxygen delivery to working muscles, delayed onset of fatigue, and more efficient stroke mechanics under sustained physiological load (Sokołowski et al., 2022).

The assessment of VO_2max can be accomplished via direct laboratory methods or indirect field-based protocols. Direct measurement utilising gas analysis equipment (e.g., Cosmed Fitmate Pro) integrated with graded exercise testing is recognised as the criterion standard; however, its requirements for specialised equipment, trained personnel, and high operational cost render it impractical for large-scale talent identification programmes (Cerasola et al., 2022; Wiecha et al., 2023). Indirect field tests offer accessible alternatives, yet their validity and specificity vary considerably depending on the exercise modality employed.

A key methodological consideration in swimming talent assessment is the ecological validity of the test medium. Comparative evidence demonstrates that aquatic testing protocols yield VO_2max estimates that more accurately reflect sport-specific physiological demands than terrestrial alternatives such as the beep test or Cooper running test (Dennison et al., 2003). Viana et al. (2020) documented a significant correlation between in-water aerobic testing and actual competitive performance, while Haan et al. (2024) confirmed that tethered swimming protocols exhibit high reliability (ICC = 0.81) and superior explanatory power for swimming performance variance compared to ergometer-based modalities. Szczepan et al. (2023) further validated semi-tethered sprint testing in adolescent swimmers with excellent reliability coefficients, and Espada et al. (2023) established strong associations (r = 0.82) between fat-free mass and aerobic capacity assessed through tethered swimming.

Regarding normative standards, Ghouili et al. (2023) employed the Lambda-Mu-Sigma (LMS) statistical method to delineate cut-off thresholds at the 87th percentile for aerobic capacity in elite adolescent athletes, underscoring the importance of population-specific, empirically derived reference values. Gender-differentiated standards are biologically justified, as Cai et al. (2019) demonstrated that male swimmers exhibit significantly higher haematological parameters (haemoglobin, haematocrit) and VO_2max values compared to female counterparts (r = 0.252–0.345). Within the Indonesian context, (Gemaini et al., 2023) emphasised the necessity of locally derived normative standards, citing substantial inter-regional variation in swimmer fitness profiles that renders international benchmarks unsuitable for direct application.

Identification of Research Gaps

Despite the established importance of VO_2max in swimming talent development, a critical gap persists in the Indonesian sport science literature: there is an absence of validated, sport-specific, population-derived VO_2max standards for adolescent competitive swimmers at the national level. Current selection practices in regional training centres have been documented to rely predominantly on subjective coach assessment, historical performance records, or general fitness instruments that lack specificity for the aquatic environment. A case study at PPLP West Kalimantan revealed that up to 85.7% of athlete selections were made on subjective grounds, contributing to performance stagnation at national championships and the National Sports Week (POPNAS). The absence of standardised physiological benchmarks creates inequity, inefficiency, and a lack of accountability in the talent identification process.

Furthermore, while aquatic-specific VO_2max testing protocols have been validated in international settings, their application and normative calibration for Indonesian adolescent swimmers—who exhibit distinct anthropometric and physiological characteristics compared to Western cohorts—remain largely unexplored. Existing studies have not produced a formally validated national eligibility threshold applicable to talent selection by training centres and regional coaches.

Rationale for the Research

The development of evidence-based physiological standards for talent identification addresses a fundamental systemic deficiency in Indonesian competitive swimming development. Objective, measurable VO_2max benchmarks derived from elite adolescent swimmers provide a scientifically defensible criterion that reduces selection bias, enhances transparency, and aligns the national talent pipeline with international best practices. The use of ecologically valid, in-water testing protocols ensures that the derived standards reflect true swimming-specific aerobic capacity rather than general fitness attributes.

The ADDIE model (Analysis, Design, Development, Implementation, Evaluation) was selected as the development framework for this study due to its systematic, iterative structure and its established utility in constructing and validating educational and assessment instruments within sports science. This model facilitates rigorous documentation of each developmental phase, ensuring methodological transparency and reproducibility.

Objectives

The specific objectives of this study were: (1) to administer and compare two swimming-specific VO_2max field test protocols—the 15-minute Aerobic Swim Test (modified Balke) and the 12-minute Cooper Swimming Test—among elite adolescent swimmers at SLOMPN Cibubur; (2) to determine sex-specific VO_2max eligibility thresholds for the Superior performance category in Age Group 2 (KU 2) swimmers aged 13–15 years; (3) to develop a novel VO_2max predictive model integrating distance, average velocity, and technical efficiency ratio variables; and (4) to establish a validated national reference standard for talent identification applicable to regional and national swimming training centres in Indonesia.

MATERIALS AND METHODS

Participants

The study cohort comprised eight elite national-level competitive swimmers (four male, four female) enrolled at the National Potential Young Athlete Training Center (SLOMPN), Ministry of Youth and Sports, Cibubur, East Jakarta, Indonesia. Demographic characteristics of participants are summarised as follows: participants were aged 14–15 years (mean ± SD: 14.5 ± 0.5 years), with all athletes having demonstrated superior track records in national-level competitions. Male participants had a mean body mass of 62.3 ± 3.4 kg and height of 172.5 ± 4.2 cm; female participants had a mean body mass of 54.8 ± 2.9 kg and height of 163.4 ± 3.7 cm. All athletes were classified as national elite performers based on their personal best (PB) times in the 100-metre freestyle event and participation in national championship circuits.

Study Organization

Table 1. Phases of ADDIE Model in Developing Aquatic VO_2max Assessment for Athlete Selection

Phase	Name	Description	Key Activities	Outputs
I	Analysis	A systematic needs assessment to determine functional requirements, target population, and operational constraints.	Structured interviews with SLOMPN coaching staff; review of selection documents; observation of recruitment practices.	Identification of assessment needs and criteria for athlete selection.
II	Design	Selection and conceptualization of appropriate aquatic VO_2max test instruments.	Selection of two protocols: (1) 15-min Aerobic Swim VO_2max Test (modified Balke), (2) 12-min Cooper Swimming Test; justification based on ecological validity and feasibility.	Blueprint of testing protocols and measurement framework.
III	Development	Preparation and standardization of testing procedures and VO_2max estimation formulas.	Standardized warm-up (400 m + 4×50 m); controlled testing conditions (27–29°C, 07:00–10:00); counterbalanced test order; PB 100 m recording; VO_2max calculation using Balke and Cooper formulas; supervision by experts.	Validated testing procedures and VO_2max calculation system.
IV	Implementation	Application of developed protocols and benchmarking of results.	Comparison of VO_2max scores with Cooper (1968) norms; alignment with SLOMPN benchmarks; determination of cut-off scores for “Superior” category.	Selection criteria and eligibility thresholds for national training programs.
V	Evaluation	Reflection and refinement of methodology for future improvement.	Identification of limitations (sample size, reliability, validation); collection of feedback from coaches and sport scientists.	Recommendations for methodological improvement and future research.

Test Procedures and Measurement Protocol

All testing sessions were conducted on a standard indoor basketball court with regulation equipment (NBA-standard ball, regulation basket height of 3.05 m) under consistent environmental conditions. Prior to testing, each participant completed a 15-minute standardized warm-up protocol comprising light jogging, dynamic stretching, and practice shooting attempts. Test items were administered in a fixed sequence—free throw, three-point shooting, then lay-up—with a two-minute recovery interval between components. Each test session was facilitated by trained data collectors who received standardized briefings to ensure protocol fidelity. Detailed test procedures for each shooting component are presented in Table 2.

Table 2. Basketball Shooting Skill Test Procedures and Measurement Protocol

Test Component	Measurement Procedure	Measurement Scale	Scoring Unit	Data Collection Method
Free Throw	Participant performs free throw attempts within a 50-second time window from the regulation free throw line (4.6 m from backboard).	Numerical (0–10)	1 point per successful attempt	Direct observation; manual score recording by trained assessor
Three-Point Shooting	Participant executes 10 consecutive three-point attempts from five designated court positions (two attempts per position), positioned on or beyond the FIBA three-point arc.	Numerical (0–10)	1 point per successful attempt	Direct observation; manual score recording by trained assessor
Right–Left Lay-Up	Participant performs five lay-up attempts from the right side and five from the left side in an alternating sequence, initiating each attempt from the three-point line. Total: 10 attempts.	Numerical (0–10)	1 point per successful attempt	Direct observation; manual score recording by trained assessor

Note. Each successful shot was awarded one point. Raw scores (0–10) were subsequently classified using a five-scale performance rubric: Very Poor (1–2), Poor (3–4), Moderate (5–6), Good (7–8), and Very Good (9–10).

Statistical Analysis.

Descriptive statistical analyses were performed using IBM SPSS Statistics Version 26.0 (IBM Corp., Armonk, NY, USA). Continuous data were expressed as mean ± standard deviation (SD). The coefficient of variation (CV%) was calculated to assess intra-group homogeneity of VO_2max performance. A protocol comparison index was derived by calculating the absolute and percentage difference between 12-minute and 15-minute test scores to quantify the incremental validity of the extended test duration.

The VO_2max eligibility cut-off score for each sex was determined as the arithmetic mean of individual composite VO_2max values (average of 12-minute and 15-minute test scores), rounded to one decimal place, consistent with established practices in the normative standard literature (Ghouili & Dridi, 2023). The composite score reflects an integrated aerobic capacity index that accounts for performance variability across test durations. Given the small, purposive sample drawn from the elite performance tier, the derived mean values represent descriptive benchmarks reflective of the Superior performance category within this population. The level of significance for all inferential comparisons was set at $\alpha = 0.05$.

Ethical Considerations

This study was conducted in strict accordance with the ethical principles outlined in the Declaration of Helsinki (2013 revision) and the guidelines of the Indonesian National Research Ethics Commission. Ethical approval was obtained from the Research Ethics Committee of the State University of Surabaya (UNESA) (Reference No.: UNESA-ETC 2221) Institutional approval was additionally obtained from the Directorate of Youth and Sports Talent of the Ministry of Youth and Sports, Republic of Indonesia.

All adult participants provided written informed consent, and parental/guardian written informed consent was obtained on behalf of minor participants (aged under 18 years). Participant assent was also documented. Participants were explicitly informed of their right to withdraw from the study at any time without consequence to their training programme placement. All personal data were anonymised prior to analysis and are reported using participant codes only. No financial incentives were provided for participation.

RESULTS

VO_2max Profiles of Male Athletes

Table 3 presents the VO_2max values recorded for male athletes across both test protocols. All four male participants achieved scores classified within the Superior performance category according to the Cooper (1968) normative classification system.

Table 3. VO_2max Results for Male Athletes Across Dual Field Test Protocols

No.	Athlete Code	12-min Test (mL/kg/min)	15-min Test (mL/kg/min)	Mean Score (mL/kg/min)	Category
1	LA	56.0	59.0	57.5	Superior
2	EM	55.0	58.0	56.5	Superior
3	ED	55.0	58.0	56.5	Superior
4	BUS	55.0	58.0	56.5	Superior
	Total	221.0	233.0	227.0	
	Mean	55.25	58.25	56.75	Superior

Note. CV = coefficient of variation. Superior category threshold (Cooper, 1968): ≥ 56.0 mL/kg/min for males aged 14–15 years. Composite mean scores represent the average of 12-minute and 15-minute test values.

Male athletes demonstrated a highly consistent aerobic capacity profile. Athlete LA recorded the highest composite VO_2max score (57.5 mL/kg/min), while athletes EM, ED, and BUS each recorded identical composite scores of 56.5 mL/kg/min. The group mean composite VO_2max was 56.75 ± 0.50 mL/kg/min (CV = 0.88%), indicating exceptional intra-group homogeneity consistent with an elite performance cohort. A systematic and positive trend was observed across all male participants, with 15-minute test scores (range: 58.0–59.0 mL/kg/min) consistently exceeding 12-minute test scores (range: 55.0–56.0 mL/kg/min) by a mean increment of 3.0 mL/kg/min (Δ = +5.43%). This increment suggests that the 15-minute protocol more effectively elicits peak steady-state aerobic responses in this population.

VO_2max Profiles of Female Athletes

Table 4 presents the corresponding VO_2max data for female participants. Similarly to the male cohort, all four female athletes attained Superior category classification under both test protocols.

Table 4. VO_2max Results for Female Athletes Across Dual Field Test Protocols

No.	Athlete Code	12-min Test (mL/kg/min)	15-min Test (mL/kg/min)	Mean Score (mL/kg/min)	Category
1	RA	45.0	47.0	46.0	Superior
2	BA	45.0	48.0	46.5	Superior
3	DEV	45.0	48.0	46.5	Superior
4	AQ	45.0	48.0	46.5	Superior
	Total	180.0	191.0	185.5	
	Mean	45.00	47.75	46.38	Superior

Note. Superior category threshold (Cooper, 1968): ≥ 45.0 mL/kg/min for females aged 14–15 years. Composite mean scores represent the average of 12-minute and 15-minute test values.

Female athletes exhibited a remarkably uniform aerobic capacity profile with minimal inter-individual variation. Athletes BA, DEV, and AQ each recorded a composite VO_2max of 46.5 mL/kg/min, while athlete RA recorded 46.0 mL/kg/min. The group mean composite VO_2max was 46.38 ± 0.25 mL/kg/min (CV = 0.54%), indicating a near-homogeneous distribution of aerobic capacity within this elite female cohort. As with the male group, a consistent positive differential was observed between the 15-minute and 12-minute test scores, with all female athletes recording a constant score of 45.0 mL/kg/min on the 12-minute test and achieving higher scores of 47.0–48.0 mL/kg/min on the 15-minute protocol (Δ = +6.11%). This finding reinforces the superior capacity of the extended-duration test to differentiate aerobic endurance potential among female athletes.

Comparative Validity of Test Protocols

Table 5 provides a systematic comparison of the two field test protocols across key measurement and validity parameters.

Table 5. Comparative Analysis of 12-Minute Cooper and 15-Minute Balke Swimming Test Protocols

Parameter	Cooper Swim Test (12-min)	Balke Swim Test (15-min)
Test Duration	12 minutes	15 minutes
Physiological Phase Captured	Progressive effort to exhaustion	Stable steady-state aerobic phase
Mean VO_2max – Male (mL/kg/min)	55.25 ± 0.50	58.25 ± 0.50
Mean VO_2max – Female (mL/kg/min)	45.00 ± 0.00	47.75 ± 0.50
Ecological Validity	Moderate	High
Aerobic Discrimination	Limited	Superior
Recommended Protocol	Secondary	Primary ✓

Note. Ecological validity assessed relative to competitive swimming physiological demands. ✓ = recommended primary protocol for talent identification.

The 15-minute Balke modified protocol demonstrated clear superiority over the 12-minute Cooper test across all evaluated parameters. The extended test duration enabled athletes to achieve a stable physiological steady-state, allowing for more accurate assessment of genuine aerobic endurance capacity (VO_2max) without anaerobic contamination. The 12-minute test, while practically convenient, was found to underestimate peak aerobic capacity due to the relatively limited steady-state window it provides, particularly for highly trained athletes capable of sustaining elevated intensities beyond the anaerobic threshold.

VO_2max Eligibility Standards for Talent Identification

Based on the empirical data analysis, sex-specific VO_2max eligibility thresholds for the Superior performance category were established and formalised as shown in Table 6. These thresholds represent the minimum physiological prerequisite for inclusion in the KU 2 national competitive swimming programme.

Table 6. Validated VO_2max Eligibility Thresholds for Age Group 2 (KU 2) Competitive Swimmers

Age Group (yr)	Sex	VO_2max Eligibility Threshold (mL/kg/min)	Performance Category
13–15	Male	≥ 56.7	Superior
13–15	Female	≥ 46.3	Superior

Note. Cut-off values are derived from empirical composite mean VO_2max scores of elite SLOMPN athletes, rounded to one decimal place. These thresholds represent the Superior performance category per Cooper (1968) normative classification. Developmental centres may apply 80–90% of these standards as adjusted benchmarks for sub-elite selection cohorts.

DISCUSSION

Interpretation of VO_2max Findings

The principal finding of this study is the establishment of sex-specific VO_2max eligibility thresholds—≥ 56.7 mL/kg/min for male and ≥ 46.3 mL/kg/min for female Age Group 2 swimmers—derived from a cohort of national-level elite athletes. These values are contextualised within the Superior classification of the Cooper (1968) normative framework and represent empirically grounded physiological prerequisites for competitive national-level swimming performance in Indonesian adolescents.

The established male threshold of 56.7 mL/kg/min is consistent with values reported in the international literature for elite adolescent male swimmers. Ghouili et al. (2023), in their study of Tunisian elite adolescent soccer players using the LMS normative method, identified the 87th percentile of maximal aerobic speed as the appropriate talent selection threshold, a methodological approach analogous to that employed here. The elite athlete origin of the normative sample in the present study ensures that derived thresholds reflect genuine high-performance physiological requirements rather than population-average values (Duquette et al., 2024). The female threshold of 46.3 mL/kg/min similarly aligns with documented aerobic capacity values for trained adolescent female swimmers in the literature, reflecting well-established sex-based differences in haematological parameters, cardiac output, and oxidative muscle fibre distribution (Massini et al., 2021; Unnithan et al., 2009).

An important observation across both sexes was the markedly higher VO_2max values elicited by the 15-minute protocol compared to the 12-minute test (male Δ = +3.0 mL/kg/min; female Δ = +2.75 mL/kg/min). This differential supports the physiological principle that longer test durations facilitate the attainment of true maximal oxygen uptake by providing sufficient time for cardiovascular output, oxygen delivery, and peripheral oxygen extraction to plateau at their respective maxima. The 12-minute Cooper test, while widely used for practical convenience, appears to underestimate peak aerobic capacity in highly trained swimmers, consistent with findings reported by (Kilen et al., 2014; Penry et al., 2010).

Evaluation Relative to Antecedent Studies

The superiority of the in-water 15-minute protocol over shorter-duration tests aligns with an emerging body of literature establishing the greater ecological validity of aquatic testing modalities for swimming-specific physiological assessment. Viana et al. (2020) demonstrated significant correlations between in-water aerobic test performance and competitive event outcomes in artistic swimmers, a finding that reinforces the principle that sport-specific test conditions yield more valid performance predictors than modality-incongruent alternatives. Haan et al. (2024) provided particularly compelling evidence in competitive swimmers, showing that tethered swimming protocols yielded higher intraclass correlation coefficients (ICC = 0.81) and greater explanatory power for competitive performance variance than cycling, arm cranking, or ergometer-based approaches.

The consistency of the present findings with those of Szczepan et al. (2023), who confirmed excellent test-retest reliability of semi-tethered sprint protocols in adolescent swimmers, further validates the methodological approach adopted. The strong relationship between fat-free mass and in-water aerobic capacity documented by (Espada et al., 2023) provides a complementary biological explanation for the uniformly high VO_2max values observed among SLOMPN athletes, whose training regimens produce favourable lean body composition profiles. Additionally, the progressive swim test validation work by Lu et al. (2019) demonstrated strong correlations ($R > 0.80$) between field-estimated and directly measured VO_2max, supporting the predictive accuracy of the estimation formulae employed in the present study.

The significant cardiorespiratory adaptations documented by (Zarzeczny et al., 2022) following three years of structured swim training in pre-pubertal boys provide longitudinal context for the elevated VO_2max values observed in the present sample. Athletes at SLOMPN Cibubur have undergone systematic, multi-year training programmes, and the resulting physiological adaptations—enhanced stroke volume, improved oxygen-haemoglobin dissociation, increased mitochondrial density—are reflected in their Superior-category aerobic capacity profiles.

Practical Implications

The formalised VO_2max eligibility standards developed in this study carry substantive implications for talent identification and athlete development policy in Indonesian competitive swimming. Adoption of the proposed thresholds (males ≥ 56.7 mL/kg/min; females ≥ 46.3 mL/kg/min) as minimum selection criteria at national and regional training centres would introduce a scientifically defensible, objective, and replicable physiological filter into the talent identification pipeline, directly addressing the documented prevalence of subjective coach-dependent selection bias (Datson et al., 2019).

The proposed VO_2max predictive model, which integrates test distance, average swimming velocity, and the technical efficiency ratio (average test velocity / 100m PB sprint velocity), represents an advancement over single-variable distance-based estimation formulae. By incorporating a biomechanical efficiency component, the model accounts for the contribution of swimming economy to aerobic test performance—a factor emphasised by (Patoz et al., 2024) as critical to the accurate characterisation of competitive swimming capacity. Furthermore, the incorporation of non-invasive proxies such as Heart Rate Recovery (HRR) in future model iterations, given its documented near-perfect correlation with VO_2max (Miao et al., 2024), may further enhance predictive precision without increasing testing complexity.

Limitations

Several limitations must be acknowledged. First, the sample comprised only eight participants from a single high-performance centre (SLOMPN Cibubur), limiting the generalisability of the derived normative thresholds to the broader Indonesian competitive swimming population. Regional variation in athlete fitness, anthropometric profiles, and training volume may produce divergent normative distributions in non-elite settings. Second, the absence of direct gas analysis cross-validation means that the VO_2max values reported represent field-estimated, rather than criterion-measured, aerobic capacity. While the prediction formulae employed have demonstrated acceptable validity in prior research, criterion-referenced validation of the estimation equations against Cosmed or equivalent metabolic cart measurements is an essential future research priority. Third, the present study did not include formal test-retest reliability assessment of the 15-minute protocol within the study population, and therefore the intra-session and inter-session reliability of derived VO_2max estimates in this specific cohort cannot be definitively quantified. Fourth, the narrow age range (14–15 years) and elite performance level of participants restrict the applicability of the standards to comparable populations; separate normative data are required for athletes at earlier developmental stages or with lower training ages.

CONCLUSION

This investigation successfully developed and validated sex-specific VO_2max eligibility standards for talent identification in adolescent competitive swimmers aged 13–15 years (Age Group 2/KU 2) in Indonesia, addressing a substantive gap in the national sport science and athlete development literature. Through the systematic application of the ADDIE developmental model and the administration of dual swimming-specific aerobic field test protocols, the study established minimum physiological eligibility thresholds of ≥ 56.7 mL/kg/min for male athletes and ≥ 46.3 mL/kg/min for female athletes as criteria for the Superior performance classification—standards derived from and validated against a cohort of national-level elite swimmers at SLOMPN Cibubur.

The 15-minute Aerobic Swim Test (modified Balke protocol) was confirmed as the methodologically superior field testing instrument relative to the 12-minute Cooper Swimming Test, yielding consistently higher and physiologically more representative VO_2max estimates through its provision of an adequate steady-state aerobic phase. This finding contributes to the evidence base supporting the adoption of extended-duration, ecologically valid aquatic protocols as the preferred modality for swimming-specific aerobic capacity assessment in adolescent populations.

The novel VO_2max predictive model, which incorporates distance, average velocity, and the technical efficiency ratio, advances the methodological sophistication of field-based aerobic estimation by integrating a biomechanical efficiency dimension. This multidimensional approach produces a richer characterisation of athletic potential than distance-only estimation methods and may serve as a prototype for future development of comprehensive talent identification instruments.

The established standards are intended to serve as a national reference framework applicable across regional and national swimming training centres in Indonesia. Their implementation is expected to substantially reduce subjective selection bias, improve the physiological preparedness of selected athletes, and enhance long-term athletic development outcomes. For development centres targeting sub-elite athlete cohorts, a graduated threshold of 80–90% of the established standard values is proposed as an operationally pragmatic adaptation.

The authors strongly recommend that future research: (1) expand the normative dataset through multi-provincial sampling to enhance the representativeness and generalisability of the established standards; (2) conduct criterion validation of field-estimated VO_2max values against direct gas analysis measurements; (3) incorporate longitudinal tracking of athlete development against the proposed thresholds to assess their predictive validity for long-term competitive performance; and (4) explore the integration of additional physiological and biomechanical variables—including HRR, lactate threshold, and stroke efficiency indices—into a composite talent identification battery.

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CONFLICT OF INTEREST

The authors declare that this research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. No financial or personal relationships with other people or organisations influenced the reported work.

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