



# Standardization of VO<sub>2</sub>max Predictive Models Based on Body Composition in Endurance Sports: A Systematic Review

Yuni Rahmayanti<sup>1</sup>, Nyak Amir<sup>2\*</sup>, Zulkarnain<sup>3</sup>, Rachmad Suhandi<sup>4</sup>

<sup>1</sup> Doctoral Program in Medical Sciences, Faculty of Medicine, Syiah Kuala University, Banda Aceh, Indonesia.

<sup>2</sup> Department of Physical Education, Faculty of Teacher Training and Education, Syiah Kuala University, Indonesia.

<sup>3</sup> Department of Physiology, Faculty of Medicine, Syiah Kuala University, Banda Aceh, Indonesia.

<sup>4</sup> Department of Public Health and Community Medicine, Faculty of Medicine, Syiah Kuala University, Banda Aceh, Indonesia.

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Corresponding Author:

Nyak Amir

[amir\\_fkip@usk.ac.id](mailto:amir_fkip@usk.ac.id)

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**Abstract:** VO<sub>2</sub>max is the main indicator of aerobic capacity that is widely used in endurance sports. However, direct measurement of VO<sub>2</sub>max requires special equipment and laboratory conditions that are not always available in the field. This study aims to examine the predictive model of VO<sub>2</sub>max based on body composition through a systematic literature review approach. Data were obtained from four scientific databases (Scopus, PubMed, Web of Science, and Google Scholar) with a publication range of 2013–2025. The selection process followed the PRISMA guidelines with inclusion criteria of human population-based quantitative studies and the use of body parameters as predictors of VO<sub>2</sub>max. A total of 15 articles met the criteria and were analyzed narratively. The results showed that parameters such as fat-free mass (FFM), body fat percentage (BF%), and body mass index (BMI) were the most commonly used variables. Linear regression and machine learning approaches were the dominant statistical methods. Although these approaches are potential, a universal model has not been found due to variations in population, measurement methods, and training conditions. This study recommends the development of population-specific predictive models and the integration of anthropometric data, biomarkers, and exercise response to improve model accuracy and applicability.

**Keywords:** Body composition; Endurance sports; Fitness prediction; VO<sub>2</sub>max

## Introduction

VO<sub>2</sub>max, or maximal oxygen uptake, serves as the primary physiological indicator of maximal aerobic capacity, reflecting an individual's ability to utilize oxygen during high-intensity exercise. This parameter plays a crucial role in endurance sports such as long-distance running, triathlon, cycling, and swimming, where it determines athletic performance and cardiorespiratory fitness (Belechriss et al., 2025; Wiecha et al., 2023). However, direct measurement of VO<sub>2</sub>max via cardiopulmonary exercise testing (CPET) requires specialized laboratory equipment, trained personnel, and controlled environments, which are often unavailable for field-based assessments or large-scale screenings (Ho et al., 2025; Wiecha et al., 2023).

Predictive models offer a practical alternative by estimating VO<sub>2</sub>max from accessible anthropometric and physiological parameters. Emerging approaches incorporate body composition indicators, including fat-free mass (FFM), percent body fat (BF%), body mass index (BMI), waist-to-hip ratio (WHR), and visceral adipose tissue (VAT), using methods from linear regression to machine learning techniques like random forest and multilayer perceptron (Grzebisz et al., 2022; Ho et al., 2025). Despite their promise, these models exhibit inconsistencies, with variability arising from differences in age, gender, maturation status, hormonal factors, and training phases (pre-season, competition, or transition), where BMI and BF% show strong negative correlations in general populations but reduced

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significance in highly fit athletes (Ho et al., 2025; Wiecha et al., 2023).

The novelty of this research lies in its targeted synthesis of body composition-based VO<sub>2</sub>max predictive models specifically for endurance athletes, an area lacking recent systematic reviews that benchmark model accuracy (e.g., R<sup>2</sup> values up to 0.91 using submaximal tests and somatic variables in runners and cyclists) and identify optimal predictors like FFM over BMI across diverse populations and sports (Wiecha et al., 2023). Unlike prior studies focused on sedentary or mixed groups, this review addresses the absence of standardized frameworks tailored to endurance contexts, evaluating external validity where existing equations often underperform (R<sup>2</sup> as low as 0.26-0.65 in elite athletes) (Ho et al., 2025; Wiecha et al., 2023). By comparing model performance in real-world athletic scenarios, it provides athlete-specific insights absent from general population analyses (Grzebisz et al., 2022).

This research is essential because standardized VO<sub>2</sub>max predictions enable coaches, clinicians, and sports programs, particularly in resource-limited settings like Indonesia, to conduct non-invasive assessments for personalized training, fitness monitoring, and injury prevention without CPET (Ho et al., 2025). Current models lack universality due to population-specific biases, hindering their application in endurance sports where precise aerobic capacity evaluation directly impacts performance outcomes and talent identification (Ho et al., 2025; Wiecha et al., 2023). A systematic synthesis is thus critical to consolidate evidence, recommend best-practice variables (e.g., FFM and BF% in step-test models), and guide future model development for broader applicability (Grzebisz et al., 2022; Wiecha et al., 2023).

In addition, interventional studies have shown that endurance training, either purely or in combination with strength training, can improve body composition and indirectly increase aerobic capacity (Kumari et al., 2025; Marano & Cereda, 2025). However, comparisons of the effectiveness of these types of training still produce conflicting evidence. On the other hand, new approaches are also beginning to explore the use of biomarkers such as NT-proBNP and CA125 as predictive indicators of VO<sub>2</sub>max, especially in clinical populations such as patients with heart failure or with renal dysfunction (Nunez-Marine et al., 2024).

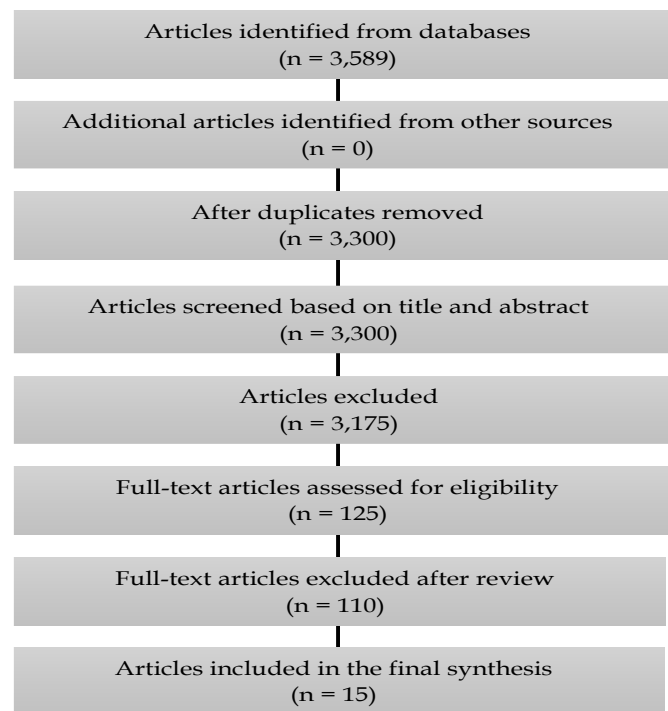
To date, there is no standardized body composition-based VO<sub>2</sub>max predictive model that can be applied universally across population groups. This poses a major challenge in the development of evidence-based training strategies, fitness monitoring, and screening of sports performance potential. Given the diversity of populations, sports types, and measurement

approaches, a systematic synthesis of previous studies is needed.

This research aims to conduct Systematic Literature Review (SLR) on body composition-based VO<sub>2</sub>max predictive models, particularly in the context of endurance sports. This review will identify the most widely used body composition variables, evaluate their statistical approaches and validity, and compare the effectiveness of the models in different population contexts. It is hoped that the results of this review can be the initial basis for developing accurate, efficient, and appropriate VO<sub>2</sub>max predictive standards for field practice and academic research.

## Method

This research uses an approach Systematic Literature Review (SLR), which is a systematic and structured literature review method to obtain conclusions from a number of relevant scientific publications. This approach was chosen because it is able to summarize previous findings, identify patterns and research gaps, and provide a strong theoretical and practical basis for the development of a body composition-based VO<sub>2</sub>max prediction model in the context of endurance sports. The main objective of this method is to collect and compare predictive models that have been used in various studies, while also examining their validity and effectiveness against various population groups and training approaches used.



**Figure 1.** Flowchart related to the steps of systematic literature review (SLR)

The data sources used in this study were obtained from four internationally reputable scientific databases, namely Scopus, PubMed, Web of Science, and Google Scholar. The search was conducted for publications published between January 2013 and April 2025, to ensure that the literature analyzed was still relevant to the latest developments in fitness science and  $VO_2\max$  prediction technology. Keywords in the search process were arranged in English using a combination of Boolean operators (AND, OR), consisting of: " $VO_2\max$ ", "maximal oxygen uptake", "prediction model", "body composition", "BMI", "fat mass", "lean body mass", and "endurance". This process was complemented by cross-reference searches (*snowballing*) from the bibliography of relevant articles to expand the scope of the data.

The inclusion criteria set include articles with the following types: *original research*, involving human subjects aged at least 12 years, and discussing prediction or estimation of  $VO_2\max$  based on body composition parameters such as fat mass, fat-free mass, or body mass index. Accepted articles must be available in full text, written in English or Indonesian, and contain quantitative data that can be further analyzed. In contrast, articles that are *review*, *editorial*, *protocol*, *case reports*, as well as articles that only discussed animal populations or used computer simulations without empirical testing, were excluded from the analysis process.

The article selection process was carried out in several stages. First, all search results were compiled in Zotero software to eliminate duplication. Next, two researchers independently screened articles based on title and abstract. Articles that passed this stage were then read in full (full text). Differences in opinion in the selection were resolved through joint discussion or, if necessary, involving a third researcher as a mediator. This process is reported in the form of a PRISMA flow diagram to illustrate the number of articles found, screened, excluded, and finally included in the final synthesis.

Data collected from each article included author name and year of publication, research design, respondent characteristics (age, gender, athletic status),  $VO_2\max$  measurement method (direct or predictive), body composition variables used, type of model or statistical method used (linear regression, multiple regression, *machine learning*, and others), as well as the main results of the study. The data are arranged in a synthesis table to be analyzed narratively and used as a basis for comparison between studies.

The analysis was conducted descriptively-qualitatively to identify patterns of association between body composition and  $VO_2\max$ , as well as differences in approaches based on population, measurement methods, and outcomes achieved. Articles were also

classified based on population (adolescents, young adults, elderly, athletes, clinical patients), as well as the type of statistical approach used to build the prediction model.

To ensure the quality and validity of the synthesis, all submitted articles were analyzed using the instrument *Modified Downs and Black Checklist* which has been adapted for predictive quantitative studies. This instrument evaluates aspects of methodological feasibility, clarity of reporting, potential bias, and strength of inference used in each study. The scores obtained are used as considerations in the process of analyzing and interpreting the results of systematic reviews.

With this systematic and multi-stage approach, it is hoped that the results of this study will be able to provide a meaningful contribution in the effort to develop predictive standards for  $VO_2\max$  based on body composition that can be adapted for various purposes—both in the field of competitive sports, general population fitness, and clinical contexts.

## Result and Discussion

The results of a systematic search on four scientific databases (Scopus, PubMed, Web of Science, and Google Scholar) obtained 3.59 articles relevant to the search keywords. After the process of removing duplicates and initial selection based on title and abstract, 125 articles remained for full content review. After being filtered based on inclusion and exclusion criteria, 15 articles were declared eligible and used in the final synthesis. The selection process is visually depicted in the PRISMA flow diagram (Figure 1).

The articles analyzed involved diverse populations. The majority of studies focused on adolescents and young adults, followed by elite athletes, healthy elderly, and clinical populations such as patients with impaired heart function (HFpEF). The distribution of articles based on the population categories studied can be seen in Figure 2.

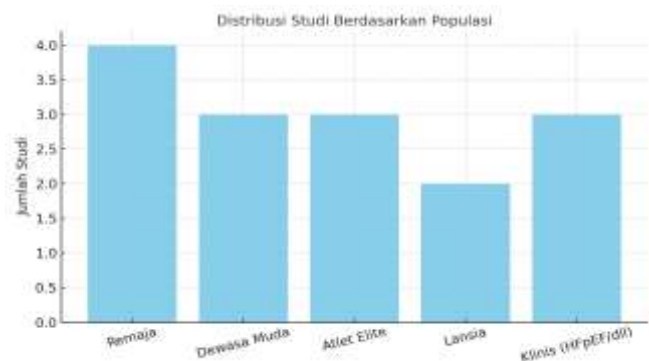


Figure 2. Distribution of studies based on population

Various methods are used in measuring or estimating  $VO_2\text{max}$ , ranging from direct measurements using *cardiopulmonary exercise test* (CPET), to indirect predictive approaches through physical tests such as 20m shuttle run, cycle ergometer, and intermittent Yo-Yo test. The reviewed articles also show variations in the use of body parameters as predictors of  $VO_2\text{max}$ . In general, the most widely used parameters in predictive models are fat-free mass (FFM), body fat percentage (BF%), and body mass index (BMI).

In addition, additional variables such as visceral adipose tissue (VAT), leg lean mass, muscle stiffness, as well as clinical biomarkers such as CA125 and NT-proBNP also found in several studies. The frequency of use of each variable in the reviewed articles is presented in Figure 3 following.



**Figure 3.** Frequency of use of body composition variables in  $VO_2\text{max}$  Prediction Studies

Analysis of the statistical methods used shows that most articles utilize simple or multiple linear regression. However, several recent studies have found the use of machine learning approaches such as multilayer perceptron (MLP) and radial basis function (RBF) to improve the accuracy of  $VO_2\text{max}$  prediction based on body composition data. These results indicate that although predictive approaches to  $VO_2\text{max}$  based on body composition have been widely used, there is still significant variation in terms of the population studied, the parameters used, and the analytical approaches applied. The results of this study show that body composition-based  $VO_2\text{max}$  prediction is a promising approach, but still faces challenges in terms of standardization of the model, especially due to differences in population, measurement methods, and training contexts (Wiecha et al., 2023; Ho et al., 2025). The advantages of this approach are its ease of application in the field and its low cost compared to direct testing (Marks et al., 2024). However, the validity of the model is still highly dependent on the type of population and body variables used.

The synthesis of findings reinforces the conceptualization of body composition, particularly fat-free mass (FFM) and body fat percentage (BF%), as

important determinants of aerobic capacity ( $VO_2\text{max}$ ). Several studies show a positive relationship between FFM and  $VO_2\text{max}$ , while body fat shows a negative correlation, supporting the theory that metabolically active fat-free tissue primarily drives aerobic fitness (Santana et al., 2024; Popp & Jesch, 2025; Vargas et al., 2018).

The integration of bioelectrical impedance vector analysis (BIVA) and phase angle (PHA) as predictors of  $VO_2\text{max}$  introduces a new physiological dimension, emphasizing cellular integrity and fluid distribution within the fat-free mass compartment as independent contributors to aerobic capacity beyond crude body composition measures (Yamada et al., 2023; Matias et al., 2022; Tortu et al., 2024). Machine learning approaches have emerged as superior to traditional multiple linear regression in predicting  $VO_2\text{max}$  from body composition and submaximal exercise variables, revealing complex and nonlinear relationships between physiological, morphological, and performance parameters (Wiecha et al., 2022; Wiecha et al., 2023; Wenzel et al., 2024).

The differential predictive accuracy of  $VO_2\text{max}$  models across populations (athletic vs. clinical, young adults vs. older adults) highlights the importance of contextualizing the effects of body composition within demographic and health status frameworks, suggesting that age-related changes and disease states modulate the relationship between body composition and aerobic capacity (Forsse et al., 2023; Heileson et al., 2022; Gajjar et al., 2024). Evidence that fat mass negatively impacts the physiological capacity of tissues to consume oxygen, while fat-free mass positively correlates with absolute oxygen uptake, supports a dual pathway model in which adiposity impairs oxygen utilization efficiency, and fat-free mass enhances oxygen transport and metabolic capacity (Köhler et al., 2018; Vargas et al., 2018).

Body composition has been shown to be a strong indicator of an individual's aerobic capacity. FFM plays a key role in muscle metabolic efficiency during high-intensity exercise, while BF% has been shown to be negatively associated with aerobic performance. However, in clinical populations such as HFpEF, recent studies have shown that biomarkers such as CA125 are more accurate in predicting  $VO_2\text{max}$  than conventional cardiovascular biomarkers such as NT-proBNP (Mondal & Mishra, 2017; Imboden et al., 2020). This suggests that integration of physiological and biochemical approaches may be needed in a more holistic prediction model.

Meanwhile, intervention approaches through training also show varying results. Endurance training has been shown to be effective in increasing  $VO_2\text{max}$  and improving body composition (Jamka et al., 2021), but several studies have found that a combination with

resistance training can provide more significant results in increasing muscle mass and reducing body fat (Tan et al., 2023). This is evidence that type of exercise, duration, and intensity plays an important role in determining aerobic capacity output, while highlighting that a good predictive model should take training dynamics factors into account.

These results also show that there is no single predictive model that can be applied universally. Therefore, a segmentative approach is needed that takes into account population characteristics, such as age, gender, fitness status, and the context of the sport being performed. Technology-based approaches Machine learning shows great potential because it can adapt models to complex and non-linear datasets.

With these findings, researchers recommend the need to develop a predictive model of  $VO_2\text{max}$ . population-specific and adaptive, and integrative between anthropometric data, biomarkers, and exercise responses. In addition, model validation through longitudinal studies or cross-population trials is also needed to ensure the accuracy and reliability of predictions in the long term.

## Conclusion

The results of this systematic review indicate that body composition-based  $VO_2\text{max}$  prediction is a potential and applicable approach, especially in the context of endurance sports. The body parameters most frequently used as predictors are fat free mass (FFM), body fat percentage (BF%), and body mass index (BMI), although a number of studies also added other variables such as visceral fat (VAT), leg lean mass, as well as clinical biomarker like CA125 and NT-proBNP in a particular population. However, there is no universal predictive model due to variations in population, methods, and statistical approaches used. Several studies have shown high accuracy in young age groups or athletes, but cannot be directly applied to the general or clinical population. This shows the importance of population segmentation in developing a more precise  $VO_2\text{max}$  predictive model. Challenges remain regarding model generalization and standardization. Many studies are limited by sample size constraints, population homogeneity (often male-dominated or athlete-specific), and cross-sectional design, which limits external validity and causal inference. Furthermore, heterogeneity in body composition assessment techniques and exercise testing modalities complicates direct comparisons across studies. The integration of bioelectrical impedance vector analysis and phase angle measurements shows promise as additional markers of cellular health and aerobic capacity but requires further validation. Future

research should prioritize longitudinal designs, include diverse demographic groups, and explore the influence of fat distribution, muscle quality, hydration status, and lifestyle factors in  $VO_2\text{max}$  prediction models.

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## Author Contributions

YR, NA, Z, and RS were involved in concepting and planning the research, YR performed the data acquisition/collection, YR calculated the experimental data and performed the analysis, YR drafted the manuscript and designed the figures, YR added in interpreting the results. All authors took parts in giving critical revision of the manuscript.

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## Conflicts of Interest

The authors declare no conflict of interest.

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