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The impact of maximal oxygen uptake (VO_2max) on athletic performance and health - a review

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Abstract

Introduction and purpose: Maximal oxygen uptake (VO_2max) is a key indicator of aerobic capacity, widely used in sports science and clinical diagnostics. It reflects the functional efficiency of the cardiovascular, respiratory, and muscular systems. Given its relevance to physical performance and health risk prediction, VO_2max has become a central focus in exercise physiology and preventive medicine. The aim of this study is to review current literature on the physiological determinants, assessment methods, modifiability, and clinical implications of VO_2max.

Material and method: A narrative review of literature published between 2000 and 2024 was performed using databases such as PubMed, Scopus, and Web of Science. Search terms included: "VO_2max," "cardiorespiratory fitness," "aerobic capacity," "exercise testing," and "training." Eligible studies involved human participants and addressed either physiological mechanisms, measurement techniques, interventions, or the role of VO_2max in disease risk. Non-peer-reviewed and animal studies were excluded.

Results: VO_2max is influenced by genetic, physiological, and environmental factors, and can be improved through structured endurance and high-intensity interval training. Direct and indirect assessment methods, including laboratory testing and wearable devices, offer various levels of accuracy and accessibility. VO_2max is also strongly associated with cardiovascular and all-cause mortality risk, especially in clinical and aging populations.

Conclusions: VO_2max is a robust, clinically relevant marker of fitness and health. Its integration into regular health monitoring and personalized training programs offers valuable potential for disease prevention, performance optimization, and public health promotion.

Keywords: VO_2max; aerobic capacity; cardiorespiratory fitness; exercise physiology; health promotion; endurance training; wearable technology; physical education; public health.

Introduction

The exploration of VO_2max as a central topic in exercise physiology and public health is motivated by its crucial role as a biomarker for cardiorespiratory fitness, which is essential for both athletic performance and overall health outcomes. VO_2max, defined as the maximal amount of oxygen that can be utilized during exercise, serves as an indicator of an individual’s aerobic capacity and endurance, making it a key focus for sports scientists and health professionals alike [1].

In the context of athletic performance, VO_2max is often considered the gold standard for measuring an athlete's ability to sustain high-intensity efforts over time. Heightened VO_2max levels are directly correlated with improved performance in endurance sports, ultimately leading to better competitive outcomes [2,3]. This correlation allows coaches and trainers to design effective training programs aimed at enhancing aerobic capacity and stamina, thus maximizing an athlete's potential [4].

Furthermore, understanding VO_2max is increasingly relevant in the face of growing public health concerns, particularly with the global rise in sedentary lifestyles and associated health complications. Research has consistently shown that low levels of VO_2max are linked to higher risks of cardiovascular diseases, type 2 diabetes, and all-cause mortality [5,6]. As such, VO_2max is not just a physiological metric for athletes but also serves as a critical health indicator that can inform public health policy and individual health interventions. Programs aimed at increasing physical activity can effectively improve VO_2max, which is associated with better metabolic health and longevity [6,7].

Moreover, innovations in technology, particularly in wearable fitness devices, are making VO_2max assessments more accessible to broader populations. These tools allow individuals to monitor their cardiorespiratory fitness conveniently, promoting self-directed health management and encouraging participation in physical activity [8]. This trend signifies a shift towards personalized health care, wherein VO_2max can guide fitness plans and rehabilitation processes, enabling tailored interventions that align with individual health goals.

In conclusion, the significance of VO_2max as a central topic lies in its utility as a robust indicator of both athletic performance and public health. Its comprehensive implications for health outcomes, coupled with the increasing emphasis on physical fitness in contemporary society, solidify its role as a fundamental measure in exercise science and health promotion.

Aim

The aim of this review is to provide a comprehensive synthesis of the literature on maximal oxygen uptake (VO_2max), focusing on its physiological basis, methods of assessment, modifiability through interventions, and clinical significance. By integrating findings from exercise physiology, sports science, and public health research, this article seeks to inform practitioners, coaches, clinicians, and researchers about the multifaceted role of VO_2max in optimizing performance and promoting health.

Materials and methods

This narrative review was conducted by systematically searching peer-reviewed literature from 2000 to 2024. Databases including PubMed, Scopus, and Web of Science were queried using terms such as “VO_2max,” “aerobic capacity,” “cardiorespiratory fitness,” “exercise training,” “submaximal testing,” and “wearable devices.” Priority was given to original research articles, systematic reviews, and meta-analyses focusing on human participants. Inclusion criteria encompassed studies exploring the determinants of VO_2max, its clinical applications, methods of measurement, and interventions aimed at improving it. Reference lists of selected articles were also screened to identify additional relevant studies.

Review and discussion

Determinants of VO_2max: The Interplay of Physiology, Genetics, and Lifestyle

Maximal oxygen uptake (VO_2max) is primarily determined by three key physiological systems: cardiovascular, respiratory, and muscular systems, each contributing to an individual's overall aerobic capacity.

The cardiovascular system plays a pivotal role in delivering oxygenated blood to active muscles. This includes components such as heart rate, stroke volume, and cardiac output, where the capacity to increase cardiac output during intense exercise directly influences VO_2max [9,10]. Studies highlight that the efficiency of these cardiovascular adaptations is crucial, particularly the relationship between increased stroke volume and VO_2max [11].

The respiratory system is essential for oxygen uptake and carbon dioxide expulsion. Effective lung function and ventilation capacity determine the volume of air exchanged during physical exertion [12,13]. Various studies emphasize that pulmonary ventilation, alongside oxygen diffusion in the lungs, significantly influences VO_2max [14].

The muscular system, particularly how well the skeletal muscles utilize oxygen, is vital. This is influenced by factors like muscle fiber type composition and mitochondrial density, which can enhance oxidative capacity [15]. Enhanced muscular oxidative capacity allows for increased efficiency in using oxygen, thereby contributing to higher VO_2max levels [16,17].

The extent to which an individual's VO_2max is genetically influenced versus modifiable through training has been extensively studied. Genetics is estimated to account for approximately 40% to 70% of VO_2max variation in individuals, indicating a significant hereditary component [18–20]. Specifically, one study highlighted that nearly 50% of the individual variability in VO_2max adaptation to exercise is genetically determined, emphasizing that some individuals may respond better to training stimuli than others due to genetic predispositions [20,21].

Conversely, training can significantly enhance VO_2max, with estimates suggesting that structured aerobic exercise programs can improve VO_2max in the range of 10% to 30% [3,22]. It is well-established that regular aerobic exercise directly boosts cardiovascular adaptations, such as increased stroke volume and enhanced oxygen extraction at the muscular level, leading to improved VO_2max [3,23]. Overall, while genetics plays a substantial role in determining baseline VO_2max, there exists considerable potential for improvement through targeted training regimens.

Maximal oxygen uptake (VO_2max) values are significantly influenced by age, sex, and body composition, with each factor contributing uniquely to aerobic capacity.

Age is a critical determinant of VO_2max, as studies show a gradual decline starting in early adulthood at approximately 1% per year and more steeply after age 50 [24,25]. This reduction is linked to physiological changes including decreased cardiac output, reduced maximal heart rate, and alterations in muscle mass and aerobic enzyme activity [25,26]. Furthermore, older adults often exhibit diminished respiratory function and lower physical activity levels, exacerbating the decline in VO_2max [27].

Sex differences also impact VO_2max, with men typically exhibiting higher values compared to women. Research indicates that this discrepancy can be attributed to greater muscle mass and lower body fat percentages in males [28,29]. After puberty, sex differences in body composition become more pronounced, influencing overall endurance and aerobic capacity [30]. Women generally demonstrate about 10-15% lower VO_2max values than their male counterparts of similar training status and age [29].

Body composition, particularly the ratio of lean mass to fat mass, plays a vital role in determining VO_2max. Higher lean mass is associated with increased muscular oxidative capacity and energy expenditure during physical activity, thus contributing to improved VO_2max performance [31,32]. Body fat percentage negatively correlates with VO_2max; as body fat increases, VO_2max typically decreases due to the added metabolic cost of carrying excess weight [32,33]. Consequently, maintaining an optimal body composition through physical activity and nutrition is essential for maximizing VO_2max.

Environmental factors such as altitude and pollution significantly influence VO_2max values. At high altitudes, the partial pressure of oxygen decreases, leading to reduced oxygen availability for aerobic metabolism. This hypoxic condition can lead to a notable decrease in VO_2max, often quantified as a reduction of approximately 10% for every 1,000 meters gained in elevation, due to impaired oxygen diffusion and reduced oxygen transport capacity [34,35]. Furthermore, adaptability to altitude can enhance VO_2max over time through acclimatization mechanisms that include increased red blood cell production and hemoglobin concentration, as indicated by various studies [36,37].

In contrast, pollutants such as particulate matter and nitrogen dioxide can also adversely affect respiratory function and cardiovascular health, leading to lower VO_2max values among individuals exposed to high pollution levels. Chronic exposure to air pollution has been associated with compromised lung function, which can diminish exercise capacity and limit VO_2max [38,39].

Assessing VO_2max: Methods, Limitations, and Innovations

Direct VO_2max testing methods, such as maximal exercise tests, provide accurate measurements by evaluating an individual's maximum oxygen uptake through metabolic gas analysis during high-intensity exercise [32,40]. However, these methods can be physically demanding and require specialized equipment, making them less accessible [32,41].

In contrast, indirect VO_2max testing methods, such as submaximal tests, allow for larger participant samples and are generally easier to administer [42]. While indirect methods can be less accurate and may involve estimation errors based on assumptions, they are valuable for population screenings [43]. Despite their practicality, they may not account for individual variability in parameters like heart rate and perceived exertion, which can lead to inaccurate assessments [44].

Submaximal and field-based protocols for estimating VO_2max are considered reliable and valid under specific conditions. Submaximal tests, such as the Astrand-Rhyming and Cooper protocols, use heart rate responses to predict maximal oxygen uptake and can effectively screen large populations without requiring individuals to exert maximum effort [45]. Studies indicate that submaximal tests can yield valid estimates of VO_2max, correlating well with measured values in various populations, including adults and patients with conditions such as stroke and Parkinson's disease [46,47].

Notably, the Ekblom-Bak submaximal test has demonstrated strong validity, especially in older adults, highlighting its utility in clinical scenarios where maximal testing is not feasible [48,49]. However, the accuracy of these estimates can vary based on the individual's fitness level and the specific submaximal test used [50]. Field tests, like the Six-Minute Walk Test, have also been validated against direct measures, making them practical for larger cohorts and providing an alternative to expensive, lab-based assessments [51]. Their simplicity and low cost enhance applicability, particularly in community health settings [52].

Wearable technology has significantly transformed VO_2max monitoring in both sports and clinical practice by enhancing accessibility, precision, and real-time data collection. These devices integrate advanced sensors, allowing athletes and clinicians to obtain continuous physiological measurements, facilitating a more comprehensive understanding of an individual's fitness levels and health status [53,54]. For instance, the use of wearable devices in clinical cardiology has demonstrated that VO_2max can be effectively measured during routine activities, enabling ongoing health monitoring without the necessity for laboratory-based tests [53].

Additionally, the improved comfort and wearability of these technologies have encouraged broader participation among users, including populations who may be less likely to engage in traditional fitness assessments, such as the elderly or those with chronic health conditions [55]. By providing immediate feedback, wearables also promote greater adherence to exercise regimens and health behaviors through real-time monitoring and personalized insights [54,56]. However, while promising, concerns remain regarding the accuracy and validity of data obtained from consumer-grade wearables, necessitating further research to establish standardized evaluation protocols [57,58]. Overall, wearable technology represents a significant advancement in health and fitness monitoring, bridging the gap between subjective self-reporting and objective measurement.

Standardization challenges in VO_2max testing across different populations and settings arise from factors including test protocols, participant characteristics, and environmental conditions. Variability in testing protocols can lead to inconsistent results; for example, different maximal and submaximal tests (e.g., Åstrand versus the Bruce protocol) produce varying VO_2max estimates, complicating cross-study comparisons [48].

Specific population characteristics such as age, gender, and fitness level may further influence VO_2max values. For instance, sedentary individuals typically achieve different VO_2max levels compared to trained athletes, as local muscle mechanics and physiological responses can differ significantly [59,60]. Additionally, the accuracy of estimates derived from indirect tests can vary based on these demographic factors, necessitating tailored predictive equations for distinct groups [49].

Environmental factors, such as altitude and temperature, can alter cardiovascular and metabolic responses during testing, impacting the comparability of results [61]. Furthermore, the subjective nature of some assessments, such as perceived exertion, can lead to variability in motivation and effort among participants [62]. Thus, establishing universally accepted protocols that account for these varying factors remains a crucial challenge in standardizing VO_2max testing.

Improving VO_2max: Evidence-Based Training and Nutritional Strategies

To improve VO_2max, high-intensity interval training (HIIT), moderate continuous aerobic training, and combined aerobic and strength training have proven to be effective methods. HIIT has been shown to significantly boost VO_2max, with improvements measurable in as little as six weeks due to the high variability in intensity and volume of work, which enhances aerobic capacity by stressing the cardiovascular system [63,64]. Additionally, a meta-analysis indicated that exercise intensity correlates more strongly with increases in VO_2max than the total training volume used, underscoring the effectiveness of intensified training modalities [65,66].

Moreover, studies suggest that combining strength and aerobic exercises can yield greater benefits than aerobic training alone. For instance, concurrent training has been shown to enhance VO_2max more effectively than strength training in isolation, benefiting both aerobic and muscular adaptations [67–69]. Thus, a training regimen integrating HIIT or continuous aerobic efforts with strength training not only optimizes improvements in VO_2max but also promotes overall physical fitness and performance [70].

High-intensity interval training (HIIT) and moderate-intensity continuous training (MICT) have distinct impacts on VO_2max improvement. Several systematic reviews and meta-analyses indicate that HIIT generally results in greater enhancements in VO_2max compared to MICT. A meta-analysis by Milanović et al. (2015) found that HIIT typically produces more significant increases in VO_2max, particularly in untrained individuals, with improvements often exceeding 10% [71,72]. Additionally, HIIT's structure—short bursts of intense effort followed by rest—may induce more extensive metabolic stress, leading to superior cardiovascular adaptations [72,73].

Conversely, MICT is effective for improving cardiovascular fitness and is often more sustainable over long periods for certain populations [74]. While MICT remains valuable, studies show that the magnitude of improvement in VO_2max with HIIT exceeds that of MICT, especially in untrained individuals and clinical populations [71,72]. Overall, while both training types are beneficial, HIIT often emerges as the more effective choice for maximizing VO_2max improvements.

Nutritional interventions, particularly in the form of nitrate supplementation and maintaining adequate iron status, significantly influence adaptations in VO_2max. Nitrate, found in foods like beetroot, enhances nitric oxide production, which improves blood flow and oxygen delivery to muscles during exercise. This physiological effect has been correlated with increased VO_2max in several studies, demonstrating nitrate's potential as an ergogenic aid for both trained and untrained individuals [9,75].

Iron status also plays a crucial role in aerobic capacity. Adequate iron is essential for hemoglobin production, which transports oxygen throughout the body. Insufficient iron levels can lead to diminished oxygen transport, subsequently impairing VO_2max. Evidence shows that iron supplementation can enhance performance measures, including VO_2max, especially in populations at risk of deficiency, such as female athletes and those undergoing intense physical training [76–78].

Population-specific recommendations to enhance VO_2max safely and effectively highlight different approaches for older adults and clinical patients. In older adults, high-intensity interval training (HIIT) has shown promising results in improving cardiovascular function and VO_2max. Studies have indicated that older participants benefiting from HIIT experienced significant increases in VO_2max, marking this method as particularly effective compared to traditional moderate-intensity training [79,80]. Additionally, incorporating strength training alongside aerobic exercises can optimize improvements in overall physical fitness and metabolic health in this demographic [81].

For clinical patients, including those with conditions such as chronic obstructive pulmonary disease (COPD) or heart disease, supervised exercise interventions have proven beneficial. Tailored rehabilitation programs combining aerobic exercises and strength training have been shown to enhance VO_2max while ensuring safety during physical activity [82,83]. Monitoring exercise intensity and duration is vital, with recommendations often suggesting lower intensity levels to account for individual health conditions [60].

VO_2max and Health: A Marker for Longevity and Disease Risk?

The association between maximal oxygen uptake (VO_2max) and cardiovascular disease (CVD) risk is well-established in clinical research. Low levels of cardiorespiratory fitness (CRF), often measured as VO_2max, are associated with an increased risk of developing cardiovascular diseases. This connection is emphasized by findings showing that improvements in VO_2max are linked to significant decreases in cardiovascular mortality and overall health risks [84–86]. Additionally, regular aerobic exercise is demonstrated to enhance VO_2max, contributing to favorable cardiovascular health outcomes [29,87].

Several studies have indicated that individuals with low VO_2max exhibit a higher likelihood of CVD and all-cause mortality, irrespective of other risk factors [86,88]. The protective effects of higher VO_2max are also posited to apply across different demographics, affirming that increased aerobic capacity promotes better heart health and longevity [87–89]. Moreover, cardiorespiratory fitness serves as a vital marker for assessing cardiovascular health, suggesting that maintaining or improving VO_2max through physical activity is crucial for reducing cardiovascular disease risk [90–92].

Maximal oxygen uptake (VO_2max) is recognized as a significant independent predictor of all-cause and disease-specific mortality. Clinical studies have consistently demonstrated that higher levels of cardiorespiratory fitness, reflected in VO_2max, correlate with lower mortality risks across various populations. For instance, VO_2max has been associated with reducing all-cause mortality risk by approximately 10% to 25% per one metabolic equivalent (MET) improvement, demonstrating its predictive value amidst various confounding factors [17,93]. Moreover, evidence shows that VO_2max serves not only as a prognostic marker in cardiovascular diseases but also in other chronic conditions, enhancing its utility in predicting health outcomes [17,94].

Furthermore, alterations in VO_2max due to interventions like exercise training exhibit direct associations with improved longevity and lower disease incidence [93,95]. This correlation holds even when accounting for multiple risk factors, affirming the robust nature of VO_2max as an essential measure in clinical practice and public health [17,96]. The consistent affirmation of VO_2max as an independent mortality predictor underscores the importance of maintaining or improving cardiorespiratory fitness for health promotion.

Low VO_2max values in patients with chronic conditions, such as heart failure and chronic obstructive pulmonary disease (COPD), are clinically significant as they indicate a deteriorated cardiorespiratory fitness level, which is closely linked to increased morbidity and mortality. For instance, studies have shown that individuals with heart failure and VO_2max <10 mL/kg/min exhibit markedly reduced survival rates, emphasizing the urgent need for regular assessments of aerobic capacity in this population [97,98]. Similarly, in COPD, low VO_2max reflects impaired exercise capacity, primarily due to ventilatory limitations and associated skeletal muscle dysfunction, putting patients at higher risk for adverse health outcomes [99,100].

Further, low VO_2max in chronic illness contexts is associated with lower quality of life and greater healthcare utilization due to the increased incidence of physical limitations and comorbidities [97]. This suggests that interventions aimed at improving aerobic fitness may be crucial in the management of such patients, potentially enhancing their functional capacity and overall prognosis. Therefore, monitoring VO_2max could serve as an essential tool in clinical practice for early identification of at-risk patients and guiding rehabilitation strategies [101].

The integration of VO_2max as a standard health screening metric has significant clinical relevance, particularly for its capacity to predict health outcomes across various populations, especially those with chronic conditions. VO_2max is a pivotal indicator of cardiorespiratory fitness, correlating with all-cause mortality and specific disease risks, making its routine assessment beneficial in primary care settings [6,102].

Several studies underscore that low VO_2max values are indicative of severe health risks, including increased mortality in patients with heart failure and chronic obstructive pulmonary disease (COPD) [97,99]. For instance, VO_2max assessments can directly influence treatment approaches in chronic diseases by identifying patients who may benefit from targeted physical activity interventions, ultimately leading to improved clinical outcomes and quality of life [97,99]. This is further supported by findings that demonstrate effective exercise protocols can enhance VO_2max and consequently health status, particularly in those with chronic pulmonary conditions [100,101].

In summary, broadening the use of VO_2max as a routine screening tool could facilitate early detection of cardiovascular impairments and guide effective management strategies, emphasizing the need for physical fitness evaluations in routine healthcare [6,102].

Conclusions

VO_2max represents a reliable and informative biomarker of aerobic fitness, with implications that extend beyond athletic performance to encompass general health, disease prevention, and longevity. As a modifiable indicator influenced by genetics, training, nutrition, and environment, VO_2max provides a valuable target for interventions across diverse populations. Advances in wearable technologies are expanding access to VO_2max monitoring, enabling more personalized and preventative approaches to health care. Routine assessment of VO_2max could enhance early detection of cardiovascular risk and support individualized training or rehabilitation programs. As such, VO_2max should be considered not only a sports science parameter but a critical tool in modern public health and clinical practice.

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