Oxygen Uptake and Endurance Fitness in Children, Revisited

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This update on oxygen uptake and endurance fitness in youth must begin with an important caveat: Despite many decades of research efforts—and this is a rather striking observation—the important question of just what determines the limits of human exercise performance remains as unanswered today as it did 50 years ago. It’s not that strong arguments haven’t been made for a variety of candidate determinants, each accompanied by supportive experimental evidence. Exercise-limiting fatigue has been considered within the construct of numerous models, including energy supply, central and peripheral neurologic stimulation, biochemical flux, hyperthermia, and psychological state; but as of the year 2013, any impartial arbiter would be hard put to conclude that a definitive answer by any of these explanations is at hand.

Within the realm of endurance exercise, most attention has been focused on exercise limitation as a manifestation of energy dependence, the ceiling of performance capacity being considered linked to depletion of substrate (i.e., glycogen) and/or the limits of oxygen delivery. Compared with other candidate determinants, the latter is readily assessed by a direct “yardstick” (measurement of maximal oxygen uptake [VO2max]), the greatest rate of oxygen utilization recorded during a progressive exercise test. VO2max is closely linked to endurance performance in both children and adults, and increased values accompany athletic training; hence, it is not illogical to conclude, as evident in standard texts, that “peak VO2 limits the capacity to perform aerobic exercise” (1, p. 269).

This brief review will address how concepts of VO2max and endurance performance in youth have evolved over the past 25 years. In such considerations, the reader must accept the caveat that today, just as two decades ago, the assumption is made that oxygen delivery and utilization play a determinant role in defining endurance performance. In fact, other candidates in the explanation for exercise fatigue which are not so readily measured as VO2max and which are thereby less well-studied (glycolytic capacity, central nervous system command, neuromuscular function, etc.) could play critical roles in changes in endurance performance as children progress through the growing years. On this aspect of understanding the development of endurance performance in children, unfortunately, little has changed.
This disclaimer notwithstanding, VO2max as both a marker and determinant of endurance performance capacity has long attracted the attention of exercise scientists seeking to identify unique aspects of exercise responses in youth. Indeed, as Armstrong et al. have concluded, “peak VO2 has become the most researched variable in paediatric exercise science” (1, p. 269). This might be viewed as a bit surprising since children are not considered, by their nature, as endurance animals. Instead, their daily activities are characterized by repetitive short bursts of physical activity which are anaerobic in nature, and episodes of sustained exercise are unusual. Still, there are abundant reasons why understanding aerobic fitness, both physiologically and functionally, continues to be considered important in this age group.

Aerobic fitness has been linked to various health outcomes in the general pediatric population, and VO2max is used as a surrogate measure of maximal cardiac functional reserve capacity in young patients with heart disease. Understanding measures of aerobic fitness influences the construction and understanding of the role of cardiac and pulmonary rehabilitation programs in young patients. And measuring VO2max in child athletes is an important aspect of identifying appropriate training regimens for immature competitors.

Importantly, too, information on the relationships between VO2max and endurance performance in children may provide some insights into the basic role of physiologic fitness in dictating physical capacity. As contrasted with adults, of course, childhood is a period marked by physiologic and morphologic change. It is a time when endurance performance and VO2max both exhibit dramatic growth. Recognizing how these two relate as they develop in parallel over time offers an opportunity to untangle the means by which one may affect the other—or not.

From both pragmatic and basic science standpoints, then, understanding VO2max and its influence on endurance performance capacity in youth continues to bear importance. Over the past two decades some of these hoped-for insights have begun to be achieved, yet, still, “the interpretation of peak VO2 during growth and maturation remains shrouded in controversy” (1, p.269).

We will begin this review with a summary of the state-of-the-art in understanding VO2max and endurance performance in youth as it existed in 1989, examine the lessons that have been learned since that time, and then look to the future, where new research tools offer to expand our knowledge.

Where We Were

In the fall of 1989 an article entitled “Oxygen Uptake and Endurance Fitness in Children: A Developmental Perspective” appeared in this journal. The article interpreted the accumulated research data on this issue to date (12). Such information consisted principally of descriptive reports of maximal testing for determination of VO2max in groups of youth older than 8 years in the laboratory setting and separate large scale investigations of age- and sex-related performance on distance running events such as a 1-mile or 880-yard run. The combined data on VO2max in both cross-sectional and longitudinal studies had previously been assembled and published (6,8), but it was clear that such information could not be considered “normative,” given the multiple centers, equipment, and small number of subjects involved in individual studies (plus the fact that such data could not be confidently interpreted.
as representing the VO2max within the general pediatric population but rather, in most cases, simply the results in youth who would volunteer for exercise testing). Nonetheless, the pattern of development of VO2max during the pediatric years was nicely established by sex, a description which has subsequently been verified in a more contemporary review (2). A number of major observations were presented in the 1989 article:

- Absolute values of VO2max increase during the pediatric years, consistent with growth of heart, lungs, and muscle mass, with values greater in boys than in girls. Values of VO2max normalized by body mass remain stable in boys until the midteen years, while those for girls gradually decline throughout childhood.

- At the same time that VO2max/kg values are stable or declining during childhood, performance on endurance events markedly improves; thus, improved endurance performance during maturation cannot be ascribed to increases in mass-relative VO2max. Instead, improvements in performance with increasing age may be related to nonaerobic factors (strength, glycolytic capacity) as well as to parallel improvements in running economy (which result in older youth performing at a lower percentage of their VO2max in such events).

- Within any group of children, VO2max/kg is directly related to endurance performance, and prepubertal endurance athletes have 30% greater values than the nonathletic childhood population. VO2max does improve with endurance training in children, but the magnitude of this response (averaging approximately +5%) is considerably lower than that observed in studies of adults. Whether improvements in endurance performance with training are similarly limited in prepubertal subjects is uncertain.

Given that multiple determinants can influence performance over time, the 1989 article concluded that there is risk in an oversimplification of the VO2max performance relationship in this age group: “Use of maximal aerobic power as an indicator of cardiovascular function, endurance capacity, or response to training may not be as appropriate in prepubertal children as in adults” (12, p. 325).

**Lessons Learned**

Research performed since 1989 has brought to light a number of new insights surrounding VO2max and endurance performance in children and adolescents. Among these has been semantic clarification of the alternative designations of peak VO2 versus VO2max in youth (as the reader will have noticed, used interchangeably in this discussion). VO2max has traditionally been defined as the greatest amount of oxygen uptake that a subject can use in a progressive exercise test, identified by a leveling or plateau of values at very high exercise intensities. Since children do not often display such a plateau, some have been reluctant to label top values as VO2max but rather as peak VO2. That peak VO2 values do, in fact represent the greatest VO2 achieved in such tests (when certain criteria of heart rate and respiratory exchange ratio are observed) has been documented with supramaximal studies (4).
Interindividual Differences in VO$_{2\text{max}}$ in Healthy Children are Mediated by Variation in Ventricular Diastolic Dimension, Not Myocardial Function

By the Fick equation, VO$_2$ is the product of cardiac output (heart rate × stroke volume) and arterial venous oxygen difference. Since maximal heart rate and arterial venous oxygen difference are independent of aerobic fitness, differences between individuals (or within the same child over time) are dictated by variations in maximal stroke volume (15). Maximal stroke volume, in turn, is a reflection of ventricular end-diastolic filling volume, as myocardial inotropic and lusitropic function at rest and during exercise are not influenced by VO$_{2\text{max}}$ (that is, myocardial contractile health is similar in high and low fit youth; 14). While heredity and growth influence ventricular size (and thus end-diastolic volume), it appears that extracardiac factors, particularly plasma volume, are responsible for alterations in ventricular size, stroke volume, and VO$_{2\text{max}}$ that occurs with physical activity and athletic training (11).

It follows that the ventricular enlargement which occurs with the normal growth process is the primary cardiac determinant of the rise in VO$_{2\text{max}}$ during the pediatric years. Evidence indicates that ventricular myocardial function is independent of age.

The Meaning of VO$_{2\text{max}}$ Expressed Per kg Body Mass as it Relates to Endurance Performance is Influenced by Body Composition

How VO$_{2\text{max}}$ should be most appropriately adjusted for body size to make interindividual comparisons (or when testing a given subject over time) is a complex and controversial subject. Since the maximal delivery of oxygen to the metabolic machinery of the muscle cell should be matched closely to its aerobic metabolic capacity, VO$_{2\text{max}}$ should be expected to be most closely linked to mitochondrial density of the contracting muscles. In practice, this is best approximated by adjusting VO$_{2\text{max}}$ values for lean body mass.

Information regarding lean body mass is not often available to researchers, however, who typically prefer to express VO$_{2\text{max}}$ values relative to the more easily obtained body mass (per kg). How this term relates to cardiovascular fitness or aerobic fitness requires an understanding of the influence of body composition on VO$_{2\text{max}}$/kg. In any general population of children, VO$_{2\text{max}}$ per kg is directly related to performance on an endurance event such as a mile run. The difficulty here is that body fat content, which is metabolically inert, is a component of the “per kg” denominator. Consequently, values of VO$_{2\text{max}}$ per kg will be inflated in thin, lean subjects but reduced in the obese simply due to body fat content. VO$_{2\text{max}}$ per kg, then provides information regarding both true cardiovascular fitness (ability to generate stroke volume and cardiac output) and body fat content. This means that if an obese subject performs poorly on a mile run test and has a low VO$_{2\text{max}}$ value of 25 ml/kg/min, one cannot discern whether these findings reflect only excessive adiposity or include depressed true cardiovascular fitness (which may have perhaps resulted from a sedentary lifestyle). In a study of factors contributing to performance on a mile run test in a general population of 12-year olds, Rowland et al. found that body fat content and true cardiovascular fitness accounted for approximately equal amounts of the performance variance (16).
The Ratio Standard ("Per kg") May be the Best Means of Adjusting VO\textsubscript{2max} for Body Size When Considering its Relationship to Performance on Weight-Bearing Endurance Events

Utilization of analytical methods such as allometric scaling, regression standards, and multilevel modeling have been demonstrated to be more accurate than body mass (i.e., per kg, the so-called “ratio standard”) in normalizing VO\textsubscript{2max} values in children for body size (13). Using multilevel modeling, Armstrong et al. found that, contrary to the developmental trends in VO\textsubscript{2max} noted above using the ratio standard, VO\textsubscript{2max} increased with age in both boys and girls independent of body size (3).

Just when such sophisticated statistical techniques should be applied to VO\textsubscript{2max}, particularly in respect to endurance performance, however, remains uncertain. Nevill et al. used a power function model and log-linear regression to examine the best predictor of 1-mile run speed in circumpubertal boys (10). Run speed was related to the product of VO\textsubscript{2max}\textsuperscript{0.99} and mass\textsuperscript{-0.96}, both factors scaling close to unity, which would indicate that “per kg” (the ratio standard) was the most appropriate means of relating performance (at least on weight-bearing endurance tasks) and maximal oxygen uptake to body size.

Improvement in Endurance Performance With Age During Childhood is Likely to Reflect Increase in Body Size Rather Than Development of Dimension-Independent Function

We know that a) absolute values of VO\textsubscript{2max} permit improved endurance performance as a child ages, but there is little or no increase in VO\textsubscript{2max} above that which can be attributed to increased body size; b) oxygen uptake per kg body mass for each stride is similar in prepubertal and mature subjects (13); and c) performance on a 1-mile run test in children is related to body mass\textsuperscript{1.0}. These findings support the conclusion that development of endurance fitness in weight-bearing events during childhood is not dictated by parallel changes in VO\textsubscript{2max} but instead can be best accounted for by increases in body size (i.e., progressively increased stride length in running). This means that performance times would be similar in a boy who was tested on a distance run at age 8 years and then again at age 16, if the distance of the run was scaled to that individual’s stride frequency or length at the time. Still, as noted previously, the extent of possible contributions of dimension-independent factors (anaerobic capacity, motivation, neuromuscular function, increases in hemoglobin concentration) to the development of endurance performance during that 8-year period remains problematic.

New Frontiers

Where do we go from here? Clearly pediatric exercise physiologists are not lacking an agenda of important unanswered questions regarding the influence of VO\textsubscript{2max} on endurance fitness which remain to be addressed.

It is evident that an increase in body size rather than a relative rise in VO\textsubscript{2max} is responsible for the improvements in endurance performance as children grow, but is
this too narrow a perspective? What about factors such as developmental changes in motor unit firing rate and recruitment, intrinsic muscle contractile force, or central inhibitory influences on maximal voluntary contraction—could they play a role?

Changes in VO\textsubscript{2max} per kg body mass are not central to improvements in endurance performance in children during the growth process but may become important in responses to endurance training; yet, the magnitude of such responses are dampened in prepubertal subjects compared with adults. Why? It’s a mystery that remains unresolved and whose untangling might provide important insight into the basic mechanisms by which endurance training triggers improvements in VO\textsubscript{2max} at all ages. As inferred from the previous discussion, the direct explanation could involve a limited rise in plasma volume in children compared with adults during training, but why this should be so is enigmatic.

New noninvasive testing modalities offer opportunities for exploring oxygen uptake with exercise in children and its relationship to performance. Recent studies using magnetic resonance spectroscopy suggest that at high work intensities, children display a lower anaerobic-aerobic metabolic profile than adults (5). Breath-by-breath measurements of oxygen uptake at onset of exercise reveal faster VO\textsubscript{2} kinetics in children compared with adults, suggesting enhanced oxidative function in the child (7). Marwood et al. have demonstrated that time constants for the fundamental phase of VO\textsubscript{2} kinetics at a work intensity of 80% lactate threshold is faster in soccer-trained compared with nonathletic 15-year-olds (9). Near infrared spectroscopy in this study reveal no differences in the two groups in hemoglobin kinetics (balance between supply and utilization), suggesting to the authors that faster VO\textsubscript{2} kinetics were due to the enhancements in both central (i.e., oxygen delivery) and peripheral (i.e., oxygen utilization) mechanisms.

These new lines of investigation suggest that a focus on maximal levels of VO\textsubscript{2} in respect to endurance performance in youth may be myopic. As Armstrong et al. emphasized, “Peak VO\textsubscript{2} does not describe fully all aspects of aerobic fitness. Exercise of the intensity and duration required to elicit peak VO\textsubscript{2} is rarely experienced by many young people. Peak VO\textsubscript{2} is neither the best measure of a child’s ability to sustain submaximal aerobic exercise nor the most sensitive means to detect improvements in aerobic fitness after a training programme” (1, p. 269).

**Summary**

While much progress has been achieved, many questions surrounding the identification of the critical factors that lie behind the development of endurance fitness during childhood remain largely unresolved. Continued efforts to solve these mysteries offer promise for not only better understanding the determinants of performance in children but also a clearer understanding of the basic mechanism underpinning exercise capacity at all ages.

It is reasonable to suggest that the conclusion of the 1989 article remains unchanged. Alterations of endurance performance in growing children are concomitantly influenced by anatomic changes (increasing stride length during the growth process), VO\textsubscript{2max} (training effects), and possibly development of dimension-independent factors (such as anaerobic capacity and neurologic function). It may be expected then that the relationship between VO\textsubscript{2max} and endurance fitness in the growing child may be more complex than that recognized in adult subjects.
References


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