The Winning Mindset

Scott Christensen

Understanding VO2 $_{max}$: Part 1 of 3

Purpose:

The purpose of CTCs *The Winning Mindset* is to collect and present articles by accomplished athletes, coaches, and business leaders in an effort to provide our readers with valuable insight into successful training, racing, business, and the characteristics of a high-performance mindset.

Subject:

Coach Christensen was asked to prepare a series on understanding **VO2 $_{max}$** and how to train and improve it. He placed significant effort into the challenge, and – coupled with his education, experience as a world-wide educator, and decades of practical application on the track – Scott has provided our readers with a thorough starting point for understanding this challenging topic.

The first article, presented here, is Scott providing an introductory lesson aimed at a reasonably educated, **first year distance coach** with a desire to expand their understanding of training principles. <u>This article and series will be challenging for many readers</u>. Scott outlines the history of the research and explains the concept of VO2 $_{max}$ quite well. Scott then advances the discussion and applies it to young track athletes. Readers new to the subject are encouraged to take detailed notes and explore the research articles listed at the end of Part 3.

The second article in this series will expand the discussion by explaining multiple ways to test for one's VO2 $_{max}$. Scott then provides more training examples that demonstrate how to specifically target aerobic power development.

Coach Christensen's Response:

For exercise scientists, there is a maximum rate of oxygen consumption that can be measured during incremental exercise, or exercise of increasing intensity. This maximum value is called $VO_{2\ max}$ (V is volume, O_2 is molecular oxygen, and $_{max}$ is maximum). Maximal oxygen consumption reflects the cardiovascular and respiratory fitness of an individual. For distance coaches, $VO_{2\ max}$ is an important determinant of endurance power during prolonged exercise and is a crucial variable in race performance.

British physiologist and recreational runner, Archibald (A.V.) Hill, introduced the concepts of maximal oxygen uptake and oxygen debt in 1919. Hill and German physician, Otto Meyerhoff, shared the 1921 Nobel Prize in Physiology and Medicine for their independent work related to muscle aerobic energy metabolism. Building on this work, scientists began measuring oxygen consumption during exercise. Notable clinical contributions were made by Americans; Henry Taylor, Philip Gollnick, David Costill, and Jack Wilmore, in the 1960s-1990s. Also, experiments by Scandinavian scientists Per-Olaf Astrand, Irma Rhyming, and Bengt Saltin in the 1950s -1980s were useful in refining the theory of $VO_{2\ max}$. Lately, clinical work by the Harvard Fatigue Laboratory, German universities, the Copenhagen Muscle Research Centre, and the Noakes Laboratory in South Africa among others have contributed to the understanding of $VO_{2\ max}$.

In 1870, German-born physician Adolph Fick proposed a theory that stated the quantity of oxygen available to muscle cells was the primary factor in determining human activity levels. Fick defended his theory by introducing both cardiac output and oxygen diffusion from "blood to muscle" ideas for the first time. He hypothesized that arterial blood headed to muscles was higher in oxygen quantity than venous blood returning from muscles. Fifty years later, A.V. Hill, used *Fick's Principle* as the foundation for his Nobel Prize-winning theory proposing that there is a maximum amount of oxygen that can be utilized by muscles based on a number of factors. Hill credited Fick by proposing a mathematical equation to express the limit of oxygen utilization. It is now universally accepted, that $VO_{2\ max}$ is properly defined by the *Fick Equation,* as $VO_{2\ max} = Q \times (C_aO_2 - C_vO_2)$. The variables for the equation are obtained during an exertion at a maximal effort where Q is the cardiac output of the heart, C_aO_2 is the arterial oxygen content, and C_vO_2 is the venous oxygen content. For the Fick equation, Q can be determined by heart rate x stroke volume, and $C_aO_2 - C_vO_2$ is also known as the arterio-venous oxygen difference (before and after oxygen content values following partial removal at the muscle cell).

Using the principles set forth by Fick and Hill, $VO_{2\ max}$ testing is now routinely done in human performance physiology laboratories every day. Accurately measuring $VO_{2\ max}$ in the lab involves a physical effort sufficient in duration and intensity to fully tax the aerobic energy system. In clinical and athletic testing, this usually involves a graded exercise test (either on a treadmill or on a cycle ergometer) in which exercise intensity is progressively increased while measuring ventilation of oxygen and carbon dioxide concentration of the inhaled and exhaled air. $VO_{2\ max}$ is reached when oxygen consumption remains at a steady state despite an increase in workload.

$VO_{2\ max}$ can be expressed either as an absolute rate in liters of oxygen per minute (L/min) or as a relative rate in milliliters of oxygen per kilogram of body mass per minute (e.g. ml/kg/min). The latter expression is often used to compare the performance of endurance sports athletes. However, $VO_{2\ max}$ generally does not vary linearly with body mass, either among individuals within a species or among species, so comparisons of the performance capacities of individuals or species that differ in body size must be done with appropriate statistical procedures, such as analysis of covariance (ANCOVA).

Most life besides plants exists on Earth because of the presence of water and oxygen. Aerobic animals (there are anaerobic animals) intake oxygen, circulate it around the body in blood, diffuse into somatic cells what is needed at any particular moment based on demand, and then release the excess along with carbon dioxide to the environment. Because of the many steps and processes involved in cellular oxygen intake, delivery, and diffusion, there is a maximum amount that can proceed all the way through the stages and become part of the aerobic reactions in the mitochondria of muscle cells. In other words, there is a measurable $VO_{2\ max}$ in aerobic animals.

All aerobic animals have a $VO_{2\ max}$ value that is a result of natural selection and is correlated with their evolutionary lifestyle. Some animals, such as those birds or mammals with high $VO_{2\ max}$ values generally are migrators. They have a high oxygen requirement to get them through their lifestyle. Lower $VO_{2\ max}$ values are generally found in aerobic animals that have no history of frequent migration, are solitary, or are hibernators. As stated previously, there is a standardized unit of measurement for animals $VO_{2\ max}$ and it is the maximum number of milliliters of oxygen, per kilogram of body mass, per minute. Because of the standard unit, $VO_{2\ max}$ can be compared from animal to animal and examples are shown in table 1.

Animal	$VO_{2\ max}$
Land crab	12 ml/kg/min
Tree sloth	22 ml/kg/min
Domestic Pig	36 ml/kg/min
Untrained female adult human	32 ml/kg/min
Untrained male adult human	37 ml/kg/min
Trained female adult human	72 ml/kg/min
Trained male adult human	82 ml/kg/min
Thoroughbred racehorse	196 ml/kg/min
Sled dog	240 ml/kg/min
Hummingbird	680 ml/kg/min

Table 1. Shown are $VO_{2\ max}$ values for various aerobic animals.

$VO_{2\ max}$ is considered a biological "infrastructure" term. Since it defines the maximum amount of oxygen that can be delivered to and utilized by working muscles; it must include all of the components that make up the system. These would include: lung micro-structures, volume and stroke capacity of the heart, quantity of blood in the organism, hemoglobin level present in the blood, oxygen saturation level in the blood, degree of capillarization in muscle fibers, quantity of myoglobin in muscle cells, mitochondria size and numbers, as well as all of the enzymes, such as citrate synthase, that allow the maximum level of oxygen consumption to be reached.

The $VO_{2\ max}$ system in humans can be improved through endurance training, as table 1 indicates. Humans can more than double their maximal oxygen consumption value if trained properly. For $VO_{2\ max}$ development, training stimuli must be mostly aerobic in design and administered in a scheme that produces little lactate. Because most of the adaptations found in improving $VO_{2\ max}$ are structural in the body, the rate of progress will be over a long time period and must be done in concert with growth and maturation of the body.

Growth and development of the body are big factors when examining the $VO_{2\ max}$ system of an individual. Immature persons, those that have not reached puberty, do not have a well-developed $VO_{2\ max}$ system because the cardiovascular network is one of the last things to reach full development in humans; however, females mature a couple of years earlier than males on average. There is no system in nature that is 100% efficient, and that is the case with oxygen delivery and cellular extraction as well. Normal saturation of oxygen is 20 ml per 100 ml of blood at sea level and is not age dependent. However, the amount of oxygen that is delivered and extracted at the muscle cell is age and/or fitness dependent. Most of the dissolved oxygen molecules found in various persons at rest circulate in the body and are not extracted by body cells, as shown in table 2. Only about 5 ml of oxygen are used per 100 ml of blood before the blood returns to the heart and lung for re-oxygenation.

Running, however, is different from rest. For both immature males and females at age 8 years old (table 2), oxygen extraction increases just slightly with exercises done at $VO_{2\ max}$, as compared to resting level. Eight-year-olds do not yet have the physical capacity for much oxygen extraction, and cannot run very far without stopping. Much of what they do is anaerobic, and no amount of aerobic training stimuli is going to change that. The rapid breathing evidenced by children after running around is an attempt to pay back the oxygen debt incurred by the anaerobic activities.

Population Examples at Sea-Level	O_2 saturation per 100 ml of blood	O_2 exiting system at rest	O_2 exiting system at $VO_{2\ max}$	O_2 consumed at $VO_{2\ max}$
Male-8 years old	20 ml/100 ml	15 ml/100ml	13 ml/100 ml	7 ml/100ml
Female-8 years old	20 ml/100 ml	15 ml/100ml	13 ml/100 ml	7 ml/100 ml
Male-13 years old	20 ml/100 ml	15 ml/100ml	13 ml/100 ml	7 ml/100 ml
Female-13 years old	20 ml/100 ml	15 ml/100ml	11 ml/100 ml	9 ml/100 ml
Male-18 years old	20 ml/100 ml	15 ml/100ml	10 ml/100 ml	10 ml/100 ml
Female-18 years old	20 ml/100 ml	15 ml/100ml	9 ml/100 ml	11 ml/100 ml
Male-18 years old-trained	23 ml/100 ml	18 ml/100ml	5 ml/100 ml	18 ml/100 ml
Female-18 years old-trained	21 ml/100 ml	16 ml/100ml	5 ml/100 ml	16 ml/100 ml
Male 23 years old-trained	25 ml/100 ml	20 ml/100ml	5 ml/100 ml	20 ml/100 ml
Female 23 years old-trained	22 ml/100 ml	17 ml/100ml	5 m/100 ml	17 ml/100 ml

Table 2. Shown are complete oxygen saturation in human blood at the lung, blood oxygen saturation returning to the lung at rest, and blood oxygen saturation returning to the lung during a $VO_{2\ max}$ exercise for various age people.

By late middle-school age, females have developed their cardiovascular system over that seen in males. At age 13, girls $VO_{2\ max}$ values are above that of boys even in untrained populations. The female maturation rate is generally two years ahead of males in key cardiovascular factors such as heart size, capillarization, and blood volume, which translates to a higher cardiac output. At this age, females are described as having a powerful, nearly mature aerobic engine in a body that is yet to add the body fat of adult females in preparation for reproduction (figure 1). By contrast, males at age 13, have an undeveloped cardiovascular system, low cardiac output, and a higher childhood body fat level than females. With high cardiac output and low body weight, running economy in females at this age is high. They can handle (and even enjoy) long aerobic runs that stimulate $VO_{2\ max}$ development even further. Girls are able to physically benefit from tempo runs done at lactate threshold, aerobic intervals done at race pace, and even aerobic runs done at maximum VO_2. If allowed to, 13-year-old girls in some cases can run fast enough to make a varsity high school cross country team and can handle the 5 kilometer distance without a struggle. Meanwhile, boys at age 13 cannot handle (or enjoy) taxing aerobic work, nor benefit from aerobic intervals done near the 5k pace, even if given many minutes of recovery between repeats. Their most effective aerobic stimulus will be maintaining short aerobic runs done at a comfortable pace transitioning to slightly longer and longer runs done at the same comfortable pace. In co-ed middle-school cross country races, girls can frequently be seen beating most of the boys because of higher $VO_{2\ max}$ values. This needs to be an important factor in determining co-ed daily workouts often done at the middle school level.

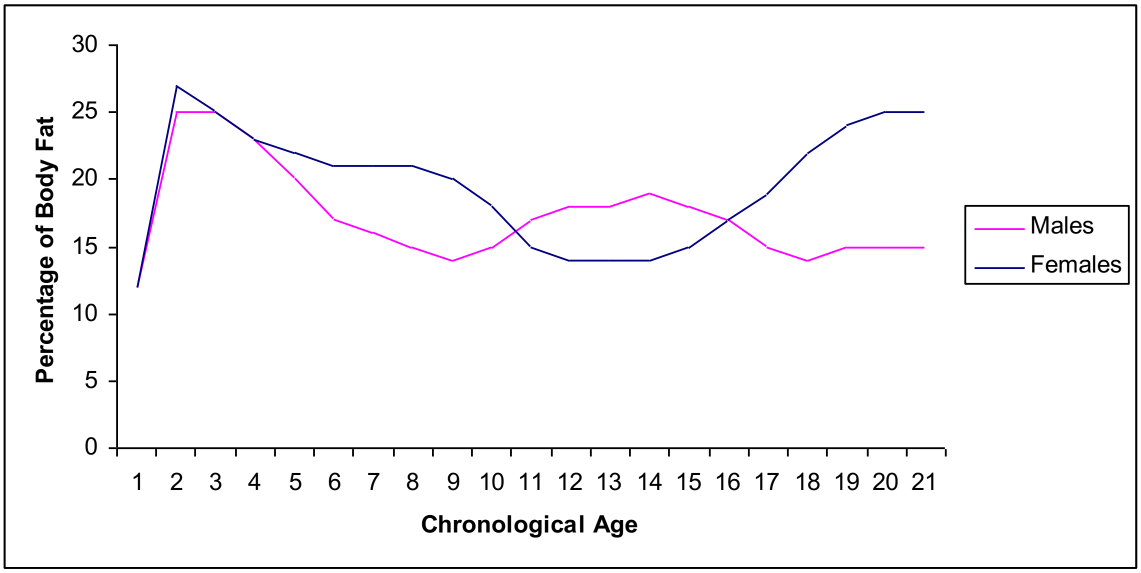

Figure 1. Percentage of body fat changes from birth to maturity in males and females.

By age 18, males have surpassed females in $VO_{2\,max}$ development for both trained and untrained populations. With aerobic training, O_2-blood saturation improves (table 2) because red blood cell numbers are higher in aerobically fit people, resulting in greater oxygen saturation. Cardiac output is higher in 18-year-old males than females because their heart is generally larger resulting in greater stroke volume. Body fat is markedly lower in males than females at age 18. Capillarization in males is greater because there is more muscle tissue than in females. Blood volume in 18-year-old males is about 10% higher than females of the same age and same fitness level. These factors add up to a slightly higher $VO_{2\,max}$ in males than females at this age. Both 18-year-old males and females do not yet have a completely mature cardiovascular-respiratory system but they are both capable of high levels of demanding aerobic work.

By age 23, aerobically fit males can extract significantly more milliliters of oxygen per 100 milliliters of blood than females can at the same age and training level (table 2), resulting in mature $VO_{2\,max}$ value differences shown between males and females (table 1). This can generally be summed up by males having more blood, greater ventricular stroke volume, more capillaries, and less body fat. At age 23, both males and females have matured cardiovascular-respiratory systems and improvement in the system will come exclusively through training stimuli. The volume and intensity of aerobic work at age 23 is not gender specific and is correlated most often with the athlete's preferred event distance.

By age 25, $VO_{2\,max}$ is declining in both untrained males and females due to loss of cardiac output resulting from a steady decrease of maximum and submaximal heart rates, as well as a slow-down in daily activity. Maximum heart rate will decrease each year past the age of 25 by a known rate. $VO_{2\,max}$ will decline by 1% each year in response to the drop in cardiac output, although maintaining a high level of aerobic activity will maintain a high stroke volume, thus slowing down decay.

The $VO_{2\,max}$ system can be separated into both a central and a peripheral component. The central component includes heart size (chiefly the left ventricle stroke volume), atmospheric gas exchange network in the lungs, blood volume, blood hematocrit (% of red blood cells in blood), angiogenesis (degree of muscle capillarization), mitochondrial proliferation and characteristics in both heart and skeletal muscle cells (size and number), and degree of aerobic enzyme activation (substrate-enzyme coefficient). The central component can best be summed up by listing all of the factors that get lots of oxygenated blood flowing past working muscle cells. A goal of aerobic training is to improve the action of everything on that list.

The peripheral component of the $VO_{2\,max}$ system consists of those biological things needed at the "blood in capillary-contracting muscle cell" interface. This is the specific process in which oxygen in the blood is transferred to muscle cell cytoplasm. Males have about 1000 mg of iron in the body and females about 300 mg (that fact brings lots of other issues to the table). Of that iron total, about 65% is found in red blood cells (hemoglobin), 35% attached to a protein storage molecule (ferritin), 5% in miscellaneous tissues, and 5% as an *intracellular* oxygen carrier (myoglobin). Blood flowing past muscle cells have O_2 molecules attached to the iron-rich hemoglobin protein that are part of red blood cells. Myoglobin is another iron-rich protein molecule found only inside the muscle cell (if it is found in the blood then there is significant muscle damage), and its action is to chemically attract the O_2 molecules flowing past the cell to transfer from the hemoglobin outside the cell membrane to the myoglobin inside the cell membrane. The peripheral component of the $VO_{2\ max}$ system improves when myoglobin concentration increases inside the cell, the semi-permeable cell membrane increases the number of gated channels that allow iron to pass through, and an increase in aerobic enzymes found inside the cell and mitochondria that improve the speed of the transfer action.

The central component of the $VO_{2\ max}$ system improves with an array of aerobic activities based on the current age and fitness of the runner. Prescribing long runs, tempo runs, base runs, aerobic intervals and recovery runs all provide stimuli for central development. At any given training age, when purposeful training re-starts again, central development can continue to improve for up to 27 weeks before a break is needed to the system. However, peripheral development does not adapt as well with just any sort of aerobic exercises or even mileage. Peripheral development adapts most effectively by exercising explicitly at the pace by which $VO_{2\ max}$ is reached in a runner. This is a pace known as $vVO_{2\ max}$ (v is velocity). It is important for those runners who are capable of improving their $VO_{2\ max}$ that they do a workout every microcycle at $vVO_{2\ max}$ to elicit improvement in the peripheral system to go along with the continuing development of the central system. Improvement to the peripheral system does not proceed for up to 27 weeks, using the “longer is better” theory, as the central system does. Rather, if done properly, peripheral development can be accomplished in 9-12 weeks before a break in training is needed. The main reason for this drastic time difference in development is rooted in the fact that central development is chiefly structural changes (i.e. heart size, capillary number, blood volume, etc.), while peripheral development is mainly biochemical changes (i.e. myoglobin and enzyme volume changes).

Aerobic training is the key to developing a more robust $VO_{2\ max}$ system in distance runners. As examples, let's look at a trio of novice to emerging runners and some different workouts they might do to stimulate the development of aerobic power in both the central and peripheral components.

1. Mason is a 7th grader on the middle-school cross country team for the first time. The middle-school race distance is 2000 meters. His mom and dad are recreational road runners and have even suggested that Mason may run some 10k road races this fall once he “gets in shape”. Right now Mason can run 1-2 miles and then needs a little break. How would the middle school coach proceed with Mason’s training? Mason has a very small heart due to his age. When he goes for a distance run his cardiac output increases to try to meet the oxygen demand, but having a small stroke volume means his heart rate has to be very high to meet his need. He can run at a high heart rate for a time, but fatigue is inevitable before he gets very far. Aerobic training will extend the distance that Mason can run, but not because of an improved central $VO_{2\ max}$ system, rather at his age, improvement will be in peripheral $VO_{2\ max}$ system development. In children, Mason’s age blood flow to active muscles during exercise is greater for a given volume of muscle than in adults because they have less peripheral resistance. So, a higher submaximal heart rate cannot completely compensate for the lower stroke volume in order to maintain cardiac output increases while exercising. Through aerobic training, Mason’s arterial-mixed venous oxygen difference ($a\text{-}vO_2$ diff) increases to further compensate for the lower stroke volume (due to the smaller body size) and lower peripheral resistance than seen in adults. Mason should not run for more than 30 minutes on a continuous run, and certainly not train for, or race a 10k. Mason will develop a love for distance running by doing short bouts of exercise that emphasize his peripheral $VO_{2\ max}$ system. Besides a couple of 25 minute runs each week, he should do

a day or two of 3 x 1k repeats on a grassy loop at a pace that is just above comfortable, with a recovery interval of 7-9 minutes between each repeat.

2. Brooke is an eighth-grade girl who wins every 2k middle school cross country race that she enters. She is a teammate of Mason's and finds the workouts that he does too easy. Should her coach continue to train them together? Brooke is ready to put some real stress on her $VO_{2\ max}$ system. Her heart is almost adult size, so her stroke volume is high. As a 13-year-old she also has the benefit of having less peripheral pressure resistance so a-vO_2 diff capacity is high. Brooke has a 13-year-old body and nearly an adult $VO_{2\ max}$ system. She can do continuous effort long runs out to 20-22% of her weekly mileage in one session. To build endurance strength to go along with her $VO_{2\ max}$ capability she should do one session per week of 4 x 4:00 hill work on a 2-3% grade if possible with a jog back down recovery of eight minutes, so repeating the hill cycle about every 12 minutes.
3. Jackson is a high school junior who plays soccer in the fall. His friends have talked him into going out for track and he wants to run the 800 meters. How should his coach proceed with his aerobic training? Soccer is a good anaerobic activity which also stimulates the development of the peripheral $VO_{2\ max}$ system. Jackson lacks central $VO_{2\ max}$ development. He needs to create a greater heart stroke volume, build more capillaries, generate more red blood cell volume, and increase his mitochondria number and size. All of these factors need to be improved without causing injuries to his legs and feet by doing too many continuous footsteps right away. In essence, Jackson needs to aerobically develop so that a standard five mile run feels easy to him. Two days per week Jackson should run 5 x 2k repeats, or something similar. Work time to recovery time should be 1:1. The pace should be comfortable for him. No set pace, just a feeling that it is a workout that he can complete. After a month of this, Jackson should feel comfortable on a five mile run and testing of his $VO_{2\ max}$ system can commence, thus adding more structure to his aerobic work.

Physiologists have provided endurance coaches with considerable information on the concepts of aerobic power and the anatomy and physiology of the $VO_{2\ max}$ system. Scientific evidence suggests that all aerobic races are shaped by aerobic power and its development to a degree, both before and after a runner reaches physical maturity. It is important these principles are applied to developing distance runners in a manner that reflects knowledge of growth, development, and maturity factors.