MAXIMAL AEROBIC POWER
(VO_{2max}/VO_{2peak})

Application to Training and Performance

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Definition of Maximal Aerobic Power (VO_{2max}):

Maximal aerobic power (VO_{2max}) is a measurement of *the maximal amount of oxygen that the body is able to use for the purpose of producing energy.* It represents the upper limit of aerobic exercise tolerance. VO_{2max} can be expressed in relative values (milliliters of oxygen per kilogram body weight per minute; ml/kg/min) or in absolute values (liters of oxygen per minute; L/min). Expressing VO_{2max} in relative values allows comparisons to be made between athletes of differing body mass. An elite aerobic athlete has the ability to sustain VO_{2max} for about 8-10 minutes.

Factors affecting VO_{2max} :

Physiological factors that affect maximal aerobic power are classified as either *central* or *peripheral*. The primary function of central factors is *oxygen delivery* from the heart to the working muscles via the bloodstream. The primary function of peripheral factors is *oxygen extraction* from the blood at the site of the working muscle. As seen in Figure 1, VO_{2max} is determined by **both** oxygen delivery (central) and oxygen extraction (peripheral).

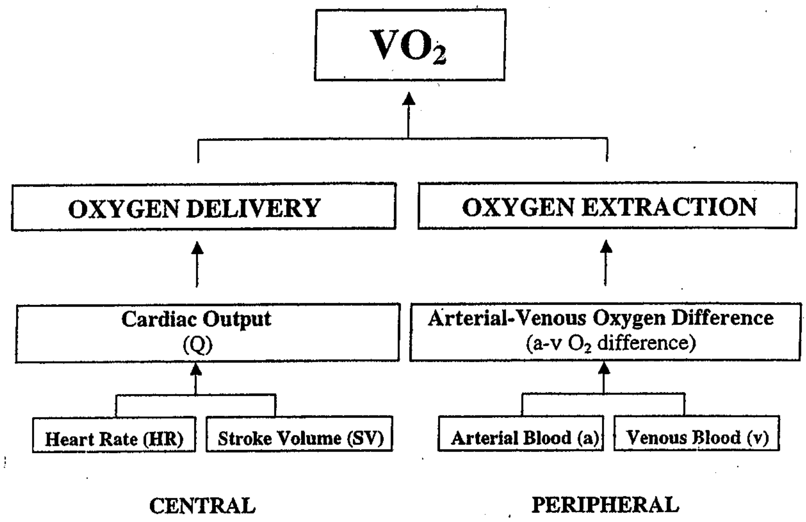
Central Factors: The most important central factor affecting VO_{2max} is **cardiac output** (Q). Cardiac output is defined as the volume of blood ejected by the heart every minute. As shown in Figure 2, cardiac output is a product of **heart rate** (HR) and **stroke volume** (SV). Heart rate is simply the number of heartbeats per minute, whereas stroke volume is the volume of blood ejected by the heart in a single heartbeat. Thus, by multiplying HR (bpm) times SV (milliliters of blood/heartbeat), one can calculate Q (milliliters of blood/min). Cardiac output can be enhanced through progressive aerobic training. This improvement in Q occurs primarily as a result of a significant increase in SV. In turn, increased SV is due to training-induced changes in total blood volume, cardiac muscle contractility, and sympathetic nervous system activity.

Peripheral Factors: The primary peripheral factor affecting VO_{2max} is the **arterial-venous oxygen difference** (a-v O_2 diff.). As shown in Figure 1, the a-v O_2 difference is simply the difference between the amount of oxygen in *arterial* blood (oxygen-rich blood going from the heart to the working muscles) and the amount of oxygen in *venous* blood (oxygen-poor blood going from the working muscles back to the heart). Thus, the a-v O_2 difference provides an accurate measure of the amount of oxygen extracted by the working muscles, which will ultimately be used for energy production. Similar to cardiac output, progressive aerobic training will produce improvements in the ability of skeletal muscle to extract oxygen during exercise. Improvements in the a-v O_2 difference are due to training-induced increases in capillary density, myoglobin, and oxidative enzymes.

Altitude: An increase in altitude results in a decrease in air density and the partial pressure of oxygen in the air. For athletes competing in events lasting longer than approximately one minute, the decrease in the partial pressure of oxygen reduces VO_{2max}. Based on a mathematical model (Peronnet, et al., 1991), one can estimate that the loss in maximal aerobic power from sea level to Colorado Springs, CO (1860 m/6100 ft) would be approximately 5 to 7 %. For example, if an athlete attained a VO_{2max} of 70 ml/kg/min in San Diego, CA, the athlete could expect a VO_{2max} of 65.1 to 66.5 ml/kg/min in Colorado Springs, CO. There is, however, a tendency for a greater loss of VO_{2max} if one has a high VO_{2max}. Thus, an athlete with a very high sea level VO_{2max} might see a greater percent decrease than someone with a low sea level VO_{2max}.

Other: Other factors which can affect VO_{2max} include the motivation of the athlete to perform maximally, familiarity with the protocol and/or equipment being used, and training status. These factors should be controlled as much as possible to achieve the best results. If the athlete has never been tested, taking some time to familiarize the athlete with all the procedures and allowing the athlete to use the equipment prior to testing is suggested.

Figure 1. Central and peripheral factors affecting VO_{2max}



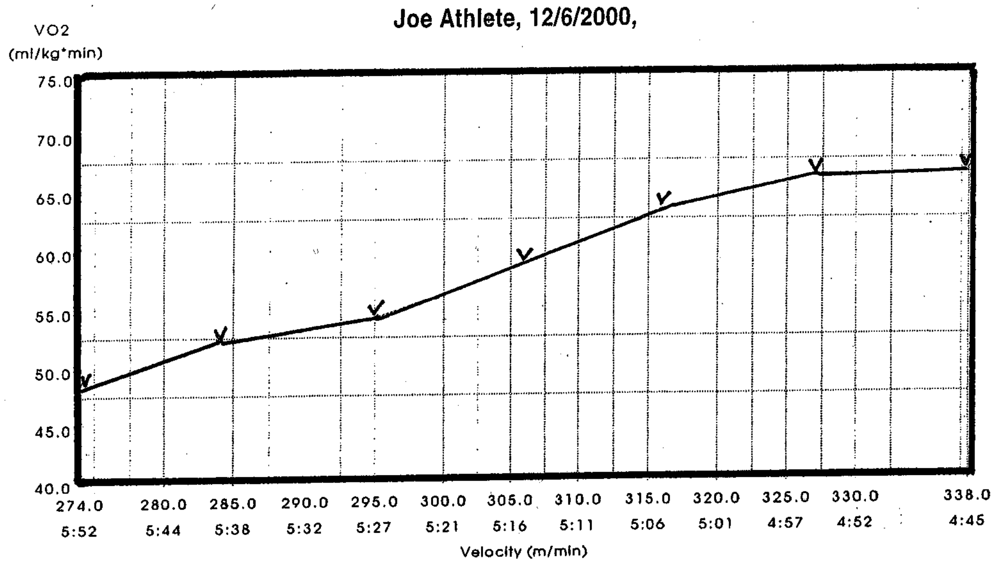
Determination of VO_{2max} in the laboratory:

Sport-specific exercise tests are used to evaluate VO_{2max} in the laboratory. These tests are designed to take an athlete through several stages of progressively intense work. Each stage lasts about 3-4 minutes, with the initial stages being relatively easy for the athlete and subsequent stages becoming progressively harder. As the intensity of the test increases, there is a greater demand for energy. This demand is met through an increase in oxygen consumption. At some point, the ability to either deliver oxygen to the muscles or to extract oxygen from the blood (or both) approaches an upper limit, and the athlete reaches exhaustion. VO_{2max} is typically seen during the final 30-60 seconds of the test. Upon completion of the test, sport scientists evaluate the data and use specific physiological criteria to verify whether the athlete reached a "maximal" level of exertion. These criteria include:

- VO_2 rises by less than 150 ml/min during the final stage of the test (the "plateau" criterion)
- respiratory exchange ratio (R) $\geq$ 1.10
- blood lactate (HLa) $\geq$ 7.0 mmol/L
- maximal heart rate falls within 5% of age-predicted maximal heart rate (220-age)

In the event that these physiological criteria are not met, the highest O_2 uptake value obtained during the test is referred to as VO_2 *peak*, as opposed to a VO_{2max}. A graphic representation of various physiological responses typically seen during an incremental exercise test is shown in **Figure 2**.

Figure 2. Incremental Exercise Test Exergraph



In Figure 2, the x-axis displays work in appropriate units of measurement and the y-axis displays VO_2, or oxygen uptake (ml/kg/min). Other variables are often recorded at each stage of the test. These include blood lactate, heart rate, and Rate of Perceived Exertion (not shown). Measurements obtained from the athlete during each stage of the test are plotted and displayed in this graphic format.

VO_{2max} and Exercise Performance:

A common misconception among athletes and coaches is that a high VO_{2max} is the best predictor of endurance performance. While VO_{2max} seems to predict performance in a group of athletes with a wide range of fitness, it is not as strong a predictor of performance in a groups of athletes with similar aerobic capacities, particularly in elite endurance athletes who have high VO_{2max} values (>60 ml/kg/min). Research shows that other variables such as power output at lactate threshold, exercise economy (oxygen consumption at a submaximal pace), power output at VO_{2max}, and muscle power may be more reliable predictors of endurance performance. The following data from elite distance runners (Conley et al, 1980) demonstrate this well.

Subject (Age)	**VO_{2max} (ml/kg/min)**	**10K Run Time**
A (25)	77.74	30.52
B (28)	67.74	30.98
C (28)	70.55	31.15
E (30)	71.95	31.75
I (20)	72.69	32.62
K (23)	71.79	33.30
L (21)	73.72	33.55

Subject B, despite having the lowest VO_{2max} of the group, placed second in this particular running event. Obviously, other factors play a large role in endurance performance success.

Summary:

Maximal aerobic power is one of many important factors contributing to successful performance in aerobically based sports. VO_{2max} is evaluated in the laboratory using a sport-specific incremental exercise test. The maximal or peak data obtained during the test can provide information on aerobic potential and adaptations to endurance training.

Scientific research has suggested that approximately 80% of an individual's aerobic power is genetically determined. However, maximal aerobic power can be enhanced through progressive endurance training. On average, VO_{2max} can be increased by 15-20% or more in untrained individuals depending on the initial level of fitness. In contrast, it is unlikely for an elite level athlete to realize an increase in VO_{2max} of greater than 3-5% due to the relatively high level of conditioning already attained by the elite athlete.

Table 1 provides representative VO_{2max} values for untrained, trained, and elite aerobic athletes (female and male). Maximal aerobic power is expressed in both absolute and relative terms. In sports such as cycling, swimming, and rowing, an athlete does not carry their own body weight during the exercise. Therefore, absolute VO_{2max} values are more significant. In sports such as running and Nordic skiing, however, body weight is an important factor in the amount of work performed. Therefore, oxygen uptake is expressed relative to the body weight of the athlete. **Table 2** lists representative VO_{2max} values of elite athletes from several sports.

Table 1. **VO_{2max} values of untrained individuals, moderately trained individuals, and elite aerobic athletes.**

	FEMALE			MALE		
	Untrained	**Trained**	**Elite**	**Untrained**	**Trained**	**Elite**
Absolute (L/min)	<3.0	3.0-3.5	>3.5	<3.5	3.5-4.5	>4.5
Relative (ml/kg/min)	26-42	40-60	55-70	36-52	50-70	60-85

Table 2. Typical values for VO_{2max} of elite athletes from different sports (ml/kg/min).

SPORT	AGE	MALE	FEMALE
Basketball	18-30	40-60	43-60
Canoe/Kayak	22-28	55-67	48-52
Cycling	18-26	62-74	47-57
Racquetball	20-35	55-62	50-60
Rowing	20-35	60-72	58-65
Skiing: Alpine Cross Country	18-30 20-28	57-68 65-95	50-55 60-75
Soccer	22-28	54-64	*
Speedskating	18-24	56-73	44-55
Swimming	10-25	50-70	40-60
Track & Field: Runners	18-39	60-85	50-75
Triathlon (running)	16-33	55-74	45-64
Triathlon (cycling)	16-33	57-83	46-68
Volleyball	18-22	*	40-56
Weight lifting	20-30	38-52	*
Wrestling	20-30	52-65	*

No data available
Source: Physiology of Sport and Exercise, p. 233.
Triathlon data from USOC Athlete Performance Lab, Colorado Springs, CO (altitude 1860m/6100ft) from 1994 to 1998.

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