

Limiting Factors of Endurance Exercise

Human capacity to perform prolonged exhaustive exercise is usually considered to be limited by three major factors:

- [Glycogen Depletion](#)
- [Water and Salt Loss and Resultant Hypothermia](#)
- [Inadequate Oxygen Transport and Lactic Acid Accumulation](#)

Glycogen Depletion

In long distance races, energy comes either from glucose (carbohydrate) stored in the form of *glycogen*, or from fat in the form of *free fatty acids*. **Heavy exercise depletes glycogen stores quickly.** In order to continue to produce the required energy after the glycogen stores have been depleted, the muscles utilize fat. However, fat requires more oxygen than glucose (approximately 7.5% more) to release the same amount of energy.

At rest, you consume approximately 40% carbohydrate, 45% fat and 15% protein. During exercise of low intensity, *fat* is the preferred fuel. However, as your running intensity increases to 70 - 75% of your maximal endurance capacity (maximal oxygen uptake), it is primarily *carbohydrate* that is used. As an example, at the start of a 10 mile road race, you are using 95% carbohydrate and 5% fat, but towards the end of the race, the glycogen reserves are becoming depleted and the runner is utilizing 20% carbohydrate and 80% fat.

FAT

The body has considerable fat stores to supply the free fatty acids for fuel. The average male has 18–25% body fat and the average female 25–31% while the best male marathoners have 6–13% and the females 14–20%.

As an adaptation to years of endurance training, **the top class runner can utilize the free fatty acids even at a high exercise intensity.** Physiological studies have shown a lessened usage of muscle glycogen and enhanced capacity for endurance capacity when there was a high level of free fatty acids in the blood circulation. The unconditioned runner, however, is only able to use carbohydrate during high intensity exercise.

CAFFEINE

Caffeine and theobromine of tea are both agents which will mobilize free fatty acids from the fat stores in the body into the blood.

Recent studies have shown that when athletes took 330 mg of caffeine (equal to 2.5 cups of coffee) one hour before exercise at 80% of their maximal oxygen uptake, the total time exhaustion was increased by 19.5%. This means **an increase of 75.5 minutes to 90.2 minutes!**

Measured metabolic parameters indicated an increased rate of fat metabolism and a reduced rate of carbohydrate oxidation, hence a glycogen-sparing effect.

The athletes taking the caffeine also subjectively rated the effort involved in the exercise as easier than did those athletes who had not been given caffeine.

MUSCLE GLYCOGEN

As previously discussed, one of the major limiting factors in the performance of long-term muscular work is the size of the preformed glycogen stores in the working muscle.

The liver may store 5–7 ounces of glycogen, and muscle tissue may store 5–10 ounces of glycogen. Total carbohydrate stores and therefore 10–17 ounces. This total glycogen will provide from 1200–2000 kcal and in a marathon, will only be sufficient for approximately 10–18 miles.

After this point in the race, **you have only fat left to burn** as fuel.

Since fat requires more oxygen for the same energy, your pace must slow. Otherwise, you will be running at a higher percentage of maximal oxygen uptake and will start to build up the metabolic fatigue product, *lactic acid*.

To ensure a successful race, you must reduce to the minimum the use of fat as fuel in the later stages of your race by consuming carbohydrates just prior to and during the event, to supplement the glycogen stores.

(Some findings recommend increasing glycogen stores by supplying the blood with 8 – 10 ounces of pure starches and glucose in liquid form.)

CARBOHYDRATE LOADING

Swedish investigators found that different combinations of diet following an exhaustive run could **increase the muscle glycogen level** three to five times.

If a high fat/protein diet was taken following an exhaustive run (over 100 minutes), the muscle glycogen level remained essentially at zero. The effect on the glycogen levels being essentially the same as complete starvation.

However, **a high carbohydrate diet** restored the glycogen level in 12–24 hours and often the muscle glycogen levels shot up to significantly higher levels than were previously present.

The highest glycogen levels occurred with three days of a fat/protein diet followed by three days of a high carbohydrate diet. Moderate training should take place during the three days of the fat/protein diet but the runner should rest or only jog while on the carbohydrate diet.

The carbohydrate loading diet is not without drawbacks and in fact can only be used a maximum of once every six to eight weeks. Best results occur when it is limited to three times per season.

You can expect to gain between six to seven pounds while loading since three water molecules are stored along every molecule of glycogen. **Some runners experience diarrhea and abdominal cramps** following a strict form of this diet.

For the reasons mentioned, many marathoners are using a modified loading diet consisting of a mixed diet for three days followed by three to four days of high carbohydrate intake.

Each runner reacts differently, you may require from three to seven days to increase your glycogen stores following an exhaustive run. (Reports suggest this is particularly true for older athletes.)

GLUCOSE DRINKS

Studies have shown that working capacity is helped considerably when blood sugar is increased. Often, uncomfortable sensations during an exhaustive run are due to low blood sugar, called *hypoglycemia*.

Hypoglycemia, besides lowering muscular performance, also depresses cerebral (brain) function.

Research has shown **beneficial effects of using a glucose-electrolyte (sodium and potassium) solution**. When using the glucose-electrolyte solution, athletes kept burning carbohydrates; whereas in athletes drinking water or not drinking at all, the proportion of fat used increased considerably.

The concentration of the sugar solution is a very important factor because, of all the ingredients in any athletic drink, **sugar has the greatest effect on the rate of gastric (stomach) emptying**. All sugars, whether glucose, fructose or sucrose, have a retarding effect on gastric emptying.

Solutions with glucose concentrations of 2-2.5 per 100ml of water are the best absorbed.

The ideal fluid, especially during hot weather competition and training, is one that is:

- low in sugar concentration (less than 2.5 g per 100 ml of water)
- cold, 8-13 degrees Celsius (25-55 degrees Fahrenheit)
- Palatable during exercise.

This solution should be consumed in volumes ranging from 100-400 ml (3-10 oz.). Drink 500 ml thirty minutes before the race, and drink 100-200 ml (3-6 oz.) every 15-20 minutes during the race.

Water and Salt Loss and Resultant Hypothermia

Body heat is produced by assimilation of food, by muscular exercise and by all the vital processes (e.g. hormonal effects) that contribute to the basal

metabolic rate. Physical exercise results in a large internal heat surplus that must be partially eliminated if the athlete expects to survive such thermal stress.

Excess heat from the athlete is lost from the body by radiation, conduction and vaporization of the water in the respiratory passages and on the skin. Small amounts of heat are also lost in the urine and feces. Therefore, the **body temperature is the balance between heat production and heat loss.**

During distance running, a very large portion of the **excess internal heat is lost through sweat evaporation.** In the distance runner the circulatory system functions first to deliver nutrients to the active tissues and to remove waste products, and secondly to regulate the heat transfer from the metabolically active muscles to the body surface. In addition, increased muscle temperature resulting from exercise and also from the outside environment causes an increase in cellular respiration, requiring greater oxygen uptake (VO₂) to accomplish any given task.

It is because of these added demands on the blood flow that body temperature regulation and circulatory capacity are significantly influenced by the environmental temperature and humidity. During competition, the circulatory system is stressed maximally to meet the demands of the active muscle.

When performing in warm, humid conditions, the circulation cannot perform both tasks (i.e. supplying nutrients to muscle and regulating body temperature) to the complete satisfaction of the body. As a result, your **performance is impaired and overheating becomes a serious problem.**

HEAT AND DEHYDRATION

Body weight loss of greater than 3-4% is considered critically debilitating. Dehydration to this degree, especially if rapid and combined with heat stress, lead to reduced endurance, slower reflexes, cramps and quite possibly total collapse. *This is a very serious and often fatal situation known as heat stroke.*

The tolerance of high body temperatures is therefore a necessary condition for success in marathon running. The fatigue and decreased competitive drive which so many marathoners experience during the last eight kilometers of a race may be due for the greater part to water deficits exceeding 3%.

There appears to be significant value in replacing body fluids: this helps maintain low body temperature, maintain low heart rates, and prevent plasma volume reduction and electrolyte changes.

However, during prolonged severe running, the rapid fluid loss, combined with limited rate of gastric emptying and feeding habits during the marathon, make this practice largely ineffective.

Stress of this kind will result in acclimatization within four to eight days. (This time is longer, of course, for those athletes who are less fit.) After acclimatization, **the athlete is able to tolerate the heat to a greater extent** and performances will dramatically improve.

The improvement in heat tolerance is associated with increased sweat production and a lowered skin and body temperature. The sweat is more profuse and more dilute with less salt loss. Studies suggest the **increased sweat rate provides the possibility for a more effective cooling of the skin** through the evaporative heat loss. And the resultant lowered skin temperature provides for better cooling of the blood flowing through the skin.

The body can therefore afford to decrease (by 40%) the skin blood flow. **Exercise heart rates are significantly lower after acclimatization.** And even though it has been reported that blood volume increased with heat acclimatization, the change is transitory. Acclimatization can occur without the change in blood volume.

FLUID REPLACEMENT

Studies have shown that during the final 60 minutes of exercise, glucose-electrolyte feedings maintained the serum electrolytes near the pre-exercise level, elevated the blood glucose and maintained carbohydrate metabolism. **The important electrolytes to be replaced are sodium, potassium, magnesium and calcium.** Further research has shown that in addition to the above mentioned electrolytes, you also lose vitamin C (ascorbic acid) in sweat.

Your fluid replacement solution should have a low sugar concentration (less than 2.5g/100ml water). Greater concentrations delay gastric emptying. **Cold drinks have been found to empty more rapidly from the stomach than do warm fluids.** The ideal temperature (no cramping) appears to be between 8-13 degrees Celsius (45-55 degrees Fahrenheit).

It was originally felt that the ideal solution should be isotonic with body fluids. However, more recent studies have shown that solutions that are hypotonic (fewer particles per unit of water than body fluids) empty more rapidly from the stomach than either isotonic or hypertonic solutions.

Studies done at the University of Washington have shown that **tomato juice is an excellent replacement fluid** after training and competition in heat. It replaces the sodium chloride and potassium lost during perspiration.

The ability to drink sufficient fluid during endurance events, to prevent a large water deficit, must be acquired through training. They suggest the ideal regimen of fluid drinking is to take about 300 ml (8 oz.) every 20 minutes. This should start 30 minutes before the beginning of the race.

In terms of marathoners, **the fluid requirement of an average weight man in cool, comfortable weather is about 1200 ml (2 pints).** In heat, however, the volume doubles to 2400 ml (4 pints) in order to keep the water deficit below 3% of body weight. Heavy men are encouraged to drink at a greater rate than light men since the rate of sweating is related to body weight.

To prevent a state of chronic dehydration when training during hot weather, you should **keep a record of your early morning weight** (taken before breakfast and after urination). Any deficiencies should then be corrected daily with liberal amounts

of tomato juice, orange juice and water. In addition, modest of salt should be added to food.

HEAT INJURIES

Heat Exhaustion

Cause: Excess loss of body fluids due to prolonged sweating.

Signs and symptoms: profuse sweating, nausea, vomiting, dizziness and headache. The skin is pale and cold and sweaty. Breathing is slow and shallow, the pulse is weak and rapid, and the temperature is normal and subnormal. There may be loss of consciousness.

Heat Stroke (Sunstroke)

Note: This can be a medical emergency which can be fatal if the victim is not cooled down immediately.

Cause: Prolonged exposure to heat and sun. The heat-regulating system of the body fails and allows the body temperature to rise over 40.5 degrees Celsius (105 degrees Fahrenheit). **The body becomes incapable of sweating.**

Signs and symptoms: sudden unconsciousness, which may be preceded by headache and vomiting. **There will be nausea and dizziness if the patient has not lost consciousness.** The skin is usually but not always hot, dry and flushed. The respiration is deep and fast and the temperature is high.

Treatment: **Decrease the body temperature as rapidly as possible.** Remove clothing; immerse in a tub of cold water or wrap in sheets, towels or clothing soaked in cold water. Keep the person in the shade or the coolest place you can find and call a doctor immediately.

Inadequate Oxygen Transport and Lactic Acid Accumulation

In order to run, or indeed to perform any physical activity, the body needs oxygen. If sufficient oxygen is taken up during a task to serve the body's needs, the work is said to be done "**aerobically**" and you "pay as you go" in oxygen. This type of work can be carried on for a long time.

If the oxygen than can be taken up during a task is not enough for the task being performed, the body continues to do the work "**anaerobically**", postponing the intake of the extra oxygen until the task is finished. Working anaerobically, the muscles manufacture lactic acid in proportion to the amount of "**oxygen debt**" being accumulated. As a result of this acid lactate, the muscle cells' environment becomes progressively worse until it eventually stops them functioning altogether. **Anaerobic work is necessary for short duration.**

Over a period of years of training, endurance athletes develop a very great ability to take up and use oxygen. These athletes can operate at close to the absolute maximum ability for long periods of time.

AEROBIC CAPACITY

As Table 1 shows, **the marathon is almost totally an aerobic event** (98% of the oxygen requirements are satisfied during the event), while even the 10 km even is 90% aerobic. Consequently, a highly developed ability to take up large amounts of oxygen is essential for good performance in these events.

Table 1: Oxygen uptake and oxygen debt in various running events

Distance	Taken up during event*	Accumulated as oxygen debt*
200m	5	95
400m	17	83
800m	34	66
1500m	50	50
5000	80	20
10000m	90	10
Marathon	98	2

*Percentage of total oxygen needs.

The **“aerobic capacity”** or **“maximum oxygen uptake”** is measured in litres of oxygen taken up by the body per minute, or in terms of millilitres of oxygen per kilogram of body weight per minutes (ml/kg/min).

Athletes with the highest oxygen uptakes are those who trained during their adolescent growth spurt.

Percentage of Aerobic Capacity Used

Top class marathoners use about 75% of their aerobic capacities. Younger runners employ 65-75% of their maximum oxygen uptake, while studies indicate that older runners (ages 40-47) are able to utilize between 80-85% of their capacities.

Years of training and competition seem to develop the runner’s ability to utilize a greater portion of his or her aerobic capacity. This could be due, in part, to cellular adaptations to the stress of regular training, such as increased capillarization; mitochondrial number; and enzyme content which increase the muscles’ oxidative capabilities. The increased oxygen extraction enables these distance runners to perform with lower muscle blood flows and hence lower cardiac output for a given pace.

The average energy cost of running is 0.9 kilocalories per kilogram of body weight per kilometer ((kcal/kg/km). **The average 64.5 kg (140lb) marathoner will therefore expend a total of $0.9 \times 64.5 \times 42.195 = 2,450$ kilocalories in completing the marathon distance.** If he runs the race in 2:30, this works out to approximately 16.3 kcal/min.

Since 1 litre of oxygen liberates approximately 5 kilocalories of energy, the total oxygen cost of a marathon is approximately 2,450 divided by 5 to equal 490 litres. Our 64.5 kg marathoner completing the distance in 2:30 (150 minute) would therefore require an oxygen uptake of approximately 490 divided by 64.5 plus 150 = 50ml/kg/min. To complete the distance in 2:10 (130 minutes) would require an oxygen uptake of $490 \div 64.5 + 130 = 58.5$ ml/kg/min.

If we assume that these performances were achieved at 75% of aerobic capacity, then our 2:30 marathoner would need an aerobic capacity of 66.7 ml/kg/min, and our 2:10 marathoner would need a capacity of 78 ml/kg/min.

Conversely, given measurements of aerobic capacity (maximum oxygen uptake), rate of oxygen consumption and lactate levels at various running speeds, **a runner's best marathon performance may be predicted.**

Limiting Factors in Oxygen Transport

Aerobic Capacity – Maximum oxygen uptake is affected by:

- The stroke volume of the heart
- Total body haemoglobin
- Capillarization of the muscles
- Possibly, mitochondrial size, mass and enzyme content

In the distance runner, all of these are increased through regular endurance training, resulting in a high maximum oxygen uptake. Larger stroke volume of the heart circulates more blood with each heart beat. **Higher total body haemoglobin increases the oxygen-carrying capacity of the blood.** Increased capillarization of the muscle makes the muscle better able to receive and remove the oxygen from the blood. Changes in the mitochondrial size, mass and enzyme content may similarly increase the muscles' ability to extract oxygen from the blood.

Lactate Accumulations – **If the runner is unable to meet the oxygen cost of the pace he or she is setting, an oxygen debt will occur.** Working anaerobically, the muscles produce lactate which accumulates in the blood. However, the increasing blood acidity inhibits the enzyme which is necessary for the aerobic work to continue, so that the use of anaerobic pathways is self-limiting.

The trained athlete can run at 60-65% of his or her maximum oxygen uptake without any increase in blood lactate level. **The marathoner runs at 75% of his maximum uptake with only a small increase in blood lactate.** However, if the running speed exceeds 70-80% of the maximum power, lactate builds up. At the 70% level an initial increase in lactate occurs.

*Note: During the course of the run, lactate levels decrease almost to resting levels because **lactate can be used directly as a fuel by the heart and skeletal muscles.***

Some of the lactate is also converted to glycogen in the liver (via what is known as the Cori cycle), and glycogen is later used as a source of energy.

The best athletes remove lactate faster because of a greater percentage of red or slow twitch muscle fibres and because of greater activity of a particular enzyme (lactate dehydrogenase – LDH). **Lactate removal following a hard race or repetition workout is also faster if you jog continuously after the session than if you simply rest.**

There is optimal body efficiency for endurance activity at a heart rate of 130-150 beats per minute. At this optimal rate, there is the largest maximum oxygen uptake accompanying the smallest possible ventilation rate (breaths taken per minute) together with the smallest possible lactate buildup.

Factors which Add to the Oxygen Cost of Running

Speed – Oxygen requirements vary with the cube of the speed of running, so it is imperative that the runner remain within strict limits of his capacities. *A minor variation in speed at a fast racing pace will put the oxygen cost of the total task dangerously close to the athlete's limit.*

To obtain your best time, it is usually better to run the last half of the race faster than the first half.

Wind and Air Resistance – Pugh (1970) found that the extra oxygen uptake associated with wind increased as the square of the wind velocity. If the wind velocity and running velocity are equal, as in running on a track in calm air, oxygen uptake will increase as the cube of the running speed.

Hill (1928) reported that a head wind of about 10 mph (16km/h) will reduce a runner's speed by about 5%.

Weight of Shoes – Turrell and Robinson (1943) found that the addition of 1 kg of weight to a person's footwear is approximately equivalent to adding a weight of 4 kg in a pack. For this reason, most marathon racing shoes are very light (0.4 kg). Increased shoe weight from 0.4 kg – 0.9 kg can account for over 500 kilocalories of extra energy expenditure in the marathon.

Stride Length – Increased beyond the natural stride length lead to dramatic increases in the oxygen cost of running.

Hills and Uneven Terrain – Hills and uneven terrain also dramatically increase the oxygen cost of running.

Supply and Resynthesis of ATP

The energy for muscular contraction is dependent upon the breakdown of the high energy phosphate ATP. Since there are no stores of ATP in the body, endurance activities like the marathon are dependent on the continual resynthesis of the needed ATP. The resynthesis takes place in the mitochondria.

The prime source of **the energy required to resynthesize the ATP comes from the breakdown of fats and carbohydrates.** Under aerobic conditions, the metabolic apparatus (Krebs cycle and electron transport chain) in the mitochondria completely oxidizes glucose (from the fats and carbohydrates) into carbon dioxide and water, producing the required ATP. Only in the initial phase and at the end of the marathon (final sprint) do anaerobic (glycolytic) processes come into play, resynthesizing ATP but at the same time producing lactate.

From an article by Jack Taunton, B.Sc., M.Sc., M.D. in TRI-FIT Quarterly, published by Steve King.