The science of endurance

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Introduction

From the time that, according to legend, the Athenian messenger Pheidippides ran the 40km from Marathon to Athens to announce the Greek victory over Persia in the Battle of Marathon and then immediately dropped dead from the effort, people have had a fascination with human limits and a compelling interest in feats of endurance.

Indeed, we have repeatedly tried to push the limits of endurance: from the 50 marathons in 50 days and the 300 miles (480km) of non-stop running by Dean Karnazes, to the average speed of 26 miles (42km) per hour by Lance Armstrong during the three-week Tour de France, to the average marathon pace of 5 minutes and 10 seconds per mile (3:12 per km) by Great Britain's Paula Radcliffe and 4 minutes and 44 seconds per mile (2:56 per km) by Ethiopia's Haile Gebrselassie, to the 1544 miles (2470km) covered by Norwegian Børge Ousland in crossing Antarctica in 64 days, to the ascent of Mount Everest without supplemental oxygen, the achievements have been nothing short of remarkable.

Coaches in the middle- and long-distance events, including race walking, are in the business of improving endurance. Understanding it, therefore, is critical to their success. This paper draws on the extensive current literature in the field to provide a general guide and starting point for further study by presenting a short overview of the elements that contribute to endurance and how these can be trained in athletes. It is written from the point of view of running, but the principles apply to race walking and other activities such as swimming, cycling, cross-country skiing, etc.

The Elements of Endurance

The main physical factors that influence endurance can be grouped as follows:

- cardiovascular,
- muscular,
- metabolic,
- neuromuscular.

Cardiovascular factors

The main cardiovascular factors that influence endurance are cardiac output and blood flow to the muscles. Cardiac output is the volume of blood pumped by the heart per minute, and it is the product of stroke volume and heart rate. Stroke volume is the amount of blood the heart pumps with each contraction of its left ventricle, and it is determined by the return of blood back to the heart through the venous circulation (venous return), the heart's ability to contract quickly and forcefully (contractility), the amount of pressure in the left ventricle (preload) and in the aorta (afterload), and the size of left the ventricle.

The larger the left ventricle, the more blood it can hold; the more blood it can hold, the more blood it can pump. One of the hallmark adaptations to cardiovascular endurance training is an increase in the size of the left ventricle. So characteristic is a large heart of genetically gifted and highly trained endurance athletes that it is considered a physiological condition, called Athlete's Heart, by the scientific and medical communities (NAYLOR et al., 2008).

Once the blood leaves the heart, its flow to the muscles depends on a number of factors, including:

- the redistribution of blood away from other, less important tissues to the active muscles;
- the resistance of blood flow through the blood vessels;
- the adequate dilation of blood vessels, which depends on the interplay between the sympathetic and parasympathetic nervous systems and their associated hormones;
- the oxygen transport capacity of the blood, which is determined by red blood cell volume and the amount of hemoglobin;
- the amount of myoglobin, which transports oxygen in the muscles;
- the density and volume of capillaries that perfuse the muscle fibres, which determine the time available for diffusion into the muscle mitochondria as blood transits the capillary network.

Men have a greater stroke volume and cardiac output to send more blood and oxygen to the muscles and more hemoglobin in their blood to transport oxygen. These two factors give them greater cardiovascular endurance than women.

Muscular factors

Once oxygen is delivered to the muscles, they have to use it to regenerate energy (ATP) for muscle contraction. The amount of oxygen extracted and used by the muscles is largely dependent on the muscles' mitochondrial and capillary volumes. The more capillaries that perfuse the muscle fibres, the shorter the diffusion distance for oxygen from the capillaries to the mitochondria, which contain the enzymes involved in aerobic metabolism. The number of mitochondrial enzymes is also an important determinant of endurance, since enzymes, through their catalysing effect on chemical reactions, control the rate at which ATP is produced.

Together, the cardiac output and the amount of oxygen extracted and used by the muscles determine aerobic power (VO_2max), the maximum volume of oxygen that the muscles can consume per minute. VO_2max is considered by many as the best single indicator of a person's aerobic fitness. Since it was first measured in humans in the 1920s, it has become one of the most often measured physiological variables in exercise physiology.

In 1930, physiologists suggested that there are marked differences in the amount of oxygen different people use when running at the same speeds, and that these differences in "economy" of oxygen use could be a major factor explaining differences in endurance performance (DILL, 1930). Running economy is the volume of oxygen (VO_2) used to run at a given speed and it is used as an important indicator of endurance. It is influenced by the individual's biomechanics, proportion of slow-twitch muscle fibres, mitochondrial density, and body weight.

For example, if two athletes have the same VO_2max, but Runner A uses 70% and Runner B uses 80% of his/her VO_2max while running at a given pace, the pace feels easier for Runner A because Runner A is more economical. Therefore, Runner A can run at a faster speed before feeling the same amount of fatigue as Runner B.

Metabolic factors

Endurance is also influenced by a number of metabolic factors, including the removal of lactate and the buffering of metabolic acidosis. For example, at relatively slow running speeds, lactate is removed from the muscles as quickly as it is produced. At greater velocities, there is an increased reliance on anaerobic glycolysis for the production of ATP, as the aerobic metabolism (Krebs cycle and electron transport chain) cannot keep up with the production of pyruvate from glycolysis. The pyruvate, therefore, is converted into lactate and lactate removal starts lagging behind lactate production, causing lactate to accumulate.

Concomitant with lactate accumulation is the accumulation of hydrogen ions in muscles and blood, causing metabolic acidosis and the development of fatigue. The lactate threshold (LT) is the running veloicty above which lactate production begins to exceed its removal. At this point, blood lactate concentration begins to increase exponentially. The LT demarcates the transition between running that is almost purely aerobic and running that includes significant oxygen-independent (anaerobic) metabolism. (There is an anaerobic contribution at any running velocity, although when running slower than LT pace, that contribution is negligible.) Thus, the LT is an important determinant of endurance performance, since it represents the fastest speed that can be sustained aerobically.

Another metabolic factor is the amount of carbohydrate (glycogen) stored in skeletal muscles (AHLBORG et al., 1967), with fatigue coinciding with glycogen depletion (SAHLIN et al., 1998). This is closely linked to the individual's ability to metabolise fat, since the supply of the muscles' preferred fuel—carbohydrate—is limited, providing enough energy for only about 100 minutes of marathon pace running. In contrast, humans' store of energy in the form of fat is greater: enough to fuel about five days of marathon pace running (NESHOLME, 1981) or about 1600km of walking for a 65kg person with 18% body fat (COYLE, 2000).

At slow running velocities, some of carbohydrate's metabolic responsibility for ATP regeneration is relieved by fat, in the form of free fatty acids in the blood and intramuscular triglyceride. Even with the contribution of fat oxidation helping to delay the depletion of glycogen, moderate-intensity running (70-75% VO_2max) can only be sustained for two to three hours (COYLE et al., 1986).

While women, as mentioned above, are at a definite cardiovascular disadvantage to men, they seem to have a greater capacity to metabolise fat and conserve glycogen (TAMOPOLSKY, 1998), which may give them an advantage for very long endurance activities. Indeed, in 2002 and 2003, a woman, Pam Reed, beat all the male competitors in the 135 mile (216km) Badwater Ultramarathon from Death Valley (85m below sea-level) to Mt Whitney Portal (2530m) in California, USA.

Neuromuscular factors

There are a number of steps in the process whereby muscles contract and produce force. First, the central nervous system sends a signal to a motor neuron, which integrates with a number of muscle fibres, creating a motor unit. When this signal reaches the end of the axon of the motor neuron, the neurotransmitter acetylcholine is released at the neuromuscular junction. This causes a change in the polarity of the muscle membrane (called depolarisation), as sodium ions rush in and potassium ions rush out. The signal, now called an action potential, propagates deep into the muscle to the sarcoplasmic reticulum, which stores calcium ions. The calcium diffuses from the sarcoplasmic reticulum into the area of the con-

Table 1: Methods for improving endurance in runners (vVO_2max = velocity at VO_2max; LT = lactate threshold)

Cardiovascular Factors
• 5 x 1000m at vVO_2max (95-100% max heart rate) with 1:<1 work-to-rest ratio
• 4 x 1200m at vVO_2max (95-100% max heart rate) with 1:<1 work-to-rest ratio
• 16 x 400m at vVO_2max with 1:<1 work-to-rest ratio
Muscular Factors
• High mileage, with progressive increases in volume (days per week and duration) over time
Metabolic Factors
• 5 to 10km at LT pace
• 5-7 x 1500m at LT pace with 1 minute rest
• Long runs of 15 to 25km
Neuromuscular Factors
• Strength training: 3-4 sets of 3-5 reps at >85% 1-rep max with 3 minutes rest
• Plyometrics (box jumps, squat jumps, leg bounds, bleacher hops, etc.)

tractile proteins—actin and myosin—and binds to a protein called troponin, which integrates with actin. Upon calcium binding to troponin, another protein called tropomyosin is removed from the active binding sites on the actin, exposing those sites to myosin. Myosin then binds to the actin, forming a cross-bridge. Finally, an ATP molecule contained inside the myosin is broken down into its constituents, releasing the energy contained within that molecule, allowing the muscle to contract.

For force production to continue, and for runners to maintain their pace, the central nervous system has to increase the number of motor units recruited and increase the frequency of stimulation of the motor units.

Training Endurance

The training typically used by endurance athletes stimulates many positive physiological, biochemical, and molecular adaptations including:

- an increase in VO_2max;
- a greater capillary network, which gives a more rapid diffusion of oxygen into the muscles;
- an increase in the number of red blood cells and hemoglobin, which improves blood vessels' oxygen-carrying capability;
- an increase in mitochondrial density and the number of aerobic enzymes through the complex activation of gene expression, which increases aerobic metabolic capacity.
- a greater storage of fuel (glycogen) in the muscles;
- an increase in intramuscular fat utilisation.

In addition, strength training may improve the neuromuscular aspect of endurance performance.

Table 1 gives a brief summary overview of the training means used by middle- and long-distance runners.

Cardiovascular factors

Long interval training (3 to 5 minutes) performed at the velocity at which VO_2max occurs (vVO_2max) provides the greatest cardiovascular load because athletes repeatedly reach and sustain their maximum stroke volume, cardiac output and VO_2max during the work periods. Therefore, they are considered the most potent stimulus for improving VO_2max (BILLAT, 2001; MIDGLEY et al., 2007). However, short intervals training (<2 minutes) can also improve VO_2max, as long as the loads are performed at a high intensity and with short, active recovery periods that keep VO_2 elevated throughout the workout.

The higher the athlete's VO_2max, the higher his/her aerobic ceiling and the more trained the athlete, the more important the intensity of training becomes for improving VO_2max, because the more cardiac-limited the VO_2max becomes. For highly trained runners, vVO_2max is about 3000m race pace. If a heart rate monitor is used as a guide, the athlete should come close to reaching maximum heart rate by the end of each work period.

Muscular factors

A large volume of endurance training may be the simplest way to increase the muscular factors associated with endurance (mitochondrial and capillary density and enzyme activity). Interval training has also been shown to increase aerobic enzyme activity (TALANIAN et al., 2007).

Metabolic factors

Running at the LT increases it to a faster speed and higher percentage of VO_2max, making what was an anaerobic intensity before now high aerobic. LT training can be done as a continuous workout or as intervals performed at LT intensity with short rest periods. LT pace is about seven to 10 seconds per kilometre slower than 5000m race pace (or about 10,000m race pace) for slower runners (slower than about 40 minutes for 10,000m). If using heart rate (HR), the pace is about 75 to 80% of max HR. For highly trained and elite runners, LT pace is about 15 to 18 seconds per kilometre slower than 5000m race pace (or about 10 to 12 seconds per kilometre slower than 10,000m race pace) and corresponds to about 85 to 90% max HR. The pace should feel "comfortably hard."

In a sense, long runs present a threat to the muscles' survival as they deplete the stores of glycogen. Depleting muscle glycogen forces muscles to rely on fat as fuel. The human body responds rather elegantly to situations that threaten or deplete its supply of fuel, synthesising and storing more than what was previously present, thus increasing endurance for future efforts. Empty a full glass, and you get a refilled larger glass in its place. The more glycogen athletes have packed into their muscles, the greater their ability to hold a hard pace.

Neuromuscular factors

A large volume of endurance training may have a neuromuscular benefit. It is possible that, just as repetition of the walking movement decreases the jerkiness of a toddler's walk to the point that it becomes smooth, repetition of a specific movement has an under-recognised neural component. With countless repetitions, motor unit recruitment patterns, all of the steps involved in muscle contraction, and possibly even the relationship between breathing and stride rate are optimised to minimise the oxygen cost and improve economy.

Neuromuscular factors and aerobic economy can also be targeted by power training. Studies have shown that both explosive strength training with heavy weights and plyometric training can improve the running economy in endurance athletes (HOFF et al., 2002; JUNG, 2003; PAAVOLAINEN et al., 1999; SPURRS et al., 2003; TURNER et al., 2003).

When strength training, coaches should make sure that athletes use a very high intensity and very few reps to focus on neural adaptation rather than muscle hypertrophy (which would decrease running economy by adding muscle mass).

Conclusion

Understanding the science of endurance will help coaches train athletes for the middle- and long-distance events, including race walking. And if they train long enough, they'll surely have the best endurance of all their competitors, good enough to even chase Pheidippides.

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