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Bioenergetics, Training and Performance in Distance Running

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List of abbreviations

$V'O_{2max}$ = maximum oxygen uptake
RE = running economy
FM = full marathon
HM = half marathon
$V'O_2$ = oxygen consumption
% $V'O_{2max}$ = percentage of $V'O_{2max}$
$vV'O_{2max}$= velocity at V'_{O2max}
O_2 = oxygen
COPD = chronic obstructive pulmonary disease
Q' = cardiac output
SDH = succinate dehydrogenase
SV = stroke volume
EMG =
GRF = ground reaction force
HIT = high intensity training
SSC = stretch shortening cycle
NO_3- = nitrate
NO_2- = nitrite
LT = lactate threshold
CP = critical power
% $V'O_{2max}$ = percentage of V'_{O2max}
1RM = 1 repetition maximum
FST = flywheel strength training
LIT = low intensity training
VT = ventilatory threshold
vVT1 = velocity at VT1
vVT2 = velocity at VT2
RV = reference velocity
TRIMP = training impulse
TID = training intensity distribution
MLSS = maximal lactate steady state

RCT = rate of compensation

POL = polarized

FOC = focused

SD = standard deviation

PET = polarized endurance training

FET = focalized endurance training

RPE = rate perceived effort

ATP = adenosine triphosphate

ADP= adenosine biphosphate

Overview

Recreational athletes represent the largest proportion of participants in several endurance sport events such as marathons, cycling races, triathlons and cross-country ski marathons; and their number continues to grow year after year. However, running seems to be the most suitable activity for people of any age, sex, experience and technical ability; it does not require too much time, equipment or a particular environment. Most of these athletes approach the practice of running just for health maintenance and then transforming this practice into a challenge with themselves. At that point they begin to train for the improvement of performance, often improvising their training programs.

Studies on running have dealt with the determinants of performance and training strategies to improve the performance of elite and well-trained athletes; but there is still little knowledge about the performance and training of recreational athletes. If determining factors are the same for any level of performance, the training strategies usually used by elite and well-trained athletes are not suitable for recreational athletes because they require a lot of time, structures and technical skills that they do not have.

The aim of this project was to define optimal training strategies for recreational runners to:

1) improve running economy (RE), the most important determinant in long distance running performance;

2) optimize the training time/performance ratio (time dedicated to practice is a limitation for recreational athletes);

Chapter 1

Introduction

Over the past decades, a steady increase in the number of participants in long distance running events such as full marathons (FM) and half marathons (HM) has been reported both in the USA and Europe (www.runningusa.org/statistics; www.maximaratona.it). In the United States, there were 30,400 running events in 2016, from 5Km runs to ultramarathons; 17,000,000 crossed the finish line. Five-point-three percent of the population participated in races. In Italy, the number of participants in marathons has doubled in the last ten years with a positive year-by-year trend, whereas in Germany the number of full marathoners steadily increased up to 2006 with a slow decline thereafter (www.marathonbestenliste.de). In recent years, half-marathon (HF) running enjoyed greater popularity than full marathon (FM) running according to participation trends of long-distance runners in the USA (www.runningusa.org/statistics). A continuous increase in the number of half marathoners since 1990 has been recorded in the USA. The highest number was reached in 2011 with a total of 1,600,000 starters corresponding to an increase of 16.2% in runners compared to the previous years. This increase was less than the historic ones -24% in both 2008 and 2009 - but still higher than in 2010 with an increase of 6.4%. In the past years, the number of full marathoners in the USA increased only slightly, in contrast with the rising numbers of half marathoners. When there was an increase of 9.9% and 8.9% in 2009 and 2010, respectively, the number of full marathoners only rose by 2.2% from 2010 to 2011. In Switzerland, the number of half marathon runners increased remarkably from 12,497 in 2000 to 48,061 in 2014. No similar data are available to date for half marathoners in Italy. These increased levels of participation have led to an increased range of abilities in participating runners, from amateur to elite levels (Ogueta-Alday and García-López, 2016). Consequently, the interest of the scientific community in studying different factors that affect performance (i.e., anthropometry, training methods, physiology and biomechanic components) has grown (Ogueta-Alday and García-López, 2016).

A change in participation trends was reported in one of the most popular city marathons - the one in New York City. In 2011, more than one third of the full marathoners in the USA were older than 40 years; in half marathons this age group rose to 40% (www.runningusa.org/statistics). The increase in full and half marathoners in the USA is most probably due to an higher number of runners older than 40 years and an increase in female runners (www.runningusa.org/statistics). Similarly, in Germany, the number of male and female full marathoners in age group 50-59 years was almost 10% higher than in age group 20-29 years. In 2016, about 75% of men and 67.5% of women marathoners in Italy were over 40 years of age, and 73% of total FM runners were 40-60 years old. This analysis showed that running is very popular among middle-aged people. It is well known that aerobic activity is one of the most important prevention tools for the most common diseases (obesity, hypertension, cardiovascular disease and metabolic problems). Aerobic activity has shown great potential in terms of health, psychological and sociological aspects and consequently of one's quality of life (Lee et al., 2014)

The definition of an adequate and optimal preparation for an endurance event in recreational runners is therefore crucial and realized not yet. It must tent to avoid sport failure and injuries, requiring a time commitment that allows people to train and compete regularly, following a detailed and structured training program compatible with their numerous job and family commitments belonging to a non-professional athlete.

Several studies on training strategies for long distance running have been done on elite or well-trained athletes. These strategies avoid errors or a waste of time in training programs if a trainer understands the specific importance of different performance determinants in a recreational athlete. Specific research in this area allows trainers to focus on their strategies to maximize improvement and reduce the number of unsatisfied athlete drop-outs.

An in-depth analysis of the physiological and functional determinants of endurance performance and the studies on their improvement strategies (training) has been carried out.

Chapter 2

The Determinants of Endurance Performance

In exercise, performance can be evaluated by the amount of time required to complete a given amount of work (power) or by the length of time that a given work rate can be maintained (capacity). The relationship between work load and work capacity is affected, however, by a complicated interaction of several factors, internal as well as external, which must be taken into consideration.

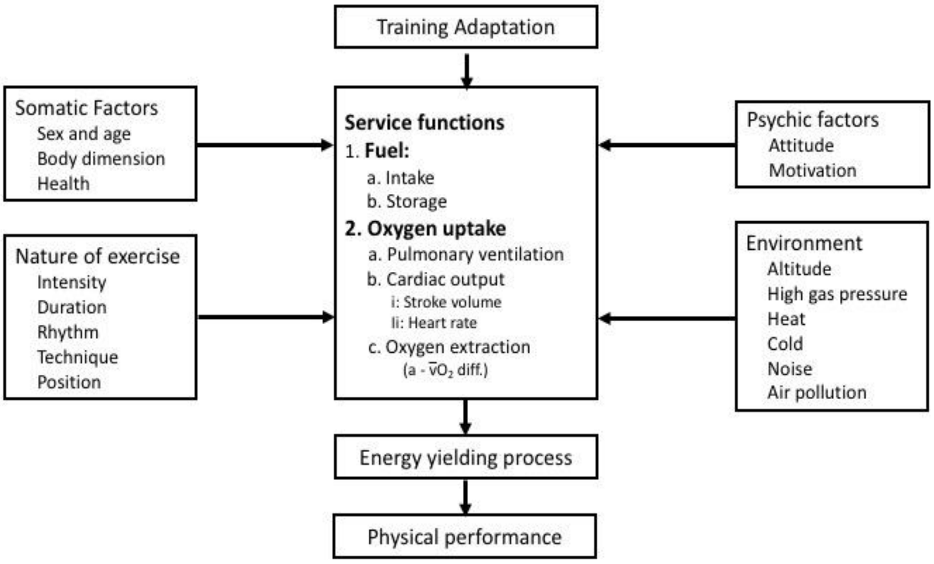

Figure 1 - Factors affecting physical performance. From Textbook of Work Physiology, Astrand

The ability to perform physical work basically depends on the capacity of the muscle cells to transform the chemically bound energy of food to mechanical energy for muscular work, that is, into the energy-yielding processes in muscle cells. This in turn depends on the capacity of the service functions that deliver fuel and oxygen to the working muscle fiber; for instance, it depends on nutritional properties, nature and quality of food ingested, frequency of meals, oxygen uptake including pulmonary ventilation, cardiac output and oxygen extraction, and the nervous and hormonal mechanisms that regulate these functions. Many of these functions depend on somatic factors, which may be partially genetically endowed such as sex, age, and body dimensions. In addition, we should remember the role of psychological factors such as motivation, attitude toward work, and the will to mobilize one’s resources in order to accomplish the task requirement. As shown in Figure 1, physical performance may also, directly or indirectly, be greatly influenced by factors in the external environment such as pollution, cold and heat, as well as by the type of work.

Focusing our attention on running bioenergetics, in order to maintain a specific work rate or running velocity over a long distance, ATP must be supplied to the cross bridge as fast as it is used. In other words, we can say that the rate at which oxygen is used during prolonged submaximal exercise is a measure of the rate at which ATP is generated. Over the years, a lot of criticism has been directed at this physiological model, but in light of several studies, the model has been confirmed as being able to explain endurance performance (Bassett & Howley, 1997).

Figure 2 shows that oxygen consumption ($V'O_2$) maintained during an endurance run, called “performance $V'O_2$” by Coyle (Coyle, 1995), is equal to the product of the runner’s $V'O_{2max}$ and the percentage of $V'O_{2max}$ that can be maintained during the run.

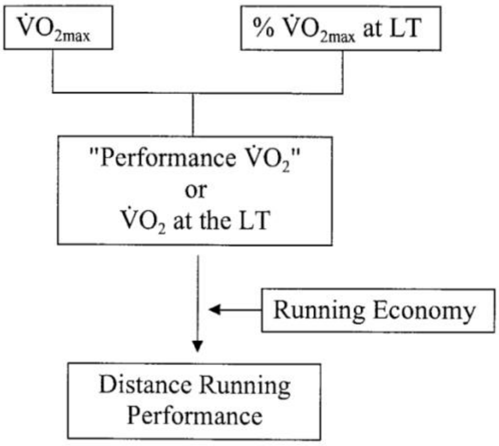

Figure 2 - Simplified diagram of the linkage between maximal aerobic power ($V^{\cdot}O_{2max}$), the percentage of maximal aerobic power (% $V^{\cdot}O_{2max}$) and running economy as they relate to distance running performance. From Basset DR et al 2000

The percentage of V'O_{2max} is related to the V'O_2 measured at the lactate threshold (LT), so in endurance events, metabolic performance is closely linked to the V'O_2 at LT. V'O_{2max} is limited primarily by cardiovascular factors (central), whereas the percentage of V'O_{2max} that can be maintained is linked primarily to adaptations in muscles (peripheral) resulting from prolonged training (Holloszy & Coyle, 1984). The actual running speed obtained by the rate of oxidative ATP generation (V'O_2 performance) is determined by the individual's ability to convert energy (e.g., running economy) into performance (Coyle, 1995; Daniels, 1985). One of the best descriptions of how V'O_{2max} and running economy interact to affect running velocity was provided by Daniels (J. T. Daniels, 1985) in his description of "velocity at V'O_{2max}" (vV'O_{2max}).

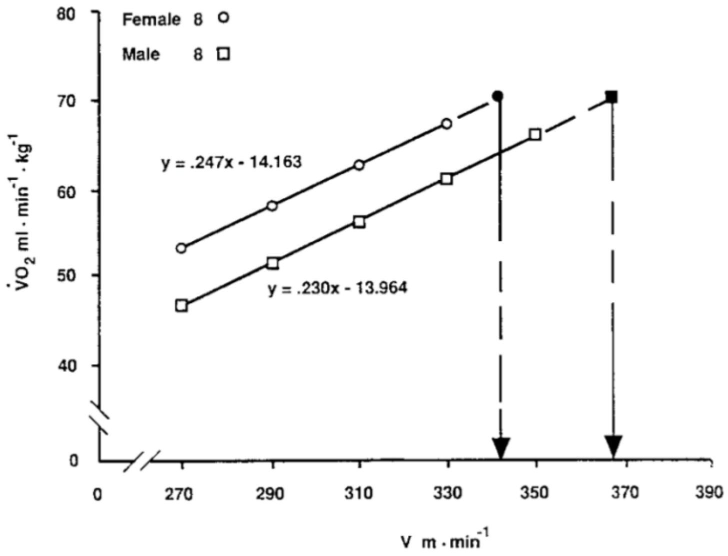

Figure 3 - Comparison of male and female runners of equal V'O_{2max}. The males are significantly favored in economy and vV'O_{2max} ($P < 0.05$).

Figure 3 shows the relationship between V'O_2 and running velocity for male and female runners - equal in terms of V'O_{2max}, but different in terms of running economy (J. Daniels & Daniels, 1992). A line was drawn through the series of points used to construct an economy-of-running line, and was extrapolated to the subject's V'O_{2max}. A perpendicular line was then drawn from the V'O_{2max} value to the x-axis to estimate the velocity that that subject would have achieved at V'O_{2max} (vV'O_{2max}). This is an estimation of the maximal speed that can be maintained by oxidative phosphorylation. In this example, the difference in running economy produced a clear difference in the speed that could be achieved if that race were run at $V'O_{2max}$. In like manner, Figure 4 shows the impact of different $V'O_{2max}$ in $vV'O_{2max}$ in groups with similar running economy values. The 14% difference in $V'O_{2max}$ resulted in a 14% difference in the $vV'O_{2max}$. Consequently, it is clear that $V'O_{2max}$ and running economy interact to set the upper limit of running speed that can be maintained by oxidative phosphorylation. However, if the distance races are not run at $vV'O_{2max}$, the ability of the athlete to run at a high percentage of $V'O_{2max}$ has a significant impact on running performance (Costill, Thomason, & Roberts, 1973).

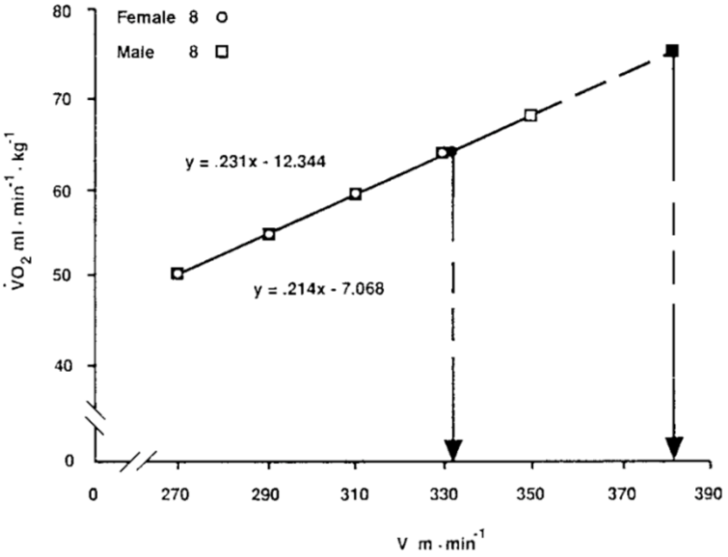

Figure 4 - Comparison of male and female runners of equal $V'O_{2max}$. The males are significantly favored in economy and in vV'_{O2max} ($P < 0.05$).

Chapter 3

Maximum Oxygen Uptake ($V'O_{2max}$)

Maximum oxygen uptake ($V'O_{2max}$) is defined as the highest rate at which oxygen can be taken and utilized by the body during strenuous exercise. It is one of the main variables in the field of exercise physiology, and it is frequently used to indicate the cardiorespiratory fitness of an athlete.

As previously shown in endurance running, performance is positively correlated with maximal oxygen consumption ($V'O_{2max}$)(Costill, Branam, Eddy, & Sparks, 1971). Costill et al.'s data were presented to show an inverse correlation (r 0.91) between $V'O_{2max}$ and time in a 10-mile run. These investigators used subjects with a wide range of $V'O_{2max}$ values (54.8 to 81.6 mL kg^{-1} min^{-1}) to study this relationship. This was an appropriate research design to see whether a correlation existed between these two variables in that such a relationship must be evaluated over an appropriate range of values. When the range of $V'O_{2max}$ is narrow, as in highly trained athletes, the correlation between $V'O_{2max}$ and performance is not as satisfactory as one would like it to be. Indeed, Conley and Krahenbuehl (D L Conley & Krahenbuhl, 1980) found only a poor correlation ($r = -0.12$) between $V'O_{2max}$ and running time in a group of 12 first-class 10Km runners. This state of affairs can be easily understood by considering, for small intersubject differences in $V'O_{2max}$, other factors like running economy, or the fraction of $V'O_{2max}$ exploited throughout the race, which may become crucial (D L Conley & Krahenbuhl, 1980; Costill et al., 1971, 1973; Maughan & Leiper, 1983). $V'O_{2max}$ is directly linked to the rate of ATP generated and maintained during a distance race, even though distance races are not run at 100% $V'O_{2max}$. The rate of ATP generation depends on the $V'O_2$ (mL kg^{-1} min^{-1}) that can be maintained during the run, which is determined by the subject's $V'O_{2max}$ and the percentage of $V'O_{2max}$ at which the subject can perform (Fig. 10). For example, to complete a 2h and 15' marathon, a $V'O_{2max}$ of about 60 mL kg^{-1} min^{-1} must be maintained throughout the race. Consequently, in a theoretical marathon run at 100% $V'O_{2max}$, the runner would need a $V'O_{2max}$ of 60 mL kg^{-1} min^{-1}. However, a marathon is typically run at about 80–85% of $V'O_{2max}$ - the $V'O_{2max}$ values needed for that performance; in this case that would be 70.5–75 mL kg^{-1} min^{-1}. This way $V'O_{2max}$ sets the upper limit for energy production in endurance events but does not determine final performance. As claimed by Bassett et al. (Bassett & Howley, 1997), there is no question that runners vary in running economy (RE) as well as in the percentage of $V'O_{2max}$ maintained in a run; both have a dramatic impact on the speed that can be maintained in an endurance race.

The O_2 pathway from the atmosphere to the mitochondria contains a series of steps, each of which could represent a potential impediment to O_2 delivery:

1) pulmonary diffusing capacity;
2) maximal cardiac output;
3) oxygen carrying capacity of the blood;
4) skeletal muscle characteristics.

The first three factors can be classified as “central” factors; the fourth is termed a “peripheral” factor.

The pulmonary system

Modern researchers have verified that the pulmonary system may limit $V'O_{2max}$ in certain circumstances. Dempsey et al. (Dempsey, Hanson, & Henderson, 1984), for example, showed that elite athletes are more likely to undergo arterial O_2 desaturation during maximal work compared with normal individuals. Trained individuals have a much higher maximal cardiac output than untrained individuals (40 vs 25 L min^{-1}). This leads to a decreased transit time of the red blood cells in the pulmonary capillary. Consequently, there may not be enough time to saturate the blood with O_2 before it exits the pulmonary capillary. This pulmonary limitation in highly trained athletes can be overcome with O_2-enriched air. Powers et al. (Powers, Lawler, Dempsey, Dodd, & Landry, 1989) performed two $V'O_{2max}$ tests (Fig. 5) on highly and normally trained subjects. In one case the subjects breathed room air and in the second they breathed a 26% O_2 gas mixture. With hyperoxic gas, the highly trained group had an increase in $V'O_{2max}$ from 70.1 to 74.7 mL kg^{-1} min^{-1} and an increase in arterial O_2 saturation (S_aO_2) from 90.6% to 95.9% during maximal work.

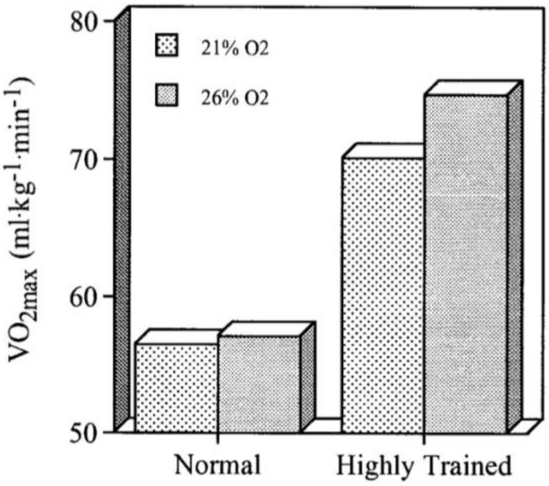

Figure 5 - Effects of hyperoxia on maximum oxygen uptake (V˙ O2max) in normal and highly trained individuals. The highly trained subjects had an increase in V˙ O2max when breathing oxygen-enriched air, showing the presence of a pulmonary limitation in these subjects under normoxic conditions. From Powers, S. K., J. Lawler, J. A. Dempsey, S. Dodd, and G. Landry. Effects of incomplete pulmonary gas exchange on V˙O2max.

None of these changes were observed in normal subjects (V'O_{2max} 56.5 mL kg^{-1} min^{-1}). Pulmonary limitations are evident in people who exercise at moderately high altitudes (3,000–5,000 m) (J. Daniels & Oldridge, 1970; Faulkner, A, & Kollias, 1968). Individuals with asthma and other types of chronic obstructive pulmonary disease (COPD) suffer from a similar problem (a reduction in arterial PO_2). Under these conditions, the ability to exercise can be increased with supplemental O_2, which increases the "driving force" for O_2 diffusion into the bloodstream (Davidson, Leach, George, & Geddes, 1988; Rooyackers, Dekhuijzen, Van Herwaarden, & Folgering, 1997). The ability to increase exercise capacity in this manner shows the presence of a pulmonary limitation.

Hill et al. (Hill & Lupton, 1923) suggested that maximal cardiac output was the primary factor that explains individual differences in V'O_{2max}. This was a major insight given the state of knowledge in 1923. Einthoven had only discovered electrocardiography a decade earlier. Hill used this new technique to measure maximal heart rates of around 180 beats min^{-1}. However, it was not until around 1930 that trained subjects were shown to have a lower heart rate at a fixed, submaximal work rate, providing evidence of increased stroke volumes. Other methods of cardiac imaging for endurance athletes (x-rays and ultrasound) were not available until 1940–1950. Given the level of technology in 1923, it is incredible that Hill et al. (Hill & Lupton, 1923) were able to deduce that endurance athletes have hearts with superior pumping capacities. In 1915, Lindhard measured the 20 l/min of average cardiac output in subjects during exercise and demonstrated the strong, linear relationship between cardiac output and $V'O_2$. Hill and Lupton (Hill & Lupton, 1923) speculated that maximal cardiac output values of 30-40 L min^{-1} were possible in trained athletes. These speculations were based on knowledge of Fick's equation and assumed values for $V'O_{2max}$, arterial oxygen content, and mixed venous oxygen content. Today, we know that the normal range of $V'O_{2max}$ values (L min^{-1}) observed in sedentary and trained men and women of the same age is principally due to variation in maximal stroke volume, given that a considerably less variation exists in maximal HR and systemic oxygen extraction. During maximum exercise, almost all of the available oxygen is extracted from blood that perfuses the active muscles. The oxygen content of arterial blood is approximately 200 mL O_2 L^{-1}; in venous blood draining maximally working muscles, it falls to about 20–30 mL O_2 L^{-1}. This shows that there is low oxygen concentration in blood that has not yet been extracted from the circulatory system during heavy exercise. Hence, the dominant mechanism to increase $V'O_{2max}$ with training must be an increase in blood flow (and O_2 delivery). It is estimated that 70–85% of the limitation of $V'O_{2max}$ is linked to maximal cardiac output (Cerretelli & Di Prampero, 1971). Longitudinal studies have shown that a training-induced increase in $V'O_{2max}$ results primarily from an increase in maximal cardiac output rather than from a broadening of the systemic a-v O_2 difference (Fig. 6).

Saltin et al. (B Saltin et al., 1968) examined $V'O_{2max}$ in sedentary individuals after 20 days of bed rest and after 50 days of training. The difference in $V'O_{2max}$ between the deconditioned and trained states resulted mostly from a difference in cardiac output. In a similar study, Ekblom et al. found that 16 weeks of physical training increased $V'O_{2max}$ from 3.15 to 3.68 L min^{-1}. This improvement in $V'O_{2max}$ showed an 8.0% increase in cardiac output (from 22.4 to 24.2 L min^{-1}) and a 3.6% increase in a-v O_2 difference (from 138 to 143 mL L^{-1}).

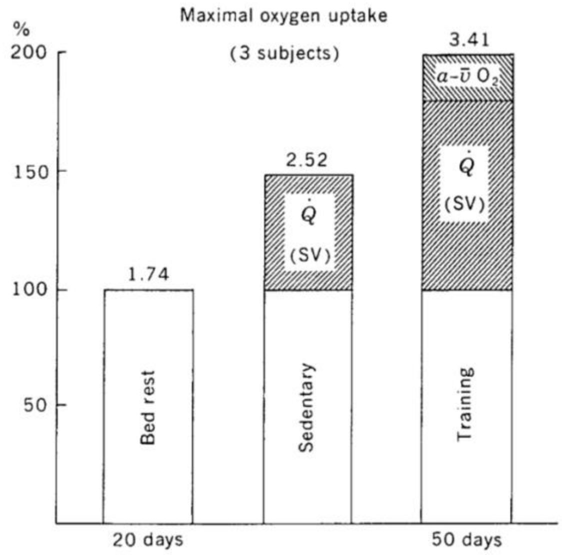

Figure 6 - Summary of changes that occur in maximum oxygen up-take (V̇O2max) following bed rest and physical training. The higher V̇O2max under sedentary conditions compared with that under bed rest results from an increased maximal cardiac output. The further increase after training results from an increase in cardiac output and, to a lesser extent, an increase in the a-v O2 difference. From Åstrand, P.-O. and K. Rodahl. Textbook of Work Physiology. New York: McGraw-Hill, 1970. Used with permission. Data from reference 71. Saltin, B., B. Blomquist, J. H. Mitchell, R. L. Johnson, K. Wildenthal, and C. B. Chapman. Response to submaximal and maximal exercise after bed rest and after training.

One way to greatly decrease cardiac output is with beta-blockade. Tesch (Tesch, 1985) wrote an authoritative review of 24 studies detailing the cardiovascular responses to beta blockade. Beta-blockers can decrease maximal heart rate (HR) by 25–30%. In these studies, maximal cardiac output decreased by 15–20%, while stroke volume increased slightly. The reduced cardiac output was partially compensated by an increased a-v O_2 difference, with consequent $V'O_{2max}$ declining by 5–15%. Tesch (Tesch, 1985) concluded that the decline in $V'O_{2max}$ seen with cardio-selective beta-blockade was caused by diminished blood flow and oxygen delivery.

Another method of altering O_2 transport to working muscles is by changing the hemoglobin (Hb) content of the blood (Ekblom, 1976). Blood doping is the practice of artificially increasing a person's volume of total red blood cells through removal, storage, and subsequent reinfusion. Gledhill (Gledhill, 1982, 1985) completed comprehensive reviews of 15–20 studies that examined the effects of blood doping. Reinfusion of 900–1,350 mL blood elevates the oxygen carrying capacity of the blood. This procedure has shown a 4–9% increase in $V'O_{2max}$ in well designed, double-blind studies (Gledhill, 1982, 1985). No improvement was observed in sham-treated individuals infused with a small volume of saline solution (Buick, Gledhill, Froese, Spriet, & Meyers, 1980). Once again, these studies provide evidence of a cause-and-effect link between O_2 delivery and $V'O_{2max}$. The evidence that $V'O_{2max}$ is limited by cardiac output, the oxygen carrying capacity, and in some cases by the pulmonary system is undeniable. This statement pertains to healthy subjects performing whole-body, dynamic exercise.

Honig et al. (Honig, Connett, & Gayeski, 1992) presented evidence of a peripheral O_2 diffusion limitation in red canine muscle. According to their experiments and a mathematical model, the principal site of resistance to O_2 diffusion occurs between the surface of red blood cells and the sarcolemma. They reported a large drop in PO_2 over this short distance. Honig et al. (Honig et al., 1992) concluded that O_2 delivery per se is not the limiting factor. They found that a low cell PO_2 relative to blood PO_2 is needed to maintain the driving force for diffusion and thus to enhance O_2 conductance.

The experimental model of Honig et al. (Honig et al., 1992) is quite different from human exercise. Simply increasing blood flow into an isolated muscle is not sufficient to cause an increase in $V'O_2$. The isolated muscle must also undergo contractions so that the mitochondria consume O_2 (drawing down the intracellular PO_2). Without a peripheral diffusion gradient, oxygen uptake will not increase. Their overall conclusion was that $V'O_{2max}$ is a distributed property, dependent on the interaction of O_2 transport and mitochondrial O_2 uptake (Honig et al., 1992). However, this model did not determine which of these two factors limits $V'O_{2max}$ in the intact human performing maximal exertion.

The mitochondria in muscle fibers are the sites where O_2 is consumed in the final step of the electron transport chain. In theory, doubling the number of mitochondria should double the number of sites for O_2 uptake in muscle. However, human studies show that there is only a modest increase in $V'O_{2max}$ (20–40%) despite a 2.2-fold increase in mitochondrial enzymes (Bengt Saltin, Henriksson, Nygaard, Andersen, & Jansson, 1977). This is consistent with the view that $V'O_{2max}$, measured during whole-body dynamic exercise, is limited by oxygen delivery (not muscle mitochondria). Holloszy and Coyle (Holloszy & Coyle, 1984) suggested that, as a consequence of the increase in size and number of the mitochondria content of skeletal muscle, exercise at the same work rate elicits smaller disturbances in homeostasis in trained muscles. Two metabolic effects of an increase in mitochondrial enzymes are i) muscles adapted to endurance exercise will oxidize fat at a higher rate (thus sparing muscle glycogen and blood glucose), and ii) there is less lactate produced during exercise. These muscle adaptations are important to explain the improvement in endurance performance that occurs with training. The main effect of increased mitochondrial enzymes is improved endurance performance rather than increased $V'O_{2max}$. Holloszy and Coyle (Holloszy, 1973; Holloszy & Coyle, 1984) noted that even in individuals with nearly identical $V'O_{2max}$ values, there can be a two-fold range in mitochondrial enzymes. Furthermore, low-intensity training may elicit small changes in mitochondrial enzymes without any changes in $V'O_{2max}$, and vice versa (Henriksson & Reitman, 1977; Klausen, Andersen, & Pelle, 1981; Orlander, Kiessling, Karlsson, & Ekblom, 1977). On the other hand, there is some evidence that the increase in mitochondria density plays a permissive role in allowing $V'O_{2max}$ to increase. Holloszy and Coyle (Holloszy & Coyle, 1984) noted that the lowest value for succinate dehydrogenase (SDH) activity in elite runners studied by Costill (Costill, Fink, & Pollock, 1976) was still 2.5-fold greater than that found for untrained individuals in the same study. The increase in muscle mitochondria content (number, size and enzymes) may allow a slightly greater extraction of O_2 from the blood in working muscles, thus contributing in a minor way to higher $V'O_{2max}$ (Holloszy & Coyle, 1984).

In 1977 Andersen and Henriksson (Andersen & Henriksson, 1977) showed that capillary density increases with training. Other studies reported a strong relationship between the number of capillaries per fiber in the vastus lateralis and $V'O_{2max}$ (mL kg^{-1} min^{-1}) measured during a cycle ergometery test (Bengt Saltin et al., 1977). The main significance of increased capillary density induced by training is not to accommodate blood flow but rather to maintain or extend the mean transit time (B Saltin, 1985). This enhances oxygen delivery by maintaining oxygen extraction (a-v O_2 difference) even at high rates of muscle blood flow. The ability of skeletal muscle to adapt to training in this way is far greater than observed in the lung (Dempsey, 1986).

Longitudinal changes in $V'O_{2max}$ in well-trained runners, reported in the literature, have mostly been small or no change occurred at all (Berg, Latin, & Hendricks, 1995; Ekblom, 1968; A. M. Jones, 1998; D. E. Martin, Vroon, May, & Pilbeam, 1986). No significant changes in $V'O_{2max}$ occurred in three well-trained runners during 5 years of training, or in seven university track and cross-country runners during 1 year of training (Berg et al., 1995) . Experimentally, it is difficult to ascertain whether a runner has reached his or her trainable limit for $V'O_{2max}$ enhancement. Laursen and Jenkins (Paul B Laursen & Jenkins, 2002b) suggested that all cardiorespiratory adaptations that could be elicited by submaximal training have probably already occurred in distance runners competing at a relatively high level. It is possible that sufficient volumes of high intensity training are not included in the training programs of many well-trained runners in order for them to reach their trainable limit for $V'O_{2max}$ enhancement. Basset et al. (Basset, Chouinard, & Boulay, 2003) reported that the well-trained long-distance runners used in their study invariably trained at running speeds below $vV'O_{2max}$ (the minimal running velocity that elicits $V'O_{2max}$ during incremental running to volitional exhaustion) (V. Billat, Renoux, Pinoteau, Petit, & Koralsztein, 1994). Robinson et al. (Robinson, Robinson, Hume, & Hopkins, 1991) reported that 17 nationally ranked distance runners performed <4% of high-intensity interval training during their training sessions, with one-third doing no interval training. Average training intensity was 64% $V'O_{2max}$. A retrospective study by Hewson and Hopkins (Hewson & Hopkins, 1995) found that most of the 123 distance-running coaches surveyed favored long slow-distance training, with limited time allocated to either ‘hard’ continuous training or high-intensity interval training. Favoring training duration over intensity is also reflected in the long weekly training distances reported for well-trained distance runners (V. Billat, Demarle, Paiva, & Koralsztein, 2002; V. L. Billat, Demarle, Slawinski, Paiva, & Koralsztein, 2001; Boileau, Mayhew, Riner, & Lussier, 1982). Studies reporting changes in the $V'O_{2max}$ of elite and well-trained runners in response to high-intensity training (Table I) suggest that the $V'O_{2max}$ values of these runners had not reached a plateau and were responsive to high-intensity training, even during relatively short training periods. However, valid inferences cannot be made from these studies due to several methodological limitations. Only one of these studies reported statistically significant increases in $V'O_{2max}$ (V. Billat et al., 2002). Other studies demonstrated meaningful but statistically insignificant increases in $V'O_{2max}$ of 2–5% (V. L. Billat, Flechet, Petit, Muriaux, & Koralsztein, 1999; Laffite, Mille-Hamard, Koralsztein, & Billat, 2003; Mikesell & Dudley, 1984; T. Smith, Coombes, & Geraghty, 2003). The small sample sizes used in these studies and the associated statistical power of <30% (Power and Precision, Biostat, NJ, USA) in all but one of these studies was probably a major cause of the statistical insignificance (Cohen, 1992). Several studies (V. L. Billat et al., 1999; Laffite et al., 2003; T. Smith et al., 2003; T. P. Smith, McNaughton, & Marshall, 1999a) reported changes in relative $V'O_{2max}$ but did not report whether any changes in body mass occurred. It is therefore not possible to quantify how much of the increase in relative $V'O_{2max}$ was due to changes in cardiorespiratory fitness or how much was due to any changes in body mass.

Training strategies to improve $V'O_{2max}$

Characterizing the physiological response to increased exercise intensity and how this response may elicit physiological adaptations that are associated with the enhancement of $V'O_{2max}$ may provide a physiological rationale for recommending a particular training intensity to enhance the $V'O_{2max}$ in distance runners.

Training-induced increases in cardiac output (Q'_{max}) are due to increased maximal stroke volume (SV_{max}), because maximal heart rate either decreases or remains the same (B Saltin et al., 1968). The main stimulus for myocardium morphological adaptation associated with SV_{max} enhancement is mechanical overload imposed by a volume overload-induced increase in ventricular diastolic stretch and increased resistance to ventricular emptying due to greater afterload (Clausen, 1977; Cooper, 1997). Neuroendocrine factors such as thyroxine, testosterone, angiotensin II, and catecholamines stimulate myocardial growth (Cooper, 1997; George, Wolfe, & Burggraf, 1991). Threshold intensities exist for the release of these hormones, and once surpassed, their rate of release increases curvilinearly with the increasing intensity of exercise (Hartley et al., 1972; Kotchen et al., 1971). Although training intensities above the anaerobic threshold appear obligatory to benefit from their potentiating effects, exercise intensity and duration interactions relating to hormone release and effects on physiological myocardial hypertrophy require further empirical research. Several study demonstated the effect of high intensity training on SV_{max} and accordingly VO_{2max} in a period of 5 to 12 weeks in both untrained and active people(T. A. Astorino et al., 2017; Todd A Astorino et al., 2018; Bacon, Carter, Ogle, & Joyner, 2013; Daussin et al., 2007).

Plasma volume, erythrocyte mass and blood volume increase in response to endurance training (B Saltin et al., 1968; D. E. R. Warburton et al., 2004). Sawka et al. (Sawka, Convertino, Eichner, Schnieder, & Young, 2000), following a review of 18 studies, underscored that plasma volume expansion plateaus increased after approximately 15 days of training and that total erythrocyte mass increased after approximately 30 days. Consequently, under normal physiological conditions, significant changes in blood volume occur only in poorly conditioned individuals, with little change in the already well-trained (Oscai, Williams, & Hertig, 1968). Even if a particular training strategy could increase blood volume in trained runners, it is unlikely to enhance SV_{max} to any significant extent. The SV_{max} of nine elite cyclists increased very little in response to an experimental 547mL increase in blood volume (D. E. R. Warburton et al., 2004), probably because trained endurance athletes are at or near their diastolic reserve capacity (Hopper, Coggan, & Coyle, 1988; D. E. Warburton, Gledhill, Jamnik, Krip, & Card, 1999).

Skeletal muscle capillarization increases in response to endurance training (Andersen & Henriksson, 1977; Ingjer, 1979) and has been considered a major physiological adaptation in the enhancement of $V'O_{2max}$ (B Saltin & Rowell, 1980). The main stimulus for inducing capillarization is increased shear stress, and capillary pressure results from a critical increase in blood flow velocity (Hudlicka, Brown, & Egginton, 1992). Since cardiac output and blood flow increase with increasing exercise intensity up to $V'O_{2max}$, there should be an intensity-dependent increase in capillary shear stress and stimulus for capillarization up to $V'O_{2max}$.

Physiological structures or processes that demonstrate substantial long-term plasticity should be the target of training-induced adaptations for the longitudinal enhancement of a distance runner's $V'O_{2max}$. Myocardial morphological adaptations that increase SV_{max} would appear most important. Other important adaptations include increased capillarization of skeletal muscle and increased oxidative capacity of type II skeletal muscle fibers. The strength of the stimuli that elicit adaptations is exercise intensity dependent up to $V'O_{2max}$, indicating that training at or near $V'O_{2max}$ may be the most effective intensity to enhance $V'O_{2max}$ in well- trained distance runners. However, Moffatt et al. suggested that as $V'O_{2max}$ is approached, the differentiation between stimuli decreases. (Moffatt, Stamford, Weltman, & Cuddihee, 1977).

Research is therefore needed to understand the chronic adaptive effects elicited by different training intensities in the range of 90–100% $V'O_{2max}$. Furthermore, the effects of such intensities on recreational athletes remain to be verified.

Highlights

- *$V'O_{2max}$ is defined as the highest rate at wich oxygen can be taken and utilized by the body during strenuous exercise*
- *$V'O_{2max}$ is positively correlated with endurance running performance*
- *$V'O_{2max}$ is affected by central (Pulmunary Diffusing Capacity, Maximal cardiac output and oxygen delivering), and peripheral (skeletal muscle caratheristics and functionality) factor*
- *The individual differences between trained/untrained subject and man/woman with same age, is principally due to variation in cardiac output*
- *To improve, $V'O_{2max}$ in well-trained and SV in recreational athletes, the most effective intensity is near $V'O_{2max}$*

Chapter 4

Running Economy

Efficient utilization of available energy facilitates optimum performance in any endurance running event. Efficiency refers to the ratio of work done to energy expended (J. T. Daniels, 1985). RE is energy expenditure expressed as the submaximal $V'O_{2max}$ at a given running speed (Anderson, 1996; D L Conley & Krahenbuhl, 1980; Morgan & Craib, 1992). The energy cost of running reflects the sum of both aerobic and anaerobic metabolism, and the aerobic demand (measured by the $V'O_2$ in L/min) at a given speed does not necessarily account for the total energy cost of running, which is measured in joules or kilojoules of work done (J. T. Daniels, 1985). Runners with good RE use less oxygen than runners with poor RE at the same steady-rate speed, and RE can vary among runners with a similar $V'O_{2max}$ by as much as 30% (J. T. Daniels, 1985). Data from Conley and Krahenbuhl (D L Conley & Krahenbuhl, 1980) were used to show a relatively strong correlation (r 0.82) between running economy and performance in a 10K run in a group of runners with similar $V'O_{2max}$ but with a range of 10-km times of 30.5–33.5 min. When they reduced the evaluation to the four fastest runners (10 km in 30.5–31 min), there was considerable variability in the economy of running (45–49 mL kg^{-1} min^{-1} at 268 m min^{-1}), which suggests a lack of association between the variables. As mentioned for $V'O_{2max}$, this is an expected result. A correlation coefficient will approach zero as the range of values for one of the variables (in this case, performance times ranging from 30.5 to 31 min) approaches zero. There is little point in looking at a correlation unless the range of values is sufficient to determine whether a relationship exists. There is a linear relationship between submaximal running velocity and V'O (mL kg^{-1} min^{-1}) for everyone. However, there is considerable variation among individuals regarding how much oxygen it takes to run at a given speed, that is, running economy.

Figure 5 shows a bar graph of the variation in running economy (expressed in mL kg^{-1} min^{-1}) measured at different relative speed among trained and untrained subject stratified by performance capability (Morgan et al., 1995a). The group of elite runners had better running economy than the other groups of runners, and all running groups were better than the group of untrained subjects. However, one of the most revealing aspects of this study was the within-group variation; there was a 20% difference between the least and most economical runner in any group (Morgan et al., 1995a).

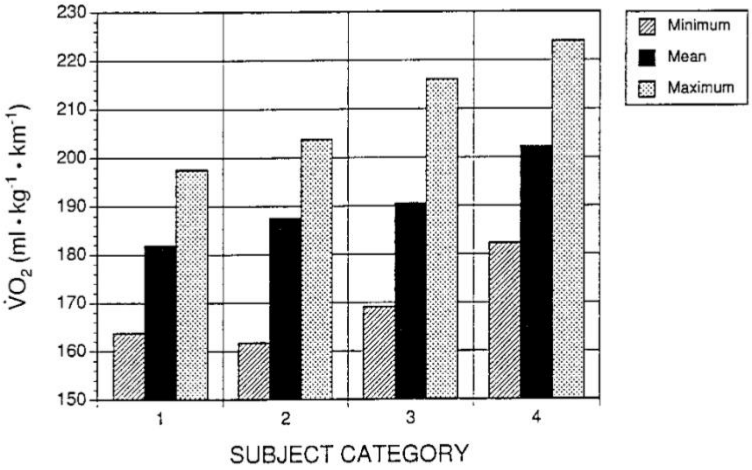

Figure 5 – Minimum, mean, and maximum aerobic demand running economy values for elite runners (Category 1), subelite runners (Category 2), good runners (Category 3), and untrained subjects (Category 4). From Morgan, D.W., D.R. Bransford, D.L. Costill, 1995

In support of this data, the study of Daniels et al. showed that RE can vary among runners with similar V'O_{2max} by as much as 30% (J. T. Daniels, 1985). In elite or near-elite runners with a similar V'O_{2max}, RE is a better predictor of performance than V'O_{2max} (Costill et al., 1973; Morgan, Baldini, Martin, & Kohrt, 1989). Weston compared the RE and performance of Kenyan and Caucasian distance runners. Despite their 13% lower V'O_{2max}, Kenyans had similar 10K race times compared with Caucasians thanks to their 5% better RE. The Kenyan runners also completed the 10K race at a higher percentage of their V'O_{2max} but with similar blood lactate concentration levels compared with Caucasian runners. In their study, Tam et al. (Tam et al., 2012) found that top-level Kalenjin marathon runners were characterized by high, but not very high, V'O_{2max} (64.9 ± 5.8 vs. 63.9 ± 3.7 ml kg^{-1} min^{-1}) compared with Europeans, an extremely high fraction of V'O_{2max} (0.825 ± 0.050 in KA and 0.836 ± 0.062 in Europeans) and a low cost of running (Cr) (3.64 ± 0.28 vs. 3.63 ± 0.31 J kg^{-1} m^{-1}). However, the dominance of Kenyan marathon runners over Caucasians cannot be explained by differences in the energetics of running since the small functional differences highlighted in this study do not fully justify the differences in performance.

Despite this controversial result, it follows that substantial improvements in RE could facilitate improved performance in elite distance runners.

In summary, the relationship between RE and performance is well documented, with many independent reports demonstrating a strong relationship between RE and distance running performance (D L Conley & Krahenbuhl, 1980; Costill et al., 1973; P E Di Prampero et al., 1993). RE is likely to be influenced by several factors (training, altitude, heat) (Fig. 6) that can reduce the oxygen cost over a range of running speeds and conceivably lead to enhanced performance.

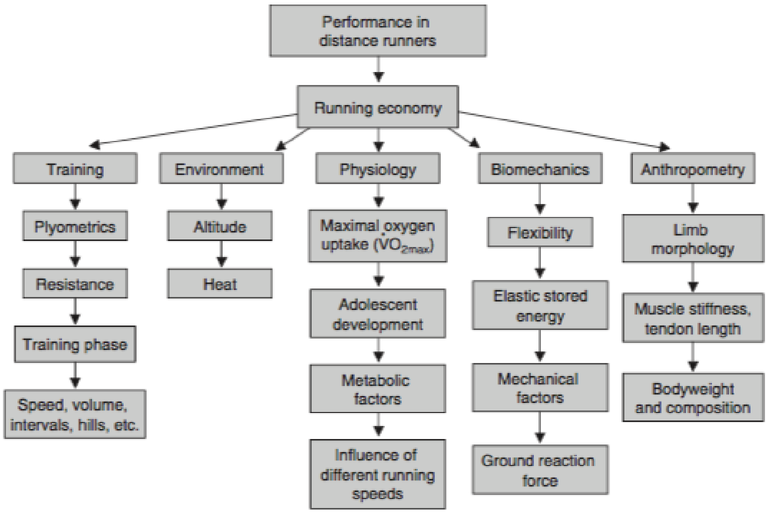

Figure 6 - Factors affecting running economy from Saunders P.U., Pyne D.B. Telford R.D. and Hawley J.A. Factors Affecting Running Economy in Trained Distance Runners, Sport Med. 2004; 34 (7); 465-485

Running involves the conversion of muscular forces translocated through complex movement patterns that utilize all the major muscle joints in the body. High performance running relies on skill and precise timing in which all movements have purpose and function (Anderson, 1996). An intuitive link exists between running technique and economy, since performing mechanical patterns with non-productive movements and applying forces of appropriate magnitude in the right directions with precise timing will result in less energy consumption at a given running speed (Anderson, 1996). In this regard several investigators attempted to explain the inter-individual variations in RE through differences among runners in the biomechanical patterns of their running style. The first descriptor of running style that was related to the energy requirement of running was stride length. Several studies (P R

Cavanagh & Williams, 1982; Hogberg, 1952; Minetti, Ardigò, & Saibene, 1994; Powers, Hopkins, & Ragsdale, n.d.) showed that runners self-select the optimal stride length for a given speed, and RE tends to increase curvilinearly as stride length changes (lengthened or shortened). Cavanagh (P R Cavanagh & Williams, 1982) reported that there is little need to dictate stride length for well-trained athletes since they already tend to display near optimal stride lengths. He suggested two mechanisms to explain this phenomenon. Firstly, runners naturally acquire an optimal stride length and stride rate over time based on perceived exertion. Secondly, runners may adapt physiologically through repeated training at a particular stride length/stride frequency combination for a given running speed (P R Cavanagh & Williams, 1982).

Several other discrete kinematic variables have been related to running economy. An early study by Cavanagh (Peter R. Cavanagh, Pollock, & Landa, 1977) indicated that economic elite runners had less vertical oscillation and were more symmetrical compared to less economic athletes. In a study carried out on elite male distance runners, Williams (Williams & Cavanagh, 1987) compared 3 groups of runners divided according to their RE at 3.6 $m \cdot s^{-1}$(low, medium and high VO_2) and found that better RE was associated with a higher shank angle with the vertical at the foot strike, less plantarflexion at toe-off and more flexed knee in the mid-support. Less amplitude of arm movements was also associated with better economy (Anderson, 1996; Williams & Cavanagh, 1987). A more recent research study (KYR??L??INEN, BELLI, & KOMI, 2001) related RE to several three-dimensional kinematic and kinetic parameters and EMG activity at different speeds. None of the considered kinematical indices (angular displacements between the ankle, knee and hip joints, joint angular velocities) was, taken alone, a good predictor of RE. Although significant differences and trends have been observed between economic and non-economic runners in some kinematical parameters, the relationships appear weak and inconsistent among studies. This is due to the complex interrelationships among the multitude of discrete mechanical descriptors of running technique that globally influence RE as also demostrated by Lussiana et al. (Lussiana et al., 2017) that found that different running patterns were associated with similar RE. Therefore, definitive conclusions cannot be confirmed on the basis of present data, and further studies using proper statistical analyses to deal with multiple variables are necessary.

Numerous studies have related descriptors of ground reaction forces (GRF) to RE. Williams (Williams & Cavanagh, 1987) found that more economical runners showed significantly lower first peaks in the vertical component of the GRF and tended to have smaller horizontal and vertical peak forces. Based on these results, they suggested that differences in kinematics, especially before the foot strike, may affect muscular demand and thus RE. Heise (Heise & Martin, 2001) investigated the support requirements during foot contact of trained male runners. Higher total and net vertical impulses were shown in the less economical athletes, indicating wasteful vertical motion. The combined influence of vertical GRF and the time course of the force application explained 38% of the inter-individual variability in RE. However, other GRF characteristics like medial-lateral or horizontal moments were not significantly correlated with RE. Kyrolainen (KYR??L??INEN et al., 2001) found that the rate of force production increased with increasing running speed and that the horizontal (braking) component of the GRF was related to RE. They suggested that increasing the pre-landing and braking activity of the leg hamstring muscles might prevent unnecessary yielding of the runner during the braking phase, with an enhancement of muscular-tendon stiffness, and a resulting improvement in RE. In summary, relationships between RE and GRF characteristics have been repeatedly shown, although the inherent mechanisms need to be more clearly understood. Insights to analyzing the inter-individual variations in RE in competitive athletes come from the field of comparative biology. Kram (Kram & Taylor, 1990) investigated the aerobic demand of locomotion in several animal species. He presented an inverse relationship between RE and contact time, indicating that the energy cost of running is determined by the cost of supporting the animal’s mass and time course of generating force (Kram & Taylor, 1990). Subsequent studies confirmed that the requirement to support body mass, expressed by vertical GRF, is the major metabolic cost of running (Chang & Kram, 1999; Farley & McMahon, 1992). However, experiments applying impending and assisting horizontal forces demonstrated that also the horizontal component of GRF significantly affects the metabolic cost of running (Chang & Kram, 1999; Cooke, McDonagh, Nevill, & Davies, 1991). Finally, recent studies carried out on running animals and humans have clearly shown that the muscular force required to swing the limb also contributes to a significant amount of energy expenditure (Modica & Kram, 2005).

Anthropometric characteristics such as limb dimensions and proportions have been addressed as potential influences on RE. Assuming that leg length contributes to angular inertia and to the metabolic cost of moving the legs during running (Anderson, 1996), it should be an important factor in determining RE. However, Williams (Williams & Cavanagh, 1987) found no differences in leg length between economic and non-economic male distance runners. As for kinematic parameters, it is quite unlikely that a single anthropometric index may discriminate among different levels of RE, since RE is complexly affected by a multitude of interacting factors, and the effect of a single factor may be hidden by the others.

In contrast, there is some evidence that leg mass and leg mass distribution may influence RE. In studies where leg angular inertia was altered when weights were added to the extremities, it was demonstrated that increasing shoe weight by only 50 g increased RE by ~1% (B. H. Jones, Knapik, Daniels, & Toner, 1986; P. E. Martin, 1985). Myers (Myers & Steudel, 1985) studied 4 athletes trained to run with additional weight on their trunks, upper thighs, upper shanks, and ankles. All limb loadings resulted in greater cost of running than when the same masses were attached to the waist, with cost increasing as the position of loads became more distal. Another study involving ankle and wrist loading revealed that RE was lowest in the unloaded condition, followed by ankle loading only, wrist loading only, and both wrist and angle loading. This research stream led to a claim that for a given body mass and a given speed, smaller and more proximally distributed limb mass results in lower kinetic energy required to accelerate and decelerate the limbs and thus a lower cost of running.

Several studies contend that flexibility affects RE (Craib et al., 1996; Gleim, Stachenfeld, & Nicholas, 1990; Godges, Macrae, Longdon, Tinberg, & Macrae, 1989). Godges (Godges et al., 1989) showed in college student athletes that RE improved with better hip flexion and extension. This finding reflected the empirical belief that improved flexibility is desirable to increase RE and may be explained by an enhanced neuromuscular balance due to greater flexibility, which elicits lower V’O_2. Contrarily, Gleim (Gleim et al., 1990) found that untrained subjects with the lowest flexibility were the most economical. This was explained by inflexibility in the transverse and frontal planes of the trunk and hip regions of the body that stabilizes the pelvis at foot strike. This may have the effect of reducing both an excessive range of motion and metabolically expensive stabilizing muscular activity. Craib et al. (Craib et al., 1996) examined the relationship between RE and selected trunk and lower limb flexibility in tests on trained male distance runners. Inflexibility in the hip and calf was associated with better RE by minimizing the need for muscle-stabilizing activity and increasing the storage of elastic energy. Another study (A M Jones, 2002) found that lower limb and trunk flexibility was negatively related to RE in elite male distance runners. The author interpreted his results stating that improved RE may reflect greater stability of the pelvis, reduced requirement for additional muscular activity at foot strike, and greater storage and return of elastic energy due to inflexibility of the lower body. Kyrolainen (KYR??L??INEN et al., 2001) found that stiffer muscles around the ankle and knee joints in the braking phase of running increased force expression in the push-off phase. Therefore, stiffer and more inflexible muscles in the legs and lower trunk could enhance RE via increased energy from elastic storage and return. According to a review by Saunders (Philo U. Saunders, Pyne, Telford, & Hawley, 2004), the findings of these studies taken together suggest that there is an optimal level of flexibility whereby RE can benefit, although a certain degree of muscle stiffness is also required to maximize elastic energy storage and return in the trunk and legs.

Training strategies to improve running economy

To date, a wide range of acute and chronic interventions have been investigated with respect to improving economy, including various forms of resistance training, endurance training and high-intensity interval training (HIT), altitude exposure, stretching, as well as nutritional supplements (Fig. 7).

Figure 7 - Diagram of strategies to improve running economy from K.R. Barnes K.R., Kilding A. E; Strategies to Improve Running Economy, Sports Medicine, 2014

Various physiological responses occur during endurance training in runners, and it is likely that the characteristics of training influence RE. Endurance training leads to increases in the morphology and functionality of skeletal muscle mitochondria (Holloszy, Rennie, Hickson, Conlee, & Hagberg, 1977; Philo U. Saunders et al., 2004). Specifically, an increase in the oxidative muscle capacity allows trained runners to use less oxygen per mitochondrial respiratory chain during submaximal running (Assumpção, Lima, Oliveira, Greco, & Denadai, 2013). Furthermore, adaptations such as improved skeletal muscle buffer capacity (Gore et al., 2001) and hematological changes (Burtscher, Nachbauer, Baumgartl, & Philadelphy, 1996; Levine & Stray-Gundersen, 1997) (i.e., increased red cell mass) have been observed following various training modalities. These adaptations could also invoke improvements in oxygen delivery and utilization that could improve an athlete's RE. While training has been suggested to elicit a range of central and peripheral adaptations that improve the metabolic and cardiorespiratory efficiency of a runner (Green, 2000), many of these adaptations are largely governed by the training load, which can be manipulated for a given athlete by increasing the volume or intensity of running over time. Successful endurance runners typically undergo several years of training to enhance the physiological characteristics important to determining success in distance running events. Indeed, the number of years of running experience and high training volumes have been suggested as being important to RE (Morgan et al., 1995b; R. C. Nelson & Gregor, 1976). Unfortunately, the few longitudinal studies that have examined this issue have yielded little consensus, with findings indicating no change (J. T. Daniels, Yarbrough, & Foster, 1978; Wilcox & Bulbulian, 1984), a slight increase, and varying degrees of reductions (1–15 %) in submaximal $V'O_2$ among trained and untrained runners engaging in different combinations of years, distance, interval and uphill training (Balsom, Seger, Sjödin, & Ekblom, 1992; Douglas L. Conley, Krahenbuhl, & Burkett, 1981; Svedenhag & Sjödin, 1984). Midgley et al. (Midgley, McNaughton, & Jones, 2007) suggested that the most important factor in improving RE may be the cumulative distance a runner has run over years of training and not short-term (several weeks to months) bouts of high training volume per se. This may be due to continued long-term adaptations in metabolic, biomechanical and neuro-muscular efficiency (Midgley et al., 2007; R. C. Nelson & Gregor, 1976). Case study data from world-class runners also suggests that RE improves over several years of training (Douglas L Conley, Krahenbuhl, Burkett, & Millar, 1984; Ingham, Fudge, & Pringle, 2012; A. M. Jones, 1998; Andrew M. Jones, 2009); however, the role played by the interaction between training volume and consistency of training in such improvements over several years of training remains unclear.

The influence of training volume on RE is not well discussed in the literature, and unfortunately, no training studies to date have examined the implications of increased training volume while controlling for potential confounding variables like training intensity. However, in a cross-sectional investigation, Pate et al. (Pate, Macera, Bailey, Bartoli, & Powell, 1992) reported that training volume was not associated with better RE. Nevertheless, the importance of training volume should not be downplayed, as high-volume training plays a major role in inducing adaptations important to successful distance running (P. B. Laursen, 2010).

Studies that incorporated flat overground HIT into the training programs of distance runners reported equivocal results in relation to improved RE. Jones and Carter (Andrew M. Jones & Carter, 2000) suggested that runners are typically more economical at the running speeds at which they habitually train. HIT at 93–120%

velocity at $V'O_{2max}$ (vVO_{2max}) and continuous running at velocity at the onset of blood lactate accumulation (vOBLA)] have both been shown to improve RE by 1–7% (Kyle R Barnes, Hopkins, McGuigan, & Kilding, 2013; V. L. Billat et al., 1999; Franch, Madsen, Djurhuus, & Pedersen, 1998; Laffite et al., 2003; Sjödin, Jacobs, & Svedenhag, 1982). Other studies using similar training intensities reported no significant improvement (Kyle R Barnes et al., 2013; Franch et al., 1998; T. P. Smith, McNaughton, & Marshall, 1999b; Yoshida et al., 1990). Morgan et al. (Morgan, Martin, & Krahenbuhl, 1989) suggested that the type of training exerts a negligible effect on improved RE, based on the observation that several studies reported no differences in changes in RE despite the fact that runners engaged in different interval training programs. Franch et al. (Franch et al., 1998) compared interval training at 94, 106 and 132% $vV'O_{2max}$ and found that RE significantly improved in the 94% and 106% groups, but not in the group that trained at 132% $vV'O_{2max}$. This suggests that very high-intensity running is not effective in improving RE, possibly because of a loss of running form at very high running speeds, or of an inability to complete a sufficient training volume to elicit a training effect (Midgley et al., 2007). Biomechanical changes could improve exercise efficiency following HIT. However, Lake and Cavanagh (Lake & Cavanagh, 1996) investigated the effects of 6 weeks of HIT on various biomechanical variables in a group of 15 males moderately trained runners (and found no relationship between changes in performance, $vV'O_{2max}$, RE and biomechanical variables at $3.36ms^{-1}$ on a treadmill. The authors concluded that improvements in performance following HIT were more likely to be due to physiological rather than biomechanical factors because there were no changes in biomechanical descriptors of running style that signaled changes in running economy.

Also, uphill running represents a frequently prescribed form of HIT in periodized training programs for distance runners. Moreover, references to its potential effectiveness as a movement-specific form of resistance training have appeared in several reviews (L. V Billat, 2001; Midgley et al., 2007; Philo U. Saunders et al., 2004). However, there are only anecdotal reports on and limited research investigations into the physiological responses to and potential improvements in performance with such training (Kyle R Barnes et al., 2013; Vukovich, 2013).

Unlike other modes of resistance training, where a transfer of learning would need to occur to improve RE, uphill running is movement specific and the mechanisms for improving RE are likely to directly affect one or more of the metabolic, biomechanical and neuromuscular systems.

Various forms of resistance training can be adopted, and several have been shown to improve RE in recreational (Taipale et al., 2010; Taipale, Mikkola, Vesterinen, Nummela, & Häkkinen, 2013), moderately trained (Albracht & Arampatzis, 2013; K. Barnes, 2014; Berryman, Maurel, & Bosquet, 2010; Guglielmo, Greco, & Denadai, 2009; Piacentini et al., 2013a; Støren, Helgerud, Støa, Hoff, 2008), and highly trained runners (Millet, Jaouen, Borrani, Candau, 2002; Sedano, Marín, Cuadrado, Redondo, 2013). Resistance training may improve RE through several mechanisms. Kyrolainen et al. (KYR??L??INEN et al., 2001) proposed that resistance training may improve RE through improved lower limb coordination and co-activation of muscles, thereby increasing leg stiffness and decreasing stance phase contact times, allowing a faster transition from the braking to the propulsive phase through elastic recoil (Cheng et al., 2012; Häkkinen et al., 2003; KYR??L??INEN et al., 2001; L. Paavolainen, Hakkinen, Hamalainen, Nummela, & Rusko, 2003; L. Paavolainen, Häkkinen, Hämäläinen, Nummela, & Rusko, 1999; Sale, 1988). Heavy resistance training may primarily cause hypertrophy of type IIA and IIB (fast twitch) fibers, but also type I (slow twitch) fibers (Staron et al., 1991, 1994), resulting in less motor unit activation to produce a given force (Moritani & deVries, 1979). Unfortunately, increases in body mass are an undesirable side effect to increases in muscle strength from resistance training that could be counter-productive to distance running performance. However, increased muscular strength might primarily come from neural adaptations without observable muscle hypertrophy since most studies have reported little or no changes in body mass, fat free mass, percentage body fat or girth measurements following heavy resistance training. Sale (Sale, 1988) reports that heavy resistance training induces changes in the nervous system which allow an athlete to increase activation of the working muscles, thus producing a greater net force with each stride. An increase in strength following heavy resistance training as a result of increased motor unit recruitment and motor unit synchronization may improve mechanical efficiency and motor recruitment patterns (Kraemer, Fleck, & Evans, 1996; Sale, 1988). Greater muscular strength following heavy or strength-endurance resistance training has previously been shown to delay muscular fatigue, resulting in a smaller increase in oxygen consumption (decreased RE) at any given speed during sustained endurance exercise (Hayes, French, & Thomas, 2011). It is well documented that initial performance gains following heavy resistance training are a result of neuromuscular adaptations rather than within-muscle adaptations (e.g., hypertrophy) (Kraemer et al., 1996; Sale, 1988). Several studies (Guglielmo et al., 2009; Millet et al., 2002; STØREN et al., 2008; Taipale et al., 2010) have reported concomitant improvements in RE and maximal strength following heavy resistance training, indicating positive neuromuscular adaptations. Other studies (Kyle R. Barnes, Hopkins, Mcguigan, Northuis, & Kilding, 2013; Berryman et al., 2010; Cheng et al., 2012; Piacentini et al., 2013b; Sedano et al., 2013) have demonstrated that the combination of strength-endurance resistance training and endurance training improves running performance and enhances RE in moderately and highly trained runners. Regardless of whether strength gains occur at the muscular level, neural level, or both, available evidence suggests that if a more efficient recruitment pattern is induced, decreases in oxygen consumption at a given speed are likely to occur (Bransford & Howley, 1977; Morgan et al., 1995a); however, more research is necessary to support these assertions.

Improved RE may also be due to increases in strength that cause positive changes in mechanical aspects of running style (i.e., improved biomechanical efficiency) (E. Johnson, Quinn, Kertzer, & B. Vroman, 1997), thus allowing a runner to do less work at a given running speed. A number of biomechanical variables have been identified that relate to RE, thereby providing support for the hypothesis that the mechanical aspects of running style do have an influence on RE (Anderson, 1996). Another possible explanation for improved RE following heavy resistance training could involve muscle fiber-type conversion from less efficient fast twitch fibers (type IIB) to more efficient oxidative fibers (type IIA and type I), though existing data in athletes is conflicting (EDWARD F Coyle, Hemmert, & Coggan, 1986; Staron et al., 1990, 1991, 1994). For example, Staron et al. (Staron et al., 1990, 1991, 1994) found concomitant decreases in submaximal V’O_2 and in type IIB fibers, with a simultaneous increase in type IIA fibers following a heavy-resistance, low-velocity, lower body resistance training program in untrained men and women. Conversely, Coyle et al. (EDWARD F Coyle et al., 1986) reported that $V'O_2$ remained unchanged for the same absolute submaximal intensity throughout a detraining period, despite a large shift from type IIA to IIB fibers when studying seven endurance-trained subjects 12, 21, 56 and 84 days after cessation of training, which suggested that muscle fiber conversion has little or no impact on RE.

The concept of movement specificity suggests that the type of resistance training used by runners should closely simulate the movement that will be performed during training and competition (Jung, 2003). Plyometric and explosive resistance training are specific forms of strength training that aim to enhance the ability of muscles to generate power by exaggerating the stretch shortening cycle (SSC), using explosive exercises such as jumping, hopping and bounding (Turner, AM, Owings, M and Schwane, 2003). Plyometric training has the potential to increase the stiffness of the muscle-tendon system, which allows the body to store and utilize elastic energy more efficiently, resulting in decreased ground contact time and reduced energy expenditure (Anderson, 1996; P R Cavanagh & Kram, 1985; Mikkola et al., 2011; Spurrs, Murphy, & Watsford, 2003). Paavolainen et al. (L. Paavolainen, Häkkinen, et al., 1999) reported that 9 weeks of explosive resistance training improved 5K run performance (mean 3.1%) and RE (mean 8.1%) with no changes in VO_{2max} in 22 moderately trained male runners. Furthermore, they observed significant improvements in velocity over a 20-m sprint (mean 3.4%) distance jumped (mean 4.6%) along with a concurrent decrease in stance phase contact times (L. Paavolainen et al., 2003). These variables are thought to represent indirect measures of the neuromuscular system's ability to repeatedly produce rapid force during intense exercise and its capability to store and utilize elastic energy (L. Paavolainen, Häkkinen, et al., 1999; L. M. Paavolainen, Nummela, & Rusko, 1999; L. Paavolainen, Nummela, Rusko, & Häkkinen, 1999). The authors suggested that improved performance was a result of enhanced neuromuscular characteristics and biomechanical efficiency that were transferred into improved muscle power and RE (L. Paavolainen, Häkkinen, et al., 1999).

The importance of neuromuscular characteristics in determining RE and thereby running performance has also been pointed out previously (Dalleau, Belli, Bourdin, & Lacour, 1998; Spurrs et al., 2003). Dalleau et al. (Dalleau et al., 1998) showed that the energy demand during running is significantly related to the stiffness of the propulsive leg. Similarly, Spurrs et al. (Spurrs et al., 2003) demonstrated that 6 weeks of plyometric training significantly improved RE, muscle-tendon stiffness, maximal isometric force, rate of force development, jump height, five-jump distance and 3-km time trial performance. Plyometric training consisted of 2–3 sessions a week of various unloaded jumps, bounds, and hops. Several other studies have provided support that simultaneous plyometric or explosive resistance training and endurance training improves RE in recreational (Taipale et al., 2010, 2013; Turner, AM, Owings, M and Schwane, 2003), moderately trained (Kyle R. Barnes et al., 2013; Berryman et al., 2010; Guglielmo et al., 2009; Mikkola, Rusko, Nummela, Pollari, & Häkkinen, 2007; L. Paavolainen et al., 2003; Spurrs et al., 2003), and highly trained runners (Philo U. Saunders et al., 2006). Saunders et al. (Philo U. Saunders et al., 2006) examined the effects of 9 weeks of plyometric training on RE in highly trained runners using loaded and unloaded exercises 3 times a week. The subjects were tested for RE at 14, 16 and 18 km h^{-1} at weeks 5 and 9; however, significant improvements were only found at week 9 for the km h^{-1} test. Other studies showed improvements in RE after 8 weeks of plyometric training in moderately trained runners with no change in $V'O_{2max}$ (Berryman et al., 2010; Mikkola et al., 2007), with the former study showing a (mean) 7% improvement in RE and (mean) 5.1% in 3-km run performance. Proposed explanations for the improvements include increased lower limb stiffness and elastic energy return, enhanced muscle strength and power, or enhanced running mechanics. Recent evidence has also suggested RE can be greatly improved (mean 6.0%) following a series of warm-up strides with a weighted vest; and this was consistent with improved lower limb stiffness (K. R. Barnes, Hopkins, McGuigan, & Kilding, 2015). Turner et al. (Turner, AM, Owings, M and Schwane, 2003), however, reported no changes in four indirect measures of the ability of the muscles to store and return elastic energy despite a (mean) 3% improvement in RE following 6 weeks of plyometric training in recreational runners. These findings suggest that either more direct measures of potential mechanisms that could improve RE need to be done in future research or other factors are yet to be elucidated as potential mechanisms for enhancing RE following plyometric training.

Ways to improve RE besides endurance and resistance training are constantly sought after by athletes, coaches and sports scientists; however, there is a paucity of data regarding environmental strategies. Training at altitude offers one potential strategy. Despite altitude exposure being reasonably well-researched over the past few decades, there is still limited data in regard to improving RE; other strategies such as training in hot, cold or humid environments are yet to be examined. Many athletes undertake some form of altitude training to gain small improvements in physiology and performance. Results from a recent meta-analysis indicate a 1–4% performance enhancement following various protocols using natural and artificial altitude exposure in highly and moderately trained athletes (Bonetti & Hopkins, 2009). Improvements in performance have been primarily attributed to increased hematological parameters that lead to an increase in maximal aerobic capacity (Levine & Stray-Gundersen, 1997; Robertson et al., 2010; Philo U Saunders, Telford, Pyne, Gore, & Hahn, 2009; Stray-gundersen, Chapman, Levine, Chapman, & Levine, 2018); however, hypoxia-induced enhancements in muscle buffering capacity (Gore et al., 2001) and RE (P. U. Saunders, 2003; P. U. Saunders, Telford, Pyne, Hahn, & Gore, 2009) have also been suggested. The literature indicates that altitude exposure for runners has no detrimental effects on their RE and that there is good evidence to suggest that it may lead to worthwhile improvements in RE at sea level. Altitude acclimatization results in both central and peripheral adaptations that improve oxygen delivery and utilization and enhance metabolic efficiency - mechanisms that could potentially explain the changes in RE. Many of the studies that did not find an improvement in RE after altitude exposure were performed close to the competition season, which emphasizes the importance of timing and training phase on the effectiveness of altitude exposure on RE.

Flexibility and Stretching

There appear to be equivocal results in regard to the effects of stretching or flexibility on RE. Some researchers have identified an inverse relationship between flexibility and RE; that is, less flexibility is associated with better RE (Craib et al., 1996; Gleim et al., 1990; A M Jones, 2002; Mikkola et al., 2011; Trehearn & Buresh, 2009). Gleim et al. tested 100 male and female subjects over a range of speeds from 3 to 12 km h^{-1} and found that those who exhibited less flexibility in a battery of 11 trunk and lower limb flexibility tests were most economical. These results suggest that the inflexibility of the lower limbs and trunk musculature as well as limited range of motion around the joints of the lower body allow for greater elastic energy storage and use in the muscles and tendons during the running gait (Gleim et al., 1990; A M Jones, 2002). Specifically, it was suggested that inflexibility in the transverse and frontal planes of the trunk and hip regions of the body may stabilize the pelvis at the time of foot impact with the ground, reducing excessive range of motion and metabolically expensive stabilizing muscular activity (Gleim et al., 1990). Furthermore, research has demonstrated that runners with tighter or stiffer musculotendinous structures store more elastic energy in their lower limbs, resulting in lower $V'O_2$ at submaximal running speeds (Kyle R. Barnes, Mcguigan, & Kilding, 2014; Craib et al., 1996; Gleim et al., 1990; A M Jones, 2002).

In contrast, other research fails to support the existence of an inverse relationship, countering that flexibility is an essential component of distance running performance (Beaudoin & Whatley Blum, 2005; Godges et al., 1989; Godges, MacRae, & Engelke, 1993; a G. Nelson, Kokkonen, Eldredge, Cornwell, & Glickman-Weiss, 2001). Godges et al. found improved RE at 40, 60 and 80% $V'O_{2max}$ in response to static stretching procedures in seven moderately trained male college student athletes when flexibility increased. They reported a reduced aerobic demand of running at all speeds when hip flexion and extension were increased (Godges et al., 1989). Improved hip flexibility, myofascial balance, and pelvic symmetry due to stretching are thought to enhance neuromuscular balance and contraction, thus leading to lower submaximal $V'O_2$ and improved RE. These results corroborate general beliefs that improved flexibility is desirable for optimal running performance.

Nutritional supplements

Beyond the typical endurance preparation of an athlete, which includes a lot of aerobic training, HIT, resistance and/or plyometric training, and various environmental exposures during a periodized season (Stellingwerff, 2013), several nutritional supplements have received attention for their effects on reducing oxygen demand during exercise, most notably dietary nitrates. Nitric oxide (NO) is an important physiological signaling molecule that can modulate skeletal muscle function through its role in the regulation of blood flow, muscle contractility, glucose and calcium homeostasis, and mitochondrial respiration and biogenesis (Andrew M. Jones, Bailey, & Vanhatalo, 2012). It is now known that tissue concentrations of nitrate (NO_3) and nitrite (NO_2) can be increased by dietary means. Green leafy vegetables such as lettuce, spinach, rocket, celery and beetroot are particularly rich in nitrate. Therefore, dietary nitrate supplementation represents a practical way to increase circulating plasma nitrite and thus nitric oxide to lower the oxygen demand of submaximal exercise (enhancing metabolic efficiency and subsequently RE) and potentially to enhance running performance (Bailey et al., 2009; Bailey, Fulford, et al., 2010; Bailey, Winyard, et al., 2010; Andrew M. Jones et al., 2012; Andrew M. Jones, Vanhatalo, & Bailey, 2013; Filip J. Larsen et al., 2011). The physiological mechanisms responsible for the reduced oxygen demand following nitrate supplementation could result from two different mechanisms. First, a lower cost of muscle contraction for the same force production (i.e., improved muscle contractile efficiency via sarcoplasmic reticulum calcium handling or actin-myosin interaction), or second, lower oxygen consumption for the same rate of oxidative ATP resynthesis (i.e., enhanced mitochondrial efficiency via improved oxidative phosphorylation) (Andrew M. Jones et al., 2012, 2013). While only one study to date has demonstrated improved RE (Lansley et al., 2011) following nitrate supplementation, reduced oxygen demand and improved work efficiency have been reported for several other types of exercise, including cycling (Bailey et al., 2009; F. J. Larsen, Weitzberg, Lundberg, & Ekblom, 2007; Filip J. Larsen, Weitzberg, Lundberg, & Ekblom, 2010; A Vanhatalo et al., 2010), walking

(Lansley et al., 2011), and knee extension exercises (Fulford et al., 2013; Andrew M. Jones et al., 2013). Larsen et al. (F. J. Larsen et al., 2007) reported that 3 days of sodium nitrate supplementation increased plasma nitrite and reduced the oxygen demand during sub-maximal cycling exercise. These findings were corroborated in a study by Bailey et al. (Bailey et al., 2009) in which nitrate was administered in the form of beetroot juice. The reduction of $V'O_2$ after nitrate supplementation was of the order of 5% in the studies of Larsen et al. (F. J. Larsen et al., 2007) and Bailey et al. (Bailey et al., 2009), in which supplementation was continued for 3–6 days. A similar reduction of steady-state $V'O_2$ was reported following acute nitrate supplementation. Vanhatalo et al. (A Vanhatalo et al., 2010) reported a significant reduction of steady-state $V'O_2$ just 2.5 h following beetroot juice ingestion. Although dietary nitrate appears to be a promising ergogenic aid, additional research is required to determine the scope of its effects on well-trained distance runners and across different competition events. Future research should also examine the efficacy of other nutritional supplements to enhance RE.

A variety of training strategies has been adopted in an attempt to improve RE by modifying one or more factors that influence metabolic, biomechanical and/or neuromuscular efficiency. The most common strategies used are resistance training, plyometric training and explosive resistance training. Each of these modes of ancillary training have been reported to improve RE in recreational, moderately trained, and highly trained runners through primarily neuromuscular mechanisms. Results from HIT studies are unclear, but the best results of improved RE appear to occur when training at near maximal or supra-maximal intensities on flat or uphill terrain. Adaptations to living and training at natural and artificial altitudes have been primarily attributed to increased hematological parameters that improve RE. There appear to be equivocal results regarding the effects of stretching or flexibility on RE. Ingestion of dietary nitrate, especially in the form of beetroot juice, also appears to hold promise as a natural means to improve RE. From a practical standpoint, it is clear that training and passive interventions affect RE, and researchers should concentrate their investigative efforts on more fully understanding which training types and mechanisms affect RE and the practicality and extent to which RE can be improved outside the laboratory.

Highlights

- *RE is the energy expenditure expressed as the submaximal $V'O_{2max}$ at a given running speed*
- *RE can vary among runner with similar $V'O_{2max}$ up to 30% and it is considered a better predictor of endurance performance*
- *RE is likely to be influenced by several factors: training, environment, physiology, biomechanics, anthropometry*
- *Economic and non-economic runners show significance differences and trend in some kinematical parameter, and biomechanical patterns but the relationship appear weak and inconsistent among studies.*
- *Vertical ground reaction forces and the time course of the force application explained 38% of the inter-individual variability in RE, but the mechanism need to be more clearly understood.*
- *Anthropometric characteristics such as limb dimensions and proportions and leg mass distribution, seems able to increase RE*
- *An optimal balance between muscle stiffness and flexibility is require to maximize elastic energy storage and return in the trunk and legs*
- *The performance dominance of Kenyan runners in half and full marathon cannot be explained just by the functional bioenergetics differences*
- *A wide range of training intervention (including resistance training, endurance and HIT training, altitude exposure, stretching and nutritional supplements) have been investigated with respect to improving RE*
- *The addition of strength training to normal endurance training has received great attention and consent in all endurance sport*
- *The most common strategies actually used are resistance, plyometric and explosive resistance training. Each of these modes of ancillary training have been reported RE improvements in recreational, moderately, and highly trained runners through primarily neuromuscular mechanisms.*

Chapter 5

Percentage of Maximum Oxygen Uptake

Percentage of maximum oxygen uptake is the fraction of $V'O_{2max}$ that can be maintained during performance. It is time and fitness related. Figure 8, from the classic Textbook of Work Physiology by Åstrand and Rodahl shows the impact that training has on one's ability to maintain a certain percentage of $V'O_{2max}$ during prolonged exercise. Trained individuals performed at 87% and 83% of $V'O_{2max}$ for 1 and 2 h, respectively, compared with only 50% and 35% of $V'O_{2max}$ for untrained subjects. This diagram clearly shows the impact that % $V'O_{2max}$ has on actual performance $V'O_2$ that a person can maintain during an endurance performance.

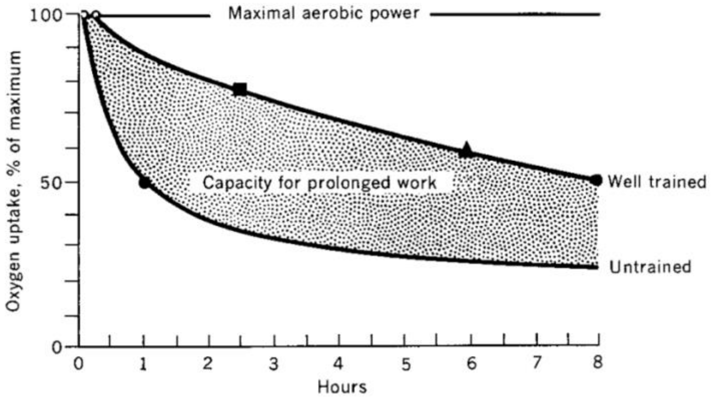

Figure 8 - A graphic illustration based on a few observations showing approximately the percentage of a subject's maximal aerobic power he/she can tax during work of different duration and how this is affected by training state. From Textbook of Work Physiology, Astrand

In addition, Figure 9, taken from the same text, shows how $V'O_{2max}$ and % $V'O_{2max}$ changed over months of training. $V'O_{2max}$ increased during the first 2 months and then leveled off, whereas % $V'O_{2max}$ continued to change over time. Consequently, while changes in both $V'O_{2max}$ and % $V'O_{2max}$ impacted changes in the performance of an athlete early in a training program, subsequent changes in performance $V'O_2$ were due to changes in % $V'O_{2max}$ alone. This classic figure was supported by later studies showing that $V'O_2$ at Lactate Threshold (%$V'O_{2max}$ at LT) increased much more as a result of training than did $V'O_{2max}$.

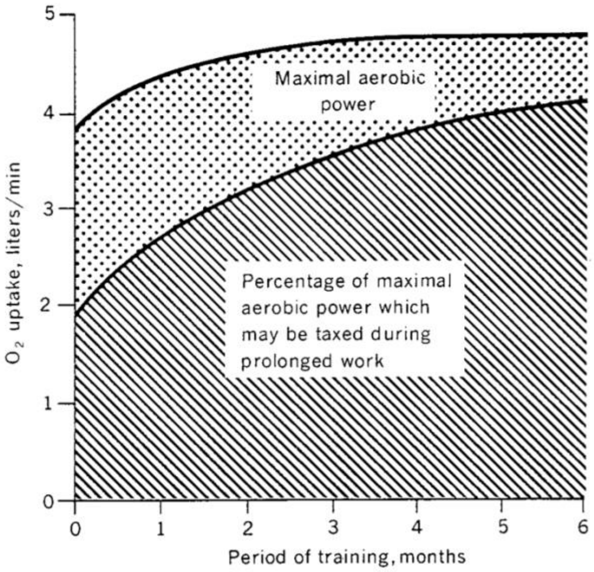

Figure 9 - Training causes an increase in maximal oxygen uptake. With training, a subject is also able to tax a greater percentage of their maximal oxygen uptake during prolonged work. From Textbook of Work Physiology, Astrand. Rodahl

The model presented earlier in Figure 2 shows how $V'O_{2max}$ and % $V'O_{2max}$ interact to determine performance $V'O_2$ and how running economy shapes final performance. In this model, $V'O_2$ at LT integrates both $V'O_{2max}$ and % $V'O_{2max}$. In another study, Basset et al. (Bassett & Howley, 1997) used a more detailed model to show that running velocity at LT integrates all three variables mentioned earlier ($V'O_{2max}$, % $V'O_{2max}$, and RE) to predict distance running performance (Fig. 10). The speed at which the lactate concentration changes in some way (e.g., to an absolute concentration, a break in the curve, a delta amount) is taken as the speed at LT and is used as the predictor of endurance performance. Numerous studies have shown the various indicators of LT to be good predictors of performance in a variety of endurance activities (e.g., running, cycling, race walking) and in both trained and untrained populations (Weltman, 1995). In most of these studies, the association between LT and endurance performance was evaluated in groups of athletes that were heterogeneous in regard to performance. This means that even though the speed at LT explains the vast majority of variances in performance in distance races (Farrell, Wilmore, Coyle, Billing, & Costill, 1979), other factors can still influence final performance. It has been known for some time (Holloszy, 1973; Holloszy & Coyle, 1984) that lactate production is related to a number of variables among which the mitochondrial content of muscle, as measured by mitochondrial enzyme activity.

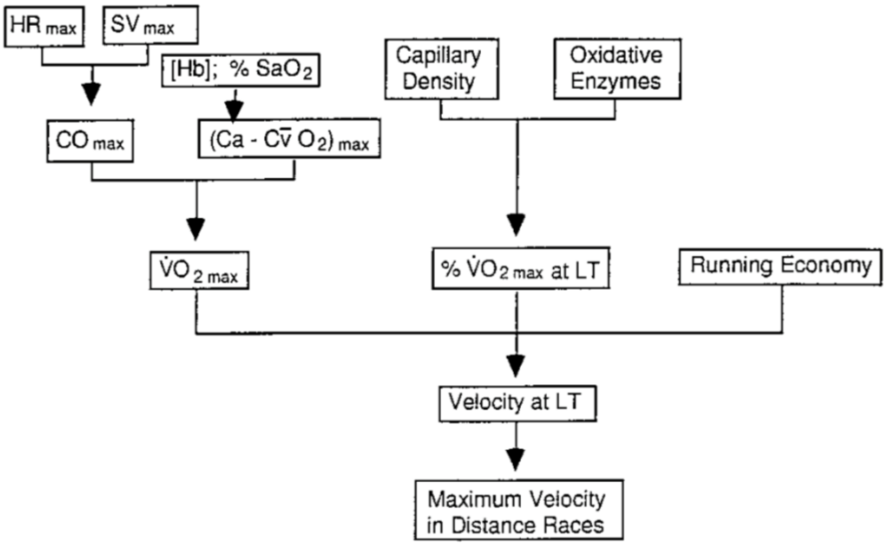

Figure 10 - Summary of the major variables related to $\dot{V}O_{2max}$ and the maximal velocity that can be maintained in distance races. From: Bassett, D. R., Jr. and E. T. Howley. Maximal oxygen uptake: “classical” versus “contemporary” viewpoints. Med. Sci. Sports Exerc

Variations in LT across diverse groups of endurance athletes and improvements in LT resulting from training are linked to differences and increases in mitochondrial enzyme activity, respectively (E F Coyle, 1995; Weltman, 1995). When muscles are working to meet a specific submaximal power output, ATP is converted to ADP and Pi and this drives metabolic reactions in the cell to meet the ATP demand associated with that work rate. In muscle cells poor in mitochondria, ADP concentrations must rise to a high level in order to drive the limited number of mitochondria to meet the ATP demand via oxidative phosphorylation. This high concentration of ADP also drives other metabolic processes, including glycolysis, because of the stimulatory effect of ADP on phosphofructose kinase (PFK). This leads to an increase in the use of carbohydrates, an accumulation of pyruvate and an increase in lactate production. As mentioned previously, training stimulates a large increase (50-100%) in the number and activity of the mitochondria. Consequently, with the same oxygen consumption, this leads to a lower concentration of ADP, less stimulation of PFK and use of carbohydrates. The result is a lower concentration of lactate because the mitochondria can use fats as fuel.

(Holloszy & Coyle, 1984; Katz & Sahlin, 1988).

A further possible explanation for the interaction between LT and % $V'O_{2max}$ was provided in a study by Coyle et al. (E F Coyle, Coggan, Hopper, & Walters, 1988). They studied 14 trained cyclists (3–12 yr of training), similar in terms of $V'O_{2max}$ (thus eliminating that as a variable), to examine the relationship between LT and time to fatigue at 88% $V'O_{2max}$. The subjects were divided into high-LT (mean 81.5% $V'O_{2max}$) and low-LT (mean 65.8% $V'O_{2max}$) groups. A performance test at 88% $V'O_{2max}$ resulted in large differences in performance (60.8 vs 29.1 min), and post-exercise lactate concentrations (7.4 vs 14.7 mM) for the high-LT and low-LT groups, respectively. The difference in performance between the groups that had the same $V'O_{2max}$, but differed in % $V'O_{2max}$ at LT, was consistent with the model described. On the other hand, the fact that the vastus lateralis of both groups had the same mitochondrial enzyme activities suggested a break in the chain of evidence linking % $V'O_{2max}$ at LT to mitochondrial activity. This created a rare opportunity for the investigators to study two groups with identical $V'O_{2max}$ and the same mitochondrial enzyme activity but with substantial differences in performance. The investigators examined the metabolic response of the cyclists to a 30-min test at 79% $V'O_{2max}$. They found that while the low-LT group used 69% more carbohydrate during this exercise bout than the high-LT group, the low-LT group reduced its vastus lateralis muscle glycogen concentration 134% more than the high-LT group. Consequently, the study by Coyle et al. indicates that the mass of muscle involved in the activity (in addition to mitochondrial density) contributes to % $V'O_{2max}$ at LT (as well as to performance) in a manner consistent with the above model.

It is noteworthy to point out here a lack in scientific literature regarding specific information about limiting factors of % VO_{2max}. The poor applicability of the measure in the field does not help to arouse interest.

Since the fraction is dependent on the duration of the effort, the concept of critical power (CP) and speed (CS), which has received great interest, is the closest model to the % $V'O_{2max}$ concept. The hyperbolic form of the power-duration relationship is rigorous and highly conserved across species, form of exercise and individual muscle/muscle groups. Crucially, CP integrates sentinel physiological, respiratory, metabolic and contractile profiles, within a coherent framework that has great scientific and practical usefulness. CP is also utilized as a fatigue threshold in the sense that it separates exercise intensity domains within which the physiological responses to exercise can (<CP), as endurance events require, or cannot (>CP) be stabilized (Anni Vanhatalo, Jones, & Burnley, 2011).

Training strategies to improve percentage of $V'O_{2max}$

As mentioned previously, the lack of definition of the factors that limit % $V'O_{2max}$ consumption does not allow researchers to identify a specific methodology for this factor of endurance performance. Actually, the purpose of training is to help athletes improve their maximum values of $V'O_{2max}$, which are sensitive to training according to the starting fitness level, as was said above, but also their ability to sustain a high percentage of it for the entire effort. In order to achieve this result, the program must contain all training exercises that involve all ranges of intensity: HIT, continuous endurance training, and strength training that is helpful in improving the ability to use less energy for the same intensity (RE).

Highlights

- *Percentage of maximum oxygen uptake is the fraction of* $V'O_{2max}$ *that can be maintained during long time performance. It is duration and fitness related.*
- *Percentage of maximum oxygen uptake is more sensitive than* $V'O_{2max}$ *to training.*
- *The interaction between LT and % of* $V'O_{2max}$ *was demonstrated. By the same percentage, cyclists with highest LT consume less carbohydrates and sustain this intensity for longer time*
- *Training program must contain exercise involving all of intensity ranges*

Chapter 6

Experimental purpose

Knowing the performance model of a studied discipline is one of the basic steps to setting up a training program. These performance models adapt to different preparation levels, male and female for both elite or amateur athletes. Their different improvement sensitivities of each limiting factors should leads to pay more attention in training manage to reach the best performance

In elite athletes the margins for improvement are lower than in recreational athletes, because have achieved maximal development of the capacity of the energy system since they were young. To support that statement several studies, as reported previously (Berg et al., 1995; Ekblom, 1968; A. M. Jones, 1998; Paul B Laursen & Jenkins, 2002a), did not find any significant variations in maximum oxygen consumption after training in elite or well-trained athletes. One study (Carlo Capelli, 1999) demonstrated through mathematical models how evolution of the different factors, in the same percentage, reflected on performance improvement. Basing on possible improvements, estimated through the differences in performance over a defined period for an elite athlete, his results showed that a 5% improvement in RE led to an overall 4.5% performance improvement regardless of the distance involved, while an improvement in performance connected to an increase in $V'O_{2max}$ increased in relation to an increase in the distance up to a maximum of 5km and then stabilized. It is therefore more convenient to focus on possible training strategies to improve RE for long distance running performance in elite athlete.

Anyone begin a training study immediately finds the necessity of having to classify the subjects. There are several possibilities, based on the aerobic capacity ($V'O_{2max}$) on the performance (Personal best), on the age, on the volume (number) of weekly or professional training sessions (professional / amateur). None of these classifications fully describes the subject, nor even his training. In scientific literature available is widespread although not clearly defined the term rr. Studies that refer to recreational athletes, report an average frequency of training by subjects not exceeding 4 times a week, and a maximum consumption of oxygen between 60

and 80 percentile of the classification provided by the ACSM normalized for age (ACSM's Guidlines for Exercise Testing and Presctription (8th ed.). Baltimore, 2010).
In our opinion, it is very important to personalize an appropriate strategy for recreational athletes, even more since they have less ability to control complex motor pattern than elite or well-trained athletes. In addition, their musculotendinous structures are not able to sustain a training load that some exercises would impose on them (for instance plyometric and heavy strength training). Furthermore, unlike elite athletes, recreational athletes require training directed towards optimizing the time spent on complementary exercises necessary to improve their performance (strength and technical skills training) in order to avoid eroding precious time available for running training. time out of training.

On the basis of these considerations we have focused our research on the issues that in our opinion could allow the best benefits in terms of performance, time saving and injury prevention in the recreational athlete. In particular we have studied two aspects, often overlooked or improvised by athletes and coaches, such as the eccentric strength training and the distribution of work intensity.

In our first study, we focused our attention on finding a safe and easy kind of strength training able to improve RE and consequently performance. As written in the relative chapter, there are many strategies for the improvement of the RE and in recent years great importance has been given to the insertion of strength training in the disciplines of endurance for elite athletes. Our choice to investigate the improvement of RE in recreational athletes using isoinertial training is dictated by the fact that it turns out to be a quick way compared to the strength training traditionally proposed in the studys referred to recreationale athlete (Millet et al., 2002; Piacentini et al., 2013b), so it meets the recreational athlete's need to contain total time spent in training, and extremely simple to perform even unlike a plyometric training.

Whereas in the second, our purpose was to compare two different training intensity distributions in order to obtain an improvement in performance in the least time possible. In this case we evaluated if running training is able to affect the performance according to the different duration and intensity of the training stimuli, which are differently distributed in the intensity scale commonly used.

Chapter 7

First Study

Effects of flywheel strength training on the running economy of recreational endurance runners

Typically, endurance running events are strongly related to different physiological factors such as maximal oxygen uptake ($V'O_{2max}$), the $V'O_{2max}$ available fraction, defined as the intensity sustained for a long period ($F_{V'O_{2max}}$), and running economy (RE), defined as the $V'O_2$ required at a given absolute exercise intensity (Bassett & Howley, 2000). RE seems to be a better predictor of endurance performance than $V'O_{2max}$ (Noakes, 1988; Philo U. Saunders et al., 2004). Some authors have suggested that anaerobic and neuromuscular characteristics together with RE are able to affect endurance performance (Nummela et al., 2006; L. Paavolainen, Häkkinen, et al., 1999). For this reason, in recent years, strength-training programs have been indicated as powerful stimuli to improve mechanical efficiency, muscular coordination, motor unit recruitment patterns and lower limb stiffness regulation with an overall enhancement in RE (Sale, 1988). In the past, it was suggested that concurrent endurance and strength training might interfere with or inhibit the development of strength or rate force development if the periods of concurrent training were too long or the training volume or intensity were too high (Häkkinen et al., 2003; Hunter, Demment, & Miller, 1987; Jung, 2003). The cause of the “interference effect” appears to be related to the divergent responses and adaptations when considering also the specificity of the training mode and its adaptations in the neuromuscular system within strength training. For example, maximal strength training with high loads (such as 70-90% of 1RM) and low repetitions per set generally result in neural adaptations responsible for muscle hypertrophy over prolonged training periods. Conversely, explosive resistance training with low to medium loads (such as 30-60% of 1RM) but high action velocity movements improves neuromuscular characteristics, especially the rapid activation of the muscles due to increased motor unit recruitment. Maximal and explosive strength training paired with endurance training, as well as plyometric training, have been shown to be more effective in improving running economy, strength, power and muscle activation in recreational endurance runners compared with concurrent circuit and endurance training (Alexander Ferrauti, Matthias Bergermann, 2010; Giovanelli, Taboga, Rejc, & Lazzer, 2017; Mikkola et al., 2011; Millet et al., 2002; L. Paavolainen, Häkkinen, et al., 1999; Taipale et al., 2010).

Guglielmo and colleagues (Guglielmo et al., 2009) demonstrated that heavy weight training (load 6-RM) was more effective in improving running economy than explosive strength training (with intermediate resistance, load 12-RM) over short (4 week) training periods in well-trained endurance runners. Moreover, Piacentini et al. (Piacentini et al., 2013b) endorsed these results confirming that total body maximal strength training (85-90% of 1RM, 4 repetitions, 4 sets) twice a week for six weeks improved 1RM by 17%, and RE by 6.1% ($p<0.05$) in master athletes.

Recreational runners represent most participants in marathon events, and their number grows year after year. These athletes train and compete regularly, and follow detailed, structured training programs despite having various work and family commitments. Adding two extra strength-training workouts a week is not feasible for most of them, if not as part of a regular running session.

Knowing the benefits of adding strength training to endurance training in order to improve neuromuscular performance and sport specific economy, we conducted this study to compare RE variations before and after a regular endurance training program performed once a week, consisting of specific, short flywheel muscle efforts on a Yo-Yo Leg Press versus low- or high-intensity training programs. According to our hypothesis, a brief flywheel strength training session in addition to endurance training would lead to an improvement in RE and, consequently, in the endurance performance of recreational runners.

METHODS

Experimental approach to the problem

In this study an 8-week training period was chosen to analyze the effects of flywheel strength training on RE, because it was thought that most adaptations in RE would occur after 4-6 weeks of strength training and that longer protocols may not add further improvements to RE (Turner, AM, Owings, M and Schwane, 2003). A parallel, 3-group, matched, longitudinal (pretest-posttest), experimental design was used for this study to investigate the possible effects on RE, anthropometric data (DEXA), $V'O_{2max}$, ventilatory thresholds, and 1RM after 3 different training programs: flywheel strength training (FST), high intensity training (HIT) and low intensity training (LIT).

Subjects

Twenty-nine recreational runners were divided into 3 experimental groups of similar age, weight, height, and $V'O_{2max}$. The University Ethical Committee approved the protocol and the participants gave their written consent before taking part (prot. N°165038, 28/06/2016). In order to avoid the influence of an athlete's current ability and preparation level, the participants included in this study had to fulfill the following criteria: they had to complete a half marathon not more than two months after the beginning of the study; and they had to have at least 3 years and maximum 10 year of endurance training experience.

Variables	**FST (n = 11)** **6 Males and 5 Females**	**HIT (n = 9)** **6 Males and 3 Females**	**LIT (n = 9)** **6 Males and 3 Females**
Age (yr)	44.2 ± 6.0	42.2 ± 8.6	45.4 ± 8
Weight (kg)	73.3 ± 9.4	70.9 ± 11.9	66.1 ± 11.7
Height (cm)	169.0 ± 9.1	171.1 ± 6.8	171.8 ± 9.6
$V'O_{2max}$ (ml min^{-1} kg^{-1})	48.8 ± 5.2	50.3 ± 3.7	50.2 ± 6.8

Value are mean ± SD

Table 1. Physical characteristics of runners. FST = Flywheel Strength Training; HIT = High Intensity Training; LIT = Low Intensity Training

Procedures

All subjects, during the week before the start of training (week #0), arrived at the laboratory for 3 sessions: aerobic capacity, running economy (T_1 and T_2 in random order) and one-repetition maximum (T_3). The sessions were separated by a 48-hour resting period, performed at the same time of day (at 19:00±2 hours) in a climate-controlled laboratory (20-22° C, 55% humidity). The participants did not perform any physical activity during the 48-hour resting periods and were requested to refrain from using caffeine-containing food or beverages, consuming alcohol, and smoking cigarettes, or using any form of nicotine intake during this period. The daily diet was requested during the first session and we have asked each subject to reproduce it for all experimental conditions. During the first session the body composition was measured.

At the end of first and second sessions, two familiarization trials (F_1 and F_2) were performed by the yoyo horizontal leg press machine for FST and by the isotonic horizontal leg press machine for all groups (see Figure 1). The first trial consisted of 4 sets of 7 repetitions at moderate self-selected intensity on each machine while the second trial was of 4 sets of 4 repetitions at submaximal self-selected intensity. The subjects repeated the same test program during the week just after the end of training (week #9).

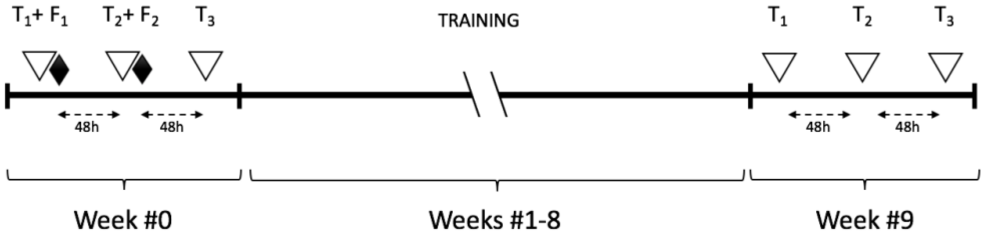

Fig. 1 – Timeline of research. Week #0 for test PRE, weeks #1-8 for training period and week #9 for test POST. Test sessions (T) and familiarization trials (F).

Body composition

In addition to standing height (measured using standard methods), body mass and body composition were measured using DEXA (QDR explorer E, Hologic, MA, USA).

Aerobic capacity

Maximal oxygen uptake ($V'O_{2max}$) and maximal running speed ($vV'O_{2max}$) were determined by an incremental treadmill running test at the laboratory. The protocol test was individualized for each subject in order to control the duration of each test. Therefore, the initial speed was determined by the subject's capacity, and it was increased by 0.5 km h^{-1} every minute until exhaustion. The running surface slope was kept at a constant +1% throughout the test (Runrace Technogym, Gambettola, Italy). Heart rate, oxygen consumption and ventilatory parameters were determined breath-by-breath using a Cosmed flow meter (Quark PFT, Cosmed, Rome, Italy). Before each test, the flow meter was calibrated with a 3-L syringe, and the analyser was calibrated with certificated gas mixtures (16% O_2 and 5% CO_2) and environmental air (20.9% O_2 and 0.03% CO_2). The ventilatory threshold (VT) was defined as the intensity at which the ventilatory equivalent of oxygen (VE'/V'O_2) began to rise without a concurrent rise in the ventilatory equivalent of carbon dioxide (VE'/V'CO_2) (Gaskill et al., 2001). This method has been shown to be valid and reliable (Amann, Subudhi, Walker, et al., 2004; Amann, Subudhi, & Foster, 2004). Two experienced evaluators performed the threshold determinations independently. If there was disagreement between the two independent observers, a third was brought in.

One-repetition maximum

Maximal strength was estimated by a 6RM test on a leg press machine. All subjects were positioned on a horizontal leg press (Technogym, Gambettola, Italy) and the knee angle (90°) was fixed to maintain the same position in all test occasions. After a 5-minute of warm-up and an appropriate rest period, the subject performed the first session with a preliminary load of 15 repetitions. Thereafter, the load was increased every step by 30% until the athlete could not successively complete a 6RM repetition (ACSM's Guidlines for Exercise Testing and Presctription (8th ed.). Baltimore, 2010). The 1RM was estimated using a conversion table. The 1RM was measured for all subjects after 2 weeks of the familiarization period.

Running economy

After 5 minutes of running warm-up at 60% of the velocity at first ventilatory threshold (vVT_1), the RE was determined by measuring submaximal steady state $V'O_2$ running for 5 minutes at 75% of vVT_1. During each test, heart rate and $V' O_2$ were monitored and recorded breath by breath with the Cosmed metabolimeter (Quark PFT, Cosmed, Rome, Italy), calibrated before each test as described above. The RE was defined as the mean $V'O_2$ collected at the last 2 minutes of test.

Training protocol

Reference velocity (RV) we defined in order to differentiate training interventions. Reference velocity is the mean velocity between the first and second ventilatory thresholds (vVT_1, vVT_2). All groups performed training sessions 3 times a week. The endurance program for FST and LIT was characterized by an intensity ranging between 70-105% of RV, while the intensity for HIT was at 95-140% of RV. A flywheel strength training session was done once a week, before the endurance workout. After a standardized warm-up, the runners did four sets of seven repetitions at maximum velocity on a Yo-Yo Leg Press (Yo-Yo Technology AB, Stockholm, Sweden), a new iso-inertial system that maximizes the eccentric phase of muscular contraction. The intensity effort was controlled with RPE after each set. If the subject gave a value in the range of 9-10 the effort was considered maximum. The rest interval between sets lasted 3 and a half minutes. To compare training the total training load (intensity X volume) was balanced using a modified version of the training-impulse (TRIMP) approach (Foster et al., 2001).

Statistical analyses

Standard statistical methods were used to calculate the means, standard deviation and standard error. Group differences were analyzed using a one-way analysis of variance (one-way ANOVA), and within-group differences (group-by-training interaction) were analyzed using two way ANOVA repeated measures. Differences between PRE vs. POST were reported in absolute values, the precision of estimates for absolute values was indicated with 90% confidence limits (CL), effect size (d) and benchmark for significance was set at $p \leq 0.05$.

RESULTS

Before the training period, the subjects did not differ in terms of any measured variable. After the 8-week program, there were no significant changes in body mass, fat free mass (FFM), lower limb fat free mass (lower limb FFM), fat mass, or percentage of body fat. The FST group showed a significant 12.9% increase ($p \leq 0.05$) in 1RM after training. In fact, pre-mean and post-mean values were 144.2±35.8 and 162.5±37.3 Kg respectively; whereas no significant differences were observed in the HIT and LIT groups (Figure 2 and 3).

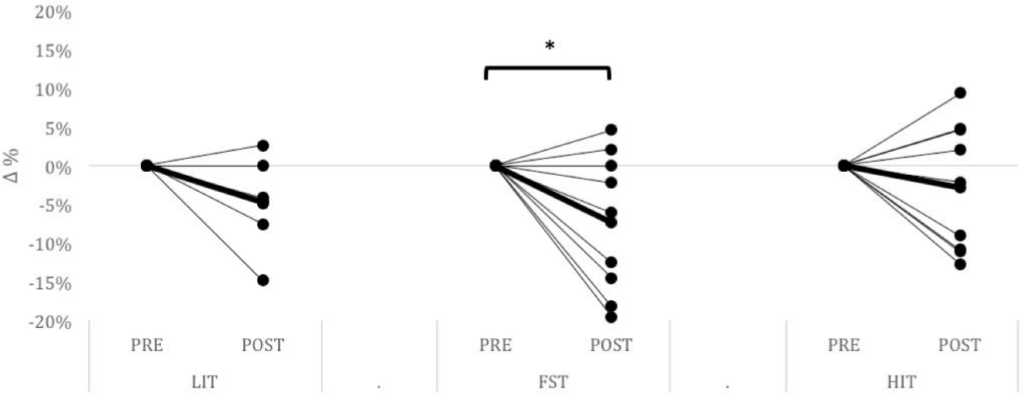

Fig. 2 - Percentage change in Running Economy on the three groups. Average in Bold line, *p≤ 0.05

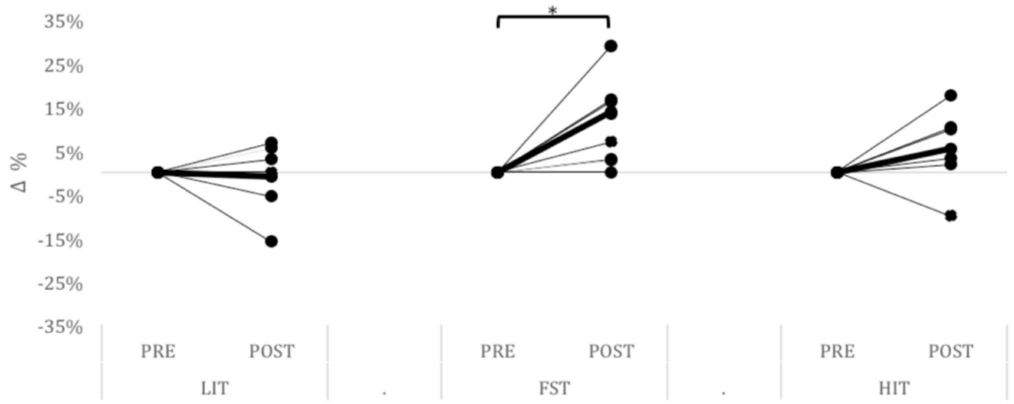

Fig. 3 - Percentage change in 1RM on three groups. Average in Bold line, *$p \leq 0.05$

RE improved significantly ($p \leq 0.05$) in the FST group (6.3%) at 75% of VT_1. The HIT and LIT groups did not show any significant improvements in RE.

All groups show significance improvement ($p \leq 0.05$) on performance +3.7% and + 6.1% for FST, +3.8% and +5.8% for HIT and +2.9% and +2.5% for LIT in average velocity on 2 km and 10 km respectively. All results concerning the pre and post training variations are summarized in table 2-4.

	Pre Training	**Post Training**	**Difference**	**Lower bound**	**Upper bound**	**Effect Size (d)**	
Weight (kg)	66.1 ± 11.7	66.2 ± 11.7	0.1	-0.9	0.6	0.0	
Fat mass (%)	21.1% ± 6.7%	20.3% ± 6.7%	0.8%	0.1%	1.5%	-0.1	
$V'O_{2max}$ (ml min)	3313 ± 765	3400 ± 842	87	-281	107	0.1	
$vV'O_{2max}$ (km h-1)	13.3 ± 2.0	13.6 ± 2.0	0.3	-0.7	0.2	0.2	
VT1 (km h^{-1})	10.8 ± 1.6	11.5 ± 1.8	0.7	-1.2	-0.2	0.5	*
VT2 (km h^{-1})	12.2 ± 1.9	12.9 ± 2.0	0.7	-1.1	-0.3	0.5	**
RE@75 (ml m^{-1} kg^{-1})	195.6 ± 28.8	197.2 ± 15.3	1.6	-17.6	14.4	0.1	
Strength							
1RM leg press (kg)	136.9 ± 37.4	135.6 ± 39.1	1.4	-2.2	4.9	0.0	
2km avg speed (km h-1)	13.7 ± 2.0	14.1 ± 2.2	0.4	-0.7	-0.2	0.3	**
10km avg speed (km h-1)	12.2 ± 2.0	12.5 ± 2.0	0.3	-0.6	-0.0	0.2	*

Value are mean ± SD. RE@75 measured on treadmill at 75% of vVT1 with 1% inclination.

* P value < 0.05 significantly different from preintervention value.

** P value < 0.01 significantly different from preintervention value.

Table 2. Physiological results in Low Intensity Training (LIT) group (n = 11)

	Pre Training			**Post Training**			**Difference**	**Lower bound**	**Upper bound**	**Effect Size (d)**	
Weight (kg)	70.9	±	11.8	69.7	±	11.5	1.2	0.4	2.0	-0.1	*
Fat mass (%)	19.3%	±	2.5%	18.5%	±	2.6%	0.8%	-0.1%	1.6%	-0.1	
V'O$_{2max}$ (ml min)	3484	±	739	3558	±	744	74.1	-217	69	0.1	
vV'O$_{2max}$ (km h-1)	13.1	±	1.3	13.7	±	1.3	0.6	-0.8	-0.4	0.4	**
VT1 (km h^{-1})	11.1	±	0.9	11.7	±	1.1	0.6	-0.9	-0.3	0.5	**
VT2 (km h^{-1})	12.4	±	1.1	13.1	±	1.0	0.7	-1.0	-0.4	0.5	**
RE@75 (ml m^{-1} kg^{-1})	222.8	±	19.6	215.8	±	19.8	6.9	-4.5	18.3	-0.3	
Strength											
1RM leg press (kg)	130.0	±	19.9	128.9	±	25.9	1.1	-5.2	7.3	0.0	
2km avg speed (km h-1)	14.0	±	1.1	14.5	±	1.1	0.5	-0.7	-0.4	0.4	**
10km avg speed (km h-1)	12.0	±	1.6	12.7	±	1.4	0.8	-1.0	-0.6	0.5	**

Value are mean ± SD. RE@75 measured on treadmill at 75% of vVT1 with 1% inclination.

* P value < 0.05 significantly different from preintervention value.

** P value < 0.01 significantly different from preintervention value.

Table 3. Physiological results in Flywheel Strength Training (FST) group (n = 9)

	Pre Training			**Post Training**			**Difference**	**Lower bound**	**Upper bound**	**Effect Size (d)**	
Weight (kg)	71.3	±	9.4	70.2	±	8.9	1.0	0.0	2.0	-0.1	
Fat mass (%)	23.9%	±	5.7%	22.8%	±	6.3%	1.1%	0.2%	2.0%	-0.2	
V'O$_{2max}$ (ml min)	3502	±	768	3475	±	699	27.0	-53	107	0.0	
vV'O$_{2max}$ (km h-1)	12.8	±	0.9	13.6	±	1.2	0.8	-1.0	-0.5	0.5	**
VT1 (km h^{-1})	10.7	±	0.8	11.5	±	1.0	0.7	-1.0	-0.5	0.6	**
VT2 (km h^{-1})	12.0	±	1.1	12.6	±	1.2	0.6	-0.9	-0.4	0.4	**
RE@75 (ml m^{-1} kg^{-1})	220.1	±	12.5	206.2	±	21.0	13.9	3.6	24.3	-0.6	*
Strength											
1RM leg press (kg)	130.7	±	28.3	135.9	±	28.9	5.2	-7.9	-2.5	0.2	**
2km avg speed (km h-1)	13.4	±	1.0	14.0	±	1.4	0.6	-0.8	-0.3	0.4	**
10km avg speed (km h-1)	11.5	±	1.0	12.2	±	0.9	0.7	-0.9	-0.4	0.5	**

Value are mean ± SD. RE@75 measured on treadmill at 75% of vVT1 with 1% inclination.

* P value < 0.05 significantly different from preintervention value.

** P value < 0.01 significantly different from preintervention value.

Table 4. Physiological results in Flywheel Strength Training (FST) group

DISCUSSION

The results of this study indicate that recreational runners may obtain improvements in RE and neuromuscular adaptation by using the flywheel strength training.

In our study, flywheel strength training was performed concurrently with a low intensity endurance training program over 8-weeks (FST), and then compared with two different equivalent endurance training programs based on high and low intensity exercises, respectively. The significant 12.9% increases in maximal dynamic strength (1RM) in the FST group is lower than that found in previous studies (L. Paavolainen, Häkkinen, et al., 1999; Piacentini et al., 2013b); but in our study it was obtained with smaller intervention. The usefulness of increasing the maximal muscle force in a runner is a debated topic in the scientific literature. Several authors have obtained it with strength exercises in addition to endurance training, others through the use of specific plyometric exercises with a strong component of eccentric muscle strength (Alkahtani, 2017; Fornasiero et al., 2017; Jhonston, R.E., T.J. Quinn, R. Kertzer, 1997; Mikkola et al., 2007; Philo U. Saunders, Richard D. Telford, David B. Pyne, Esa M. Peltola, Ross B. Cunningham, 2006; Sedano et al., 2013; Støren, Helgerud, Støa, & Hoff, 2008). Also, in our data, the maximal dynamic force (1RM) increased in FST, contrary to the other two groups (HIT and LIT). This result could be justified by the plasticity of muscle fibers in accordance with the results obtained by Piacentini (Piacentini et al., 2013b). However, regarding anthropometric measurements, we did not measure changes in free fat mass in the lower limbs. This means that the gains in terms of strength of the FST group are not due to a structural change, but mainly to neural adaptations such as increased activation, a more efficient recruitment, motor unit synchronization and excitability of the motor neurons or decreased At-Golgi tendon organ inhibition (Häkkinen et al., 2003), in agreement with the results obtained by Taipale et al. (Taipale et al., 2010) using plyometric training. In other words, flywheel training increases the capacity to store and reuse elastic muscle energy and this seems to have a protective effect against muscle damage due to the intense activity of races. Consequently, there is a 6.3% decrease in RE in FST, confirming the strong relationship between muscle force and RE (10,19,20). This has never been demonstrated before and confirms our initial hypothesis that one session a week of four sets of seven repetitions at maximum velocity on the Flywheel Leg Press (Yo-Yo Technology AB, Stockholm, Sweden) could significantly improve RE in recreational runners.

Both FST and HIT groups showed a significant increase in velocity related to $V'O_{2max}$ of 6.0% and 4.7%, respectively. None of the three experimental groups showed a significant increase in $V'O_{2max}$ values. A significant increase in velocities, correlated with two ventilatory thresholds, was found in all groups. These increases were: 6.8% and 5.3% for the FST group, 5.5% and 5.9% for the HIT group and 6.2% e 5.9% for the LIS group. Millet et al. (Millet et al., 2002) obtained the same results in their study on 14 triathletes. The protocol consisted of a 14-week regimen based on concurrent endurance and strength training programs. The strength training was based on intensities near the maximal and low numbers of repetitions (Millet et al., 2002). Millet's study showed that it is possible to obtain an improvement in the velocity of ventilatory thresholds and $V'O_{2max}$ without improving $V'O_{2max}$ values due to adaptations that occur at the muscle level. This can be partially confirmed by analyzing the different intensities of the three training programs. FST and LIS training programs were based on the intensity of 100% of RV. The average 112% RV intensity is capable of arousing the appearance of $V'O_{2max}$. Intensities used for our study could not improve central physiological adaptations, which are very important for an increase in V’O_{2max}. Although the high intensity intervals were achieved approximately at 130% of RV, the HIT group did not obtain any significant increase in VO_{2max} values due to a reduced duration of the intervals. (V. L. Billat et al., 1999; Midgley, McNaughton, & Wilkinson, 2006).

The participants of our study achieved significant improvements in two track tests consisting of 2000 and 10,000m runs. We can correlate the 10km performance with the velocity at the second ventilatory threshold. Traditionally, amateur athletes running at this intensity achieve the best results at this distance. This is confirmed with the 0.91 correlation between the 10km performance and the value corresponding to the value of the second ventilatory threshold determined by laboratory testing. This interpretation cannot be verified in the 2000m tests. On the contrary, this test should measure results that are easily associable with improvement in VO_{2max}. The significant increase in average velocity during field test on 2000 m did not bring the same increase in VO_{2max} values. By collecting feedback from the athletes at the end of the 2000m run, we found that the trial was hard to manage in terms of intensity, distance and duration. Amateur runners are not used to maximal efforts mainly because they tend to run races of 10km or more and therefore never run at the intensity close to their maximal. Furthermore, this type of sport often makes runners fear that they won’t be able to finish the race. This fear could prevent athletes from achieving their possible maximum performance.

The results connected to endurance performance demonstrate that FST and HIT groups have similar improvements although the subjects of FST group improved their RE. The 2k and 10 k performance are mainly connected to the V02max and the running velocity connected to the anaerobic threshold, while RE alters the performance lasting more than 1h.

CONCLUSION

The results of this study indicate in recreational runners a specific sensitivity to including muscle strength components in training as in HIT and in particular in FST. Flywheel strength training allows to improve functional abilities as RE and 1RM. This is attributable to a development in muscle strength, in particular due to the eccentric component. It is to be regarded as one of the determining factors of RE in endurance performance. The benefits in RE obtained by FST are, as known, proportional to effort duration and as found no different to HIT for 2Km, slightly better in 10km and probably much better for long distance runs.

Eight weeks of once-a-week training was an effective stimulus to induce adaptations and therefore it should be taken into consideration in the training programs of amateur athletes.

PRACTICAL APPLICATION

The results of this study shown the exercises with eccentric (or combined) components as compatible with training programs in recreational runners. They have been shown to improve running economy and strength that can enhance performance. Therefore, strength-enhancing exercises with eccentric and concentric components should be considered by athletic trainers for training programs of recreational runner.

Chapter 8

Study Two

Effects of a Focused Training Model on Recreational Runners

Introduction

To maximize endurance performance, coaches and scientists can manipulate the characteristics of training - intensity, duration and frequency of training session - during the entire training process. There is general agreement on the physiological factors that limit performance (C Capelli et al., 1998; Edward F Coyle, 2007; Pietro Enrico di Prampero, 2003); however, there is still no agreement on how a daily training program must be organized to improve physiological factors and performance.

Training intensity distribution (TID) in endurance training programs is determined by the percentage of time spent exercising at low (zone 1, typically identified below the lactate threshold (LT), or ventilatory threshold (VT); moderate (zone 2, typically located between LT and maximal lactate steady state (MLSS) or respiratory-compensation threshold (RCT); and high (zone 3, typically above MLSS or RCT) intensities (Faude, Kindermann, & Meyer, 2009; K. S. Seiler & Kjerland, 2006). Endurance athletes and coaches frequently adopt two different exercise TID models (K. S. Seiler & Kjerland, 2006). First, a polarized endurance training model (PET) that consists of a high percentage of exercise time at low exercise intensity (75-80%) with little time at moderate intensity (5-10%) and the remainder spent at high intensity (15-20%). In contrast, the second model involves threshold training distribution (THR), in which the time distribution is 45% at low, 35% at moderate and 20% at high intensity. Several studies have reported the TID of well trained and highly trained endurance athletes in different disciplines (Esteve-Lanao, Foster, Seiler, & Lucia, 2007; Plews & Laursen, 2017; K. S. Seiler & Kjerland, 2006), and there is substantial evidence that PET may optimize adaptation to exercise while providing an acceptable level of training stress. Several studies have investigated the relationship between adaptations and intensity of training and they affirm that LT is positively affected when a high proportion of training is done at low intensity (Esteve-Lanao et al., 2007; Esteve-Lanao, San Juan, Earnest, Foster, & Lucia, 2005;

Ingham, Stephen A. Carter, Helen Whyte, Gregory P. Doust, 2008). These authors suggest that the proportion of time in zone 1 is a key aspect that drives endurance adaptations and performance outcomes. However, several other studies observed improvements in a 40km time trial when high intensity training (zone 3) is added to the schedule of well-trained cyclists (Lindsay et al., 1996; Westgarth-Taylor et al., 1997; Weston et al., 1997). Moreover, in a case study on an international 1500m runner, the choice to move through a more polarized training model showed that maximal oxygen consumption (V'O2max), running economy (RE) and running performance all improved. As Seiler stated, regarding highly trained athletes training 10 to 25h/week, polarized intensity distribution may allow maximal adaptive signaling while minimizing autonomic and hormonal stress responses and reducing the risk of overtraining (S. Seiler, Haugen, & Kuffel, 2007).

Concerning recreational athletes, it is still unknown which intensity distribution is optimal and whether the intensity distribution is or is not critical. These athletes train 3-5h/week and the density of stimuli allows them to train above LT for a longer time compared with elite athletes because overtraining is not likely when training is much less frequent. In their study, Munoz et. al (Muñoz et al., 2014) found that the polarized training model had a better impact on 10km performance in recreational runners compared with the threshold training model after 10 weeks of practice (-3.5% for THR and -5% for POL), but they concluded that there was not enough evidence in their overall findings to support one approach over the other.

In an attempt to present evidence in favor of the correct approach, the goal of the present study was to compare the effects of a POL training model on condition and performance with those of a focused (FET) training model on changes in limiting factors.

Methods

Experimental approach to the problem

A two-group pretest-posttest design was used. We studied the effects of different training programs on performance in 2km runs and through an analysis of the changes in the values of limiting factors measured during a test in the laboratory before and after the training session. The main difference between the training models was the time spent in zone 2. One group of athletes performed a relatively higher percentage of their total training volume in zone 1, below their VT. The second group spent 50% of their total training volume in zone 2, between VT and RCT, while training less in zones 1 and 3. To compare training types, the total training load (intensity X volume) was balanced using a modified version of the training-impulse approach (TRIMP) (Foster et al., 2001).

Subjects

Forty-three recreational runners were recruited to participate in this study. All of them had been training consistently for over 4 years and their mean training volume before the study was 3.2±0.5h a week. The University Ethics Committee approved the protocol (Prot. N. 165038, 28 June 2016) and all participants gave their written consent before taking part.

The recruited runners were randomly assigned to 2 different training groups (each n = 19) (see Table 1) for an 8-week period. Dropout rate for the focalized endurance training group (FET) was 21% (two subjects were excluded from the analysis due to training program adherence <96%; two abandoned the experiment for personal reasons). Dropout rate for the polarized endurance training group (PET) was 5% (one subject abandoned the study for personal reasons). The groups' characteristics are shown in Table 1. The groups were similar in age, body mass, height, and V'O2max (See Table 1).

Variables	Polarized Endurance Training (PET)	Focused Endurance Training (FET)
N. (m / f)	15/4	16/3
Age (yr)	43.2±8.4	39.4±8.5
Weight (kg)	72.0±7.7	70.9±10.1
Height (cm)	175.2±5.9	172.5±4.3
$V'O_{2max}$ (ml min^{-1} kg^{-1})	52.9±8.1	53.4±8.3

Table 1 - Physical characteristics of runners included in the study. Data are presented as mean ± standard deviation

Training and periodization

The training programs were designed to achieve a similar score for both total TRIMP accumulated over 8 weeks (2492 ± 72 TRIMPs) and mean TRIMP accumulated each week (311 ± 9). We prescribed the training in terms of time goals rather than distance to track the relative time in each zone for each athlete and to control the training load. The PET program was designed to achieve a total percentage distribution in zones 1, 2 and 3, corresponding to 77/3/20 based on HR, respectively. The FET plan had a percentage distribution of 40/50/10 in zones 1, 2 and 3, respectively.

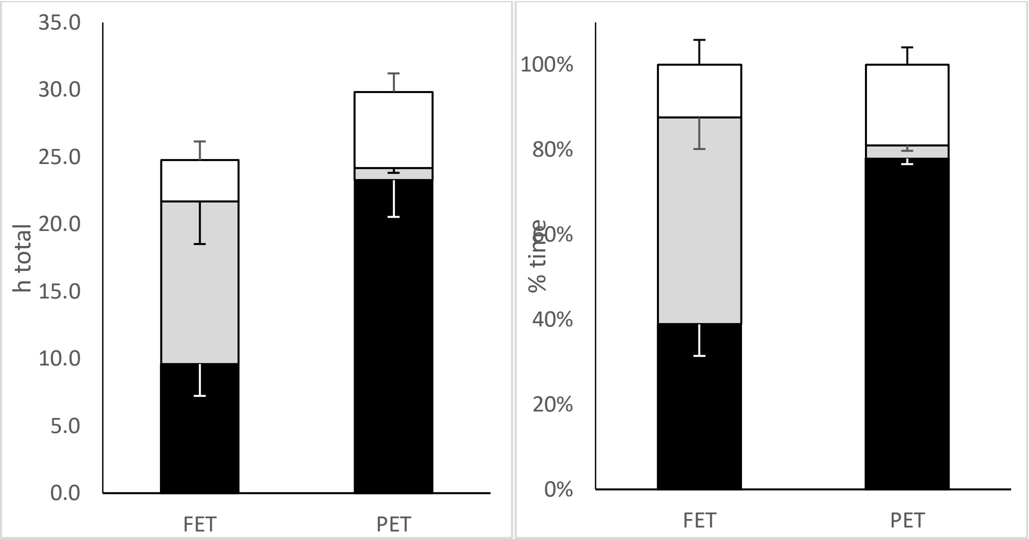

Fig. 1: Real cumulative training time: black for zone1; grey for zone 2; white for zone 3. On left expressed in hours (A); on right on percentage of total time (B)

The program was divided into two weeks comprised of an introductory period identical for all subjects and two 3-week micro-cyles following a 2:1 load structure. The relative intensity distribution of the groups was maintained during both the loaded and unloaded weeks. The weekly schedule for the PET group included four sessions, two of which were hard with intervening or repeated workout sessions at high intensities, one at a moderate, average intensity and one easy run. The FET group's training included three sessions, all of which had medium and long repetitions at moderate intensity. Moderate and high intensities are essential in a training program since they involve large muscle mass and could lead to better resistance to fatigue during distance running (Boccia et al., 2017).

Laboratory testing

Laboratory and field running tests and muscle function tests were done during week 0 and week 9. The tests were separated by a 24-hour resting period. All the tests were performed at the same time of day ± 2 hours in a climate-controlled laboratory (20-22° C, 55% humidity). The participants did not do any physical activity during the 24-hour resting periods and were requested not to consume food or beverages containing caffeine. All the subjects performed familiarization trials. All tests were randomized; however, the same order for everyone was followed in the pretests and posttests.

Incremental test to exhaustion

The three intensity zones were established based on the results of treadmill testing performed in the laboratory at week 0. Maximal oxygen uptake ($V'O_{2max}$) and heart rate (HR) were measured and recorded during a treadmill incremental stress test by breath-by-breath analysis of oxygen consumption and carbon dioxide production (Quark PFT; Cosmed, Rome, Italy). Before each test, the flow meter was calibrated with a 3-L syringe, and the analyser was calibrated with known gas mixtures (16% O_2 - 5% CO_2) and environmental air (20.9% O_2 - 0.03% CO_2).

The protocol test was individualized for each subject to control the duration of each test. Therefore, initial speed was determined by the subject's capacity, and it was increased by 0.5 km h-1 every minute until exhaustion. The duration of the test was expected to be between 10 and 15 min. The treadmill (Run Race 800; Technogym, Gambettola, Italy) was maintained at 1% grade throughout the test, a standard method to simulate level running on a treadmill. All subjects were familiarized with running on a treadmill.

V'O2max was defined as the highest 30s average achieved during the test. The first ventilatory threshold (VT) was defined as an increase in $VE \cdot V'O_2^{-1}$, corresponding to a break in linearity of VE, but without an increase in $VE \cdot V'CO_2^{-1}$. The respiratory-compensation threshold (RCT) was defined as the intensity where $VE \cdot V'CO_2^{-1}$ also began to rise. Two independent evaluators made the threshold determinations. If there was discordance between the 2 observers, a third was brought in (Beaver, Wasserman, & Whipp, 1986).

Running economy

Running economy (RE) was determined by measuring submaximal V'O2 while the subject ran on a treadmill (Kyle R Barnes & Kilding, 2015): 4 minutes at 1 km h-1 slower than the last individual marathon pace (8.9 ± 0.2 km h-1) after a standardized warm up (4’ at 90% of marathon pace). Before each test, the flow meter was calibrated with a 3-L syringe and the analyser was calibrated with known gas mixtures (16% O2 and 5% CO2) and environmental air (20.9% O2 and 0.03% CO2). During each test heart rate was monitored and recorded using a Cosmed flow meter (Quark PFT, Cosmed, Rome, Italy). RE was defined as the mean V’O_2 collected at the final 1 minute. RE was measured at week 0 and after completing the training program at week 9. All tests were performed at the same time of day for everyone.

2km performance

Before and after training, following a standardized warm-up session, the subjects participated in a 2 km simulated race on a 400m running track. Performance time was the mean value between the times recorded by two people manually. The race-test was done on the same weekday and at the same hour of day.

One-repetition maximum

Maximal strength was estimated with a 6RM test on a leg press machine. All subjects were positioned on a horizontal leg press (Technogym, Gambettola, Italy) and the knee angle (90°) was fixed to maintain the same position in all test occasions. After a 5-minute warm-up and an appropriate rest period, the subject performed the first session with a preliminary load of 15 repetitions. Thereafter, the load was increased every step by 30% until the athlete could not successively complete a 6RM repetition (ACSM’s Guidlines for Exercise Testing and Presctription (8th ed.). Baltimore, 2010). 1RM was estimated through a conversion table, and 1RM was measured for all subjects after proper familiarization.

Jumping performance

All subjects performed a squat jump (SJ) and counter movement jump (CMJ) test. Vertical jump ability was assessed using the SJ and the CMJ tests according to the procedures suggested by Bosco et al. (Bosco, Luhtanen, & Komi, 1983). Jumping height was calculated from flight time using a kinematics equation (Lehance, Croisier, & Bury, 2005). Flight time was recorded using an infrared photocell connected to a digital computer (Optojump System, Microgate SARL, Bolzano, Italy). All tests were performed in a randomized order; however, the same order was followed during tests at the end of a training period.

Exercise training load

HR was recorded continuously for all subjects during each training session over the training period. To get comparable results, the different training models were chosen to determine the total exercise load (intensity X training volume) using the method suggested by Foster et al for calculating TRIMP (Foster et al., 2001). This method was also used by Munoz et al to estimate the exercise load of 10 weeks of training in recreational runners (Muñoz et al., 2014) as well as to monitor the exercise load of 3 weeks of a professional cycling race (Santalla, Earnest, Marroyo, & Lucia, 2012). This method integrates heart rate data with volume and relative intensity in the three zones detected by heart rate at VT and RCT. Heart rate values for VT and RCT were determined from the incremental test results and then the time spent in each intensity zone was quantified: zone 1, HR below the VT; zone 2, HR between VT and RCT; and zone 3, HR above RCT. TRIMP was computed by multiplying the accumulated time in each zone by an intensity weighted coefficient (1 for zone 1, 2 for zone 2 and 3 for zone 3) to obtain a score. The total TRIMP load was then obtained by summing the 3 zone scores.

Training monitoring

During the training period, each session was recorded and uploaded on a network platform that allowed the recording of the time spent in each intensity zone during each session. A 100 point rating perceived exertion (RPE) (Borg & Kaijser, 2006) was obtained at the end of each session.

Statistical analyses

Independent t-tests were used to determine the significance of differences in the measured variables indicative of fitness levels before training between groups. To ensure that total training load and distribution in intensity zones were different, total TRIMP and total time spent in zones 1, 2 and 3 were also compared. A 2x2 repeated ANOVA measure was done after training for all variables using Bonferroni's correction method. Differences between PRE vs. POST were reported in absolute values, the precision of estimates for absolute values was indicated with 95% confidence limits (CL), effect size (d) and benchmark for significance was set at $p \leq 0.05$.

Results

Total training time over 8 weeks was significantly different and was 29.8 ± 3.07 hours and 24.8 ± 1.96 for the PET and FET groups, respectively. Weekly 308.0 ± 1.4 and 307.2 ± 1.0 and total 2464 ± 12.4 and 2455.9 ± 15.9 TRIMP scores (PET and FET, respectively) were not different between the two groups ($P > 0.05$). Total training times spent were: in zone 1 (PET = 23.3 ± 2.7h vs FET = 9.1 ± 2.4h, $P < 0.0001$), in zone 2 (PET = 0.9 ± 0.4h vs FET = 11.5 ± 3.2h, $P < 0.0001$) and in zone 3 (PET = 5.7 ± 1.4h vs FET = 3.1 ± 1.4h, $P = 0.0001$).

	Group	
	PET (n = 19)	FET (n = 19)
Total running time	29.8±3.1	24.8±2.0
TTT in Zone 1 (h)	23.3±2.7	9.1±2.4
TTT in Zone 2 (h)	0.9 ± 0.4	11.5±3.2
TTT in Zone 3 (h)	5.7±1.4	3.1±1.4
TTT % in Zone 1 (%)	78±9.2	36.7±9.6
TTT % in Zone 2 (%)	3.1±1.3	46.4±12.8
TTT % in Zone 3 (%)	18.9±4.6	12.4±5.7
mean RPE session	60.9±15.5	65.4±14.6
Total TRIMPs (au)	2464±124	2558.2±10.94
mean TRIMPs/wk (au)	308.0±47.46	319.8±28.1

Table 2. Results of the training load over the 8-week total training time (TTT). Mean ± SD

No significant differences were found in the comparison between the groups in any investigated variable before and after training. However, significant improvements from pre-training to post-training were observed in both PET’s and FEC’s physiological parameters. In the PET group there were significant improvements in speed at $V'O_{2max}$ ($vV'O_{2max}$) of 3.2% (12.9 km h^{-1} ± 1.7 km h^{-1} vs 14.3 km h^{-1} ± 1.5 km h^{-1}, $P < 0.001$), speed at VT of 4.0% (10.5 km h^{-1} ± 1.2 km h^{-1} vs 10.9 km h^{-1} ± 1.2 km h^{-1}, $P < 0.001$), speed at RCT of 5.7% (12.1 km h^{-1} ± 1.5 km h^{-1} vs 12.8 km h^{-1} ± 1.4 km h^{-1}, $P < 0.001$), RE of 5.3% (226.3 ± 35.2 vs 214.3 ± 33.0 ml min^{-1} km^{-1}, $P = 0.03$), and average velocity in a 2km run of 3.5% (13.8 ± 2.0 vs 14.3 ± 1.7 km h^{-1}). Also for the FET group we recorded significant improvements in the same variables for speed at $vV'O_{2max}$ of 4.0% (13.8 km h^{-1} ± 1.9 km h^{-1} vs 14.3 km h^{-1} ± 1.8 km h^{-1}, $P = 0.01$), speed at VT of 3.2% (10.8 km h^{-1} ± 1.4 km h^{-1} vs 11.1 km h^{-1} ± 1.5 km h^{-1}, $P = 0.03$), speed at RCT of 3.4% (12.4 km h^{-1} ± 1.7 km h^{-1} vs 12.8 km h^{-1} ± 1.7), and average velocity on a 2km run of 3.0% (13.9 ± 1.9 vs 14.3±1.9 km h^{-1}).

	Pretraining	Posttraining	Difference	Lower Bound	Upper Bound	Effect Size (d)	
STRUCTURAL							
Weight (kg)	72.0 ± 7.7	71.8 ± 7.3	-0.22	-0.56	1.00	0.0	
Fat mass (%)	19.9 ± 5.9	17.4 ± 4.9	-2.52	0.69	4.34	0.4	*
FUNCTIONAL							
$V'O2_{max}$ (ml min^{-1} kg^{-1})	53.0 ± 5.9	53.6 ± 4.8	0.63	-2.01	0.75	0.1	
$vV'O2_{max}$ (km h^{-1})	13.9 ± 1.7	14.3 ± 1.5	0.45	-0.67	-0.22	0.3	*
vVT (km h^{-1})	10.5 ± 1.2	10.9 ± 1.2	0.42	-0.62	-0.22	0.3	*
vRCT (km h^{-1})	12.1 ± 1.5	12.8 ± 1.4	0.68	-0.94	-0.43	0.4	*
RE (ml kg^{-1} km^{-1})	226.3 ± 35.2	214.3 ± 33.0	-12.02	1.39	22.64	0.4	*
1RM leg press (kg)	223.7 ± 64.6	223.9 ± 61.1	0.23	-31.39	30.92	0.0	
SJ (cm)	22.7 ± 4.6	23.3 ± 4.4	0.64	-2.03	0.75	0.1	
CMJ (cm)	24.9 ± 5.3	24.9 ± 4.9	0.07	-1.41	1.26	0.0	
PERFORMANCE							
avg velocity 2 Km (km h^{-1})	13.8 ± 2.0	14.3 ± 1.7	0.48	-0.86	-0.11	0.1	*

Table 3. Structural, functional and performance results in the PET groups. Results are presented as mean ± SD. * p value PRE vs POST <0.05.

	Pretraining	Posttraining	Difference	Lower Bound	Upper Bound	Effect Size (d)	
STRUCTURAL							
Weight (kg)	70.9 ± 2.5	69.9 ± 2.5	-1.0	0.08	1.87	0.1	
Fat mass (%)	18.5 ± 1.8	16.9 ± 1.7	-1.6	-0.15	3.41	0.3	*
FUNCTIONAL							
$V'O_{2max}$ (ml min^{-1} kg^{-1})	53.7 ± 1.9	53.2 ± 1.9	-0.5	-1.00	2.00	0.1	
$vV'O_{2max}$ (km h^{-1})	13.8 ± 0.5	14.3 ± 0.4	0.5	-0.85	-0.15	0.3	*
vVT (km h^{-1})	10.8 ± 0.3	11.1 ± 0.4	0.3	-0.65	-0.04	0.3	*
vRCT (km h^{-1})	12.4 ± 0.4	12.8 ± 0.4	0.4	-0.67	-0.14	0.3	*
RE (ml kg^{-1} km^{-1})	231.8 ± 9.1	211.6 ± 6.3	-20.2	8.88	31.54	0.6	*
1RM leg press (kg)	210.5 ± 18.8	193.8 ± 15.5	-16.8	-11.92	45.47	0.3	
SJ (cm)	24.1 ± 1.7	25.3 ± 1.7	1.2	-3.02	0.62	0.2	
CMJ (cm)	27.1 ± 1.9	27.1 ± 2.0	0.1	-1.49	1.35	0.0	
PERFORMANCE							
avg velocity 2 Km (km h^{-1})	13.9 ± 0.5	14.3 ± 0.5	0.4	-0.62	-0.18	0.1	*

Table 4. Structural, functional and performance results in the PET groups. Results are presented as mean ± SD. * p value PRE vs POST <0.05.

Discussion

The main purpose of our study was to evaluate the effects of different intensity distributions in laboratory tests and field performance. Both groups, polarized and focused (intensity distribution 77/3/20 and 40/50/10, respectively) showed significant improvement in velocity at $V'O_{2max}$, VT, RCT, running economy and in performance in a 2km run, without any variations in the values of $V'O_{2max}$. There were no significant differences between groups that could support one approach over another regarding recreational athletes. In their study on recreational runners, Seiler et al. found improvements in 10K run performance between pre- and post-training, but no differences between groups that followed their training programs diligently with emphasis on a polarized intensity distribution and threshold emphasis distribution.

The changes recorded in our study are in agreement with the results reported in several training studies that used different training modalities for 8 weeks for recreational runners. In a recent study by Pugliese et al (Pugliese et al., 2018), there was an improvement in speed at $V'O_{2max}$ of about +6% and speed at VT of about +5% with no increment in $V'O_{2max}$; whereas improvement in a 5K run performance was about 3%. Similar results were observed also in master runners following concurrent strength and endurance training (Piacentini et al., 2013a). Also, changes recorded for RE were aligned with changes reported in other studies (Piacentini et al., 2013a; Spurrs et al., 2003).

To date, these are the only studies that have analyzed the effects of different intensity distributions on recreational runners. A study by Neal et al. (Neal et al., 2013) observed superior performance effects of polarized training in a group of cyclists with a better fitness level than in our current study runners. Their study was well controlled and the differences between the groups were emphasized because they eliminated all training above the RCT (zone 3) in their threshold group.

While there is strong agreement that the polarized training model is widely used among elite coaches and athletes, and several studies have shown that it allows them to achieve greater improvements in performance, no evidence has yet emerged among the compared models concerning recreational athletes.

The polarized distribution is necessary for athletes who perform a large volume of training to prevent overtraining or a steady state of performance. Moreover, by accumulating less effort, the quality of high-intensity sessions is better and this could lead to greater improvement compared to threshold or focused models (Muñoz et al., 2014). The average volume for recreational runners is 3 to 5 hours a week, and the probability of overtraining is very low; they seem to show that they have good tolerance to accumulating time at such intensity.

Practical application

The limited amount of training hours spent by recreational athletes is determined primarily by their availability of time to train. The focused model seems to better meet the needs of recreational athletes to maximize improvement from training.

Conclusions

The focused endurance training model seems to better meet the needs of recreational athletes and to achieve an improvement in performance similar to polarized endurance training by saving about 17% of time in 8 weeks.

Chapter 9
Discussion

The purpose of this thesis was to identify training strategies that can improve running performance in long distance in recreational athletes. The first thing we want to emphasize is that the model of the "recreational runner" is capable of satisfying the needs of this kind of research. Recreational runners showed an interest in changing their training routines, even if that meant sacrificing some of their time in order to improve their performance. In addition, the data collected was of good quality and consistent when compared with the results of high-level athletes. It is worth remembering that elite athletes have training schedules that are not compatible, or compatible with a complex scientific approach, with training protocols that this type of research requires and that cannot be applied without affecting their performance.

The decision to concentrate the study on RE and the distribution of training intensity originated from the need to answer questions regarding strategies to improve performance in recreational runners that previously had no answers, but which are fundamental for elite athletes.

As shown in the results of study 1, and as reported abundantly in the literature regarding elite athletes, strength training is essential to improving performance even for endurance sports such as running, cycling, cross country skiing, and the triathlon. The benefits of strength training translate into an improvement in RE even among amateur athletes.

The Yo-Yo Leg Press, a machine that uses the isoinertial system, allows to emphasize the eccentric component (such as plyometric training) during the execution of exercises without overloading the muscle-tendon structures and thereby avoiding possible injuries, an aspect that should not be underestimated where amateur athletes are concerned. The other aspect that should not be underestimated is the duration of this kind of training, based on about 20-25 minutes including the warm-up, which means that the time dedicated to the running itself does not need to be reduced, and in this case it is based on about 3-4.5h a week.

Improvements in the value of RE and performance obtained in this study are similar to those obtained with strategies of strength training among both elite and amateur athletes .

In the second study, focus was on investigating possible differences in improvement between two modes of intensity distribution. The aim, besides verifying the effects of the polarized distribution model on a group of amateur athletes, was also to propose an alternative training program that would achieve the same improvements, but which would be able to reduce the time dedicated to training. The results of the study are not able to conclude if one of the two models is better to achieve greater improvement. In fact, no differences were found between the polarized method (intensity distribution 77-3-20% respectively in Z 1,2,3 of the total training time) and the focused method (40-50-10%, respectively), between the physiological parameters obtained in the laboratory and those recorded during field performance. The only important difference was that the improvements in the focused training group were achieved with 15% of time saved compared with the polarized group, without encountering any injuries or other problems.

The RE has shown to be sensitive to the training volume at high intensity. In subjects exclusively trained at aerobic or poorly anaerobic intensity, indeed, the RE did not improve. Differently, it has significantly improved in massively-trained groups at medium or high intensity. This implies the need to insert the high intensity exercises into the training plans with meaningful volumes. This is not always possible, due to time constraints and the low tolerability of these regimes in recreational runners. However, the RE was sensitive to improvement even to specific activities with massively eccentric work, although of very short duration. It results therefore, after opportune familiarization a valid alternative in recreational runners that, have no possibility to invest too much time in the training at medium and/or high intensity.

It may be important to work on techniques that integrate a strength workout with a careful intensity distribution training. It is necessary to lengthen training periods in order to investigate whether any improvement takes place only in the first weeks or if such changes occur constantly.

Alongside its scientific contribution, this work provides practical evidence and ideas applicable and useful to coaches and amateur athletes in order to achieve the best possible performance even with this kind of athlete.

Chapter 10

Conclusion

The scientific literature related to running training presents studies regarding all aspects that determine performance. Most of the studies refer to elite athletes and only recently the interest shifted to amateur athletes because they represent the largest number of participants and therefore also arouse great interest for companies producing apparel, shoes and technological tools.

Given the traumatic nature of the race on joints and muscle-tendinous apparatus, training strategies used for elite athletes and amateurs must take count of individual's technical skills and ability to sustain certain training loads due to intensity, the nature of the training stimulus and the progressive increase of these loads. This will subsequently lead to a greater ability to support these stressful stimuli.

Recently, strength training has received great attention in endurance sports because it allows the improvement of energy cost as shown in studies realized with cyclists, cross-country skiers, swimmers and runners, and because of its essential role in preventing injuries. Another important tool for injury prevention is the management of the training load. To do this, we tried to identify patterns of intensity distribution able to enhance improvements without causing injuries, trying to optimize the time / benefit ratio for amateur athletes who have little time to train.

During these years I also realized that the research can be used by few people and that it would be better to promote the dissemination of the results obtained in a way that everyone can understand them. In this way, the research would become more important than practice and experience, as for now these three make a mixture where solely research adopts the objective way of explanation of the adaptation phenomena that training induces.

This reflection fits into a context already taken in consideration in the past, leaving an important legacy on the purpose of the research to those who are approaching this path.

“Sin dagli albori del mondo sportivo moderno il desiderio e la necessità costanti dei tecnici, degli allenatori, dei medici e degli atleti delle diverse discipline sportive sono stati quelli di studiare ed ottimizzare il gesto tecnico e l’eventuale attrezzo da *gara, rendere oggettive le esperienze maturate sul campo e analizzare gli avversari più forti.”*

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