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TRACK COACH

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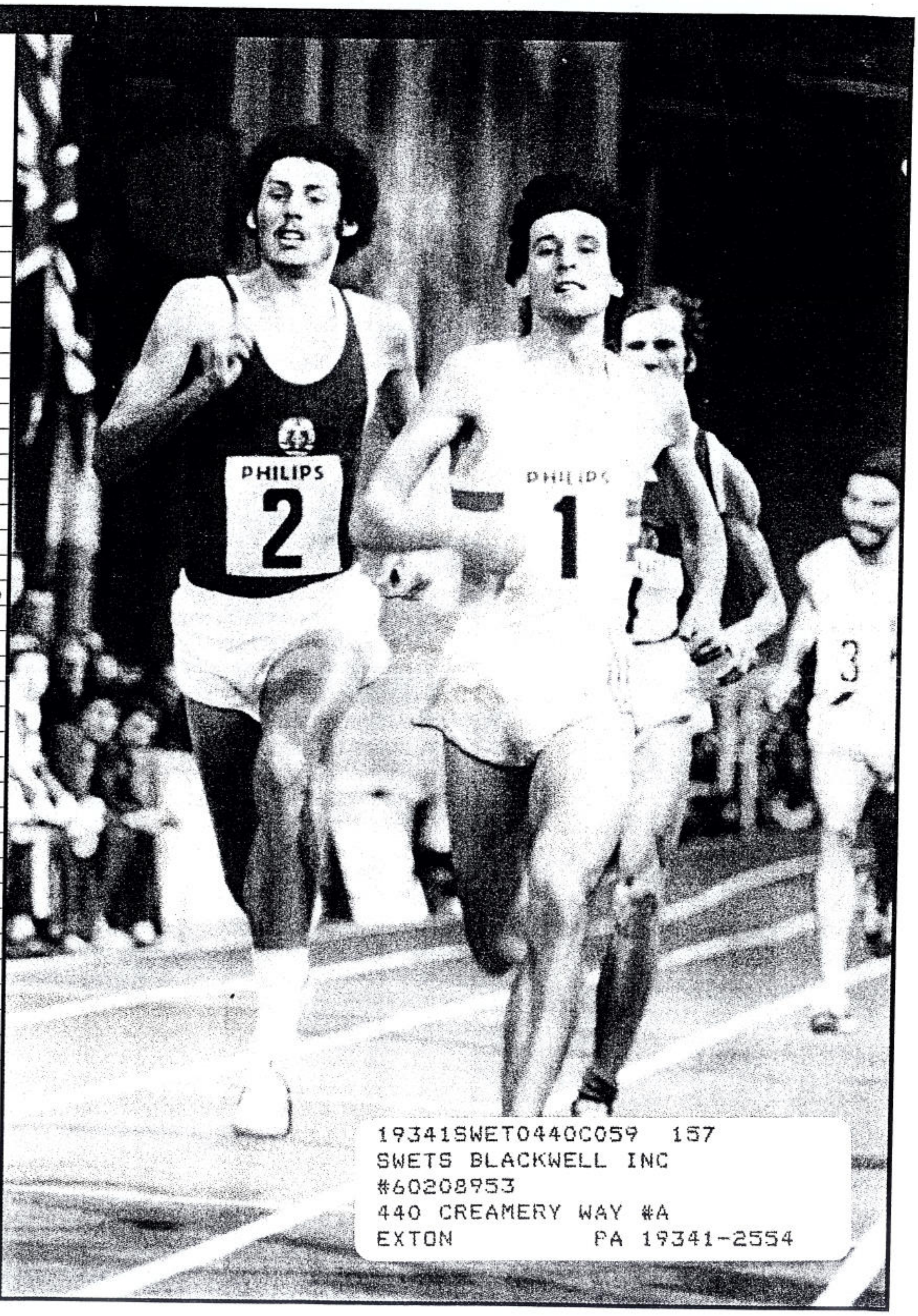
CONTENTS

Fall
2001

157



Middle Distance Athlete Development

The following text discusses some of the factors that can play an important role in the development of talented junior middle distance runners, recognizing that the development of every athlete is unique and that there is no perfect training system. The article is based on an extract from the author's Level III qualifications dissertation under the Australian Track and Field Coaches Association's National Coaching Scheme.

Reprinted from Modern Athlete and Coach, *Volume 38, No. 2, April, 2000*

INTRODUCTION

The coach is mindful of the fact that the athlete, because of his background, may be more underdeveloped in one area than another. Still, a trademark of a talented young middle distance runner is his ability to complete training tasks at a range of durations and intensities and, of course, to perform at least quite well at distances ranging from 200m to 3000m.

Obviously the coach's role is to develop this talent. To do this he makes use of science, the training of champions and intuition guided by a detailed record of training.

Science alone would be inadequate because a "jump" would be required to its application. For example, an exercise physiologist may find it difficult to comprehend why a particular athlete performed at a level far superior to what testing and his training suggests he is capable of.

Simply mimicking the training of a champion would be dangerous because it ignores the individual nature of each athlete.

Intuition alone is also likely to be extremely misguided.

PHYSIOLOGY

A middle distance athlete is required to develop aerobic, lactic and phosphagen energy system qualities. The aim is to develop aerobic qualities so that he can run with minimal acidosis at a given submaximal intensity.

He aims to develop lactic anaerobic qualities so that his body is taught to buffer the hydrogen ions that accumulate while working anaerobically and tolerate those that remain.

He develops phosphagen energy system qualities so that he can accelerate well at the start and move at submaximal speed while running quickly to establish position early in the race. Development of this system is also partly responsible for allowing an athlete to accelerate during a race, but this ability is also heavily dependent upon the extent to which the endurance qualities mentioned above are developed.

Many authors have suggested the percentage contribution that these three energy systems make to performance at the different race distances. Examination of some of these figures for the 1500m event emphasizes the difference of opinion. The relative contribution of the phosphate, lactate and aerobic energy systems respectively, are proposed as being 2%/22%/76% (Martin and Coe, 1991, p. 127), 20%/55%/25% (Aust. Track and Field Coaches Association Level I Course Handout, 1991) and 10%/30%/60% (*Better Coaching*, p. 46).

It is usually not made clear whether these results are from research or simply estimates. Since these figures aim to provide guidelines for training program design, the discrepancies appear to be quite alarming.

Should a 1500m runner devote 25% or 76% of training to the devel-

By Philip Moore, Australia

opment of their aerobic energy system?! For that matter, what does it mean to devote 25% of training to aerobic energy system development (for example, 25% of training sessions, or 25% of training time, or 25% of running time)?

It is helpful to realize that those who suggest the aerobic contribution to performance for a given race distance is low are likely to suggest the same thing for a given session relative to the other authors. Importantly, for any race distance, unchanging ratios of work contributed by the various energy systems cannot be honestly stated because they vary depending on the 1. current physiology of an athlete, the 2. training he performs and the way in 3. which he runs the race.

Still, careful consideration must be given to what extent training is geared towards developing a given energy system at a given time. Of course, anaerobic energy system development generally should be emphasized later in each training cycle (generally, approximately 6 or 12 months) and a 1500m runner will accentuate aerobic training more than an 800m runner, while it is appropriate for all middle distance runners to include some alactic anaerobic running throughout the training cycle, emphasizing good technique.

An athlete's stage of overall development should also be taken into account. For example, a 15-year-old with 8 weeks and 3 sessions per week to train for a 800m race may devote some time each week to the development of each energy system. A typical fortnight may be:

Week 1
Tuesday
3 x 1000m (4 min recoveries)
Thursday
10 x 150m
(2 min recoveries) + 25 min run
Sunday
6 x 300m (3 min recoveries)

Week 2
Tuesday
14 x 200m (40 sec recoveries)
Thursday
5 x 80m relaxed
5 x 80m, 2nd half fast
4 x 60m fast + 25 min run, last 10 min fast
Sunday
6 x 300m (3 min recoveries)
4 x 400m (5 min recoveries)

This type of training enables a talented runner to perform well enough to foster his interest in the sport. In contrast, a very talented 19-year-old may be asked to devote approximately 75% of his training for the year to aerobic development so that he is able to absorb larger training loads in the future and achieve the training background required to ultimately reach his potential.

While this approach may be considered "risky," it is possible that in the long term such a strategy would be justified. Importantly, any coach who believes that his current approach needs modification should change any shift in emphasis gradually, choosing the appropriate time of year.

LEARNING FROM CHAMPIONS

It is also possible to glean valuable information by identifying trends in the training programs of champion middle distance runners. The Kenyans are known to establish good training volume from a young age simply by using running as a means of transport and some of their training is well documented in *Train Hard, Win Easy.* It is, however, naive to deny that, for a middle distance runner, being born at altitude is also of great value, especially now that research is revealing altitude training is likely to provide both aerobic and anaerobic benefits.

So, for convenience, consider the training of the outstanding British athletes Ovett, Coe and Cram (all of whom were born near sea level), which is extremely sound. While there are certainly some differences in their training (for example, Coe had lower peak running volumes than the other two but included more weights and circuit training), there are several similarities:

- A gradual buildup of weekly training volume, emphasizing continuous running.
- Some training weeks of significantly more than 100km per week (Coe's peak weeks reportedly being approximately 120km);
- Increased emphasis on faster running at a range of intensities (from faster than 800m race pace to 5000m pace), once volume has been established with sufficient continuous running to maintain aerobic conditioning during this time.
- Reduced training volume just prior to and during the racing period; even most of their continuous runs were completed at a steady pace of approximately 3:20 to 3:30 min/km, and some were run faster than this. This certainly appears to be a key point given that the No. 1 800 and 1500m runners of 1998 (respectively, Kimutai and El Guerrouj) are both known to perform much of their continuous running very quickly indeed. Of course, it is inappropriate for a developing runner to complete all his runs at approximately 3:20 min/ km pace.

Despite several setbacks, training with these qualities enabled Oveft, Coe and Cram to reach the highest level.

DETAILED RECORD OF TRAINING

A well established and long-standing relationship between athlete and coach is of value in many ways. Not least of these is that the coach can develop a thorough understanding of the individual's response to training. A coach who knows in detail what an athlete has done in the past (what worked and what did not), where they are at now and where they want to be with training in the future, is able to orchestrate a smooth transition in training from year to year.

To achieve this, it is essential for the coach to keep a detailed record of the training that the athlete actually completes (training diary). This has several benefits. Simply keeping a record of monthly training programs is not appropriate because, for a variety of reasons, modification to training may be appropriate. Also, daily entries of training completed, combined with feedback from the athlete about how they are feeling (for example, lively, sore, tired, enthusiastic, lethargic, content) allow ongoing modifications to training if adaptations have occurred earlier or later than was expected.


KNUT ED. HOLM

The great British middle distance runners—Steve Ovett, Steve Cram and Sebastian Coe—were all born near sea level. Here, Ovett wins the 1984 Bislett 1500 final in Oslo over José Gonzales (93) and Ray Flynn (90).

Especially during a phase of training when an athlete is training across a large range of running intensities, careful consideration must be given to the sequencing of sessions. Sufficient recovery must be scheduled between difficult sessions without reducing the training load below what is going to permit optimal progress.

Study of the record of past training and understanding of physiological responses permit appropriate sequencing. For example, a 19 to 20-year-old 800m runner four weeks before nationals in a week of training in which there is no race:

Monday: a.m. 20 min run av. 3:40/km; p.m. 6km, 2nd half solid.
Tuesday: a.m. 20 min av. 3:40/km; p.m. speed drills, 20 x 200m (50 sec recs) on grass track.
Wednesday: a.m. rest; p.m. light circuit of drills and exercises + 30 min run av. 3:45/km.
Thursday: a.m. 6km run av. 3:40/km; p.m. speed drills 400m, 2 x 300m, 2 x 200m (recs of 8, 6, 6, 2 min).
Friday: a.m. rest; p.m. rest.
Saturday: a.m. 2 sets of 3, 2 1 min (recs of 3, 2, 3, 3, 2 min) on grass; p.m. 20 min run av. 3:40/km.
Sunday: a.m. 6km run av. 3:40/km; p.m. speed drills, 5 x 80m with 2nd half fast, 10 x 20 sec (1:40 recs) on a hill.

With appropriate use of science, history and intuition, complemented by suitable implementation of training sessions, the coach goes a long way towards giving direction to athlete development.

BIOMECHANICS

The biomechanical development of a talented middle distance runner must also receive careful attention. Of course, there is interaction between this and physiological development. Much of the training aimed at biomechanical modification is able to achieve its desired effect because of physiological adaptations it evokes.

The way in which an athlete runs is largely a talent. However, ongoing reinforcement of appropriate movement patterns with modifications to inappropriate ones is beneficial to performance, both indirectly and directly. It directly impacts performance by improving speed and economy of movement, but also acts as a means of injury prevention thus facilitating training consistency and so ultimately performance.

When the young athlete begins with a training group he must be introduced to:

- General speed drills for the development of neuromuscular coordination and stride frequency.
- A regular stretching routine to optimize mobility.
- General muscular strength and endurance exercises to train muscle fibers that would likely remain underdeveloped if exposed to running alone, and to help ensure balanced development of the major muscle groups.

All this must be complemented by the regular completion of relaxed run-through. Here, of course, the athlete receives feedback from the coach but, by closely observing the way in which the athlete moves, the coach also receives feedback about how the athlete's strength or mobility may be changed to improve their biomechanics.

From his late adolescent years onwards a talented young athlete will often begin working with a physiotherapist. The manipulation that the athlete receives, along with more specific exercises that may be prescribed, can be invaluable, facilitating biomechanical improvement and injury prevention.

It is important that attention be paid to the biomechanical development of an athlete from a young age, because the longer his training history, the more difficult it becomes to modify running technique. So, if physical training is approached from solely a physiological point of view, an athlete's potential will be limited from the start more than it would otherwise have been. Moreover, this problem is compounded by the fact that generally the athlete will be more injury prone.

Although I do not know the training of a lot of Australia's middle distance runners, it is possible that the training of our successful juniors has been characterized by appropriate running volume and distribution of work to aerobic and anaerobic means but with insufficient attention paid to the athlete's movement patterns. Physiological and biomechanical development must occur in partnership. Although movement pattern is only one determinant of running economy, improved smoothness of movement at a given speed makes and athlete more economical at that speed. Also, improved endurance means improved maintenance of running technique when fatigued.

PSYCHOLOGY

The athlete will only be able to consistently complete the required training and perform when it counts if he is strong psychologically. At the stage when he has been successful as a junior and is looking to progress to the next level, it is likely that he will be holding down a regular job or completing a university degree. It is essential for him to be very well organized so that difficulties in part of his life—for example, completing assignments at the last minute—do not affect his running. Although the coach may do much to develop the young athlete's interest in middle distance running, for an athlete who is to reach the top, there will in time be a transition to his being *intrinsically* motivated.

The athlete must be prepared to follow a systematic approach to training, trusting his coach and the program that has been set. He must be focussed for each training session once he gets to training (not wasting time and energy thinking about it during the day), clearly understanding the objective and striving with confidence to achieve it. Clear and regular communication between athlete and coach is crucial and helps avoid any unnecessary misunderstandings.

Some difficulties and setbacks (for example, in training, making teams, racing, illness, injury, other areas of life) are inevitable. Some of these situations may be beyond the athlete's control at the time, but it is the way in which he reacts to them that is critical.

It is essential that he has the character to persevere. Just as important is for the athlete never to become complacent after some success. Rather, he must have in view what is required for further progress. When it comes to competing, the athlete must have a calculated understanding of how he should run the race to perform at his best. This may include several tactical options, especially if the aim is to win rather than to run fast. He also needs to be confident, not fearful of any athlete, and sufficiently aggressive to establish and maintain the position he wants in the pack of runners.

CONCLUDING REMARKS

For a talented junior middle distance runner a relatively smooth transition to elite senior level is most likely to take place in the context of a long-term relationship with one coach. Ideally, the coach will always look to put the athlete's needs before his own, examining his own attitude to ensure that his aim is to help his athlete reach his potential; he will not seek adulation for himself.

It is important for the coach to develop a system of support while maintaining confidence in his own system of training so as not to be misled by the proclamation of supposed ideal training session or methods. The *implementation* of the training program is critical, not just its content.

The talented young runner must be(come) extremely determined, focussed not on achieving material recognition, but on following a systematic plan, aimed at steady improvement year after year. The value of specific experience gained by athlete and coach, that can only be attained as they work together over a period of years, should never be underestimated.

For the hard-working middle distance coach, who has the privilege to work with a very talented junior, it is important not only to know track and field but particularly to know the 800m and 1500m events and what is required for elite level performance in these events.

It is also essential that the coach come to know the athlete very well while maintaining a logical mind and a character of integrity. Of course, humans have limited control over outcomes in their lives. But for a talented young middle distance runner and a distance running coach, who meet at an appropriate time in both of their lives, achievement of elite level middle distance performance is more likely that it would be otherwise.

be executed without discomfort extra resistance was added via a backpack. At the end of a 12-week period all participants had recovered sufficiently to resume running at their pre-injury level with minimal, if any, pain.

Although the reasons for the effectiveness of eccentric exercises in the treatment of tendinitis have not been physiologically explained, there is no doubt that the method has a high success rate. It is speculated that one of the reasons involves the tensile strength of the tendon, or the effect of lengthening of the muscle-tendon unit and consequently reducing strain during ankle joint motion.

Whatever the reason, you can't ignore the impressive success rate of eccentric exercises in comparison to conventional treatments, such as cortisone injection and surgery. It appears that the Swedish research findings have important implications for preventing and rehabilitating tendon injuries in a cost effective and timely fashion. Of course, consult a doctor or physiotherapist before you try the eccentric exercise method.

Modern Athlete and Coach
(Australia)

STRENGTH DEVELOPMENT IN DISTANCE RUNNING

By Ants Nurmekivi

The author, in an article discussing physiological factors in the planning of training in endurance events, draws attention to the problems that can occur in the development of strength in conjunction with the development of aerobic endurance. He comes to the conclusion that it is possible for no conflict to take place in their development in parallel up to a certain intensity level. However, when the intensity and volume of strength development exercises are substantially increased, a hypertrophy of myofibrils can lead to a drop of oxidative qualities and should be avoided.

A sudden increase in the intensity and volume of strength development exercises is responsible for a rise of hydrogen ion concentration in mitochondria and can lead to their functional disturbances and reduced endurance capacity. Slow-type muscle fibers are capable of compensating or removing hydrogen ions in mitochondria only when the strength development exercises are performed at an intensity that does not exceed the adaptability of slow-twitch muscle fibers.

These and other facts from several studies clearly indicate that the coach must pay close attention to an optimal combination of aerobic and strength development training means. In essence, we are dealing here with a harmonious development of the fundamental components of aerobic and anaerobic thresholds and the different strength components should be carefully balanced.

But how to evaluate whether the intensity and volume of strength training has been superfluous? Apparently the simplest solution is to control the level of endurance during strength training phases. There are reasons to presume that the share of strength development exercises has been excessive when speed drops at the aerobic threshold level.

University of Tartu Sport Studies
(Estonia)

SUPRAMAXIMAL SPRINT LOADS

By Dietmar Koszewski

Sprinting speed is influenced by the mechanical parameters of stride length and stride frequency. Using supramaximal running speeds in training processes is a highly specific method to develop these parameters in an effort to improve maximal sprinting speed. Supramaximal sprints also help to avoid, or to eliminate, dynamic motor stereotypes that restrict speed development. The following supramaximal loads are commonly used in training:

- Downhill runs
- Speedy Pro-assisted runs
- Electric motor-assisted towing runs
- Elastic band-assisted towing runs.

All these supramaximal training loads have both positive, as well as negative aspects, and involve injury risk. Mechanically towed and assisted runs, for example, are more risky because athletes are not in control of their own speed. On the other hand, athletes can adjust the running speed in downhill runs according to their individual feelings.

Supramaximal sprint loads are usually employed in the specific training phase at the end of each preparation period. Such training units should be in the weekly training plan when the athlete is well recovered and ready for the high intensity workout. Supramaximal loads immediately after a tempo running or sprint unit should be avoided. It also is sensible to allow a day of regeneration or rest after a supramaximal training session.

An adaptation of athletes to perform supramaximal sprint loads varies considerably and often depends on the methods. The same applies to the duration of the transfer of the influence of supramaximal loads to the actual improvement of maximal sprinting speed, which could take two to three weeks.

Leichtathletik Konkret (Germany)

ENERGY SYSTEM CONTRIBUTION DURING 400 TO 1500M RUNNING

By Matt R. Spencer, et al.

Recent research into the relative contribution of the energy systems to highly intensive exercise suggests that the contributions made by the aerobic system have in the past been underestimated. To confirm this the authors conducted a study to evaluate the aerobic and anaerobic energy systems' contribution during an exhaustive treadmill running test that simulated speeds and durations of the 400, 800 and 1500m events.

Looking at the energy system models of the three events revealed that, although the sprint athletes registered a significantly lower VO_2 peak than their middle distance counterparts, results still indicate that the aerobic contribution of 46% in the 400m event is a sufficient reason for these athletes to devote more of their training time towards developing their aerobic energy system.

It also is interesting to note that the quantity of anaerobic energy used in the three events is very similar, indicating that the remaining energy requirements are supplied by the aerobic system. As the available anaerobic energy is limited, it must be used optimally and efficiently in each event. This means that optimal training must in each event strike a fine balance between the development of aerobic and anaerobic energy systems.

Given the importance of maintaining speed, an appropriate approach to the development of aerobic energy may be in the employment of interval and fartlek training, rather than overemphasizing long slow runs. It also would make sense to emphasize long interval sessions in the preparation period, while concentrating on more traditional speed work during the precompetition and competition phases. Long sprint and middle distance athletes are well advised to devote more of their training time to the development of their aerobic system without compromising their anaerobic system.

New Studies in Athletics (IAAF)

THE SECOND RUSSIAN REVOLUTION IN POLE VAULTING

By Alan Launder

The technical model for the pole vault developed by the coaches of the former Soviet Union, led by Vitaly Petrov, has been revolutionary in many aspects. The model introduced several innovations, all designed to enable vaulters to grip higher and make more effective use of stiffer poles.

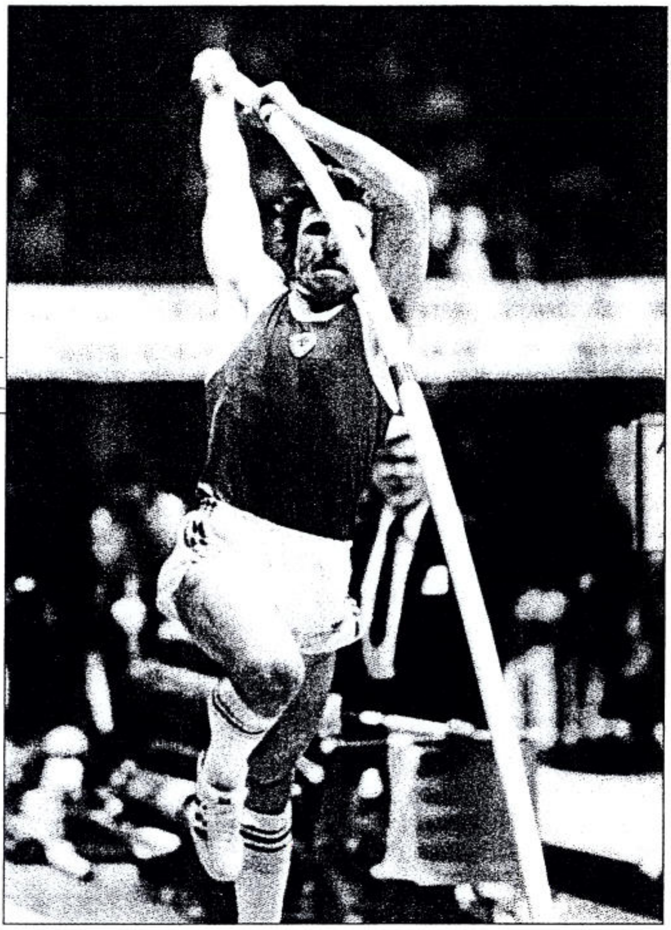
Besides the important innovation of the "pre-jump," the Russian technical model also places emphasis on a radically different approach to the "inversion," or what is usually termed the "rock-back." Petrov considers that "the rock-back and upswing on the pole must be complete when the vaulter has managed to cover the arc of the pole with his hips and legs, while the legs serve as the continuation of the upper end of the pole."

This, of course, is in complete contrast to the traditional approach in which the vaulter rocked back into a tight tuck with both legs bent.

Bearing in mind that the vault is a continuous movement, it also is interesting to consider Petrov's claim that the transfer from the hang takes place with no pressure of the front arm in the takeoff. This "soft front arm" allows the vaulter to fractionally extend the takeoff drive before inversion is initiated. It also creates an elastic pre-stretch of the muscles of the trunk and the trailing leg, which in turn makes the subsequent phases more powerful and easier to execute.

In the next phase the vertical position is achieved by the athlete driving the hips and legs above the shoulders, which appear to be moving down relatively to the rest of the body. It seems likely that, at least in Bubka's case, he is still able to put more energy into the pole during this phase and so at least maintains the pole bend longer while he positions himself to fully exploit the recoil. In fact, in each of these phases it appears that Bubka is able to put more energy into the pole and to make and keep the pole bend fractionally longer.

Modern Athlete and Coach
(Australia)



DON CHADEZ

Sergey Bubka—able to put more energy into the pole.

TRACK COACH

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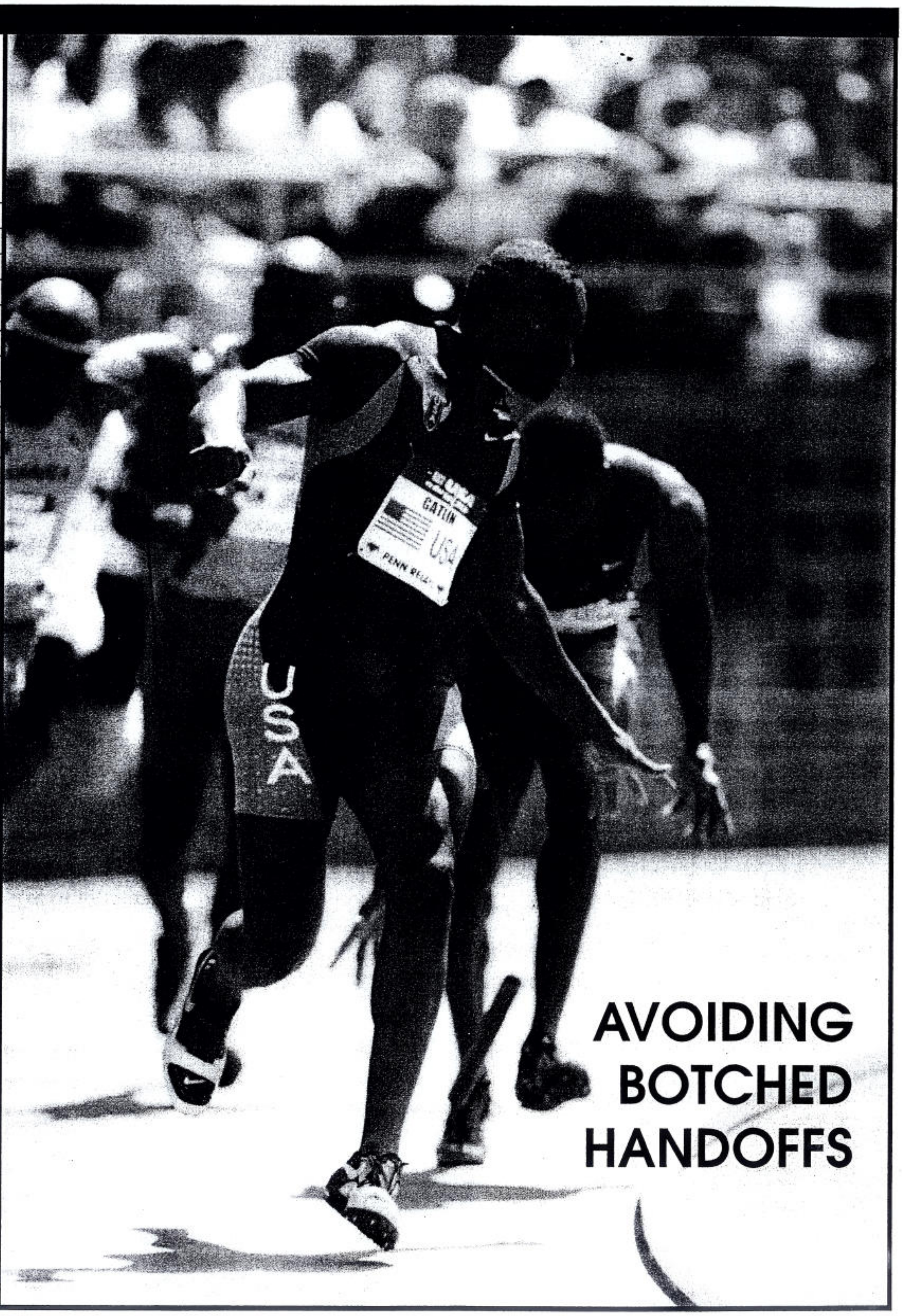
CONTENTS

WINTER
2006

174



AVOIDING BOTCHED HANDOFFS

TRACK COACH

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174

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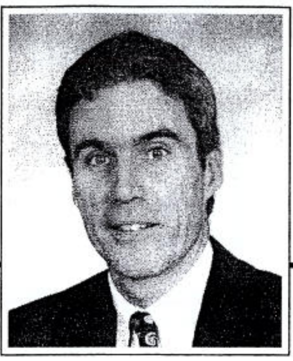
From the Editor

Russ Ebbets



THE RULE OF FOUR

Or more.

We've all seen it. Week in, week out, the same athletes from the same school in the same three or four or more events. The season progresses and their season regresses. The next year the same coach does it again, because he can. New faces, same places, the fast lane to a short career. The coach never gets it, just the athlete.

I learned a lot about coaching as a golf course greenskeeper during my college years. When we mowed the greens everyday they burned out. If we gave them a day off they'd come back strong and always stayed green.

High school and Junior Olympic programs should be for development. I know, I know, I've heard the speech. Most kids probably won't compete in college or beyond so get it while you can. Spend the future on the present, just like a credit card.

But the big difference is when you pay off the credit card you get to use it again. With a career it's gone. Maybe they never would have made it. There isn't much certainty in that "maybe."

It's long been said that great athletes make great coaches. You don't have to spend too long with a watch and a whistle to realize that. But abusing or overusing an athlete is just an excuse not to coach.

One of the lunchtime topics at the recent USATF Level 2 School in Virginia generated some lively debate over high school participation. Many people had a lot to say. So in this issue of *Track Coach* we will conduct a brief survey to see where we stand on this issue with the goal being to develop a responsible approach to athlete development.

One can't legislate responsibility but armed with facts one can lobby for good sense. Great athletes do make great coaches but it is the truly great coaches who make champions—now and in the future.

(For survey, see page 5569)

On the cover: Olympic champions Shawn Crawford and Justin Gatlin fumble the baton at Penn 2003. Greg Armstrong photo.

The 800 And 1500 Meters: Racing Fast And Controlled

Coaches: Don't neglect the various psychological considerations involved in middle distance running. You can spend months having your athletes do the workouts and the conditioning, preparing their bodies to a fare-the-well, but if they haven't done the mental preparation, it could spell the difference between winning and losing. This article is adapted from a chapter in the new book, The Psychology of High Performance Track and Field, *Ralph Vernacchia and Traci Statler, editors, published by Tafnews Press (Book Division of Track & Field News). Jennifer Bessel, Ph. D., was an All-American in the 5000m when she ran at California State University, Long Beach. She is now a licensed psychologist and is a member of the USA Track & Field Sport Psychology Team and has provided services to athletes, coaches and teams through her consulting practice in San Diego.*

The 800 and 1500 meters are exciting races. They require a combination of speed and stamina unique in the world of track and field, and this makes them amazing to watch for both participants and spectators. Even if athletes are in peak physical condition, they will often have to "gut out" their race at the end. Racers learn how to kick after sprinting either 600 meters or 1200 meters.

These two races are fast, yet unlike the 100 meters, there is time to make up for minor mistakes. Just when you may think the winner is clear, a racer can "tie up" or another racer can surge and run past. The two races are long sprints, as they are fast for 2 or 4 laps, depending on the race. Although the world's top racers make it look easy, those who have attempted to run these distances know how demanding the race pace can be.

The first key to success in the 800 and 1500, of course, includes the basics: biomechanics, being in good physical condition, completing appropriate workouts throughout the season, and staying injury-free. An additional step that can add to all of the physical hard work is to be mentally prepared. This article will focus on specific mental skills to prepare for the 800 and 1500 meters. Specifically, key mental preparation components will be discussed. Strategies for applying the techniques to a training routine will also be addressed. Finally, some common racing errors will be identified, along with some potential solutions.

KEY MENTAL PREPARATION COMPONENTS

For the 800 and 1500 meters some key components of a mental skills training program can be developed to maximize performance. These specific aspects include: race-specific goal setting, understanding the rhythm of the race, understanding race strategy, developing an

By Jennifer Bessel

ability to "race" and respond, and being able to cope with pain.

Setting Clear and Obtainable Goals

The process for setting clear and obtainable goals includes a series of steps. The steps include setting long-term performance goals, season-specific performance goals, competition-day goals and training goals (Orlick, 1986).

Long-term performance goals. It is important to dream a little when setting long-term goals in sport. Long-term performance goals are these dreams. With knowledge of an athlete's strengths, challenges, current ability, motivation and commitment, a long-term goal can be set. Long-term goals can range from "I want to run in the Olympics," to "I want to be on the traveling team at school." Sport research shows that having a "dream" is integral to helping athletes to maintain motivation, to continually challenge themselves, and to work hard (Orlick, 1985).

Seasonal performance goals. The next step is to develop seasonal goals. Often athletes set dream goals, but do not go the extra step and set goals that are more within their reach. Only setting dream goals can result in loss of motivation and a feeling of failure, as dream goals take time to reach. Here is a strategy for setting seasonal goals. At the end of each season, after a short break, it is helpful to plan ahead for the upcoming year. Typically, athletes begin with their long-term goal, which could be to become an "All-American" in the 1500 meters within four years. If an athlete sets this goal during his or her first competition year, then she or he can begin to plan for race times that would need to be reached each season to meet this goal. Once a goal for the season is set then the year can be planned.

Questions to ask: What is your long-term goal? What do you need to do each year to progress toward this long-term goal? What do you need to do during the off-season, preseason, beginning of racing season, mid-racing season and end of season to meet your yearly goal? Include all aspects of training: physical, mental, nutritional, etc.

Setting competition-day goals. The next important step in setting goals is to set goals for competition day. Athletes can forget that each race is part of a seasonal plan and they can get frustrated when they do not run their fastest race every time.

Competition-day goals include two parts: the ideal mental state for racing and a specific race goal. Each athlete needs to understand how he or she feels when "ready to go" vs. "anxious, worried and nervous."

Example of an "Ideal Mental State": "I feel ready to go and confident. I like to feel relaxed, yet have a certain feeling of energy in my legs. I know that I am ready to go when I have rested just enough to have energy and I am not worried about who I am competing against. I know I am ready when I stand on the starting line, take a deep breath and say to myself, 'I can do this.'"

In addition to specifically writing down how athletes feel when they are at their best, specific race goals should be emphasized. A coach can help an athlete with this task, as the coach and athlete need to be in communication about the athlete's training cycle, what the focus of the race should be, and how fast the athlete should be able to run. Specific race goals can be more than a race time as they can help a runner focus on the last 100 meters of the race, to feel a pace, to practice surges, or to reach a specific time or place in the race.

Example of a "Specific Race Goal": "The focus of my 1500 meters is to run at a consistent race pace for all four laps. On the backstretch of each lap I will surge for 50 meters to feel what it feels like to change my rhythm during the race. The end time is not relevant to this race goal. My goal is to surge, no matter how I feel physically. I will be mentally strong and surge with confidence."

Setting training goals. The final goal-setting technique is to set goals for training and workouts. Setting training goals keeps athletes focused, alert, and "on-track" to reach longer-term goals.

Developing Awareness of Race Rhythm

Once a goal is set, then it becomes easier to know what pace needs to be run during races. Knowing the pace of the race is the key step in learning to understand the rhythm of your race.

Why is rhythm important to the 800 and 1500 meters? Rhythm is the feeling that a runner has, both physically and emotionally, that "I am on pace." As the 800 and 1500 meters are not all-out sprints and require the ability to pick up the pace or to adjust to other runners in the race, a basic understanding of rhythm is important for each individual runner. This is only a first step, as knowing one's rhythm also requires the ability to adjust as needed to meet the demands of the race.

Developing a Race Strategy

Although these two races are fairly short, they each have key components that need to be considered when developing a strategy for competition. Having a strategy that is clear and has some built-in flexibility allows an athlete to go into a race with confidence and composure. The calmer and more confident an athlete is going into a race, typically, the smarter race he or she will be able to run. There is a danger with the 800 and 1500 meters of just going along with the crowd. If an athlete is just "holding on for dear life," it will be difficult to sprint during the final 100 meters, or to respond with confidence to changes in the race.

Developing Flexibility and an Ability to Respond

The 800 and 1500-meter races are races of planning, patience, flexibility and an ability to respond with confidence to changes in the race. Training an athlete to be mentally flexible and feel confident in his/her ability to respond to surges, sprints, or a slow pace at any time during a race can help the runner perform under control.

Mentally Coping with Pain

Of course running can be a physically painful process for all track and field competitors, especially during the final 50 meters if muscles become so tight that an athlete "ties up." The 800 and 1500 meters, in particular, require an ability to adjust to the pace and to deal with physical pain as lactic acid builds up in the muscles. As noted in the introduction, being able to mentally push yourself through physical pain to get to the finish line can mean the difference between going to the Olympics or staying home, even for top athletes.

APPLICATION OF THE BASIC COMPONENTS TO TRAINING FOR THE 800 AND 1500 METERS

Mental Training During Practice

It has been said, "practice makes perfect." This applies to both the physical and mental components of racing. The following strategies can help an athlete develop increased mental skills specifically in the middle distance races.

Developing awareness of pace. Workouts should be designed to allow athletes to experience and feel their race pace. Allowing athletes to acknowledge and feel the pace of the race will allow them to learn their goal pace. Throughout the season, this goal pace adjusts as the athlete gets physically faster. During practice, it is important to share with the athlete what pace he/she is running. Providing information on the goal of the workout, and on which intervals are designed to help runners feel the pace of the race vs. intervals that are faster than the pace, will help them become more aware of what their body feels like physically.

Sprinting through pain. It is common for workouts to end with fast sprints. For 800 and 1500-meter runners, this strategy is helpful for them to feel their body as it may feel at the end of their race. In order to help them mentally prepare, set the stage with your athletes by taking a moment to have them stop and visualize being at the end of a race. Give them a verbal prompt such as: "Now, you are at the end of your race, you have run hard, you are relaxed and in good position. These sprints are for you to practice racing the last 100 meters." Oftentimes we expect athletes to sprint, but we have not mentally prepared them to have confidence that they can sprint, even though they are tired or have tight muscles.

Practicing surges during workouts. Many ways exist in training to practice surges during workouts. Surging can be practiced during intervals or during longer roadwork. The mental aspect of surging is just as integral to improving race performance as the physical effects of surges. In order to surge on demand, athletes need to be aware of cues in their surroundings that signal a change in the pace. If a runner is too narrowly focused on his own performance, then he may miss an important cue from another racer that it is time to shift the pace. One strategy during practice is to simulate racing conditions by "surprising" your athletes into a surge mode so that they cannot always predict when they need to shift their leg speed.

Setting Up a Mental Imagery Script

When developing an imagery script for the 800 and 1500, it is important to break the race into stages. The main stages of each race include: start position, managing and maintaining race position, surges, and the kick. Imagery scripts that contain cues for all senses, including visual, hearing, touch, taste, smell, and kinesthetic, are most helpful to the athlete in enhancing performance (Orlick, 1985). Research has also found that several other factors are important when developing an imagery script, such as physical awareness, environmental awareness, task skills, timing, emotional awareness, and an "I feel myself running" perspective (Holmes & Collins, 2001).

Imagery for Starting Position

The 800 meters has a protected first turn, which is important to consider. Write an imagery script that focuses the racer on his or her specific pace. Specifically, address what the runner should physically feel like during this beginning turn to be in an ideal placement when merging together at the turn with the other competitors.

The 1500 meters starts on the straightaway with the competitors looking forward. Often the 1500 meters is crowded on the starting line. A racer should imagine himself or herself responding to the gun, going straight rather then directly to the curb, feeling the elbows and breathing of runners all around, and confidently getting set in a placement position that fits the racer's goals.

DOUG WELLS/THE DES MOINES REGISTER

A good kick is strong, confident, relaxed and fast.

Imagery for Maintaining Race Position

The 800 meters is fast and an athlete could easily lose touch with the front runners if he gets stuck in the back of a pack. Imagining potential race position (front, middle, back) and how to move into another position is a key to racing a fast 800 meters. The 800 meters can be a rough race with elbows and bumping, especially in international competition. Imagining responding to bumps or elbows calmly and with quick return to being in control can lower arousal and help maintain an athlete's concentration.

The 1500 meters has two laps to maintain pace and prepare for the finish. It is critical to establish a position goal for each lap with imagery centered around staying in this position. Imagining oneself moving into position on each lap will help the athlete be more in control of the race. The third lap of the 1500 meters can often be the "slow lap." Imagery work on this third lap can help a runner experience running through tiredness, surging to pick up leg speed, and staying focused on the race.

Imagery for Surging and Sprinting

For both the 800 meters and the 1500 meters an athlete should practice imagining initiating a surge, responding to a surge, and kicking the final 100 meters. Imagining oneself initiating a surge in the race with control and confidence will help an athlete surge to meet race strategy goals. However, as athletes race others who have their own strategy, it is just as important to imagine making the necessary adjustments in leg speed to respond to another athlete who surges earlier during the race. Think of the cues of other runners that will signal surges. For example, when you focus on the back of the person in front of you, you might notice a speed-up in arm pumping indicating a surge. The key to responding to surges is to predict that they will happen and feeling confident that you can respond physically.

All racers kick in the final meters of a race, however, all racers do not mentally practice kicking strongly on the final straight. Imagery practice that includes the 100-meter straightaway can be the difference between going to the Olympics and missing a spot on the team. A good kick is strong, confident, relaxed and fast. Mentally imagining these components in addition to practicing the sprint physically can help an athlete finish the race with confidence and strength.

Imagery for Race Strategy

In larger competitions, the 800 and 1500 meters often have several heats. Placement, not time, often becomes the goal in these heats. Imagining placement, surges and the necessary kick is important to having a confident race strategy. Also, planning goals for each heat is an important ingredient. It takes time, but it is worth the effort, to mentally imagine how to race each heat.

IDEAS FOR COMMON RACING ERRORS

The Error of Sprinting Too Early

Both the 800 and 1500 meters are races of patience. Being patient may mean not sprinting from the starting line too fast, leaving the competition behind, at a pace that an athlete cannot hold, or holding on to the sprint speed until the last 100 meters. The error of sprinting too early often ends in an athlete not having "enough" to get them through the finish line at the same pace with which they started, or worse, tying up and losing ground to other racers.

The Error of Settling in to a Slow Pace

A racer can start out at a slow pace and have difficulty picking up the pace when the race begins to quicken. This can occur during heats when racers are attempting to save their energy, or at qualifying meets when place is the important outcome rather than race time. It is not uncommon for a big name athlete who knows that he has a torrid kick to set a slow pace in hopes that the other racers will settle in and not be able to match his kick at the end of the race. To deal with this error, utilize these mental skills components. First, set goals for the race. Next, prepare mentally for the challenges of switching gears physically. Finally, use imagery techniques to build confidence to take charge of a race when necessary so that a racer can control the pace to utilize his strengths.

The Error of Not Knowing the Competition

Competition in this sense includes the race site, level of competition, level of freedom to move around, number of heats, and characteristics of other racers. While at a World Junior Championship, one 1500-meter runner stated, "It does not matter, I don't care who is in the race, or what I run, I just want to finish." Another runner said, "I know some of the runners will be fast, so I will let them go. I know a couple of the runners who I can keep up with that will lead me to a good race. I am not sure if I will make the final, but I will at least run a good time." The difference in the outcome of the races of these two runners can be surmised: The runner with knowledge of how he/she fits in with the competition had a goal he could reach, ran that goal, and felt good about his performance. Resist the urge to avoid "knowing anything" about your competition. This impedes your ability to set realistic goals and make a plan for a realistic race strategy.

CONCLUSION

In conclusion, setting up a comprehensive mental training program for athletes in any sport is a key to peak performance and maintaining consistency of performance over time. For the 800 and 1500 meters, some specific components can be integrated into the mental skills training program to help the athlete meet the unique needs of these two fast, yet controlled races with confidence. Good luck in your racing!

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Winter Work: The Foundation For All Seasons

This article is excerpted and adapted from a piece in the British publication, The Coach *(November/December 2004), and though it is directed at running in the U.K., much of it applies to running in the U.S. and elsewhere. Lowes is a UKA-Level 4 coach, an Athletics Development officer for Durham Sport, and chair of the BMC Coaching Committee.*

The winter season for the middle and long distance athlete is a crucial period of training and development no matter your goals.

For many middle and long distance runners the winter is the start of a lengthy phase of races on various cross country courses with many major races taking place from January through to March. Other athletes may treat the winter as the start of the following summer season with the main aim to compete, but to work mainly on strengths and weaknesses that will produce success later on the track. There are even a select few who use the winter to prepare for the summer and who rarely compete and may even abstain from competition altogether.

Is running cross country essential for success in the summer season? Absolutely not. However, there are many who compete throughout the year at road, cross country and track and some include indoors as well. In this article, I'd like to take a closer look at just how an endurance athlete can maximize his or her winter work to pay the greatest dividends.

THE WINTER ATHLETE

First of all there are several different categories of "winter" athletes:

- Good at cross country, but poor on the track
- Uses cross country as strength work for the track
- Uses cross country as a preparatory phase for the indoor season
- Doesn't compete at all, but does higher quantity work with the summer in mind
- Doesn't compete initially, but targets the indoor season with extra mileage as preparation for the outdoor season
- Some runners are unique, although not rare, in that they are equally good on all surfaces.

The fact that there are two distinct running seasons for British athletes—winter and summer—can be put down to two reasons:

- The cross country season is run mainly when the weather is poor—cold and wet, not the conditions for running fast times on a track
- It can be thought of as a strength phase and also a mental and physical break from the rigors of racing and training on the track.

If an athlete were to prioritize track racing all year round, it would almost certainly lead to injuries along with physical and mental staleness. Therefore, the winter allows athletes to readjust their

By David Lowes, U.K.

training and work on strengths and weaknesses so that come the better weather of the spring months they are in a position to test their fitness levels in competition.

Athletes who use the cross country racing strategy are usually 5000m and 10,000m specialists; some 800m and 1500m specialists are often reluctant to run over such demanding terrain. There are always exceptions to the rule and some of the famous names who have for the most part avoided or run minimal cross country are athletes such as Hicham El Guerrouj, Gabrielle Szabo, Kelly Holmes, Seb Coe, Wilson Kipketer and Maria Mutola. Of course athletes such as Steve Ovett, David Moorcroft, Paul Tergat, Kenenisa Bekele and Paula Radcliffe have thrived on the track as well as the mud.

The best endurance athlete in the world at the moment is 5000m and 10,000m world record holder Kenenisa Bekele. He is undoubtedly a "runner's runner." He is simply the best on any surface and he runs in all three categories during the year—track, cross country and some indoor races.

The cross country athlete needs to be very versatile, being able to run equally well on bone-dry flat courses, hilly courses and also stamina-sapping mud baths and sometimes a mixture of all of those. Some of these courses will be short laps with many tight turns and most will have an open inviting start which will mean starting at breakneck speed. Either way, cross country is a very demanding sport.

THE WINTER BASE PERIOD

If the winter is the start of preparation for the summer then many imponderables have to be addressed before embarking on eight months of endeavor. Some of these are what targets have been met, exceeded, or not met at all and the reasons why these have happened and, more importantly, how any shortcomings can be improved. Also, perhaps more relevant is what are the targets that are currently being pursued. If the summer season has been a success, does the athlete/coach try to replicate the work that has been done or try something slightly or even totally different?

Personally, I think it is unwise to

JEFF JOHNSON/GEEK MEDIA

Cross country—taking it out at the start!

try and duplicate exactly the work done in a previous season/year. The reason is that the body feels and reacts differently each and every day and also to the sessions that have been done. For previous work to be productive you would have to have the same amount of sleep, eat the same sort of food, live the same lifestyle and encounter the same climatic conditions. All variables that are very difficult to replicate.

What is more realistic is to include most of the successful work and improve and adapt sessions that fulfill the needs of the athlete at a particular time. If the athlete has been ill or feeling below par then the coach needs to be creative in giving the athlete something that deviates from their plan until the athlete is back on the road to recovery.

The same goes when the athlete is injured: the coach needs innovation in his or her delivery to get athletes back to where they were and then move them on quickly. This usually entails psychological techniques to make the athlete believe that any enforced break will not affect long-term aims.

The winter is without doubt the start for whatever facet of running you choose, cross country, road running, indoors or the ultimate outdoor summer season. The traditionalists who maintain that for success on the track you must run cross country races don't really understand the physiology behind their reasoning.

If an athlete were to run 14 races in a winter season, this would mean 14 races over an approximate 7-month period (28 weeks) = one race every two weeks. However, what makes an athlete great on the track come summer is the work done in that period of time (196 days) which could mean 196 training sessions or even 300+ sessions for the twice-a-day trainer. Therefore, the gains in fitness by one 10k cross country race are far outweighed by the specific training that could be done throughout the winter period.

Although rest days or days missed through niggles or illness are as essential as hard training, it is worth taking a different slant on how many days you actually have off from training. If you look at a year's training from the perspective of training six times per week with one rest day, that adds up to 52 days off in that year. If you add to that 2-3 weeks missed through injury/illness then the total now adds up to 52 + 21 = 73 days. Finally, the traditional two-week break at the end of the track season makes the number of days "missed" or "rested" = 87 days, which in terms of weeks = 12.

It is worth taking this into account before starting to think about your plan for the year/season. Rest is good if it promotes performance or encourages recovery, physical and/or mental. *There is a limit to how much rest can be taken before fitness diminishes or advancements can be made.* Obviously, some loss of training is unavoidable and other forms of fitness work may have to be undertaken to maintain muscle tone and aerobic fitness.

Over the winter months much heavy work can be undertaken in inclement weather and the distribution of the work can go awry if not planned carefully. At the start of the winter work period in September/October athletes can be very enthusiastic to train hard. This eagerness however can diminish quickly through boredom and longevity of the season.

For many, the hard work completed in the winter months can be wasted in the summer if the transition from one season to another is not done correctly. Likewise, as in the winter, the spring months—where the athlete prepares for the first track races of the season—the enthusiasm levels are high and this is when many do Personal Bests through pure anticipation and ebullience. Even though the track season is comparatively short, form can be lost very quickly through a lack of application, both physically and mentally.

Athletes should come out of a winter season much stronger than ever before, that is, with much better endurance levels than previously. They should also be in a position to start to run faster than before due to increased levels of work and tests throughout the winter. Many athletes lose their winter gains through inappropriate training in the summer by neglecting the emphasis on endurance and concentrating solely on "short" speed.

More athletes get disillusioned more quickly in the summer season than in the long winter months through tougher, more intense sessions which lead to higher levels of fatigue. Some of these sessions include increased anaerobic work which is not only faster but with much shorter recoveries and all are usually against the stopwatch. Therefore, if targets are not being met on a regular basis then confidence levels and self-discipline can drop dramatically, and if competition outcomes are poor, many inappropriate thoughts can occur leading to total apathy and disillusionment.

Current targets in the winter are obviously cross country competitions and these can be short-term (immediate races) or medium-term (future races). Indoor competitions are medium-term, allowing a three- or four-month training period before competing in January and February. Longer-term targets are in the following summer track season and this allows 7-8 months of thorough preparation to excel in specific events.

For realistic targets to be met over the winter some solid criteria need to be set before training begins in the new season:

- What things did I do well in the previous season?
- What things did I not do well in the previous season?
- What things did I do satisfactorily but that can be improved?

For the middle distance and distance athlete these might be categorized as follows:

- Endurance and cruising speed good, Personal Bests improved
- Sprint finish poor
- Tactics reasonable, but room for improvement.

CHANGE OF PACE NEEDS TO BE ADDRESSED

These are some of the points that require consideration when setting out the winter plan, and a number will need more attention than others. If we consider the perfect plan that will deliver peak performance, then positives and negatives need to be worked upon in varying degrees.

Although the winter season is around 28 weeks in duration it is not as long as it may seem if problems are encountered. Injury or illness in this period can quickly pass with a loss of the work that is necessary for success. This may mean using the end of the winter or early spring as a phase of "winter" training until fitness levels are suitable and starting the "summer" training in mid-season with the main target to just get one or two PBs.

If the athlete struggles with sprinting at the end of a race it is probably down to two things: either the athlete lacks the necessary speed to sprint or the athlete cannot produce a finishing sprint due to a lack of endurance. Both can be improved in varying degrees over the winter with endurance being the easiest to develop. Short sprinting speed can be subdued by genetic make-up, but any advancement in speed needs to be given priority throughout the winter.

It may even mean training with a sprint group once or twice a week for the whole 28 weeks. After all, there are no medals for leading any race over any distance with the finishing post in sight and then getting passed by the opposition. This is one area—speed—where endurance athletes are reluctant to change from the norm, yet it is one of the most neglected, yet beneficial ways of improving performance in competition.

Most athletes tend to think about speed in terms of the summer months, but why take months to get it and then put it on hold throughout the winter? *If you want to improve speed you need to develop it in the winter months.* This may not necessarily mean running fast all of the time and may require the enhancement of other facets which will improve speed such as improving running style and efficiency, strengthening of physical deficiencies, e.g., quads, hamstrings, calfs, core strength, flexibility and mobility, drills, circuits and weights.

One of the biggest frustrations for athletes is not doing the necessities to develop physically in the winter; they perform at exactly the same levels in the summer months and therefore there are few if any PBs at all when they want them. Providing development is feasible due to age, and a clean bill of health, etc., it is a transgression not to be in a better position physically and mentally than the previous season.

If speed needs to be maintained and nurtured during the winter, the methods of practicing it may be different from the summer sessions due to the colder, inclement weather. If standard sessions in the summer are 12x400m in 58sec with 60sec recovery or 2(5x400m) in 56sec with 2min recovery, then to develop and encourage speed in the winter months similar or alternative sessions must be done.

Weather conditions must be reasonable to deliver quality sessions, but the athlete can't keep putting off doing sessions if the weather is poor (it is a fact that many athletes thrive *because* of the adverse circumstances). Many elite athletes are lucky enough to be based at or near a high-performance center where these speedy sessions can be done indoors. Others go to warmer climates in the winter to be able to carry out these sessions.

However, it needs to be understood that even if our weather was good all year round, to excel in the track season would still require a season of endurance running to recuperate and reevaluate rather than trying to keep the quality "summer" sessions going all year round.

If the summer-type sessions mentioned are deemed unsuitable or impracticable for winter work then speed elements need to be added as "bolt-ons" to the main session of the day, e.g., 6x1000m +400m at the start and/or end of that work at maximal speed.

The first 400m would be defined

as speed work, whereas the 400m at the end would be a speed endurance element which would create high lactate levels due to escalating fatigue levels. Similar sessions done on a regular basis will keep speed levels intact during the winter and it is always wise to finish off the main session with 50-100m sprints to maintain speed and cadence. It is also worth remembering that hill work, depending on the length, is in actual fact speed work, only against a resistance.

Those running an indoor season need to implement speed at an earlier stage in the winter, along with the heavy endurance work. Levels of speed work will be different for specific events, e.g., 800m will be much more speed-oriented than will 3000m. Once the indoor season is over it is imperative to go back to early winter endurance work before embarking on the pre-summer work to reinforce the elements needed for a specific event.

Speed is vital for cross country runners as well, especially if they aspire to world levels. World Cross Country male medalists not only need to be capable of running faster than 13 minutes for 5000m and 27 minutes for 10,000m; they need to capable of doing those performances in March.

If you are a summer track specialist then the winter work gives you the capability to produce the performances when you want them most. As the weather improves in the spring it is then that the specific training begins and with the improvements gained through the cold winter months it is expressed in better sessions which are faster, better in quality through shorter recoveries and more repetitions.

The winter can be viewed as a development and enhancement phase while the spring is the time for preparation and fine tuning while the summer is where all these elements are put together for the delivery of peak performances. Therefore, it is without doubt that the winter is the key phase for all seasons and all forms of endurance running and can be defined and addressed as follows:

- Training phase for cross country (September to March)
- Training phase for indoor season (September to January)
- Training phase for summer season (September to March)
- Training phase for a spring marathon (September to April)
- Training phase to work on strengths and weaknesses (September to April).

Whatever phase you fit into, it is undeniably an essential pathway to success and cannot be neglected. Winter training doesn't necessarily mean cross country running but it is without doubt the foundation work for whatever category you aspire to.


JEFF JOHNSON/GEEK MEDIA

Whether you run cross country or not, winter training supplies the foundation for peak-season competition.

racing SPECIAL

All the training in the world will be wasted if you don't show a bit of tactical nous when the gun goes off. Here's the low-down on how to run your best race

By Owen Anderson
Photo by Allsport

tactical weapons

You've done your intervals and tempo work, you've completed your long runs. Now you're ready for the big day – the 10K, half-marathon or marathon you've been looking forward to for so long. You're in great shape and ready to run, so don't spoil your chances of a PB by neglecting to do the important – but often forgotten – 'little things' which will ensure a successful effort.

THE PERFECT WARM-UP

A warm-up should do much more than just loosen your hamstrings and unkink your Achilles tendons: it should raise leg-muscle temperature and heart rate, push blood and oxygen towards your leg muscles, fire up your nervous system, enhance your coordination and increase your desire to work hard.

First, prepare your body by flexing, extending and rotating your key joints, starting with the fingers and working in through the wrists, elbows, shoulders, neck, lower back, hips, knees, ankles, feet and toes. Flow smoothly from joint to joint, performing 8-10 flexions, extensions and rotations at each area. Then walk (forwards and backwards) for 30m, skip (forwards and backwards) for 30m, side-shuffle (to the left and right) for 30m, jog (forwards and backwards), grapevine-run (moving sideways by letting one foot cross in front of and then behind the other), jog while doing bum kicks, and then while doing windmills with your arms. You should be in motion for 8-10 minutes altogether.

If you need to do any static stretching, do it now. Then start some quicker movements. Focusing on a smooth, fast, rhythmic foot strike, stride for 60 metres or so at about 80 per cent of maximum speed. Rest for a few moments and then skip quickly for another 60 metres. Stride and skip once more, rest for a minute, and then perform two acceleration runs of about 50 metres, during which you start slowly and accelerate to around 90 per cent of maximum speed.

Plan this routine so that it ends just a few minutes before the race start. Then stay in motion (jogging on the spot if necessary) until the gun goes off, so that your heart rate doesn't drop below 120 beats per minute or so. (If it does, research suggests that your performance may be slower.)

THE CRUCIAL TWO MINUTES

Although the first two minutes after the gun goes are just a small fraction of the total race time, they play a huge role in determining your fate. Most runners go off too fast, because a powerful blend of adrenaline and excitement prevents you from feeling too much discomfort to begin with, even when you're running far too quickly. But if you do, you'll pay for it, as increases in intramuscular acidity in your legs will inevitably lead to some lethargic later miles.

Concentration and patience are the keys: stay relaxed and focus totally on running at somewhat slower than your practised race pace during the first two minutes. As you continue through the rest of the first mile, you can gradually move up to your goal pace.

The second mile should be the anchor point for the rest of the race. By the first mile marker, you should have settled comfortably into your planned pace: your job is simply to hold this pace tenaciously until you reach the two-mile point – and then to proceed to the third mile at the same speed. Starting cautiously and zeroing in on goal pace in the second mile is critical, because studies show that 10K racers tend to run the third mile of the race at the same speed as the second. If you go too fast during the first mile, you probably won't be able to run the second mile at goal speed; thus your third mile will also be too slow, and your chances of a PB will be slim indeed.

To develop a strong feel for your goal pace, make sure that you've done regular training sessions during which you run 800m at what you think is your goal pace. At the end of – not during – the 800m, check your watch to see if you've actually been running at that goal speed. Rest for a bit and then run 800m again, speeding up or slowing down according to how the first interval went. Most runners can do about six of these 'pace-check' intervals per session.

Bear in mind that easing into race pace is also extremely important in the marathon. Studies show that marathoners who exceed average race pace by more than two per cent during the opening miles have the highest risk of glycogen depletion and the biggest chance of hitting the wall.

Don't worry, a cautious first mile won't hurt your chances of a PB. Studies suggest convincingly that negative splitting (running the second half of your race faster than the first) produces the best possible race times. More precisely, research shows that a 51-49 scheme (ie running the first half of the race in 51 per cent of your total time and the second in 49 per cent) may chop about three per cent from your usual time if you have previously been an even or positive splitter. The cautious-first-mile scheme outlined above should bring you home in about 51-49.

WHEN TO MAKE YOUR MOVE

Of course, you hope you'll feel so great during the second half of the race that you'll be able to increase your speed beyond goal pace and set a remarkable time. But when should you put the pedal to the metal? In a 10K, wait until you've covered five miles before hitting the accelerator, or four-and-a-half if you're really feeling good. In a half-marathon you can gradually step up your speed after eight miles or so. In a marathon, wait until the last two or three miles.

If the race feels tough throughout, save your surge for the final 800-1200m, a short enough distance for a little mental toughness to be able to help you deal with a lake of lactic acid in your leg muscles. To become a feared kicker, imitate the Kenyans; do training sessions in which you run for 45-60 minutes until fatigued, and then zip along at a brisk pace for three-quarters of a mile.

If you follow these tips, you'll be able to use all the power and efficiency you've gained in training, and you'll head home with a shiny new PB to brag about! ■

2001

Σπυρνιωτη Κ

MENS 1500 HUNDRED METRES
HOMMES 1500M

Following the disappointment of the Seoul Olympic 1500m, a race severely affected by injuries to several of the leading contenders, the 1500m in Tokyo was eagerly anticipated. Again, however, injuries took their toll. Peter Elliott, the Commonwealth champion and winner of the 1991 Dream Mile in Oslo, never even got as far as the heats. He returned home to Britain after aggravating an Achilles tendon injury while training in Japan. Another who had to scratch was Abdi Bile of Somalia, the reigning world champion. Elliott's compatriot, the 1983 world champion Steve Cram, was eliminated in the semi-finals, as was Olympic gold medallist Peter Rono of Kenya, while Moroccan world record holder Said Aouita – who had made a promising comeback following surgery for compartment syndrome – lost contact with the leaders when the pace increased on the last lap.

What a fast last lap that was, for Noureddine Morceli, the 21 year-old Algerian who won the world indoor title and has been unbeaten at the distance all year with three runs between 3:31.00 and 3:31.01, sped around the final 400m in 51.54. His winning time of 3:32.84 took almost four seconds off Bile's championship record and his winning margin of exactly two seconds was the biggest at this level of championship racing since Kip Keino's runaway win over Jim Ryun in the 1968 Olympics.

The race was not particularly fast in the early stages as David Kibet of Kenya led through 400m in 58.02 and 800m in 1:57.43, closely followed by Morceli who went ahead shortly before the bell, reached in 2:41.30. His acceleration left his rivals floundering. He flashed past the 1200m mark in 2:54.10 (12.8 for that 100m) with a five metre advantage and by the finish he was 15m clear of Wilfred Kirochi, the Kenyan who had beaten him for the world junior title three years ago. A German duel for the bronze medal resulted in Hauke Fuhlbrügge pipping European champion Jens-Peter Herold, who paid the penalty for celebrating too soon.

Morceli, whose world title came one day after Hassiba Boulmerka, in the women's 1500m, became Algeria's first ever winner, remarked: "I am not very tired, because I am used to running fast. Aouita has been the athlete of the eighties, I will be that of the nineties."

Suite à la déception que provoqua le 1500m des Jeux Olympiques de Séoul, course sévèrement marquée par les blessures des prétendants au titre, c'est avec impatience que l'on attendait le 1500m de Tokyo. Mais il y eut, là encore, des victimes. Peter Elliott - champion du Commonwealth et vainqueur du Dream Mile d'Oslo en 1991 - n'atteint même pas les éliminatoires. Il dut retourner en Grande Bretagne après l'aggravation de sa blessure au tendon d'Achilles lors de son entraînement au Japon. Autre coureur qui dû abandonner : le Somalien Abdi Bile, Champion du Monde actuel. Steve Cram, compatriote d'Elliott et Champion du Monde en 1983, fut éliminé en demi-finales, tout comme le fut Peter Rono (Kenya), médaille d'Or Olympique, alors que le recordman du monde, Said Aouita (Maroc) - qui avait fait un retour prometteur après s'être fait opéré d'un "compartment syndrome" - se fit distancer par le peloton de tête alors que les coureurs accéléraient au dernier tour.

Quelle ne fut pas la vitesse du dernier tour de Noureddine Morceli, l'Algérien de 21 ans qui remporta le titre mondial en salle et qui fut toute l'année imbattable en course de fond avec trois performances oscillant entre 3'31"00 et 3'31"01, courant les derniers 400m en 51"54. Ses 3'32"84 lui permirent de l'emporter avec une avance de pratiquement 4 secondes sur le record de championnat de Bile et son avance d'exactement deux secondes fut la meilleure des courses de championnat de 1500m depuis la course triomphante de Kip Keino sur Jim Ryun aux Jeux Olympiques de 1968.

Au départ, la course ne fut pas particulièrement rapide. Le Kényen David Kibet menait au 400m avec 58"02 et au 800m avec 1'57"43, talonné par Morceli qui prit la tête peu de temps après le signal du dernier tour en réalisant 2'41"30. Sa pointe de vitesse désarma ses opposants et celui-ci dépassa le 1200m en 2'54"10 (12"8 sur ces 100m), avec une avance de 5 mètres. A l'arrivée, il avait 15 mètres d'avance sur Wilfred Kirochi, le Kényen qui lui avait pris le titre de Junior du Monde il y a trois ans. Lors de la dispute des prétendants allemands à la médaille de bronze, Hauke Fuhlbrügge battit le Champion d'Europe Jens-Peter Herold qui dut payer cher pour s'être réjoui trop tôt.

Morceli - qui remporta le titre mondial un jour après Hassiba Boulmerka dans le 1500m féminin - devint le premier vainqueur algérien de tous les temps. Celui-ci remarqua : "Je ne suis pas très fatigué car je suis habitué à courir vite. Aouita était l'athlète des années 80, je vais être celui des années 90 ."

Heats (Aug 29) (First 6 & 6 fastest to semi-finals) Ht 1: 1, Morceli 3:43.45; 2, Benito 3:43.88; 3, Aouita 3:43.93; 4, Rono 3:44.37; 5, Scammell 3:44.60; 6, Svensson 3:44.66; 7, Cram 3:44.69; 8, Karol Dudij POL 3:44.89 ; 9, Mbigyani Thee BOT 3:45.04; 10, Edgar de Oliveira BRA 3:45.59; 11, Alex Geissbuhler SUI 3:46.38; 12, Terrance Herrington USA 3:47.28; 13, Dale Jones ANT 3:55.41; 14, Lucas Eningo Elonga GEQ 4:31.24; Abdi Bile SOM DNS (400m: Rono 63.54; 800m: de Oliveira 2:07.54; 1200m: de Oliveira 3:04.44); Ht 2: 1, Herold 3:41.21; 2, González 3:41.48; 3, Doyle 3:41.50; 4, Thiébaut 3:41.50; 5, Kirochi 3:41.64; 6, Tirelli 3:41.77; 7, Guldberg 3:42.00; 8, Melnikov 3:42.15; 9, Zeki Oztürk TUR 3:42.86; 10, Luis Nuñez DOM 3:48.54; 11, Fabian Franco GIB 4:03.94; Daoude Kassougue MTN, Han Kulker HOL & Jim Spivey USA DNS (400m: Guldberg 60.38; 800m: Guldberg 2:00.95; 1200m: Doyle 3:00.36); Ht 3: 1, Kibet 3:38.07; 2, el Bsir 3:38.29; 3, Cacho 3:38.31; 4, Silva 3:38.37; 5, Di Napoli 3:38.63; 6, Fuhlbrügge 3:38.65; 7, Suleiman 3:38.89; 8, Yates 3:39.30; 9, Okuyama 3:40.35; 10, N'Tyamba 3:41.05 NR; 11, Alemayehu Roba ETH 3:42.76; 12, José Lopez VEN 3:45.61; 13, Luis Martinez GUA 3:46.39; Joe Falcon USA DNS (400m: Roba 58.36; 800m: Suleiman 1:57.54; 1200m: Suleiman 2:57.08) Cram reinstated after protest

Semi-Finals (Aug 31) (First 5 & 2 fastest to final) Ht 1: 1, Morceli 3:39.90; 2, Kirochi 3:40.73; 3, Cacho 3:40.83; 4, Di Napoli 3:40.84; 5, Silva 3:40.94; 6, Yates 3:41.24; 7, Fuhlbrugge 3:41.41; 8, Peter Rono KEN 3:41.76; 9, Rachid el Bsir MAR 3:42.89; 10, Mikael Svensson SWE 3:43.69; 11, João N'Tyamba AHO 3:44.64; 12, Pat Scammell AUS 3:45.17 (400m: Di Napoli 60.91; 800m: Di Napoli 2:03.95; 1200m: Di Napoli 3:01.53); Ht 2: 1, Herold 3:41.23; 2, Aouita 3:41.45; 3, Suleiman 3:41.48; 4, Doyle 3:41.52; 5, Kibet 3:41.54; 6, Teo Benito ESP 3:41.61; 7, Steve Cram GBR 3:41.67; 8, José Luis González ESP 3:41.71; 9, Dövide Tirelli ITA 3:43.08; 10, Mogens Guldberg DEN 3:44.34; 11, Sergey Melnikov URS 3:44.62; 12, Pascal Thiébaut FRA 3:45.18; 13, Mitsuhiro Okuyama JPN 3:49.96 (400m: Cram 62.20; 800m Cram 2:03.63, 1200m: Cram 3:01.42)

FINAL (SEP 1)

1	Noureddine MORCELI	ALG	3:32.84	CBP
2	Wilfred KIROCHI	KEN	3:34.84	
3	Hauke FUHLBRÜGGE	GER	3:35.28	
4	Jens-Peter HEROLD	GER	3:35.37	
5	Fermin CACHO	ESP	3:35.62	
6	Mario SILVA	POR	3:35.76	NR
7	David KIBET	KEN	3:36.03	
8	Gennaro DI NAPOLI	ITA	3:36.56	

9, Mohamed Suleiman QAT 3:38.12; 10, Matthew Yates GBR 3:38.71; 11, Saïd Aouita MAR 3:39.49; 12, Simon Doyle AUS 3:41.54

(400m: Kibet 58.02; 800m: Kibet 1:57.43; 1200m: Morceli 2:54.10)

SOS Προσοχή !!

Πίνακας: 12 Δείχνει την μέση ταχύτητα δηλαδή το ρυθμό του δρόμου σε μέτρα ανά δευτερόλεπτα για τα αγωνίσματα ημιαντοχής – αντοχής (Σύμφωνα με F. Wilt).

μ/δ	100	200	300	400	600	800	1000	1200	1500	2000
8,70	11,5	23,0	34,5	46						
8,52	11,75	23,5	35,25	47						
8,33	12,0	24,0	36,0	48						
8,22	12,25	24,5	36,75	49						
8,00	12,5	25,0	37,5	50						
7,84	12,75	25,5	38,25	51			1000			
7,69	13,0	26,0	39,0	52	1:18,0	1:44,0				
7,55	13,25	26,5	39,75	53	1:19,5	1:46,0				
7,41	13,5	27,0	40,5	54	1:21,0	1:48,0	2:15,0			
7,27	13,75	27,5	41,25	55	1:22,5	1:50,0	2:17,5	2:45,0		
7,14	14,0	28,0	42,0	56	1:24,0	1:52,0	2:20,0	2:48,0	3:30,0	
7,02	14,25	28,5	42,75	57	1:25,5	1:54,0	2;22,5	2:51,0	3:33,7	
6,90	14,5	29,0	43,5	58	1:27,0	1:56,0	2:25,0	2:54,0	3:37,5	
6,78	14,75	29,5	44,25	59	1:28,5	1:58,0	2:27,5	2:57,0	3:41,2	4:55,0
6,67	15,0	30,0	45,0	60	1:30,0	2:00,0	2:30,0	3:00,0	3:45,0	5:00,0
6,56	15,25	30,5	45,75	61	1:31,5	2:02,0	2:32,5	3:03,0	3:48,7	5:05,0
6,45	15,5	31,0	46,5	62	1:33,0	2:04,0	2:35,0	3:06,0	3:52,5	5:10,0
6,35	15,75	31,5	47,25	63	1:34,5	2:06,0	2:37,5	3:09,0	3:56,2	5:15,0
6,25	16,0	32,0	48,0	64	1:36,0	2:08,0	2:40,0	3:12,0	4:00,0	5:20,0
6,15	16,25	32,5	48,75	65	1:37,5	2:10,0	2:42,5	3:15,0	4:03,7	5:25,0
6,06	16,5	33,0	49,5	66	1:39,0	2:12,0	2:45,0	3:18,0	4:07,5	5:30,0
5,97	16,75	33,5	50,25	67	1:40,5	2:14,0	2:47,5	3:21,0	4:11,2	5:35,0
5,88	17,0	34,0	51,0	68	1:42,0	2:16,0	2:50,0	3:24,0	4:15,0	5:40,0
5,80	17,25	34,5	51,75	69	1:43,5	2:18,0	2:52,5	3:27,0	4:18,7	5:45,0
5,71	17,5	35,0	52,5	70	1:45,0	2:20,0	2:55,0	3:30,0	4:22,5	5:50,0
5,56	18,0	36,0	54,0	72	1:48,0	2:24,0	3:00,0	3:36,0	4:30,0	6:00,0
5,41	18,5	37,0	55,5	74	1:51,0	2:28,0	3:05,0	3:42,0	4:37,5	6:10,0
5,26	19,0	38,0	57,0	76	1:54,0	2:32,0	3:10,0	3:48,0	4:45,0	6:20,0
5,13	19,5	39,0	58,5	78	1:57,0	2:36,0	3:15,0	3:54,0	4:52,5	6:30,0
5,00	20,0	40,0	60,0	80	2:00,0	2:40,0	3:20,0	4:00,0	5:00,0	6:40,0
4,88	20,5	41,0	61,5	82	2:03,0	2:44,0	3:25,0	4:06,0	5:07,5	6:50,0
4,76	21,0	42,0	63,0	84	2:06,0	2:48,0	3:30,0	4:12,0	5:15,0	7:00,0
4,65	21,5	43,0	64,5	86	2:09,0	2:52,0	3:35,0	4:18,0	5:22,5	7:10,0
4,55	22,0	44,0	66,0	88	2:12,0	2:56,0	3:40,0	4:24,0	5:30,0	7:20,0
4,44	22,5	45,0	67,5	90	2:15,0	3:00,0	3:45,0	4:30,0	5:37,5	7:30,0
4,35	23,0	46,0	69,0	92	2:18,0	3:04,0	3:50,0	4:36,0	5:45,0	7:40,0
4,17	24,0	48,0	72,0	96	2:24,0	3:12,0	4:00,0	4:48,0	6:00,0	8,00,0
4,00	25,0	50,0	75,0	100	2:30,0	3:20,0	4:10,0	5:00,0	6:15,0	8:20,0
3,85	26,0	52,0	78,0	104	2:36,0	3:28,0	4:20,0	5:12,0	6:30,0	
3,70	27,0	54,0	81,0	108	2:42,0	3:36,0	4:30,0	5:24,0	6:45,0	
3,57	28,0			112		3:44,0	4,40,0	5:36,0	7:00,0	
3,45	29,0			116		3:52,0	4:50,0			
3,33	30,0			120			5:00,0			

Σμυρνιώτου

ΣΜΥΡΝΙΣΤΟΥ

Training the Track & Field Athlete Through the Energy Systems

Θυμάσιζε! ΠΡΑΚΤΙΚΗ

Θεωρητική βάση

Α΄ ΕΤΟΣ

2004-05

By Jack Ransone, Ph.D., Associate Professor of Human Performance
Oklahoma State University
USATF Coaching Education Level II and Level III Instructor

In track and field, as in many other sports, theorist and practitioners reside in different camps with inadequate communications. The blame rests with all of us. Coaches are responsible for the effectiveness of their training methods. New techniques allowed to remain in the minds of scientists or on silent pages in trade journals do nothing for the leaders of track and field.

American athletes, if trained correctly, are invincible. Our societal system is second to none in producing motivated, aggressive and self-asserted young men and women. Our scientific establishment is totally superior in human, as well as material sources, in its capacity to find quick answers to pressing problems. A carefully planned meeting of these two institutions will one day produce the greatest athletes the world has ever seen. We need to establish a system that is already present in many countries of the world--A coordinated mechanism of immediate dissemination of new information from the laboratory to the track, and a trusting relationship between the coach and scientist. Such a goal remains, as yet, a distant ideal in this country I will address many of those topics that remain lost in the halls of science.

There is no secret or mystery about the energy systems and their effectiveness when clearly understood. Track and field coaches must understand the energy system capabilities and limitations to design sequenced training programs. In teaching athletes to listen to their bodies during training sessions, adjustments can be furnished in the sequenced workout with careful understanding of the energy system. It is my intention to provide the coach with a workout training system based on accurate scientific knowledge as it relates to the energy systems. **

1 Adenosine Triphosphate, or simply, ATP, is the immediate usable form of chemical energy for muscular activity. This is one of the most important of the "energy rich" compounds which is stored in all cells, particularly muscle cells. All forms of chemical energy available from the food we eat must eventually be transferred into ATP form before they can be utilized by the muscle cell. The amount of ATP in the muscle cell is limited and could be depleted in 1-2 seconds unless recharged to maintain muscular activity, thus, immediate synthesis of ATP is necessary. ATP supplies must be kept at peak concentration and must never fall below 60% of its resting levels for muscular activity to continue. The three systems of metabolic pathways available to replace ATP concentrations are: 1) Anaerobic Phosphagen (ATP-PC) Energy System, 2) Anaerobic Lactate (Glycolytic) Energy System and 3) Aerobic Energy System. *

An energy rich compound called Creatine Phosphate (CP) is present in the muscle cell. This compound is used for the immediate resynthesis of ATP following high intensity exercise. The amount of ATP that can be resynthesized can last for 4 to 5 seconds. Remember, the 1 to 2 second supply from ATP stores, so collectively, you have about 5 to 7 seconds of ATP production. This system is referred to as the Anaerobic Phosphagen Energy System with no oxygen used to produce energy. To challenge this system, high intensity, workouts of 4 to 7 seconds are necessary. For example, 30 to 50 meters of maximal sprinting or 3 to 5 repetition-sets of weightlifting. * SOS

High intensity work (Sprints) involves moving the limbs at the highest possible velocity. More specifically, it involves the selective recruitment of motor unit pathways to improve the efficiency and firing of correct motor units that are available depending on the TYPE, INTENSITY, and DURATION of work executed. * SOS This motor learning must be rehearsed (practiced) at high speeds to develop and implant the complex recruitment for synchronized firing of these motor units. Points that must be followed in the training sessions: 1) the speed component of anaerobic metabolism should be trained when no fatigue is present, 2) most athletes require 24 to 36 hours of rest with low intensity work before doing maximum speed work again, 3) work sets of around 3-4 repetitions with 2-3 minutes recovery between repetitions, and 8-10 minutes recovery between sets is recommended for maximum results to occur, 4) the time period necessary for the proper resynthesis of ATP and CP recovery rates for CP resynthesis and 5) four (4) sets, involving 600 meters (ie. 4x4x65m) in total distance in a practice session is sufficient to stimulate this system.

2 The demand for energy (ATP) dictates which energy system will be challenged. The muscle will adjust to the necessary energy system. To challenge the lactate (glycolytic) system, the breakdown of glucose or glycogen anaerobically produces energy plus lactate and hydrogen ions (H+). When the demand for energy exceeds the body's ability to produce energy with oxygen, the muscle will become acidic. The presence of hydrogen ions, not lactate, makes the muscle acidic which will eventually shut down the system. For each lactate formed, one corresponding hydrogen ion is formed. This system operates in the muscle cell and its chemical reaction is: GLUCOSE + Pi + ADP + ATP + LACTATE + H+. SOS

The formation of lactate is not necessary for the delivery of energy, but it serves as a storehouse for the hydrogen, and thereby, keeps the reaction going. Under anaerobic conditions, the accumulation of hydrogen ions is the limiting factor causing fatigue in runs of 300 to 800 meters. SOS

The task now is to link this scientific information for design of accurate and working methods to developing training sessions for the lactate energy system. Distances of 300 to 600 meters may be used by coaches to do high lactate work. It is necessary to mentally and physically prepare to do this type of work due to the possibility of injury. High quality lactate work can shock the body and the central nervous system. SOS Thus, loads (Total Distance and Volume) and intensities (Percent of Maximum) must be progressively sequenced. For example, sequencing workouts to prevent injuries may be achieved by planning each day of the week of an entire year. Each workout is a single unit of preparation designed to produce a desired result and each session is more demanding than the previous.

Recovery sessions from high quality lactate work must be sequenced in a set pattern. The duration of the exercise bout should be representative of the ration of recovery. If you have 60 seconds of exercise (400m), recovery should be 120 seconds if you wish to have a 1:2 ration. Other examples SOS are 1:1.5, 1:1 depending on the goal of the training session. Prior knowledge of the athletes' work SOS capacities and prior experience is essential in dictating the load and intensity in each unit. A first year athlete will not work at the same level that a fourth year athlete would. To fit into a "real live" training session, for example, the athletes on the same team would run the same distance and time on the interval (ie., 60 seconds for 400m). The novice athlete would rest (jog during rest) on every other repeat to fully recover from the high lactate work (a 1:4 ratio). The veterans would run at a 1:2 ration, since they are experienced and have developed the fitness to tolerate this high lactate work. Thus, allowing one coach to complete individual goals while training a large group. The intensity (ie. 60 seconds for 400m) is key to this type of training along with the recovery (a 1:4 or 1:2 ration). *

SOS

The accumulation of lactate in working skeletal muscle will terminate this system after 50 to 60 seconds of maximum effort. Although all energy systems basically turn on at the same time, be aware that progressive recruitment of alternative pathways or systems occurs when one system is challenged more heavily, since another energy source has been depleted. Because of the very high quality work involved in the lactate system, in most cases, only 1 to 5 reps with full or near full recovery can be done twice a week. Only by challenging the right energy system will the desired physiological change and improved performance occur. Understand, at times, less work gives greater rewards.

③

The aerobic system is capable of utilizing proteins, fats and carbohydrates (Glycogen) for resynthesizing large amounts of ATP without simultaneously generating fatigue by-products with respect to sports. It is easy to see that the aerobic system is particularly suited for manufacturing ATP during prolonged endurance type activities. The intensity of the run dictates which energy system will be challenged and the method of ATP production in the muscle.

In the aerobic system, pyruvate from the glucose, glycogen and/or fatty acids (Stored Fats) are first converted to acetyl CoA, which is then oxidized to Carbon Dioxide (C02), and water (H20). Oxidation of acetyl CoA occurs in the Krebs Cycle (Citric Acid Cycle) and the electron transport system located in the mitochondrian of the muscle wall. For each molecule of blood glucose oxidized aerobically, 38 molecules of ATP are produced while muscle glycogen produces 39 molecules of ATP. Muscle glycogen is capable of producing 1 more molecule of ATP than blood glucose because it takes 1 ATP molecule to transfer blood glucose into the cell. The energy production in aerobic metabolism is 18 times greater than in the anaerobic system production of ATP.

Note that for this system to function, oxygen must be available, hence the term aerobic. It is the availability of oxygen in the cell which determines to what extent the process is aerobic and anaerobic. If the aerobic energy system cannot supply enough oxygen (anaerobic), pyruvate becomes a hydrogen acceptor and forms lactate. This is the critical step in the whole process when lactate forms, since it will eventually shut down all the energy systems. Note that lactate levels can become quite high using intensive tempo work since it borders on speed endurance and special endurance. Remembering that all energy systems turn on at basically the same time, intensive tempo running makes high demands on both the aerobic and anaerobic, and thus, is a sharing system.

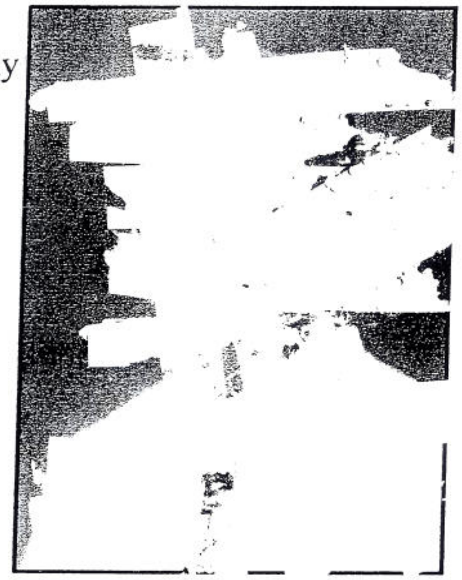
ΣΜΥΡΝΙΩΤΟΥ

Energy Demands and Event Specific Exercise Training

Α' ΕΤΟΣ

2004-05

By Jack Ransone, Ph.D., Associate Professor of Human Performance
Oklahoma State University
USATF Coaching Education Level II and Level III Instructor



In athletics today, some coaches succeed and some fail. What determines success and failure is dependent on many variables and, in the words of one famous coach, "a little luck." This article will examine the relationship between energy production and exercise demands.

The three metabolic pathways by which the body can produce ATP include: the anaerobic (ATP-CP) energy system, the anaerobic lactate (glycolytic) energy system, and the aerobic energy system. In order to get specfic adaptations from each of the energy systems, the coach must scientifically design workouts to challenge them. Anaerobic capacity is limited by the production of lactic acid and the system's ability to tolerate or buffer these acids. Anaerobic training involves high intensity work, such as speed work, stressing the lactate system. Aerobic training is associated with the capacity to deliver oxygen and the ability to utilize oxygen. In that vain, aerobic training involves both intensity and duration, depending on whether the emphasis is on power or endurance. The aerobic energy system is stressed by having athletes engage in continuous, extensive, and intensive tempo runs. In particular, speed endurance and special endurance workouts stress the lactate system in different ways. To summarize, if a coach has a general understanding of the energy systems, they can more effectively design workouts that meet the specific energy demands for the events that their athletes compete in.

In either the aerobic or anaerobic energy production, the predominant muscle fiber type is highly determinant of inherent capacity for energy production. In track and field, various activities recruit different muscle groups. The physiological specificity of these events is of utmost importance to training methodology. Furthermore, performance time determines whether an event is primarily aerobic or anaerobic. For example, the physiological demands of the 800 meter runner are radically different from those of a 5000 meter runner.

A runner's ability to perform work is not the only function of his/her aerobic capacity (VO2), but demands an efficient anaerobic energy metabolism. The demands for running derive from aerobic and anaerobic sources. The relative contribution of each to the total energy production depends on the demand of the actual event. To successfully design a workout does not only require a knowledge of the energy systems, but how these systems can be integrated together to form a full training cycle or session. One technique involves

~~The accumulation of lactate in working skeletal muscle will terminate this system after 50 to 60 seconds of maximum effort. Although all energy systems basically turn on at the same time, be aware that progressive recruitment of alternative pathways or systems occurs when one system is challenged more heavily, since another energy source has been depleted. Because of the very high quality work involved in the lactate system, in most cases, only 1 to 5 reps with full or near full recovery can be done twice a week. Only by challenging the right energy system will the desired physiological change and improved performance occur. Understand, at times, less work gives greater rewards.~~

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the integration of the energy systems and the energy continuum. The chart below illustrates how the relative contributions of aerobic and anaerobic energy sources contribute to energy production during various durations of maximal exercise.

	ATP-CP		Lactic Acid Systems					Oxygen Systems			
% Aerobic	0	10	20	30	40	50	60	70	80	90	100
% Anaerobic	100	90	80	70	60	50	40	30	20	10	

How does the energy continuum help in workout design? Following the philosophy of Dr. Joe I. Vigil of Alamosa, Colorado, elite distance running lecturer and coach, the relationship between the demand for energy for each given event relates directly to the annual training program design. For example, an 800 meter running event requires approximately 30% aerobic and 70% anaerobic. The annual training load should encompass 30% aerobic and 70% anaerobic. This doesn't mean that these percentages should be incorporated in every daily training workout. The early general preparation, possibly consisting of one 8 week period, may actually incorporate 90% aerobic and 10% anaerobic workouts. The final peaking period may actually be made of 20% aerobic and 80% anaerobic. Again, Dr. Vigil's theory relates to annual training plan. If your 800 meter athlete runs 1500 miles a year, than 450 miles (30%) should be done aerobic and 1050 miles (70%) run anaerobic.

SOS

How would you train a 5000 meter runner? Almost the exact opposite percentages in demand being 70% aerobic and 30% anaerobic. If your athlete's annual training load is 2000 miles, then 1400 miles would be performed aerobically and 600 miles done anaerobically. If this sounds all too simple, that's actually what it is-- very simple. The art of coaching ~~is~~ when to increase or decrease these ratios within a given cycle and knowing how to ~~monitor~~ the athletes for signs of overtraining or injury.

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Nutritional strategies to optimize training and racing in middle-distance athletes

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Abstract

Middle-distance athletes implement a dynamic continuum in training volume, duration, and intensity that utilizes all energy-producing pathways and muscle fibre types. At the centre of this periodized training regimen should be a periodized nutritional approach that takes into account acute and seasonal nutritional needs induced by specific training and competition loads. The majority of a middle-distance athlete's training and racing is dependant upon carbohydrate-derived energy provision. Thus, to support this training and racing intensity, a high carbohydrate intake should be targeted. The required energy expenditure throughout each training phase varies significantly, and thus the total energy intake should also vary accordingly to better maintain an ideal body composition. Optimizing acute recovery is highly dependant upon the immediate consumption of carbohydrate to maximize glycogen resynthesis rates. To optimize longer-term recovery, protein in conjunction with carbohydrate should be consumed. Supplementation of β-alanine or sodium bicarbonate has been shown to augment intra- and extracellular buffering capacities, which may lead to a small performance increase. Future studies should aim to alter specific exercise (resistance vs. endurance) and/or nutrition stimuli and measure downstream effects at multiple levels that include gene and molecular signalling pathways, leading to muscle protein synthesis, that result in optimized phenotypic adaptation and performance.

Keywords: *Periodized nutrition, middle distance, recovery, adaptation, supplements, performance*

Introduction

The middle-distance runner is the most diverse athlete in the athletics arena when it comes to the utilization of a myriad of energy systems to supply adenosine triphosphate (ATP) to meet energy demands. Highly trained athletes can achieve 20 times resting oxygen uptake ($\dot{V}O_2$) values (Daniels & Daniels, 1992), and in a 1500-m race athletes work at $\sim$115% of maximal oxygen uptake ($\dot{V}O_{2\max}$) for approximately 4 min, with post-race blood lactate concentrations exceeding 20 mmol $\cdot$ l^{-1} (Osnes & Hermansen, 1972). However, $\sim$60 and $\sim$75% of energy production is still derived from aerobic sources in 800-m and 1500-m events, respectively (Spencer & Gastin, 2001).

Thus, middle-distance athletes must develop all energy pathways and muscle fibre types through a dynamic continuum in training volume, duration, and intensity. The remarkable diversity of training stimuli is evident when examining athletes' schedules (Martin & Coe, 1991). During the aerobic development phase a middle-distance athlete's volume will rival that of a marathon runner, but during the competition phase, it will nearly mimic a sprinter's intensity. Moreover, most athletes undergo resistance and plyometric exercises to develop neuromuscular and nervous system adaptations. This understanding of the different energy systems, and required fuels to produce ATP, must be taken into consideration when recommending both acute and seasonal nutritional intakes to optimize training adaptations and race performance.

Therefore, the aim of the current review is to outline nutrition recommendations during training and racing specific to middle-distance athletes, with an emphasis on the 800-m and 1500-m events. This paper will focus on modern science in conjunction with practical training and racing constraints to develop usable guidelines. Finally, some of the limitations that athletes face, such as global championship racing schedules, as well as some emerging data on supplements and training adaptations, are also explored.

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Periodized nutrition for yearly periodized training

Periodization involves the progressive cycling of various aspects of a training programme during a specific period of time into discrete phases, to optimize the yearly training structure towards a peak championship performance (Martin & Coe, 1991). In short, the training stimuli during these different phases can differ drastically in terms of intensity, volume, and duration, and thus so do the types of fuels that are used to generate ATP (Tables I and II). A brief overview of energy systems, fuel utilization, and associated muscle fibre types used during exercise will set the structure for the subsequent nutritional recommendations.

Energy metabolism

During the transition from rest to maximal exercise intensity, the demand for ATP can increase more than 100-fold in elite athletes, and carbohydrate provides the majority of the fuel for exercise intensities exceeding 75% $\dot{V}O_{2max}$. Carbohydrate can act as a fuel for ATP provision for both substrate phosphorylation and oxidative phosphorylation (also collectively referred to as "anaerobic" glycolysis and "aerobic" metabolism, respectively), while fat is exclusively metabolized via oxidative phosphorylation (Table II). Oxidative phosphorylation provides the bulk of ATP provision during training of low to moderate intensity, primarily utilizing fat as a fuel. Fat can be provided in both endogenous muscle stores (intramuscular triacylglyceride) and as fat stored in peripheral adipocytes and released as plasma free fatty acids. During low-intensity exercise, primarily Type I slow twitch oxidative fibres are recruited, which have a high oxidative capacity to utilize primarily fat. However, during exercise that involves increasing intensity, when ATP production from oxidative phosphorylation cannot match the rate of ATP hydrolysis, the shortfall in oxidative energy supply is met by substrate phosphorylation. Substrate phosphorylation provides energy via phosphocreatine utilization, and the metabolism of muscle glycogen, via the glycolytic pathway with lactate formation (Saltin, 1990). During high anaerobic energy production, there is an increased firing of Type IIa fibres. These fibres have both a high oxidative capacity as well as a large capacity for glycolysis, leading to an increased reliance on carbohydrate as a fuel. Since these fibres can provide energy via both aerobic and anaerobic means, it is not surprising that elite middle-distance runners have highly developed Type IIa muscle fibre morphology (Saltin, Henriksson, Nygaard, Andersen, & Jansson, 1977). Finally, at very high workloads, Type IIb glycolytic muscle fibres become activated to maintain the high demand of ATP provision via anaerobic glycogenolysis (Table II). This leads to the extreme levels of lactate production associated with all middle-distance races and many training situations. Therefore, middle-distance athletes have several highly developed energy-producing pathways that utilize different blends of phosphocreatine, carbohydrate, and/or fat, coupled with greater muscle buffering capacity, to handle a range of different metabolic demands during varying training intensities and racing.

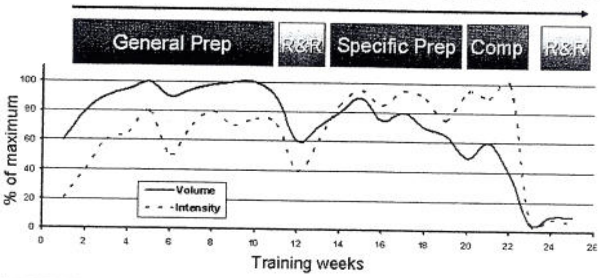
General macronutrient recommendations

Carbohydrate. When exercising above 75% $\dot{V}O_{2max}$, the amount of carbohydrate used during exercise rises abruptly (Romijn *et al.*, 1993). During resistance exercise, the body also relies heavily on anaerobic ATP production, with declines reported in muscle glycogen of 25–40% after a multiple-set resistance exercise bout (Koopman *et al.*, 2005). Since much middle-distance training is performed at or above 75% $\dot{V}O_{2max}$, and this dependency on carbohydrate-based ATP provision increases throughout the training year towards a championship peak, carbohydrate-rich foods must provide the majority of the energy provision. Bergstrom and colleagues (Bergstrom, Hermansen, Hultman, & Saltin, 1967) were the first to show that a high carbohydrate diet results in augmented glycogen stores, translating into an increased time to exhaustion, compared with a low carbohydrate diet. Conversely, low carbohydrate diets (3–15% carbohydrate) have uniformly been shown to impair performance in high-intensity and endurance-based exercise (Coggan & Coyle, 1991). Consequently, recommendations have been made to endurance athletes to eat a diet chronically high in carbohydrate, which will enable longer and harder training sessions to optimize the training adaptation. However, mixed results have been published about whether a high carbohydrate diet (60–70% of total energy) provides increased performance benefits over a moderate carbohydrate diet (50–55% of total energy) (Burke, Kiens, & Ivy, 2004), and new evidence suggests the possibility of conducting *some* training in a glycogen-depleted state for improved adaptation and performance (see "Future Directions").

In dietary recall records, male endurance athletes report consuming between 8.4 and 9.1 grams of carbohydrate per kilogram of body weight per day (g CHO · kg BW^{-1} · day^{-1}), which is within the recommended range (Burke, Cox, Cummings, & Desbrow, 2001). The diet of world-class African runners is also predominantly carbohydrate (Onywera, Kiplamai, Boit, & Pitsiladis, 2004). In contrast, female endurance athletes report much

Table I. Daily macronutrient intake recommendations during different yearly training phases.

Training phase



	General prep.		Specific prep.		Competition		Transition/R&R	
	Light	Heavy	Light	Heavy	Light	Heavy	Light	Heavy
Estimate weekly training volume								
km · week^{-1}	< 100 km	> 150 km	< 80 km	> 130 km	< 70 km	> 90 km	< 15 km	> 50 km
h · week^{-1}	5–8 h	10 h+	4–7 h	6–9 h	3–5 h	4–7 h	< 2 h	2–4 h
Training intensity	Low		Moderate to high		Tapered training volume and intense racing		Very low to complete rest	
Recommended daily macronutrient intake (g · kg^{-1} · day^{-1})								
CHO	7	10	7	10	7	10	4	6
FAT	1.5	2	1	1.5	0.8	1.2	1	1.5
PRO	1.5	1.7	1.5	1.7	1.2	1.5	0.8	1.2
Percent of total daily energy intake								
%CHO	~60%		~66%		~70%		~57%	
%FAT	~28%		~22%		~18%		~32%	
%PRO	~12%		~12%		~12%		~11%	
Total daily energy intake								
kJ	~13900	~18900	~12600	~17600	~11700	~16600	~8200	~12400
kcal	~3300	~4500	~3000	~4200	~2800	~4000	~2000	~2900

Note: Nutrition recommendations for a 70-kg athlete (adapted from Burke *et al.*, 2001, 2004; Tarnopolsky, 1999; Tipton & Wolfe, 2004). Prep, preparation; CHO, carbohydrate; FAT, fat; PRO, protein; kJ, kilojoules; kcal, nutritional calorie. R&R, rest & recovery/transition phase.

lower relative daily carbohydrate intakes (5.5 g CHO · kg BW^{-1} · day^{-1}), and also lower values for mean energy intake per kilogram of body weight, than male athletes [170 kJ · kg BW^{-1} · day^{-1} for females; 230 kJ · kg BW^{-1} · day^{-1} for males (Burke *et al.*, 2001)]. Hence, a greater emphasis needs to be placed on helping females meet their recommended carbohydrate and energy intake needs. It is also vital during situations of high carbohydrate intakes that athletes do not neglect the other important macro- and micronutrients. Therefore, to maintain immune function (Gleeson, 2002), recover glycogen storage (Costill, Bowers, Branam, & Sparks, 1971), and reduce over-reaching (Achten *et al.*, 2004), a habitually high carbohydrate diet (7–10 g CHO · kg BW^{-1} · day^{-1}) is recommended.

Fat. Fat provides fuel at a low to moderate exercise intensities. Fat also provides about 4-fold more ATP per molecule (~145 vs. 38 ATP) than carbohydrate, but the ATP provision per litre of oxygen is about 10% less when fat is the fuel than when carbohydrate is oxidized. When oxygen supply is limiting, this difference is critical. However, due to its energy density, over-consumption of dietary fat can lead to unwanted increases in body weight. The majority of fat is stored in adipose tissue, but skeletal muscle also stores a significant amount of fat in the form of intramuscular triacylglyceride (IMTG). There continues to be considerable interest in the function of IMTG as a fuel source during exercise (Watt, Heigenhauser, & Spriet, 2002), and whether a lack of post-exercise lipid intake can influence IMTG content enough to limit endurance performance or decrease the training load (Decombaz, 2003). Interestingly, Koopman *et al.* (2005) recently reported a 27% decline in IMTG after a 45-min resistance exercise protocol, which suggests that IMTG can also contribute significant energy during intense exercise. It was recently reported that a "fat-adaptation/carbohydrate-restriction" protocol, in which individuals consumed elevated amounts of

Table II. Acute post-exercise dietary recommendations with respect to the adaptations incurred by periodized training.

Training objective, development, and adaptation	Examples of training sessions	Vol./Time	Inten.	Energy system	Fibre type	Fuels utilized	Acute dietary recommendations
Aerobic capacity – oxidative Enzymes/fat metabolism/ endurance	easy/recov. run of 30–75 min long runs 1–3 h	High	Low	Oxid. phos.	ST Oxid.	Mainly FATS	*During aerobic training:* CHO: ~1–1.4 $g \cdot kg^{-1} \cdot h^{-1}$
Aerobic power – oxidative & glycolytic enzymes/anaerobic threshold/lactate tolerance	8 × 3 min reps on 3-min recov. 1–2 min reps on 2–4 min recov. hill runs of 45–60 s	↑	↑	↑	↑	↑ FATS/CHO	*Short-term (<4 h) recov:* CHO: 1.2–1.5 $g \cdot kg^{-1} \cdot h^{-1}$
Anaerobic capacity – glycolytic enzymes/CHO metabolism/lactate tolerance/ muscular strength	8–10 × 1 min on 1 min recov. 45–90 s reps on 3–6 min recov.					↕ CHO ↕	*Longer term (>20 h) recov:* CHO: ~1 $g \cdot kg^{-1} \cdot h^{-1}$ EAA: ~0.1 $g \cdot kg^{-1} \cdot h^{-1}$ over first 2 h post-exercise
CP capacity & power – near maximal repeatable muscular contraction strength	15–30 s reps with ~3–4 min rests	Mod.	Mod.	Subs. phos.	FTa Oxid./ Glycolytic	CHO & ATP/PCr	
Muscular endurance – sub-maximal repeated muscular strength	Circuit-based training e.g. 3–4 sets of 15–20 reps lower weight	↓	↓	↓	↓	↓	
Muscular strength – maximal contraction ability & muscular hypertrophy	Weight training 2 or 3 sets of 1–5 reps near maximal weight						*During resistance exercise and 2 s post-exercise:* CHO: ~0.5 $g \cdot kg^{-1} \cdot h^{-1}$
Neural firing – Technique, economy & effectiveness of effort	Plyometric training, sprints, speed & hurdle drills	Low	High	CP energy	FTb Glycolytic	ATP/PCr	EAA: ~0.1 $g \cdot kg^{-1} \cdot h^{-1}$

Note: Nutrition recommendations adapted from Burke *et al.* (2004), Tarnopolsky (1999), and Tipton and Wolfe (2004). ATP, adenosine triphosphate; CHO, carbohydrate; CP, creatine phosphate; EAA, essential amino acids; FTa, fast-twitch oxidative Type II muscle fibre; FTb, fast-twitch glycolytic Type II muscle fibre; Int., intensity; Mod., moderate; Oxid. phos., oxidative phosphorylation; recov., recovery; reps, repetitions; ST, slow-twitch oxidative Type I muscle fibre; Subst. Phos., substrate phosphorylation; Vol., volume.

fat (>4 g fat · kg BW^{-1} · day^{-1}) while training for 5 days, followed by a carbohydrate loading day, resulted in a decreased use of carbohydrate by measured decreases in glycogenolysis and pyruvate dehydrogenase activation (Stellingwerff *et al.*, 2006). This "glycogen use impairment" would most likely decrease performance for a middle-distance athlete by inhibiting glycogen breakdown and aerobic carbohydrate oxidation via pyruvate dehydrogenase. Therefore, it is currently not recommended for middle-distance athletes to undertake any type of dietary fat adaptation in search of increased performance enhancement. However, fat is an important component of a healthy balanced diet.

Protein. Protein serves several key functions, which include roles as enzymes, the processes of cell signalling, and as fibrous structural proteins that comprise cell cytoskeletons and muscle fibres. During endurance exercise, protein oxidation accounts for only 2–5% of total energy expenditure. However, this proportion of amino acid oxidation can increase when training at higher intensities, during longer exercise durations, or when carbohydrate stores are depleted (for reviews, see Tarnopolsky, 1999; Tipton & Wolfe, 2004). Since protein (PRO) intake in excess of 1.7 g PRO · kg BW^{-1} · day^{-1} has been shown to be oxidized, Tarnopolsky (1999) has estimated that highly trained endurance athletes who undertake a large and intense training load should ideally aim for between 1.5 and 1.7 g PRO · kg BW^{-1} · day^{-1}. Some athletes (primarily females) are over-mindful of the benefit that low body weight brings to performance, and many believe that post-exercise protein consumption may bring unwanted gains in muscle mass, ultimately leading to weight gain. However, recent evidence has suggested that the specific exercise stimulus (resistance vs. endurance), rather than the nutrition intervention, plays a more dominant role in the divergent signalling pathways and the types of proteins that are synthesized after exercise, which explains the adaptive response and divergent phenotypes (Atherton *et al.*, 2005). Aerobic exercise also reduces the stimulus for hypertrophy (Hickson, 1980) and increases mitochondrial, instead of myofibrillar, proteins (Holloszy & Coyle, 1984). Therefore, it could be hypothesized that protein intake after endurance exercise is necessary not only for the recovery and repair of damaged myofibrillar proteins, but also for the optimized synthesis of mitochondrial and possibly sarcoplasmic proteins.

Despite some reservations regarding protein intake by endurance athletes, the scientific discussion regarding the optimum daily protein intake for athletes appears irrelevant. Dietary studies in endurance athletes from Western countries have consistently shown that athletes generally consume more protein than any elevated dietary recommendation (Tarnopolsky, 1999). In summary, it appears that elite endurance athletes in a hard training phase should ideally consume between 1.5 and 1.7 g PRO · kg BW^{-1} · day^{-1} (Table I). For a 70-kg athlete consuming 3500 kcal · day^{-1}, this would require only about 12% energy intake from protein, which can easily be met in a balanced diet without the need for protein supplementation.

Ultimately, all of the above general macronutrient recommendations need to be appropriately implemented within the individual athlete's training plans and competition goals. Therefore, periodized nutrition recommendations will be made across the four primary mesocycles of (1) general preparation, (2) specific preparation, (3) competition, and (4) transition (Table I). The recommended macronutrient intakes in each training phase are broad enough to cover a wide range of training programmes and caloric needs, but individual fine-tuning may be needed to meet the specific nutrition goals of each phase.

General preparation phase: Aerobic and strength development

Training. Aerobic training during this phase comprises large training volumes at lower intensities ($\sim$50–75% $\dot{V}O_{2max}$), in which fat can be the dominant fuel, but large amounts of carbohydrate are oxidized at exercise intensities approaching the onset of blood lactate accumulation. Aerobic conditioning improves oxidative capacities in heart and in Type I skeletal muscle fibres, through the proliferation of mitochondrial and capillary density (Holloszy & Coyle, 1984). Contemporary training regimens during this phase also place great emphasis on strength-based training, such as resistance exercises, circuit training, and short-hill repeats. Furthermore, due to the large energy expenditures during this training phase, athletes can gradually improve body composition goals (percent body fat, weight) towards the competition phase.

Nutrition. The general preparation phase is dominated by elevated energy expenditure to support the large training load. Thus, carbohydrate intake should be high, ranging from 7 to 10 g CHO · kg BW^{-1} · day^{-1}. Due to the large contribution of fat stores to aerobic ATP production, recommended fat intake is highest during this phase (1.5–2.0 g fat · kg BW^{-1} · day^{-1}), translating into $\sim$30% of total energy. With high training volumes, coupled with resistance exercise, recommendations for protein during this phase are 1.5–1.7 g PRO · kg BW^{-1} · day^{-1} (Table I).

Specific preparation phase: Anaerobic, power, and speed development

Training. In the specific preparation phase there is an increased emphasis on anaerobic capacity and aerobic power, while still maintaining the developed aerobic capacity from the previous mesocycle. Furthermore, there is continued development of anaerobic tolerance ($\sim 75-90\%$ $\dot{V}O_{2max}$), with some sessions targeted at $\dot{V}O_{2max}$. The primary adaptations include maximizing the heart and cardiovascular system ($\dot{V}O_{2max}$ sessions), activating more Type II fibres, increasing glycolytic enzyme density, and progressively adapting skeletal muscles to higher levels of muscle acidosis. Any final body composition goals should be met during this period, prior to the start of the competition phase. Over-restriction of energy and/or carbohydrate intake can hinder performance and impair immune function (Gleeson, 2002). Thus, the athlete should not attempt either rapid or considerable weight loss regimes before, or during, the competition phase.

Nutrition. The primary fuel for the type of intense training dominated by the specific preparation phase is carbohydrate, and thus intake remains at $7-10$ g $CHO \cdot kg\ BW^{-1} \cdot day^{-1}$. Due to the decreased total energy expenditure, the relative intake of dietary fat can be reduced to about $20-25\%$ of total energy, or $1-1.5$ g $fat \cdot kg\ BW^{-1} \cdot day^{-1}$. Protein recommendations should be maintained at $1.5-1.7$ g $PRO \cdot kg\ BW^{-1} \cdot day^{-1}$ (Table I).

Competition phase: Taper and peaking

Training. The competition phase is characterized by short, intensive exercise and tapering of training volume towards a championship peak. This results in a decrease in total energy expenditure, but most workouts and races are conducted at very high intensities, ($< 130\%$ $\dot{V}O_{2max}$) and at nearly maximum speed to fully develop lactate tolerance. The enhancement of neural firing capacity needs to be developed through the full activation of all fibre types. The primary goal is to have the athlete reach a physiological and psychological peak, in which the year's best performances are achieved.

Nutrition. The ever increasing intensity of training and racing demands a consciously high carbohydrate intake of $7-10$ g $CHO \cdot kg\ BW^{-1} \cdot day^{-1}$. Fat intake is reduced further during the competition phase to ~ 1 g $fat \cdot kg\ BW^{-1} \cdot day^{-1}$, while protein intake should be at a level to maintain lean muscle mass ($1.2-1.5$ g $PRO \cdot kg\ BW^{-1} \cdot day^{-1}$) (Table I). Finally, it has been shown that *ad libitum* energy intake is not immediately matched by reduced energy expenditure, as found during the competition phase (Stubbs *et al.*, 2004). Therefore, athletes need to make conscious decisions about limiting their total energy intake during this phase to maintain an ideal peak body composition.

Transition phase/rest days: Physical recovery

Training. The primary goal of the transition phase or rest day is to recover from the previous meso- or microcycle, allowing for training adaptations to occur while preventing over-reaching symptoms. Thus, training volume and intensity are generally very low. Although small shifts in body weight and percent body fat will occur during the transition phase, the athlete should attempt to maintain a relative weight balance throughout the year. Weight gains should be limited to less than 5% of total body weight. Accordingly, the training load and required energy expenditure throughout each training phase vary significantly, and thus the total energy intake should also vary accordingly (Table I).

Nutrition. Due to the diminished training volume and intensity, nutritional energy intake during this phase/day must be reduced, and thus the macronutrient recommendations are much the same as for the general public (Table I).

Acute and specialized nutrition recommendations

Nutrition strategies during training

A large body of evidence has shown the beneficial performance effects of carbohydrate and fluid intake during prolonged endurance exercise (for a review, see Coyle, 2004). Since middle-distance events are only a few minutes in duration, it is vital that athletes commence their races euhydrated and with full muscle glycogen stores. However, given that some endurance training sessions approach 2 h in total length, there is ample opportunity to benefit from carbohydrate and fluid intake during training, and current recommendations are set to about $30-60$ g $CHO \cdot h^{-1}$ for athletes during exercise (American College of Sports Medicine, 2000; Table II). More information on carbohydrate and fluid intake recommendations during exercise are covered by Burke and colleagues (Burke, Millet, & Tarnopolsky, 2007) and Shirreffs and colleagues (Shirreffs, Casa, & Carter, 2007), respectively. Tipton and co-workers (Tipton, Jeukendrup, & Hespel, 2007) highlight the potential benefits of consuming protein and amino acids before and during resistance training to enhance net protein balance.

Nutrition for optimized recovery

After a hard training session or competition, the overriding priority for every athlete should be recovery. The primary roles of post-exercise nutrition are to (1) immediately maximize glycogen resynthesis rates in the short term (<4 h), and (2) replenish endogenous fuel stores, repair muscle damage, and increase protein synthesis over the longer term (24 h+).

Short-term recovery (<4 h). Enhancing immediate recovery is especially important when an athlete is faced with a short recovery period, such as between rounds of races at a major championship event, or between hard training sessions on the same day. The highest rates of muscle glycogen synthesis occur during the hour immediately after exercise (Ivy, Katz, Cutler, Sherman, & Coyle, 1988), due to glycogen phosphorylase activation from the preceding glycogen-depleting exercise (Wojtaszewski, Nielsen, Kiens, & Richter, 2001) and greater post-exercise insulin sensitivity (Richter, Mikines, Galbo, & Kiens, 1989). Ivy *et al.* (1988) also showed that delaying the ingestion of a carbohydrate supplement post-exercise (>2 h) will result in a reduced rate of muscle glycogen storage. The type of carbohydrate consumed during recovery may also influence glycogen synthesis rates. Burke and colleagues (Burke, Collier, & Hargreaves, 1993) showed that 24-h glycogen recovery was enhanced when participants consumed high glycaemic index (GI) carbohydrates, compared with low GI carbohydrates. To maximize post-exercise glycogen resynthesis rates, contemporary studies suggest using frequent smaller doses (20–30 g carbohydrate every 20–30 min) for an overall intake rate of 1.2–1.5 g $\text{CHO} \cdot \text{kg BW}^{-1} \cdot \text{h}^{-1}$ for the first several hours of recovery (van Hall, Shirreffs, & Calbet, 2000; van Loon, Saris, Kruijshoop, & Wagenmakers, 2000b) (Table II).

It is well known that certain amino acids are insulinotropic [e.g. leucine, phenylalanine (van Loon, Kruijshoop, Verhagen, Saris, & Wagenmakers, 2000b)], so this theoretically could result in enhanced glycogen recovery through the addition of protein to a carbohydrate-based recovery drink to increase the response of insulin-mediated glycogen synthesis. Several studies have shown augmented glycogen storage when protein is added to carbohydrate ingested after exercise (Berardi, Price, Noreen, & Lemon, 2006; Ivy *et al.*, 2002; Zawadzki, Yaspelkis, & Ivy, 1992), but the majority of studies have found no further effect of the co-ingestion of carbohydrate and protein mixtures on post-exercise glycogen recovery (Carrithers *et al.*, 2000; Tarnopolsky *et al.*, 1997; van Hall *et al.*, 2000; van Loon *et al.*, 2000b). These conflicting results can be explained by differences in experimental designs, the amounts of carbohydrate and protein used, and the dosing patterns, but most likely the fact that several of the earlier studies featured nutritional interventions of varying energy content between treatment groups. Taken together, it would appear that when carbohydrate intake is sufficient for maximal glycogen resynthesis rates (1.2–1.5 g $\text{CHO} \cdot \text{kg BW}^{-1} \cdot \text{h}^{-1}$; Table II), the addition of protein will not further increase glycogen storage.

Long-term recovery (>24 h). During longer-term recovery, protein intake in conjunction with carbohydrate is vital to maximize muscle glycogen resynthesis, protein synthesis rates, and the repair of damaged muscle tissues, which is primarily accomplished through the intake of regular meals (for reviews, see Tarnopolsky, 1999; Tipton & Wolfe, 2004). Delaying the timing of post-exercise protein intake (>3 h) can also result in a negative net protein balance (Levenhagen *et al.*, 2001). Several recent studies have suggested a positive effect of attenuating muscle damage and perceived muscle soreness after running when protein was added to a carbohydrate-based recovery drink (Luden, Saunders, & Todd, 2007; Millard-Stafford *et al.*, 2005). The explanation for the decreased muscle soreness found in the latter study is confounded by the addition of antioxidants in conjunction with carbohydrate and protein in the recovery drink. Despite the protein + carbohydrate drink decreasing muscle soreness after two runs to fatigue separated by 2 h, performance during a 5-km time-trial conducted 24 h later was unaffected (Millard-Stafford *et al.*, 2005).

In summary, current literature suggests that, during longer-term recovery, to initiate acute post-exercise protein synthesis, athletes should consume ~ 0.1 $\text{g} \cdot \text{kg BW}^{-1}$ of essential amino acids (Tipton & Wolfe, 2004), together with 1–4 g $\text{CHO} \cdot \text{kg BW}^{-1}$ within 4 h after exercise (Table II). Decombaz (2003) has suggested that carbohydrate intake should be the immediate priority during the initial 6–8 h after hard training, with increasing amounts of dietary fat taken through subsequent regular meals. However, it remains to be clarified what is the best macronutrient blend, feeding pattern, type of carbohydrate and/or protein, and the intake timing to optimize recovery and adaptation after different types of exercise stimuli.

For athletes at major championships that feature multiple races, recovery after each race can be the key to success in the final. Thus, it is imperative that the athlete have a sound and well-practised nutrition regimen, as outlined below:

- Before a championship, evaluate several individualized pre-competition meal options during training that are convenient, readily available, and feel "right" for the athlete (no gastrointestinal discomfort). These meals should be high in carbohydrate ($1-4$ g · kg BW^{-1}) and consumed $1-6$ h before competition.

- Athletes should aim for between 400 and 600 ml of either a sport drink and/or water with electrolytes in the $60-120$ min before competition, unless the weather is cold and/or they are sure that they are well hydrated.
- A common mistake during the high stress of major championships is when athletes become *too* aware and compulsive about eating and drinking, or are influenced by what other athletes might be consuming. Athletes then tend to consume too much, too little, or drastically change their normal habits to mimic others. The key is to focus on what works for the individual, and consume the same amount and types of fluids/foods as during previous competitions. Implement a specific nutrition plan for athletes susceptible to compulsive eating.
- Many athletes also consume a small snack (e.g. sports bar, fruit) and sports drinks $1-3$ h before warming up for an event.
- It is vital that the athlete and coach plan ahead and always have the proper amount of post-race foods and fluids available *immediately* to optimize post-race glycogen and muscle recovery. Carbohydrate-rich foods and fluids with a medium to high glycaemic index at an intake rate of about $1-1.5$ g CHO · kg $BW^{-1} \cdot h^{-1}$ for the first 4 h should be the target.
- Due to usual competition constraints, it is normally very difficult to get a meal immediately after the race. Sports nutrition products can meet many of these initial carbohydrate and protein needs, and are convenient and familiar, until a normal meal can be consumed.

Supplements and the middle-distance runner

Fatigue during any maximal-intensity exercise lasting from ~2 to 10 min is a consequence of the limitations imposed by anaerobic glycolysis. Although anaerobic glycolysis can regenerate ATP at a very high rate, the resultant metabolic acidosis from the production of lactate (La^-) and hydrogen ions (H^+) can alter acid–base homeostasis. This augmented H^+ production causes a drop in intramuscular pH, which has been shown to inhibit glycolytic enzymes, interfere with calcium handling, and inhibit actin–myosin interactions (Maughan & Greenhaff, 1991). Thus, any process that can directly buffer intramuscular H^+, or increase the rate of H^+ efflux from the muscle, will theoretically lead to a performance increase. It has long been known that metabolic alkalosis can be induced through the consumption of sodium bicarbonate ($NaHCO_3$) or sodium citrate (Dill, Edwards, & Talbot, 1932), and a plethora of studies with mixed findings have followed (for a review, see McNaughton, 2000). Researchers have examined both the acute and chronic dosing effects of $NaHCO_3$ on high-intensity exercise performance. More recently, the effects of β-alanine on intramuscular H^+ buffering have been examined. All of these substances are not on the World Anti Doping Agency's (WADA) prohibited substances list. [For further information on other ergogenic substances, see Maughan, Depiesse, and Geyer, 2007).]

Acute bicarbonate loading

A meta-analysis of 29 studies on the performance effects of sodium bicarbonate, featuring predominately untrained individuals, found that bicarbonate supplementation resulted in a performance effect that was 0.44 standard deviations better than in the control trial (Matson & Tran, 1993). An improvement of 0.44 of the standard deviation would bring the 2006 average men's 800-m Golden League time of 1:46.36 down to 1:45.52, which is a worthwhile improvement.

In summary, most data suggest that the ingestion of 0.3 g · kg BW^{-1} of either sodium bicarbonate or citrate administered in solution approximately $1-2$ h before exercise offers a small, but significant, effect on middle-distance race performance (McNaughton, 2000). Given that some individuals exhibit urgent gastrointestinal distress with $NaHCO_3$, such as vomiting and diarrhoea, a pragmatic and individualized approach needs to be taken. It is important for athletes to experiment with bicarbonate in training that features daily consecutive races, since much of the gastrointestinal distress seems to occur after a race (semi-finals), which could limit performance in any subsequent race (finals).

Multi-day bicarbonate ingestion

Several recent studies have shown more favourable gastrointestinal tolerance effects after chronic multi-day $NaHCO_3$ supplementation (Douroudos *et al.*, 2006; McNaughton & Thompson, 2001), as compared to acute pre-exercise single-dose administration. These chronic $NaHCO_3$ supplementation studies found the effective daily dose to be 0.5 g · kg BW^{-1} taken over 5 days (sometimes split up into four daily doses). A recent study showed a 12% improvement in the average power output during Wingate testing (Douroudos *et al.*, 2006). Further evidence suggests that performance in high-intensity exercise may be enhanced for a full 2 days after cessation of chronic $NaHCO_3$ supplementation (McNaughton & Thompson, 2001), which might alleviate many of the severe gastrointestinal side-effects found with acute bicarbonate loading. Notwithstanding these results, more research is needed to show performance efficacy for chronic $NaHCO_3$ ingestion protocols in elite athletes, and to better elucidate the dosing and time-course effects between the cessation of dosing and exercise performance testing.

β-alanine/carnosine supplementation

It has been known for over 50 years that muscle carnosine (β-alanyl-L-histidine) can act as an intracellular buffering agent (for a review, see Begum, Cunliffe, & Leveritt, 2005). Recent evidence suggests that β-alanine supplementation may lead to an increase in muscle carnosine content, leading to an increase in performance during exercise where muscle acidosis may be a limiting factor. It appears that muscle carnosine synthesis may be limited by the intracellular availability of β-alanine (Harris *et al.*, 2006b). In support of this, chronic β-alanine supplementation can lead to significant increases in muscle carnosine content (Harris *et al.*, 2006b; Hill *et al.*, 2007). Dosing protocols include taking a single daily dose of 3.2 g, or up to eight daily doses of 0.4 – 1.6 g β-alanine per single dose, to reach a total daily ingestion of $3.2-6.4\ g \cdot day^{-1}$ (Harris *et al.*, 2006b; Hill *et al.*, 2007). These daily dosing protocols appear to lead to a 50 – 60% increase in muscle carnosine contents in about 4 weeks (Harris *et al.*, 2006b).

Large acute doses of β-alanine appear to induce mild pseudo-allergic skin reactions of paraesthesia (mild flushing and tingling sensations) (Harris *et al.*, 2006b; Hill *et al.*, 2007). However, these vasodilation type responses appear to be short-term side-effects that dissipate within about 2 h, as many individuals have reached a total intake of 400 g β-alanine over several weeks without any reported adverse health consequences (Harris *et al.*, 2006b; Hill *et al.*, 2007). In short, chronic supplementation of β-alanine appears to be safe, despite some acute side-effects of mild flushing with large single doses, but there are no data to show whether long-term supplementation would lead to adverse health issues.

Despite the relatively consistent finding that β-alanine supplementation leads to an increase in muscle carnosine, the subsequent performance effects have not been so obvious. During a cycling time to exhaustion test of ~15 min, there was no effect on performance (Zoeller, Stout, O'Kroy, Torok, & Mielke, 2006). However, at steady-state cycling at 110% maximum power output, there was a 15% increase in total work done over a test of approximately 2 min 45 s duration (Hill *et al.*, 2007). In support of this, Harris *et al.* (2006a) found an 11% improvement in endurance time (8 s increase in time over a ~75-s test) during isometric knee extensor exercise at 45% of maximal voluntary contraction. The ventilatory threshold was improved in one study with β-alanine supplementation (Stout *et al.*, 2006), but not in another (Zoeller *et al.*, 2006). Alternatively, muscular strength as assessed by one-repetition maximum testing was found to improve with 10 weeks of supplementation (Hoffman *et al.*, 2006).

Much work remains to determine if chronic β-alanine ingestion can lead to a clear-cut improvement in exercise performance and to establish the effective dosing protocol. Despite some positive findings on performance with β-alanine supplementation, the current evidence is inconclusive and a definitive recommendation pertaining to middle-distance athletes cannot be made. Finally, the use of any ergogenic aid should be closely monitored between the athlete, coach, and possibly health professional to be conscious of any possible supplement contamination issues, adverse effects or athlete habituation and dependency.

Future directions for new advances in nutrition and training adaptations in middle-distance runners

Concurrent training, which many middle-distance athletes undertake, has been described as "the concomitant integration of endurance and resistance training in a periodized training plan" (Coffey & Hawley, 2007). It has been established that with a specific and regular exercise stimulus (resistance vs. endurance), skeletal muscle is highly adaptable, from a molecular perspective, leading to functional phenotypic alterations. Recent reviews have attempted to elucidate these complex and divergent molecular mechanisms (Baar, 2006; Coffey & Hawley, 2007). Several emerging and future scientific directions for nutrition and exercise adaptations for athletes undertaking concurrent training will be highlighted below. [For further discussion, see Hawley, Gibala, and Bermon, 2007).]

A given acute stimulus of either exercise and/or nutrition leads to altered synthesis of specific proteins (e.g. mitochondrial vs. myofibrillar), which, over time, results in an exercise-specific and optimized remodelling of skeletal muscle. However, opposing results have been found when examining the net protein balance, or skeletal muscle protein turnover rate, between resistance and endurance exercise stimuli (for reviews, see Tarnopolsky, 1999; Tipton & Wolfe, 2004). Recent molecular data suggest that athletes undertaking daily endurance and resistance training should phase these differing exercise stimuli with at least several hours of nutritional recovery between bouts (Coffey & Hawley, 2007). However, much research is needed to better characterize the adaptations induced by concurrent training on divergent responses in molecular signalling that lead to functional protein synthesis.

Previous recommendations contend that athletes should consume carbohydrate immediately after exercise to ensure subsequent training bouts are conducted in a glycogen-compensated state. However, anecdotal reports exist of elite athletes purposely undertaking training in a glycogen-depleted state, attempting to "force the muscle to adapt to the next level". Accordingly, a recent training study reported increased adaptation and performance when 50% of endurance training was undertaken in a glycogen-depleted state (Hansen *et al.*, 2005). This has resulted in a degree of uncertainty behind the idea that athletes should *always* strive to endurance train with ample exogenous and endogenous carbohydrate available. Conversely, it appears that the molecular responses to resistance training are optimized when training with full muscle glycogen stores (Churchley *et al.*, 2007; Creer *et al.*, 2005). Perhaps athletes may need to cycle glycogen stores during concurrent training regimens of endurance and strength/power for optimal adaptation to these varied stimuli. Ultimately, future studies need to utilize a completely integrative approach by altering specific exercise and/or nutrition factors and measuring downstream effects at multiple levels that include gene and molecular signalling pathways, leading to muscle protein synthesis, that result in optimized phenotypic adaptations and performance.

Conclusions

Training involves meticulous planning, in which there is an ideal time, place, duration, and intensity of training that is periodized for optimal performance. This same rigorous approach should also be applied to nutritional interventions. Nutrition, training, and racing interactions need to be monitored closely and continually altered and individualized. We outline below the key messages to optimize an athlete's acute and long-term training and racing. Future developments will need to look to integrate practical nutritional and training applications of all these varied stimuli into a periodized/individualized approach for each athlete. Peaking at the exact time of a major championship is one of the most difficult things to achieve. However, realizing the important and integrated role of nutrition in this quest will bring the athlete one step closer to their goals.

Summary of nutritional guidelines for middle-distance athletes

Consensus for:

- A periodized nutritional approach that takes into account acute and seasonal differences in training volume and intensity should be implemented.
- Carbohydrate-rich foods must provide the majority of the daily energy provision ($7-10$ g CHO $\cdot$ kg BW$^{-1}\cdot$ day^{-1}).
- Daily protein intake should be targeted at $1.5-1.7$ g PRO $\cdot$ kg BW$^{-1}\cdot$ day^{-1} during periods of hard training.
- To maximize glycogen resynthesis rates during short-term recovery (<4 h), aim for approximately $1.2-1.5$ g CHO $\cdot$ kg BW$^{-1}\cdot$ h^{-1}.
- The ingestion of $NaHCO_3$ may offer a small increase in performance.

Consensus against:

- Low carbohydrate diets ($3-15\%$ of total energy) have uniformly been shown to impair high-intensity and endurance-based performance.

Issues that are equivocal:

- Future studies need to elucidate if athletes need to "cycle" their glycogen stores during concurrent training regimens of endurance and strength/power for optimum adaptation to varied stimuli.
- For optimum recovery, it remains to be clarified as to what are the best macronutrient blends, feeding patterns, type of carbohydrate and/or protein, and the intake timing after different types of exercise stimuli.
- Recent evidence suggests that prolonged β-alanine supplementation may improve high-intensity exercise performance.

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Nutrition for distance events

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Abstract

The goal of training is to prepare the distance athlete to perform at his or her best during major competitions. Whatever the event, nutrition plays a major role in the achievement of various factors that will see a runner or walker take the starting line in the best possible form. Everyday eating patterns must supply fuel and nutrients needed to optimize their performance during training sessions and to recover quickly afterwards. Carbohydrate and fluid intake before, during, and after a workout may help to reduce fatigue and enhance performance. Recovery eating should also consider issues for adaptation and the immune system that may involve intakes of protein and some micronutrients. Race preparation strategies should include preparation of adequate fuel stores, including carbohydrate loading for prolonged events such as the marathon or 50-km walk. Fluid and carbohydrate intake during races lasting an hour or more should also be considered. Sports foods and supplements of value to distance athletes include sports drinks and liquid meal supplements to allow nutrition goals to be achieved when normal foods are not practical. While caffeine is an ergogenic aid of possible value to distance athletes, most other supplements are of minimal benefit.

Keywords: *Carbohydrate loading, marathon, refuelling, protein requirements, caffeine, iron deficiency*

Introduction

Many events involve prolonged effort within the IAAF umbrella of track and field, road running, cross country, and race-walking. Events commonly undertaken by elite competitors include the 5000-m and 10,000-m track events, the half-marathon and marathon, the 20-km and 50-km walks, and cross-country runs (8 km for females and 12 km for males). In addition, a vast array of "fun runs" and community events around the world attract large fields, ranging from the elite to the weekend warrior. Nutrition plays a key role in assisting distance athletes of all standards to achieve their training and competition goals.

Training for distance runners and walkers

Distance runners follow a periodized training programme (see Stellingwerff, Boit, & Res, 2007), split into base training (8–16 weeks), a pre-competitive period (8–16 weeks), and a competitive period (if track events) or a tapering phase (up to 3 weeks) before a marathon followed by a short transition/recovery phase. Heat acclimatization before competition in a hot environment and altitude training are other specialized training techniques often undertaken by distance runners and walkers. Altitude training remains a controversial area, with coaches and scientists still arguing over the benefits of periods in a hypoxic (lower oxygen) environment on performance at sea level. Distance athletes who usually reside at low altitudes have a variety of options for undertaking altitude training (see Hawley, Gibala, & Bermon, 2007).

Since athletes of East African origin (Kenya, Ethiopia and, more recently, Eritrea and Uganda) dominate distance running, the reasons for their superiority have been studied extensively (Billat *et al.*, 2003; Lucia *et al.*, 2006; Saltin *et al.*, 1995). Of the key physiological factors of distance running performance [maximal oxygen uptake ($\dot{V}O_{2max}$), the maximal fraction of $\dot{V}O_{2max}$ sustained during the event, the velocity at the lactate threshold, and the running energy cost], it would appear that East African runners have mainly a greater running economy (Lucia *et al.*, 2006) and a higher fractional utilization of $\dot{V}O_{2max}$ than Caucasian runners (Lucia

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et al., 2006; Saltin *et al.*, 1995). The underlying mechanisms of these differences are still contradictory but are a combination of social, genetic, and anthropometric/biomechanical factors. The effects of the residence/training altitude *per se* or of nutritional differences have not been identified. Although high running distances in training (80 – 150 km · week^{-1} in 3000 – 5000 m runners; 150 – 220 km · week^{-1} in marathon runners during base training) are commonly observed in all distance runners, several studies have reported that most African runners spend a greater part of their weekly training at high relative intensity. The current trend in distance running is for a "polarized training" model – that is, a large percentage (70 – 75%) at strictly aerobic intensity, a small percentage (< 10%) of "tempo" training at around or above lactate threshold, and 15 – 20% at high intensity.

Competition in distance events

Although most distance events involve a single race, some events require heats and finals (e.g. 5000 and 10,000 m at the Olympic Games and World Championships). Most distance runners and walkers peak for several important events in a year (e.g. a Big City Marathon or the World Championships). However, there may be other times when they compete in a series of races, including the lucrative professional circuit in Europe, meets within a university circuit such as the NCAA season, or in the cross-country schedule for club athletes. In general, the main competition for track and field occurs in summer, whereas cross-country has an autumn and/or winter season. Most road races attracting large fields of both elite and community-based participants are scheduled over the warmer months from spring to late autumn when heat and hydration are more of an issue. The schedule of Big City Marathons, which includes races in Boston, Chicago, New York, London, and Paris, extends from April to November.

Aerobic metabolism typically accounts for more than 95% of the energy production of long-distance events, especially half-marathon and marathon races and the longer walking events. However, there are critical times in all distance races requiring anaerobic effort – for example, a surge, a hill, or a sprint finish – that may be the ultimate factor in determining the order of race finishers. The factors that limit the performance of distance runners and walkers vary according to the duration and environment of the race, and nutrition is an important factor in success in the event. Because many of these factors (e.g. fluid balance, the availability of carbohydrate fuel, disturbance to acid – base status arising from anaerobic glycolysis) can be manipulated by dietary strategies, nutrition is an important component of the athlete's preparation for competition.

Nutritional issues and challenges

There is a range of common nutritional issues in long-distance running and walking related to optimal physique, training, and race day performance. This review will provide an overview of the major issues.

Physique

Very low levels of body fat are a striking feature of successful distance athletes. However, it is hard to distinguish whether this is a critical factor in determining successful performance or the outcome of the high training volumes needed for successful performance. Low levels of both total mass (which determines the total energy cost of running) and fat mass (dead weight that must be transported) assist fast and economical movement. These traits become even more important when the event involves long distances or moving against gravity (e.g. running up hills in a road or cross-country race). Because the upper-body musculature is unimportant for running performance, elite runners and walkers typically exhibit minimal evidence of muscle development in their arms and upper torso. Although there is variability in the size of long-distance runners and walkers, the winners of "hot weather" races tend to be small and light. A small and compact physique offers thermoregulatory advantages, both by reducing the absolute amount of heat that is produced (smaller muscle mass) and by achieving a more efficient dissipation of heat generated by the body (enhanced ratio of surface area to volume). Data from both modelling (Dennis & Noakes, 1999) and laboratory (Marino *et al.*, 2000) sources show that lighter runners store less heat at the same running speed and enjoy an advantage in conditions where heat dissipation mechanisms are at their limit.

Some runners and walkers achieve a small and very lean frame as a result of their genetic background and training programme. However, other runners with naturally larger frames or greater adiposity feel that they must whittle themselves down to an "unnatural" size and low percentage of body fat to be competitive. Although many male runners eat and train specifically to reduce their body fat and racing weight, the battle for a low percentage of body fat and weight control is most often identified as a problem for female athletes. This may be because females generally need to push their body characteristics further from their natural shape than male runners to achieve the leanness that is considered ideal. Attempts to deviate body fat further from the apparent biological "default" can have negative effects, including "penalties" resulting from the low body fat *per se*, such as a lack of insulation against cold. Other penalties arise from the nutrition and training methods used to manipulate weight and body fat, including restricted intakes of energy, protein, carbohydrate, and micronutrients (Burke, 2007). Some athletes develop frank medical or psychiatric problems such as eating disorders, osteopaenia, and chronic menstrual dysfunction. More develop sub-clinical versions of these problems; the spectrum of restrained eating, menstrual dysfunction, and poor bone health within the "female athlete triad" is covered in greater detail by Manore and colleagues (Manore, Kam, & Loucks, 2007) and similar issues should also be considered in the evaluation of some male athletes.

The problems associated with poor bone health lie not only with the risk of a premature onset of osteoporosis but also with the immediate problem of stress fractures. Recurrent or chronic stress fractures can prevent the athlete from competing at important times and interfere with his or her ability to undertake the training volume necessary for high-level performance. Many athletes have had promising careers ended by this injury pattern. Distance runners and walkers should be encouraged to set realistic weight and body fat goals; these are specific to each athlete and must be judged by trial and error over a period of time. Further discussion on dietary strategies to assist with loss of weight and body fat is found in the review by O'Connor and colleagues (O'Connor, Olds, & Maughan, 2007).

Poor iron status

There is a common belief that endurance athletes, particularly distance runners, are at high risk of iron deficiency. This has been given apparent credibility because the target levels for iron status measures such as serum ferritin are often set well above those of normal population standards to provide a "safety margin" for athletes whose performance are underpinned by the roles of iron in oxygen transport (haemoglobin and myoglobin) and enzyme function (for a review, see Deakin, 2006).

The depletion of the body's iron stores progresses through a number of stages with different functional and diagnostic criteria (see Deakin, 2006). The literature is unclear, in part because of methodological concerns, whether iron depletion, in the absence of anaemia, impairs exercise performance (Fogelholm, 1995). Some studies of iron supplementation in iron-depleted but non-anaemic female runners (Klingshirn, Pate, Bourque, Davis, & Sargent, 1992; Newhouse *et al.*, 1989; Powell & Tucker 1991) failed to find differences in performance changes between supplementation and placebo treatment groups, even when serum ferritin increased with iron therapy (Klingshirn *et al.*, 1992; Newhouse *et al.*, 1989). However, in other studies, female runners with low ferritin levels experienced a performance improvement, albeit in conjunction with an increase in haemoglobin, after iron supplementation (Lamanca & Haymes, 1993; Schoene *et al.*, 1983). Of course, athletes are also concerned whether iron depletion affects their ability to recover between workouts or races. Brownlie and colleagues (Brownlie, Utermohlen, Hinton, & Haas, 2004) exposed previously untrained participants with non-anaemic iron depletion to a 4-week training programme and found that those with a tissue iron deficiency (based on abnormal serum transferrin receptor concentrations) had an impaired adaptation to this training compared with a similar group who received iron supplements. In contrast, iron supplementation did not affect endurance cycling performance at the end of the training programme in the iron-depleted group who were not tissue iron-depleted.

In summary, the true prevalence of iron-deficiency anaemia in distance runners and walkers is probably not greater than in the general population (Fogelholm, 1995). However, reduced iron status does occur and may be problematic for performance or adaptation to training, particularly altitude training (see Hawley *et al.*, 2007). The cause is essentially the same as that in the general population: a lower than desirable intake of high bioavailability iron. Iron requirements may be increased in distance athletes because of increased gastrointestinal or haemolytic iron losses (for a review, see Deakin, 2006). However, the most important risk factor is still the low-energy or low-iron diet. Females, vegetarians, and those following diets with restricted quantity and variety are at highest risk. Dietary interventions to reverse or prevent a decline in iron status involve strategies to increase total iron intake as well as to increase the bioavailability of this iron.

The management and prevention of iron deficiency requires careful diagnosis using a variety of clinical, haematological, dietary, and medical data. Haematological and biochemical tests that are routinely measured to indicate iron status should be undertaken in a way that minimizes or standardizes the effect of exercise on the results. In athletic populations, ferritin concentrations lower than 30–35 $\text{ng} \cdot \text{ml}^{-1}$ (Nielsen & Nachtigall, 1998) are generally marked for further consideration or review, especially where it makes a change in the established iron status history of the individual. New tests that include the measurement of serum transferrin receptors and the characteristics of reticulocytes may offer new opportunities. However, these tests are not routinely available in all laboratories and need to be evaluated carefully in relation to iron status in athletes.

Many distance athletes are tempted to self-medicate with iron supplements that can be purchased over the counter. However, there are several risks involved with the consumption of iron supplements in the absence of a confirmed iron status problem, including haemosiderosis or iron overload. Typically, a 3-month period of supplementation, in the form of a daily dose of 100 mg of elemental iron, is needed to restore depleted iron stores (Nielsen & Nachtigall, 1998). In some cases, when it is not possible to enhance dietary iron intake sufficiently, iron supplementation is continued at a lower dose to prevent ongoing iron drain. In cases of extreme iron depletion or where oral iron intake is not tolerated, intramuscular injections of iron can achieve a rapid increase in iron stores. However, there is no evidence of additional performance benefits over oral supplementation, and there are higher risks of side-effects. Iron injections will not increase haemoglobin levels or other iron parameters in people who are not otherwise suboptimal in iron status (Ashenden *et al.*, 1998).

Carbohydrate needs for optimal training and recovery

Distance runners and walkers must be able to rapidly recover their muscle fuel stores between daily or twice-daily sessions, and between races on the competition circuit. A high carbohydrate intake enhances the performance of a single bout of prolonged running as well as the recovery and performance of a subsequent running bout (Fallowfield & Williams, 1993). However, muscle glycogen concentrations might not recover completely within 24 – 48 h following a very strenuous running session (e.g. marathon) or unaccustomed eccentric loading, despite a plentiful carbohydrate supply (Asp, Rohde, & Richter, 1997; Sherman *et al.*, 1983). Unaccustomed muscle damage may cause a disruption to muscle cell function and could require an increase in total carbohydrate intake in the first 24 h of recovery (Doyle *et al.*, 1993) or a greater recovery time (up to 7 days) for full replacement of muscle glycogen.

Logically, the benefits from enhancing acute recovery between sessions should translate over time into better training adaptations and long-term performance gains. However, the literature, which includes three studies involving runners, is curiously unclear in showing that high carbohydrate diets provide superior training outcomes to moderate carbohydrate intakes (Burke, 2007). Kirwan *et al.* (1988) studied well-trained runners who increased their training by 150% for 5 days while consuming either high ($8\ g \cdot kg^{-1} \cdot day^{-1}$) or moderate ($4\ g \cdot kg^{-1} \cdot day^{-1}$) intakes of carbohydrate. Muscle glycogen concentration gradually declined in both treatments but was better preserved with the higher carbohydrate diet; additionally, running economy at two different running speeds was better. In contrast, Sherman and colleagues (Sherman, Doyle, Lamb, & Strauss, 1993) followed 7 days of training in two groups of runners who consumed carbohydrate intakes of either $5\ g \cdot kg^{-1} \cdot day^{-1}$ (gradually reduced muscle glycogen concentrations) or $10\ g \cdot kg^{-1} \cdot day^{-1}$ (maintained muscle glycogen concentrations). At the end of this period, the groups did not differ in their capacity to undertake two treadmill runs to exhaustion at 80% $\dot{V}O_{2max}$ with a short recovery interval at the end of a training session.

Finally, in another study well-trained runners undertook 7 days of intensified training supported by both moderate ($5.4\ g \cdot kg^{-1} \cdot day^{-1}$) and high ($8.5\ g \cdot kg^{-1} \cdot day^{-1}$) carbohydrate diets (Achten *et al.*, 2004). Muscle glycogen utilization decreased during submaximal running on the moderate carbohydrate diet and there was a decline in speed over 8-km (treadmill) and 16-km (outdoor) time-trials. However, the high carbohydrate treatment was associated with a smaller decrease in 8-km speed and maintenance of 16-km performances. The authors concluded that a high carbohydrate diet reduced symptoms of overreaching in runners during intensified training compared with a moderate carbohydrate diet but could not prevent it entirely.

n emerging interest is that of dietary periodization – the so-called "train low, compete high" approach – in which distance athletes deliberately train with low glycogen or carbohydrate availability to enhance metabolic adaptations to the training stimulus, then replete carbohydrate to enhance their competition performance (see Hawley *et al.*, 2007). Currently, there is inadequate scientific support to recommend that distance athletes should practise carbohydrate restriction for prolonged periods Indeed, the potential disadvantages of this practice include an increased risk of illness and injury (see Nimmo & Ekblom, 2007) and reduced well-being or capacity to train (see Burke & Kiens, 2006). In fact, the available study supporting a "train low" approach (Hansen *et al.*, 2005) achieved glycogen depletion for some, but not all, training sessions by manipulating the training timetable rather than dietary intake. Indeed, it is likely that elite athletes spontaneously periodize carbohydrate availability within their microcycles of training because the practicalities of their lifestyle and training mean that some sessions are taken after an overnight fast, or without complete refuelling between workouts.

Unless more sophisticated research can identify benefits from deliberately "training low", distance athletes should eat to promote carbohydrate availability, at least for the most important training sessions of the week. Recent recommendations for daily carbohydrate intake (Burke, Kiens, & Ivy, 2004) acknowledge that fuel requirements for distance athletes differ according to body size and training loads. The targets of $7-10\ g \cdot kg^{-1} \cdot day^{-1}$ for high volume training and $5-7\ g \cdot kg^{-1} \cdot day^{-1}$ for more moderate exercise loads provide a general target that must be fine-tuned according to overall nutritional goals and performance feedback from each athlete. Such recommendations may be unfeasible for runners, particularly females, whose focus on low body mass and percent body fat requires energy restriction and, by association, a lower carbohydrate intake. The compromise is to periodize nutrition goals and dietary carbohydrates intakes over the season, so that lower intakes and physique goals are the priority of training periods, whereas greater carbohydrate intakes are allowed during competition preparation and recovery to maximize glycogen stores.

Although total intake of carbohydrate is probably the most important determinant of post-exercise refuelling, during periods of high volume training the distance athlete should use other dietary strategies to promote recovery. Speedy intake of carbohydrate after exercise will maximize the period of effective refuelling time (Burke *et al.*, 2004). Carbohydrate-rich foods in recovery snacks and meals should be chosen according to the need to meet practical challenges (e.g. finding portable foods when the athlete is "on the go") or to meet additional nutritional goals (e.g. to provide a source of iron, protein or other nutrient need). It is probably useful to co-ingest protein with carbohydrate-rich recovery snacks. Although the effect of protein on glycogen resynthesis is likely to be minimal in most circumstances (see Tipton, Jeukendrup, & Hespel, 2007), various issues of recovery and adaptation require protein synthesis. Indeed, in addition to refuelling, the distance athlete needs to consider a range of recovery eating goals after training and races, including rehydration (Shirreffs, Casa, & Carter, 2007), repair and adaptation (Hawley *et al.*, 2007), and preserving the immune system (Nimmo & Ekblom, 2007).

Protein requirements during training

Data from studies of essentially recreational exercisers have led to the belief that protein requirements are not altered by any form of physical activity. However, the high volumes of training and the training intensities possible only in elite athletes result in estimated protein requirements that are nearly twice those of sedentary individuals, $1.6-1.7\ g \cdot kg^{-1} \cdot day^{-1}$ (Tarnopolsky, MacDougall, & Atkinson, 1988; Friedman & Lemon, 1989). Even for modestly trained individuals, there is an increase in protein requirements estimated from nitrogen balance experiments (Meredith, Zackin, Frontera, & Evans, 1989; Phillips, Atkinson, Tarnopolsky, & MacDougall, 1993). Although no study has specifically calculated protein requirements for elite female athletes, nitrogen balance data imply that the requirements for women are about 25% lower than those for men – that is, $1.2-1.3\ g \cdot kg^{-1} \cdot day^{-1}$ (McKenzie *et al.*, 2000; Phillips *et al.*, 1993). Most athletes will achieve these protein intakes from an everyday diet providing 10–15% of energy as protein and adequate energy. Nevertheless, it is important to evaluate protein intake on a grams per kilogram basis as opposed to a percentage of the diet to avoid low intakes that can be seen in energy restricting athletes. A low energy intake will also have a negative effect on protein requirements (Calloway, 1975).

There are benefits to the timing of nutrient delivery, especially when undertaking high volumes of training. When female athletes consumed a nutritional supplement immediately after each workout during a training camp, they achieved an improvement in nitrogen balance, less weight loss, and improved performance on a trial completed at the end of the week than when the supplement was consumed after breakfast (Roy, Luttmer, Bosman, & Tarnopolsky, 2002).

Fuelling up for competition

Preparation for racing should ensure that muscle carbohydrate stores are matched to the anticipated fuel needs of the event. For races of 60–90 min duration, normalized muscle glycogen stores are adequate and can generally be achieved by 24–36 h of high carbohydrate intake. Carbohydrate loading in preparation for prolonged exercise resulted from pioneering studies undertaken in the 1960s using percutaneous biopsy techniques to examine fuel utilization and enzyme activities in the muscle. These studies on healthy but untrained men produced the classic 7-day model to supercompensate muscle glycogen stores; a 3- to 4-day depletion phase of hard training and low carbohydrate intake followed by a 3- to 4-day loading phase of high carbohydrate intake and exercise taper (Bergstrom, Hermansen, Hultman, & Saltin, 1967). Early field studies of prolonged running events showed that this strategy enhanced sport performance, not by allowing the athlete to run faster but by prolonging the time that race pace could be maintained (Karlsson & Saltin, 1971).

A modified version of carbohydrate loading was developed when well-trained runners were shown to supercompensate their glycogen stores without a severe depletion or glycogen stripping phase (Sherman, Costill, Fink, & Miller, 1981). The modified protocol, consisting simply of 3 days of high carbohydrate intake and taper, was offered as a more practical competition preparation that avoided the fatigue and complexity of the extreme diet and training requirements of the previous depletion phase. More recently, muscle glycogen concentrations were measured after 1 and 3 days of rest and a high carbohydrate intake ($10\ g \cdot kg$ body $mass^{-1} \cdot day^{-1}$) in well-trained male athletes (Bussau, Fairchild, Rao, Steele, & Fournier, 2002): this study found that optimal refuelling is probably achieved within 36 – 48 h following the last exercise session, at least when the athlete rests and consumes adequate carbohydrate.

Theoretically, carbohydrate loading can enhance performance in distance races that would otherwise be limited by the fatigue caused by glycogen depletion. Studies in well-trained runners have failed to detect benefits of carbohydrate loading for 10-km treadmill running (Pitsiladis, Duignan, & Maughan, 1996), a 20.9-km race on an indoor track (Sherman *et al.*, 1981), and a 25-km treadmill run (Sullo *et al.*, 1998). By contrast, carbohydrate loading has been shown to enhance performance of a 30-km cross-country run (Karlsson & Saltin, 1971), a 30-km treadmill run in trained men (Williams, Brewer, & Walker, 1992), and a 25-km treadmill run in moderately trained men (Sullo *et al.*, 1998). Typically, carbohydrate loading is associated not with an increase in overall running speed but with maintenance of race pace during the last part of the run compared with the control trial or group. Therefore, runners and walkers should consider carbohydrate loading for races of 30 km and longer.

Fat adaptation – a twist on depletion prior to carbohydrate loading

Distance runners and walkers should have a high capacity for fat oxidation during exercise as a legacy of their training. However, this capacity can be further up-regulated by as little as 5 days of training while following a low carbohydrate ($<2.5\ g \cdot kg^{-1} \cdot day^{-1}$), high-fat ($\sim 65 – 70\%$ of energy) diet. In trained individuals, "fat adaptation" achieves a markedly increased fat oxidation and reduced utilization of muscle glycogen ("glycogen sparing") during subsequent submaximal exercise (Burke *et al.*, 2000). This effect persists even when followed by acute strategies to carbohydrate load, and eat carbohydrate before and during the bout (for a review, see Burke & Kiens, 2006). Such a combination of dietary strategies would seem the perfect preparation for a marathon or distance walking event, simultaneously optimizing carbohydrate stores while maximizing the capacity for fat oxidation. Curiously, the effect on endurance and ultra-endurance performance is unclear (Burke & Kiens, 2006).

There is now evidence that what was initially viewed as glycogen sparing may, in fact, be a down-regulation of carbohydrate metabolism or "glycogen impairment". Fat adaptation/carbohydrate restoration strategies are associated with a reduction in the activity of a key enzyme regulating carbohydrate metabolism, pyruvate dehydrogenase (Stellingwerff *et al.*, 2007). Such a change would impair rates of glycogenolysis at a time when muscle carbohydrate requirements are high. This explains the observation that when fat adaptation/carbohydrate restoration is applied to exercise protocols that mimic a real-life race – self-pacing, and the interspersing of high-intensity and moderate-intensity exercise – there is a compromised ability to performance high-intensity sprints (Havemann *et al.*, 2006) In many endurance events, the critical activities in a race – the breakaway, the surge up a hill, or the sprint to the finish line – are all dependent on the runner's ability to work at high intensities. With growing evidence that this critical ability may be impaired, it now seems clear that fat adaptation or pre-loading depletion strategies should not be undertaken by distance athletes.

Fluid and fuel intake during races

In distance running and walking events, especially road races, a network of aid stations allows competitors to consume fluids during the race. In large community participation events, a supply of water, sport drinks, and sponges is on hand, although elite competitors are usually provided with opportunities to supply their own race beverages at specially marked tables. There is still debate on the ideal hydration plans for distance events, with the observation that most top runners are conservative with fluid intake while some of the "back of the pack" participants in large community events risk serious problems from over-consumption of fluids (Noakes, 2002; Almond *et al.*, 2005). These issues are covered in greater detail by Shirreffs *et al.* (2007).

The use of carbohydrate – electrolyte drinks (sport drinks) during races of 60 min or longer provides the runner or walker with the potential to replace fluid and carbohydrate simultaneously, with the option of altering the carbohydrate concentration of the drink (typically $4 – 8\ g \cdot 100\ ml^{-1}$), according to the priority of rehydration or refuelling in a particular event. Sports gels and confectionery are other readily available sources of carbohydrate often consumed by distance athletes. There is good evidence of the benefits of carbohydrate intake during prolonged (>90 min) exercise (Hargreaves, 1999), with reports dating back to the Boston marathon in the 1920s that the consumption of sweets during the race prevented hypoglycaemia and enhanced running performance (Gordon *et al.*, 1925; Levine, Gordon, & Derick, 1924). Recent studies in which carbohydrate ingestion enhanced a running protocol include a 40-km outdoor run in the heat (Millard-Stafford, Sparling, Rosskopf, & Dicarlo, 1992), a 30-km road run (Tsintzas, Liu, Williams, Campbell, & Gaitanos, 1993), a marathon run on a treadmill (Tsintzas, Williams, Singh, & Wilson, 1995), and an approximately 2-h treadmill protocol to exhaustion at 70% $\dot{V}O_{2max}$ (Tsintzas, Williams, Wilson, & Burrin, 1996b). The generally accepted mechanisms of performance enhancement include prevention of hypoglycaemia, sparing of liver glycogen, and provision of an additional muscle fuel substrate (Hargreaves, 1999). However, in the case of running, there is some evidence of muscle glycogen sparing, at least in selected fibres (Tsintzas *et al.*, 1993; Tsintzas, Williams, Boobis, & Greenhaff, 1996a).

The effect of carbohydrate intake during shorter distance events is unclear, with the potential mechanism of any performance enhancements being attributable to effects on the central nervous system rather than provision of muscle fuel (see Burke, 2007). One study involving a 15-km treadmill run in a hot environment found an improvement in speed over the last, self-paced portion of the run when carbohydrate was ingested immediately before and during the run compared with a placebo trial (Millard-Stafford, Rosskopf, Snow, & Hinson, 1997). By contrast, carbohydrate intake during an 18-km run failed to enhance performance of a large group of runners or the fastest runners in the group compared with water (Van Nieuwenhoven, Brouns, & Kovacs, 2005), and highly trained runners experienced a trivial effect on performance when carbohydrate was consumed during a half-marathon (Burke, Wood, Pyne, Telford, & Saunders, 2005). Further studies are needed to determine the full range of events that might benefit from carbohydrate intake immediately before and during the race.

Differences in nutrition strategies between the sexes

It has been assumed that dietary advice for female distance athletes would be a simple extrapolation from male athletes, scaled to their smaller size. However, numerous studies have found that females oxidize more fat and less carbohydrate than men during endurance exercise (see Tarnopolsky, 2000). An early study found that increasing dietary carbohydrate intake from 55% to 75% of habitual energy intake for 4 days neither increased glycogen storage nor enhanced cycling performance in female athletes, in stark contrast to the results seen in males (Tarnopolsky, Atkinson, Phillips, & MacDougall, 1995). Of course, the relatively low energy intake of the females limited carbohydrate intake to $< 6.5\ g \cdot kg^{-1} \cdot day^{-1}$ even in the "loading" phase. A follow-up study provided an additional trial in which 75% of a higher energy intake achieved carbohydrate intakes $> 8\ g \cdot kg^{-1} \cdot day^{-1}$ (Tarnopolsky *et al.*, 2001). With higher carbohydrate and extra energy, females increased muscle glycogen, albeit to levels that were about 50% of the increase seen in males. From a practical perspective, carbohydrate loading is of use to female athletes only if they are prepared to consume adequate energy and carbohydrate.

In contrast to the limited ability of women to carbohydrate load, the dietary recommendations for men and women with respect to sport drink consumption during exercise (Riddell *et al.*, 2003; Wallis, Dawson, Achten, Webber, & Jeukendrup, 2006), and for post-exercise glycogen re-synthesis (Tarnopolsky *et al.*, 1997), appear to be similar.

Sport foods and supplements

Many distance athletes, even recreational athletes, are consumers of sport foods and supplements. Products such as sports drinks and liquid meal supplements are specially designed to help a runner or walker meet specific needs for energy, fluid, and nutrients in circumstances where everyday foods are not practical to eat, although the expense must be considered (see Burke, 2007). Nutritional ergogenic aids have generally been poorly tested or have failed to live up to their claims when rigorous testing has been undertaken on distance running/walking performance. The exception is caffeine, which may enhance the performance of some runners (for a review, see Graham, 2001). Recent research has focused on the use of small doses of caffeine before and during endurance exercise, since the benefits appear to be similar to those achieved by larger doses of $6-9\ mg \cdot kg^{-1}$ (see Maughan, Depiesse, & Geyer, 2007). Caffeine intakes of as little as $3\ mg \cdot kg^{-1}$ have been shown to enhance running performance, including a worthwhile improvement of $\sim 1\%$ in an 8-km track protocol (Bridge & Jones, 2006). However, runners who were provided with very small amounts of caffeine ($\sim 1.3\ mg \cdot kg^{-1}$) during an 18-km road race did not show a detectable improvement in performance (Van Nieuwenhoven *et al.*, 2005).

While bicarbonate supplementation is typically considered a strategy for middle-distance running (see Stellingwerff *et al.*, 2007), it has been shown to improve performance of the longer track events (e.g. 5000-m races) (Oopik *et al.*, 2003; Oopik, Saaremets, Timpmann, Medijainen, & Karelson, 2004). Creatine loading has become synonymous with the enhancement of repeated sprint training or exercise bouts (see Tipton *et al.*, 2007) and is typically considered inappropriate for use by distance athletes. In fact, runners recorded a slower time to complete a 6-km cross-country run after creatine supplementation (Balsom, Harridge, Soderlund, Sjodin, & Ekblom, 1993), presumably due to the accompanying increase in body mass. In spite of recent evidence that prior creatine loading enhances the muscle's capacity for glycogen loading or resynthesis (Nelson, Arnall, Kokkonen, Day, & Evans, 2001; van Loon *et al.*, 2004), it is likely that the increase in body mass would hinder performance in distance running events, particularly if the course is hilly. Further research is needed to test the hypothesis that glycerol hyperhydration can enhance thermoregulatory function in conditions in which thermal stress limits running performance.

Finally, the claims made in support of the majority of other supplements and compounds marketed as ergogenic aids are not supported by scientific research (see Burke, 2007). Of course, more research is needed, using rigorous control and carefully chosen protocols to test the claims for most products. In many cases, particular (proposed) ergogenic compounds that are used by distance athletes have not been tested appropriately and no further comments can be made about these products. The reader is therefore referred to the general conclusions provided by Maughan *et al.* (2007).

Summary of nutrition guidelines for distance athletes

Consensus for:

- Distance athletes should follow established guidelines to meet the carbohydrate needs for their training loads and to enhance recovery after each training session. These strategies are particularly important to promote performance and recovery for key training sessions.
- Distance athletes should consume sufficient carbohydrate to prepare fuel stores that are adequate for their event. Carbohydrate loading or glycogen supercompensation will be of benefit to longer events such as the marathon or 50-km walk. A prolonged depletion phase is unnecessary and may even impair performance.
- Carbohydrate and fluid intake during an event is possible and of probable value for races lasting longer than 60 min. Each athlete should experiment to find a plan that is practical and provides benefits for their performance.
- Iron deficiency may be a problem for some distance runners, but this is a diagnosis of exclusion and other causes need to be ruled out. Nutritional counselling to increase the intake of bioavailable iron is an important goal of prevention and therapy.
- Some sports supplements such as sports drinks and liquid meals may be useful in providing a practical way for distance athletes to meet their nutrition goals. Moderate doses of caffeine can provide an ergogenic benefit to distance running and may be useful for some runners.

Consensus against:

- Distance athletes should not practise extreme levels of energy restriction to achieve loss of body weight/body fat without considering the effect on their ability to meet goals for carbohydrate, protein, iron or other nutrients. Hormonal balance, bone health, and the immune system are also critically impaired by inadequate energy intakes.
- Routine supplementation with iron or iron injections in the belief that it enhances performance should be strongly discouraged in the absence of documented iron depletion or anaemia. Supplementation in the absence of deficiency can lead to serious medical conditions such as haemosiderosis.
- The majority of supplements that are promoted to distance athletes are unlikely to provide substantial benefits, and should not replace sound eating and training practices.

Issues that are equivocal:

- It is unclear whether distance athletes will enhance adaptations and performance outcomes by undertaking deliberate strategies to restrict carbohydrate availability during training. In the real world, elite athletes will probably achieve some level of periodization of carbohydrate status within the microcycles of their training programme. Any benefits of more prolonged carbohydrate depletion need to be balanced by the possible disadvantages.

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Nutrition for the sprinter

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Abstract

The primary roles for nutrition in sprints are for recovery from training and competition and influencing training adaptations. Sprint success is determined largely by the power-to-mass ratio, so sprinters aim to increase muscle mass and power. However, extra mass that does not increase power may be detrimental. Energy and protein intake are important for increasing muscle mass. If energy balance is maintained, increased mass and strength are possible on a wide range of protein intakes, so energy intake is crucial. Most sprinters likely consume ample protein. The quantity of energy and protein intake necessary for optimal training adaptations depends on the individual athlete and training demands; specific recommendations for all sprinters are, at best, useless, and are potentially harmful. However, if carbohydrate and fat intake are sufficient to maintain energy levels, then increased protein intake is unlikely to be detrimental. The type and timing of protein intake and nutrients ingested concurrently must be considered when designing optimal nutritional strategies for increasing muscle mass and power. On race day, athletes should avoid foods that result in gastrointestinal discomfort, dehydration or sluggishness. Several supplements potentially influence sprint training or performance. Beta-alanine and bicarbonate may be useful as buffering agents in longer sprints. Creatine may be efficacious for increasing muscle mass and strength and perhaps increasing intensity of repeat sprint performance during training.

Keywords: *Muscle hypertrophy, training adaptations, net muscle protein balance, creatine, power-to-mass ratio*

Introduction

The sprint events cover distances from 60 to 400 m. These running and hurdle events rely primarily on the development of power through anaerobic energy, the phosphocreatine (shorter events, e.g. 100 m and 200 m), and glycolytic (longer events, e.g. 400 m) systems for energy. A sprint consists of an all-out effort for a short period of time; performance is determined by the ability to achieve maximal velocity and to limit the loss of power as the sprint progresses. Biomechanical, neuromuscular, and metabolic factors all influence performance.

Nutritional support for athletic performance is a popular and widely covered topic. However, most sports nutrition research has focused on endurance performance. Relatively little has been written about nutrition for sprinting performance. Although the potential for an effect is arguably somewhat less than for endurance sports, especially during an event, nutritional choices and strategies will contribute to adaptations to training and to performance in sprinters.

Early work demonstrated that elite sprinters have muscles composed predominantly of fast-twitch fibres (Costill *et al.*, 1976). Thus, success requires large, powerful muscles. Accordingly, the major role for nutrition may be to modulate muscle hypertrophy from training. In this review, we focus on the role of nutrition for increasing muscle mass and strength, as well as the potential for nutritional choices to influence competition day performance.

Nutritional support for athletes is often considered for two general situations: training and competition. Important considerations for the sprinter are:

- maintaining energy levels during training;
- quick recovery from training;
- optimizing training adaptations with nutrition;
- achieving a high power-to-weight ratio, thus maximizing muscle mass and maintaining low body fat;
- staying focused, sharp and maintaining concentration during competition days;
- improved reaction times.

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Nutrition for sprint training

Sprint training is focused on developing lean body mass capable of generating the power necessary to carry the athlete as rapidly as possible. Adaptations to training are specific to the mode, intensity, and duration of the exercise. These adaptations stem primarily from the exercise stimulus on the muscle fibres, but may be influenced by nutritional factors. Nutrition most certainly will influence muscle hypertrophy and this aspect of nutrition is usually the focus for sprinters. Besides specific sprint training, weight training with the goal of developing muscle mass is the primary form of training throughout the year. However, it is important to recognize that optimum mass may not equal maximum mass for a sprinter. At some point, the power-to-mass ratio may begin to decline with extra mass regardless of composition. Some aspects of the nutritional influence on training adaptations are also covered in other reviews in this issue (Hawley, Gibala, & Bermon, 2007; Houtkooper, Abbot, & Nimmo, 2007).

Recent evidence on the molecular and metabolic levels indicates that training adaptations occur as protein levels change due to the response to each bout of exercise (Hawley, Tipton, & Millard-Stafford, 2006). Muscle mass is determined by changes in protein levels, particularly myofibrillar proteins. Increased myofibrillar proteins result from net positive balance of myofibrillar synthesis and breakdown over a given period. The primary changes occur in response to exercise plus nutrition.

The bulk of the response of net muscle protein balance occurs following, rather than during, exercise (Durham *et al.*, 2004); increased muscle protein synthesis, rather than decreased breakdown, is responsible for the increased balance (Tipton & Wolfe, 2004). Elevation of muscle protein synthesis is delayed after exercise (Pitkanen *et al.*, 2003), presumably due to inhibition of translational pathways due to elevations in AMPK (Bolster *et al.*, 2003; Koopman, Zorenc, Gransier, Cameron-Smith, & van Loon, 2006). Once activated, muscle protein synthesis and net muscle protein balance remain elevated for up to 48 h after the exercise bout (Phillips, Tipton, Aarsland, Wolf, & Wolfe, 1997); however, protein balance does not become positive without provision of exogenous amino acid sources (Biolo, Tipton, Klein, & Wolfe, 1997).

Consumption of a source of amino acids following exercise increases the response of muscle protein synthesis in an additive manner resulting in positive muscle protein balance (Biolo *et al.*, 1997; Borsheim, Tipton, Wolf, & Wolfe, 2002). The response of net muscle protein balance is due primarily to the essential amino acids (Borsheim *et al.*, 2002; Tipton, Ferrando, Phillips, Doyle, & Wolfe, 1999). Thus, consumption of a source of essential amino acids, be it an intact protein or a free amino acid mixture, will stimulate uptake of amino acids for synthesis of muscle proteins necessary for muscle growth. The optimum amount of amino acids has yet to be determined, but it is clear that a relatively small amount of exogenous amino acids (about 12 g) results in positive protein balance (Borsheim *et al.*, 2002). However, it remains to be seen if chronic consumption of a small amount of amino acids capable of stimulating a transient metabolic response is enough to stimulate muscle hypertrophy in the long term.

It is clear that the metabolic and thus phenotypic responses to exercise and thus training adaptations are mediated by intracellular signalling. Recent reviews have examined the response of these pathways to exercise and nutrition in detail (Rennie, 2005; Tipton & Sharp, 2005). Signalling aspects of muscle adaptation to training are also discussed elsewhere in this issue (Hawley *et al.*, 2007).

Both translational (Bolster, Jefferson, & Kimball, 2004) and transcriptional (Creer *et al.*, 2005; Psilander, Damsgaard, & Pilegaard, 2003) mechanisms are stimulated by resistance exercise, but the bulk of the increase in muscle protein synthesis is translational (Chesley, MacDougall, Tarnopolsky, Atkinson, & Smith, 1992). Rates of muscle protein synthesis are increased with no increase in total RNA, suggesting that it is the efficiency of translation – that is, an increase in synthesis per molecule of RNA – that is increased by resistance exercise (Chesley *et al.*, 1992). Resistance exercise increases phosphorylation of many translation initiation pathway components (Coffey *et al.*, 2006; Karlsson *et al.*, 2004; Koopman *et al.*, 2006). Adaptations that influence muscle growth also stem from transcriptional regulation (Coffey *et al.*, 2006; Williamson, Gallagher, Harber, Hollon, & Trappe, 2003); transcriptional activity of genes for muscle growth factors and myosin heavy chain is stimulated by resistance exercise (Psilander *et al.*, 2003; Raue, Slivka, Jemiolo, Holon, & Trappe, 2006). At this juncture, it is somewhat difficult to discern detailed influences of these pathways due to differences in study design and methods among the studies. Much work needs to be done to address the gaps in our knowledge.

Nutrition has a clear effect on the signalling pathways related to muscle protein synthesis. Previous reviews have detailed the response of intracellular signalling to exercise and nutrition (Kimball, Farrell, & Jefferson, 2002; Tipton & Sharp, 2005). The influence of amino acids on muscle protein synthesis is primarily through the mTOR signalling pathways (Kimball *et al.*, 2002; Tipton & Sharp, 2005). Leucine is particularly effective in stimulating initiation of translation following exercise (Anthony *et al.*, 2000; Gautsch *et al.*, 1998). In humans, the administration of branched-chain amino acids after resistance exercise increased phosphorylation of p70s6k 3.5-fold above the increase due to exercise when measured at 1 and 2 h after exercise (Karlsson *et al.*, 2004). However, the time course of signalling events relative to muscle protein synthesis has yet to be examined in humans and much has yet to be determined.

Increased insulin levels resulting from carbohydrate intake are clearly a major controller of translation initiation pathways (Kimball *et al.*, 2002). Thus, carbohydrates seem to play a role in the response of muscle protein synthesis to feeding after exercise. Insulin stimulates these translation signalling pathways primarily through phosphoinositol-3-kinase (PI3k), Akt, and mTOR (Kimball *et al.*, 2002). Interestingly, post-exercise hyperinsulinaemia only minimally stimulates muscle protein synthesis above normal post-exercise levels (Biolo, Williams, Fleming, & Wolfe, 1999). Moreover, Anthony *et al.* (2000) demonstrated that the response of translation initiation to amino acids is mediated by insulin. Taken together, these results suggest that combining carbohydrates and proteins may be the best strategy for stimulation of anabolic pathways. Indeed, utilization of ingested amino acids for synthesis of muscle proteins is greatest when carbohydrates are ingested concurrently with an amino acid source (Tipton & Witard, 2007). Furthermore, leucine has been demonstrated to be an effective insulin secretagogue (Koopman *et al.*, 2005).

Carbohydrate intake may be important for muscle anabolism in other ways as well. Depletion of muscle glycogen is possible, given the multiple sprints common to a sprint training session (Gaitanos, Williams, Boobis, & Brooks, 1993). Thus, carbohydrate intake should be sufficient to maintain glycogen levels, not only to prevent fatigue development and maximize training potential, but also perhaps to optimize muscle anabolism. Low glycogen availability may influence the adaptive response to training (Churchley *et al.*, 2007; Creer *et al.*, 2005), suggesting that the maximal anabolic response to resistance exercise may not be possible when exercise is initiated with low glycogen levels. Thus, sprinters should consume sufficient carbohydrate to maintain glycogen during training.

Clearly, protein intake is important for muscle hypertrophy, but the amount of dietary protein necessary for a sprint athlete to optimize muscle gains and performance is difficult to determine. A high protein intake is often thought to be critical for muscle growth, repair, and enhancement of training adaptations, and a huge supplement industry has been built upon this assumption. The scientific evidence for the efficacy of high protein intakes for increasing muscle mass is, at best, equivocal, and has been extensively debated in the scientific community. The reader is referred to previous reviews for discussions of the merits of increased protein requirements in athletes (Phillips, 2006; Rennie, Wackerhage, Spangenburg, & Booth, 2004; Tipton & Witard, 2007; Tipton & Wolfe, 2004).

It is likely that the disparity of opinions regarding overall protein needs arises primarily from two sources: methodological limitations (nitrogen balance and leucine oxidation) and, perhaps more fundamentally, a lack of consideration for the principal reason athletes ingest protein (Tipton & Witard, 2007). Rather than the attainment of nitrogen balance, the amount of protein that optimizes muscle hypertrophy and maximizes performance is the most salient factor. Attainment of nitrogen balance is unlikely to concern sprinters; rather, they endeavour to consume the amount of protein necessary to optimize muscle mass and power.

For many, if not most athletes, including sprinters, the point may be inconsequential. Most athletes ingest enough protein to cover even the higher estimates of $\sim 1.2-1.5\ \mathrm{g \cdot kg^{-1} \cdot day^{-1}}$ (Phillips, 2006; Tarnopolsky, 2004). Thus, recommending increased protein intake would not be necessary for the majority of athletes consuming a well-chosen diet that meets energy needs. Moore *et al.* (2007) recently demonstrated that increased nitrogen balance and lean body mass result from 12 weeks of intense resistance training while consuming $1.4\ \mathrm{g \cdot kg^{-1} \cdot day^{-1}}$. Thus, habitually high intakes, often greater than $2\ \mathrm{g \cdot kg^{-1} \cdot day^{-1}}$, appear to be unnecessary for muscle hypertrophy and increased strength and power. It is likely that protein intake in excess of $1.7\ \mathrm{g \cdot kg^{-1} \cdot day^{-1}}$ is simply oxidized (Tarnopolsky, 2004). Of course, it should be noted that these results come from previously untrained individuals and it is arguable that years of training may change these responses.

On the other hand, a relatively high protein intake is unlikely to be detrimental, even if not entirely necessary. Given the high energy intakes necessary to support increased muscle mass, habitual protein consumption is likely to ensure maximum muscle accretion. Although protein and amino acid supplements may be convenient sources of essential amino acids, no evidence exists to suggest the anabolic response to protein from food sources is inferior to commercially available supplements (Elliot, Cree, Sanford, Wolfe, & Tipton, 2006; Phillips, 2006).

It is not possible to make a broad recommendation for a specific amount of protein for all sprinters based on current scientific evidence. Any such recommendations are based on the presumption that muscle protein accretion is linear in relation to the amount of protein ingested (Tipton & Witard, 2007). In fact, much of the evidence casts doubt upon such broad recommendations. Metabolic studies clearly demonstrate that the anabolic response to feeding is dependent on many factors, including, but not limited to, the amount of protein ingested. The type of protein ingested will affect the utilization of the amino acids for synthesis of muscle proteins (Wilkinson *et al.*, 2007), the anabolic response to protein ingestion will vary with ingestion of other concurrently ingested nutrients (Borsheim, Aarsland, & Wolfe, 2004a; Elliot *et al.*, 2006), and, finally, the timing of ingestion of an amino acid source will influence the anabolic response of muscle (Tipton *et al.*, 2001, 2006). Taken together, it is clear that ingestion of a given amount of protein may result in a variable metabolic response depending on several factors other than solely the amount of protein. Training adaptations may depend less on the amount of protein ingested, and more on the type of proteins ingested, timing of ingestion, and other nutrients ingested in the same meal.

A risk–benefit approach might offer some insights for recommendations of protein intake for athletes. If risk is minimal and there is a rationale for potential benefit, then there is no reason to recommend against increasing protein intake. Health problems, such as kidney damage and bone loss, have often been given as reasons for avoiding high protein intakes. Whereas these issues are theoretically associated with high protein intake, to date there is no evidence for kidney damage from high protein in those with no predisposing kidney maladies (Zello, 2006). A major component of bone is protein and, in fact, synthesis of bone collagen responds similarly to muscle proteins following ingestion of an amino acid source (Babraj *et al.*, 2005). Thus, it appears that reasonably high protein intakes offer little in the way of health dangers to sprinters and other athletes. The relationship between high protein intake and chronic diseases has not been firmly established, but it should be noted that individuals with pre-existing kidney disease should not consume high-protein diets (Zello, 2006). For many athletes, the primary risk of high protein intakes is a necessary reduction in carbohydrate intake, which may then affect performance (Macdermid & Stannard, 2006). Glycogen depletion is likely during training sessions involving repeated sprints (Balsom, Gaitanos, Soderlund, & Ekblom, 1999; Gaitanos *et al.*, 1993) and so sufficient carbohydrate intake to support these training sessions is clearly necessary. However, sprint athletes habitually consume ample carbohydrate and protein (Burke, Millet, & Tarnopolsky, 2007) to support training.

Protein nutrition is most often the focus of athletes whose goals include increased muscle mass. However, it is clear that energy balance is just as important, if not much more so, for muscle hypertrophy than is protein intake. It is not possible to maintain positive nitrogen balance during an energy deficit (Todd, Butterfield, & Calloway, 1984). Up to about one-third of the variability in nitrogen balance is likely due to energy intake (Pellett & Young, 1992). As early as 1907, Chittenden demonstrated that as long as energy intake is sufficient, athletes will gain muscle mass and increase strength even during periods of low protein intake. More recently, positive energy balance has been demonstrated to be more important than the amount of protein ingested for gains in lean body mass during resistance training (Rozenek, Ward, Long, & Garhammer, 2002).

The arguments rendered above are contingent upon one primary assumption, namely that the acute metabolic response of muscle to exercise and nutrition represents the potential for long-term muscle gain. Clearly, the ideal study to determine the effect of various feeding strategies on sprinters would be to measure changes in muscle mass, strength, power, and speed – ultimately sprint performance – during periods with different feeding strategies. Unfortunately, these studies are virtually impossible to perform, primarily due to difficulties in controlling all variables (Tipton & Witard, 2007; Tipton & Wolfe, 2004). A series of recent investigations suggests that results from acute metabolic studies adequately represent the potential for changes in muscle mass in response to training and nutrition (Paddon-Jones *et al.*, 2004; Tipton, Borsheim, Wolf, Sanford, & Wolfe, 2003; Tipton & Witard, 2007). Results from studies at the molecular level support this contention (Coffey *et al.*, 2006; Hawley *et al.*, 2006; Psilander *et al.*, 2003).

Since the balance between synthesis and breakdown ultimately determines the amount of each protein in muscle, a decrease in muscle protein breakdown rates should contribute to increased muscle mass. Thus, nutritional strategies aimed at decreasing rates of muscle protein breakdown following exercise are often recommended. Amino acid ingestion following resistance exercise can reduce muscle protein breakdown (Biolo *et al.*, 1997; Tipton *et al.*, 1999). Utilization of amino acids from ingested amino acid sources by muscle has been shown to increase when carbohydrates are ingested simultaneously (Borsheim *et al.*, 2004a, 2004b). The effect of carbohydrates is presumably due to the associated insulin release. Insulin increases net muscle protein balance following resistance exercise primarily by blocking the rise in muscle protein breakdown (Biolo *et al.*, 1999). Thus, it is often recommended to consume protein plus carbohydrates after exercise to maximize net muscle protein balance and increase muscle mass.

Recent data suggest that the role of protein breakdown for muscle hypertrophy may not be as clear. After a resistance exercise bout, rates of muscle protein breakdown increase and are associated with the increased rates of synthesis (Biolo, Maggi, Williams, Tipton, & Wolfe, 1995; Phillips *et al.*, 1997). Furthermore, transient changes in gene expression and mRNA levels of both myogenic (Psilander *et al.*, 2003) and atrogenic (Churchley *et al.*, 2007; Jones *et al.*, 2004) genes following resistance exercise suggest that increases in both the synthesis and breakdown of proteins are important for changes in protein levels. These data suggest that muscle protein breakdown may play an important role for accretion of muscle. Clearly, more research on the effect of nutrient intake on specific muscle degradative pathways is warranted.

Nutrition for racing

The acute influence of nutritional intake for sprinting is not likely to be as great as for endurance events. The length of the race alone prevents a large influence from acute intakes. Although sprint events only last seconds, competition can be rather drawn out. A typical competition day involves a number of heats and finals with variable amounts of waiting around in between. For example, at the World Championships in Osaka in 2007, the schedule for the 100 m is:

- Day 1, 12:10 h, men's 100 m heats
- Day 1, 20:15 h, men's 100 m quarter-finals
- Day 3, 20:10 h, men's 100 m semi-finals
- Day 3, 22:20 h, men's 100 m final

On day 1, there are 8 h between rounds 1 and 2, but on the third day only 2 h between the semi-finals and final!

During the time in between heats, athletes should stay hydrated but avoid over-drinking, maintain blood glucose levels, and avoid behaviours, including feeding, that may contribute to discomfort, particularly gastrointestinal discomfort. Careful consideration of what *not* to eat is probably more important than what to eat. It is likely that there is no common way to achieve these goals in every athlete. There is almost certainly large individual variation and preference in ways to achieve these goals. Experimenting in training is therefore essential to develop a good routine on race day.

Supplements for the sprinter

There are a few supplements that should be addressed in relation to sprint performance. We will concentrate primarily on supplements for which there is sufficient evidence of their efficacy. Others that are often considered to be important for aspects related to sprint performance (e.g. hydroxymethylbutyrate, ribose) will not be included in this discussion. The results from studies on most supplements are equivocal and it is difficult to recommend usage by sprinters at this time. More detail on these and other supplements can be found in another review in this issue by Maughan and colleagues (Maughan, Depiesse, & Geyer, 2007) and in previous reviews (Hespel, Maughan, & Greenhaff, 2006; Maughan, King, & Lea, 2004).

When maximal exercise is performed for more than 30 s, most of the energy is derived from anaerobic glycolysis. These high rates of glycolysis have been associated with increased muscle acidity and this may eventually impair muscle contraction. Increasing the buffering capacity is theoretically a way of improving performance in such events (>30 s up to about 7 min; 400-m running may just be long enough to benefit from an increased buffering capacity).

Beta-alanine (β-alanyl-L-histidine)

Beta-alanine is a non-essential amino acid that is common in many foods, especially meats. Beta-alanine is believed to be the rate-limiting substrate for synthesis of carnosine, which is an important intracellular buffer (Dunnett & Harris, 1999). Carnosine is found primarily in type IIa and type IIx fibres in skeletal muscle and contributes to intracellular buffering of H^+. Thus carnosine attenuates the decrease in intracellular pH associated with anaerobic metabolism. Interestingly, carnosine concentrations in athletes, such as sprinters, appear to be higher than those of marathoners or untrained individuals (Abe, 2000; Tallon, Harris, Boobis, Fallowfield, & Wise, 2005). Furthermore, intense physical training may increase muscle carnosine concentrations (Hill *et al.*, 2007). Four weeks of beta-alanine supplementation increased muscle carnosine by 59% and 10 weeks of supplementation increased it by 80% (Hill *et al.*, 2007).

In theory, increasing skeletal muscle carnosine levels (via beta-alanine supplementation or intense training) should increase buffering capacity, delay fatigue, and increase exercise performance. Higher carnosine concentration in muscle was associated with higher mean power from a 30-s maximal sprint on a cycle ergometer (Suzuki, Ito, Mukai, Takahashi, & Takamatsu, 2002). Beta-alanine supplementation has been demonstrated to increase muscle carnosine content and to be associated with increased performance (Stout *et al.*, 2007).

Future studies need to confirm the limited results that are available and examine the combined effect of beta-alanine supplementation and training on muscle carnosine in highly trained athletes.

Sodium bicarbonate

The primary buffers in the muscle are phosphates and tissue proteins. The most important buffers in the blood are proteins, including haemoglobin, and bicarbonate. During intense exercise, the intracellular buffers (including carnosine) are insufficient to buffer all the hydrogen ions formed. The efflux of H^+ into the circulation increases, and bicarbonate has a role in buffering these H^+ ions. Bicarbonate ingestion (in the form of sodium bicarbonate) is the traditional method of increasing the extracellular buffering capacity, although sodium citrate is often used as well. The mechanism by which bicarbonate supposedly exerts its action is through this buffering of H^+ in the extracellular fluid. This increases the H^+ gradient and increases efflux of H^+ from the muscle.

Reviews of the available literature suggest a dose–response relationship between the amount of bicarbonate ingested and the observed performance effect (Horswill, 1995). A dose of 200 $mg \cdot kg^{-1}$ body mass ingested 1–2 h before exercise seems to improve performance in most studies, but 300 $mg \cdot kg^{-1}$ body mass appears to be the optimum dose (with tolerable side-effects for most athletes). Doses of less than 100 $mg \cdot kg^{-1}$ body mass do not affect performance. Intakes of more than 300 $mg \cdot kg^{-1}$ body mass tend to result in gastrointestinal problems. Most of these studies, however, used exercise lasting longer than 1 min and in most the exercise intensity and duration were comparable to middle-distance running not sprints.

No studies have shown an effect on performance in high-intensity exercise lasting less than 1 min. Therefore, a window for efficacy of bicarbonate has been identified between approximately 1 and 7 min and sprint events are not likely to be affected. Nevertheless, the use of bicarbonate is common in 400-m running, with anecdotal support for its efficacy.

Creatine

Creatine is a natural guanidine compound that occurs in meat and fish in concentrations between 3 and 7 $g \cdot kg^{-1}$ (Walker, 1979). Synthetic creatine supplements exist as creatine monohydrate or various creatine salts, such as creatine citrate or creatine pyruvate. The latter are soluble and stable in solution and thus can be included in sports drinks or gels. On the other hand, creatine monohydrate must be consumed soon after it is brought into solution.

The effects of creatine intake on strength and power, primary determinants of sprint running performance, have been investigated extensively since Harris and co-workers first reported that a few days of high-dose oral creatine supplementation can increase muscle creatine content (Harris, Soderlund, & Hultman, 1992). However, to the best of our knowledge, only two well-controlled studies have looked specifically at performance in well-trained sprint athletes. Skare *et al.* (2001) investigated the effect of creatine intake on sprint velocity during a 100-m sprint followed by 6 × 60-m sprints in locally competitive sprinters. Creatine intake (20 $g \cdot day^{-1}$ for 5 days) marginally increased running velocity in the initial 100-m sprint and in five of the 60-m sprints. Conversely, performance in sprinters at national level was not increased by creatine intake (0.35 $g \cdot kg^{-1}$ body mass for 7 days) in a 6 × 40-m (2-min rest intervals) intermittent exercise test (Delecluse, Diels, & Goris, 2003). Other studies utilizing various types of athletes provide equivocal results (Glaister *et al.*, 2006; Mujika, Padilla, Ibanez, Izquierdo, & Gorostiaga, 2000). Importantly, none of the available studies has reported impaired performance.

Direct determination of a beneficial effect of creatine supplementation on sprint performance is difficult. First, the performance benefit of creatine intake as a rule is very small, and conceivably within the limits of day-to-day variability in performance, thus the reliability of sprint tests "in the field" may be too small to demonstrate a significant effect of creatine in a small sample of individuals. Second, the available data pertain predominantly to very short sprints (15–60 m) where start reaction time as well as running skill (coordination) are major determinants of performance. Creatine intake is unlikely to be beneficial to either of these important factors. Finally, it is important to emphasize that results from well-controlled laboratory studies consistently indicate that creatine supplementation can enhance power output during short maximal exercise (Terjung *et al.*, 2000), in particular during intermittent series (10–30 s) of maximal muscle contractions (Casey, Short, Curtis, & Greenhaff, 1996; Greenhaff *et al.*, 1993) interspersed by 1–2 min rest intervals. Heavy resistance training accounts for an important fraction of the total training volume in elite sprinters. It has been well documented that creatine supplementation can potentiate the gains in fat-free mass and muscle force and power output that accompany resistance training (Hespel *et al.*, 2001; Volek *et al.*, 1997). Thus, creatine supplementation conceivably could contribute to improving sprint performance by enhancing the efficacy of resistance training.

A classical creatine loading regimen consists of an initial loading phase (15 – 20 g · day^{-1} for 4 – 7 days) followed by a maintenance dose (2 – 5 g · day^{-1}) (Terjung *et al.*, 2000). However, individual responses vary and there are indications that a positive effect on muscle mass may diminish after 8 – 10 weeks (Derave, Eijnde, & Hespel, 2003). Although solid data are lacking, it may be advisable to add wash-out periods to periods of creatine supplementation for optimum impact. Individuals with a low initial muscle creatine content, such as vegetarians (Burke *et al.*, 2003), respond better to creatine supplementation than others with high a natural muscle creatine content. Therefore, creatine intake probably is an adequate adjuvant to a vegetarian diet in sprinters. Furthermore, ingesting creatine in conjunction with training sessions can stimulate muscle creatine uptake, as exercise is known to facilitate the disposal of ingested creatine into the musculature (Harris *et al.*, 1992). It is probably also worthwhile considering the possibility of ingesting creatine supplements in combination with post-exercise carbohydrate – amino acid – protein supplements in order to enhance muscle creatine retention due to increased insulin concentrations (Steenge, Simpson, & Greenhaff, 2000). Creatine is not on the doping list and its intake is generally found to be safe in healthy adults provided the aforementioned guidelines are followed (Terjung *et al.*, 2000). Creatine intake does result in increased body mass from intracellular water accumulation. Increased water content may be problematic for some athletes, particularly sprinters desiring optimal power-to-mass ratios.

The physiological mechanisms underlying the effects of creatine supplementation are only partly understood. Some indicate that an increased muscle creatine content can facilitate flux through the creatine kinase reaction and thereby prevent net ATP degradation during high-intensity muscle contractions (Casey *et al.*, 1996). This flux could also explain the shortening of muscle relaxation time seen after creatine loading (Van, Vandenberghe, & Hespel, 1999) possibly contributing to increased stride frequency during sprinting with creatine intake (Schedel, Terrier, & Schutz, 2000). Given that the importance of phosphocreatine to energy production (relative to muscle glycogen) increases as the duration of a sprint is shortened, the ergogenic effect of creatine may be more important in the 60- and 100-m sprints than in the longer sprint events (200 – 400 m). Furthermore, stimulation of muscle phosphocreatine resynthesis may contribute to enhanced recovery between intermittent sprint bouts (Casey *et al.*, 1996; Greenhaff, Bodin, Soderlund, & Hultman, 1994), thus enhancing sprint training.

The mechanisms underlying the potential of creatine to stimulate muscle anabolism during resistance training are unclear. Creatine intake may increase the stimulation of satellite cell proliferation (Olsen *et al.*, 2006) or intracellular signalling pathways (Deldicque *et al.*, 2005; Louis, Van, Dehoux, Thissen, & Francaux, 2004). However, direct evidence that creatine can stimulate net protein synthesis in human muscle is lacking (Louis *et al.*, 2003; Parise, Mihic, MacLennan, Yarasheski, & Tarnopolsky, 2001). Alternatively, changes in muscle protein accretion can occur as a consequence of individuals performing more work during high-intensity training programmes while consuming creatine (Kreider *et al.*, 1998).

Caffeine

Caffeine is a popular stimulant used by most individuals, including athletes. Caffeine is contained in coffee, tea, chocolate, and many other caffeinated food sources like cola and so-called "energy-booster" drinks. The primary mechanism of action by which caffeine can beneficially affect performance probably is by enhancing central drive and/or improving muscle fibre recruitment (Graham, 2001). It is well known that small doses of caffeine (1 – 2 mg · kg^{-1} body mass) can beneficially influence mental alertness and thereby shorten reaction time (Haskell, Kennedy, Wesnes, & Scholey, 2005), which is obviously crucial to sprint success. However, care must be taken to determine the optimum dose during training because overdosing will have a negative effect on reaction time. Because sprinters typically compete on an empty stomach, caffeine will be very rapidly absorbed, and if ingested during the pre-competition warm-up period, the potential performance benefits may be reduced during the competition to follow (Bell & McLellan, 2002). Caffeine should be ingested in an isolated formulation (capsules or tablets) rather than in the form of strong coffee because the latter is more likely to cause gastrointestinal distress (Tarnopolsky, 1994).

Responses to caffeine intake and withdrawal vary greatly among individuals depending on the degree of habituation (Bell & McLellan, 2002; Magkos & Kavouras, 2004). Therefore, individual tuning of the dosage in the context of training is very important. Frequent high-dose caffeine intake results in rapid desensitization and will require the use of an even higher dose.

The common use of caffeine as a "social stimulant" probably proves that low-dose caffeine intake should be considered to be safe. However, high-dose caffeine intake is well known to be associated with adverse health effects, in particular at the level of the cardiovascular system (Tarnopolsky, 1994). In 2004, the World Anti Doping Agency (WADA) removed caffeine from the list of banned substances and its use is currently being monitored.

Summary of nutritional guidelines for sprinters

Consensus for:

- Carbohydrate intake should be sufficient ($\sim 5\ \text{g} \cdot \text{kg}^{-1}$ body mass) to maintain glycogen stores during training.
- Energy intake should be carefully considered: if increased muscle mass is desired, energy intake should be increased; if muscle mass is optimal, energy intake should be maintained and perhaps monitored.
- Protein intake is likely adequate for the majority of sprinters, but if energy intake is increased a portion of this increase could, and perhaps should, be protein.
- Type of protein and timing of protein ingestion should be considered if increased muscle mass is the goal.
- Race day nutrition should be developed individually with the goal of avoiding gastrointestinal distress and dehydration.
- Creatine supplementation may enhance increases in muscle mass and strength, but sprinters must consider the extra weight gain associated with creatine use.

Consensus against:

- A single broad recommendation for protein intake for all sprint athletes is non-sensical.
- Since power/mass is the most critical element of sprinting success, automatically assuming strategies that may increase muscle mass are desirable could be a mistake if increased mass decreases the power-to-mass ratio.
- Use of supplements as sources of protein and amino acids in the belief that they provide superior quality to foods.
- There is insufficient evidence to recommend other supplements (e.g. ribose, hydroxymethylbutyrate, vanadyl sulphate) to sprinters at this time.

Issues that are equivocal:

- Relationship of type of protein and timing of ingestion of proteins for muscle anabolism.
- The role of muscle degradative pathways for adaptation to training.
- The impact of nutrition on muscle degradative pathways for training adaptations.
- Effect of nutrients and the interaction with training on signalling pathways and gene expression in muscle.
- Efficacy of beta-alanine for increasing muscle carnosine in well-trained sprinters.
- Efficacy of bicarbonate in sprinters.

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ustralia (front L) competes during the women's Steeplechase final at
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Middle- and long-distance races viewed from the perspective of complexity: Macroscopic analysis based on behaviour as a power law

By Juan M. Garcia-Manso, Juan M. Martin-González, Enrique Arriaza, Lucia Quintero

ABSTRACT

The term 'power law' describes the organising principle that very few nodes will maintain a large percentage of links in a network or system. In a continuation of an earlier work, the authors use this idea to characterise the different performance levels into which top-class male athletes in the middle- and long-distance races in athletics can be grouped. They assume that the total system has a critical behaviour and that the performances in these races should strictly follow a power law. Using the best times of the all-time top 550 ranked performers in the events from 1500m to marathon (excluding the steeplechase) on 30 October 2003 as basis for analysis, they attempt to detect those values (performances) that show clearly abnormal behaviour within their performance level and thus compare the level of one event to the others. A box-plot of the residuals from the regression model is used to analyse exceptional performers or outliers, who act as targets, barriers and/or powerful attractors that increase the level of performance in one event in comparison to the other distances analysed.

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Introduction

In an earlier paper (GARCIA-MANSO et al., 2005), we verified that performances in the middle- and long-distance athletics races behave as power laws when time (or average velocity) and distance are related, regardless of their individual characteristics. This suggests the presence of critical phenomena. We also emphasised the importance of the *universe* (the

of people involved in the activity) but ed the study to the world's best ath- each competition distance, referring rly to the world records for each dis-

present study, we used the top 550 in the all-time world rankings for 3000m, 5000m, 10,000m, half ı and marathon events as samples. e only the best time for each of the running the different competition . The world records represent the icially recognised as such as of 30 2003 and the times used for the f the other positions correspond to letes occupying that position in the orld ranking as of the same date.

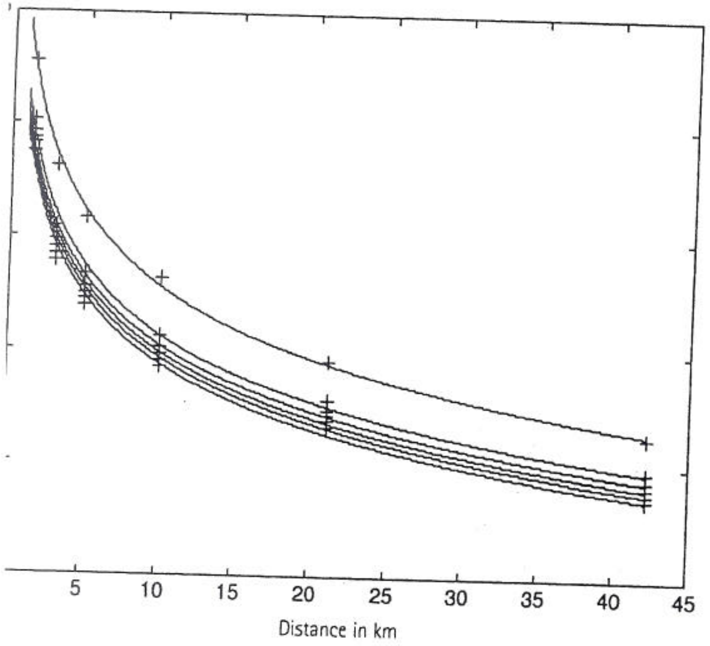
a we utilised showed that, in spite formance level (world ranking posi- ıe individual concerned, when the

average velocity of a race is related to the distance covered, the same type of scaling law is always found:

$$V(r) = C(r)\, d^{-\alpha(r)} \qquad (r = 1^{st}, 2^{nd}, \dots, 100^{th}, \dots) \qquad (1)$$

In Equation 1, r is the athlete's position in the all-time world ranking, *C(r)* and *α(r)* are constants at each level of performance r, while d represents the competition distances covered. The value *log(C(r))* represents the intersection point of the regression line at each level with the axis *log(v)* and, to some extent, is an indicator of how average race velocity decreases as we go down the world ranking. This fact led us to define *C(r)* as "Performance Index" (PI), which also seems to roughly follow a scaling law.

A deeper analysis of the PI shows the existence of natural barriers, in the evolution of the times, which seem to correspond to per-



ic representation of equation (1) fitted for specific examples of athletic performance (1st, 100th, 200th, d 550th ranked performers).

Table 1: Numerical results obtained for the differences $u^d(r)-\hat{u}^d(r)$, where $u^d(r)$ is the logarithm of the average velocity of subject r^{th} for competition distance d, and $\hat{u}^d(r)$ is the value given by the regression line. The table shows only some of the positions.

Ranking	1500m	3000m	5000m	10,000m	Half-marathon	Marathon
1st	0.0064	-0.0087	-0.0040	0.0063	0.0018	-0.0018
10th	0.0081	-0.0096	-0.0044	0.0039	0.0032	-0.0012
50th	0.0103	-0.0106	-0.0041	-0.0005	0.0047	0.0002
100th	0.0104	-0.0092	-0.0059	-0.0005	0.0044	0.0008
150th	0.0117	-0.0106	-0.0060	-0.0009	0.0045	0.0013
200th	0.0121	-0.0104	-0.0071	-0.0007	0.0048	0.0013
250th	0.0121	-0.0108	-0.0067	-0.0006	0.0051	0.0010
300th	0.0125	-0.0115	-0.0065	-0.0009	0.0057	0.0007
350th	0.0124	-0.0113	-0.0064	-0.0014	0.0059	0.0008
400th	0.0124	-0.0114	-0.0063	-0.0013	0.0061	0.0005
450th	0.0125	-0.0116	-0.0064	-0.0012	0.0059	0.0007
500th	0.0127	-0.0118	-0.0063	-0.0012	0.0056	0.0009

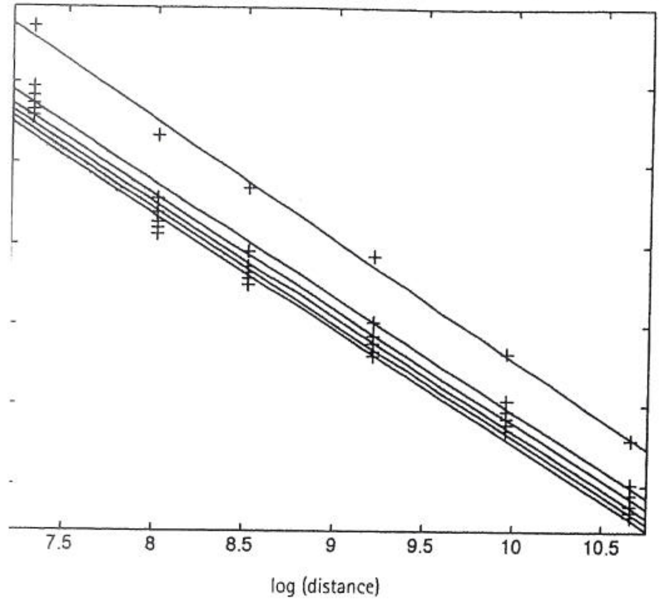
formance levels, or significant times, in an athlete's evolution towards better results and world records. Furthermore, the way in which PI times are distributed on different scales seems to show an underlying multifractal structure.

The sporadic appearance of subjects able to deliver times that are clearly better than those existing, would define new goals or targets that would act as attractors or reference points for other athletes. At the same time, a new elite group or area specific to the race in question would be established. As this happens, Equation 1 would be defined more clearly as a power law to which all the values would evolve in these resistance races.

The present study will analyse the current situation of three groups of athletics running events (middle-distance, long-distance and marathon) in terms of the corresponding power laws that characterise the different performance levels that group together the athletes occupying the top 550 positions of the all-time world ranking for the respective distances. We will thus try to detect those values that show clearly abnormal behaviour within their performance level. With this intention, we shall assume that the total system has a critical behaviour and that the races should strictly follow the power-law shown in the Equation 1. Or, in other words, the differences in each average velocity value (or time taken) to the curve (or logarithms to the regression line) should be or tend towards zero. To this end, we have taken Equation 1 to a logarithmic form:

$$u(r) = \log(v(r)) = \log(C(r)) - a((\_r))\log(d) \qquad (2)$$

From this point onwards, we will use this equation as a reference base for each position in the ranking. We calculated the differences (residuals) from the actual data (time or velocity) to the value suggested by the regression model. This allows us to compare the position or state of each race to the rest, as well as to organise the times for each competition distance. We will thus have $D^d(r)= u^d(r)-\hat{u}^d(r)$ where $u^d(r)$ is the logarithm of the average velocity of subject r^{th} for competition



lot of equation (1) for the same levels (1st, 100th, 200th, 300th, 400th and 550th) in the men's all-, together with their regression lines.

$\hat{u}^d(r)$ is the value given by the . The numerical values, for sitions, are given in Table 1.

he results we shall use a box-natrix $D^d(r)$, with r = 1st, r each value of *d*. The box-plot and whisker plot for each d ıas lines at the lower quartile, upper quartile values. The es extending from each end of the extent of the rest of the -plot analysis, an outlier cor-me whose value is more than ter-quartile range away from ottom for the specific box for ıce.

atypical the races

the competition distances in see that in each event there y runners whose performance levels do not conform to the norm of the compiled data. The incidence of this situation is not the same, either in the way it occurs or in proportion, in the different distances studied.

Thus, we can see (Figure 3) that this type of runner (known as an *outlier*), capable of recording times that are significantly different to those of most of the athletes analysed in the series used for each distance, is more frequent in the 1500m (34 athletes) and 5000m (27 athletes). By contrast, the tendency is something different for the 3000m (11 athletes), 10,000m (16 athletes), half marathon (7 athletes) and marathon (15 athletes) races.

We understand that outliers act as a kind of target, barrier and/or powerful attractor leading the event towards a greater position in comparison with the other distances analysed. The importance of the outliers and their effect on the evolution of such a system depends on many factors. However,

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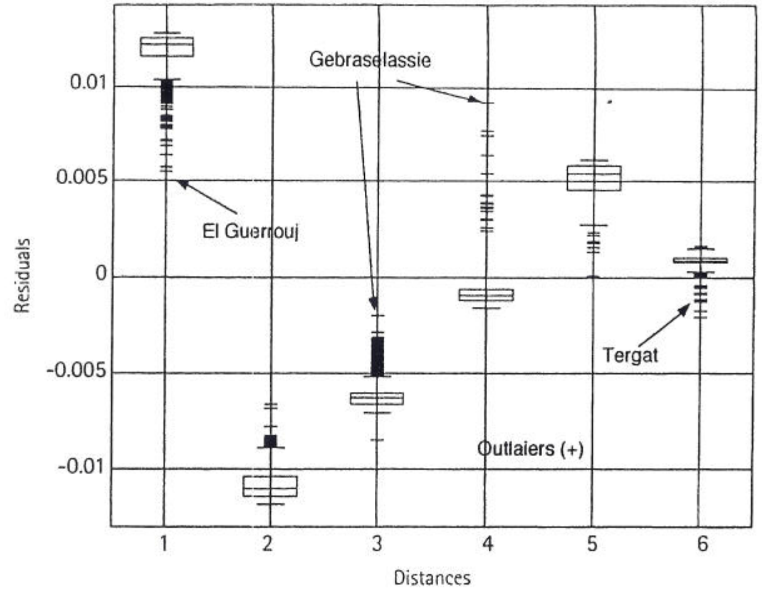

Figure 3: Box-plot of the matrix Dd(r), with r = 1st, 2nd,…,550th for each of the distances considered di, (i = 1,…,6), equivalent to 1500m, 3000m, 5000m, 10,000m, half marathon and marathon, in this order.

given the practical experience that characterises these races, we can mention the most relevant factors: the potential value of the time, the number of outliers in the event and the circumstances in which the exceptional times are run. The quality of the behaviour in this case is relevant given that, according to our initial hypothesis, these attractors are responsible for leading the system (composed of competition distances) to a critical state.

For example, the record and/or times for 10,000m and marathon races behave like outliers in comparison with the rest of the times that appear in the ranking used, although they do so in different ways. The outlier for the 10,000m (difference 0.0063, in Table 1) shows the extraordinary merit of the world record (26:22.75) recognised at the time this table was produced, not to mention the subsequent performances by Bekele (ETH). Other athletes at this distance will find the record extremely difficult to beat. Sometimes, although it is not this case, experience shows us that extraordinary times can be attributed to the effect of variables that are not connected with the athlete. These may include particularly favourable competition conditions (excellent pace-marker, ideal weather conditions, significant competition incentives, sea level, etc.). Alternatively, factors that are difficult to control may come into play (these might include doping). Besides these considerations, proximity to the fit and the presence of an outlier, the 10,000m shows a relatively compact behaviour, with a normal distribution of recorded times and low dispersion of times (Figure 3).

The overall behaviour of times in the marathon is very similar to that observed in the 10,000m, with concentrated times and a low level of dispersion, showing the internal normality of this race, particularly if we consider the top positions. The previous world record (2:05:38) by Khannouchi (USA), seemed, at the time, to differ significantly

verage behaviour of other values or this distance. However, at that lue could be considered as low in with the rest of the times record- r races and for the same distance ore, open to improvement in the by a fair number of specialists. This ned by the times recorded by dif- tes at the end of 2003, particular- (KEN) and Korir (KEN), who broke g world record during the Berlin with their respective times of 1 2:04:56. Despite this latest qual- nge in the all-time records, an ysis of the event seems to indicate nking list will undergo significant er coming seasons.

thesis of the future can also be om a physiological point of view. and that a runner with a low BMI Index), a VO_2max near to 80 and the ability to run the distance ity close to 90% of this value with nomy (~0.185-0.190 ml.kg⁻¹.m⁻¹), to beat these marks or others of l.

y race groups

nalysis, we organised the compe- ces into three categories (middle- g-distance and marathon), which imilar distances in terms of the o are successful in each category. ach of these categories could be based on the individual profile of but we do not think this step is sary or helpful in this overall race e middle-distance group includes 3000m and 5000m; the long-dis- covers the 10,000m and the half hile the third category includes rathon.

istances

t situation of races traditionally middle-distance events consti- interesting case (Figure 3). From point of view, runners of 3000m and 5000m races have the maximum requirements for aerobic power, which correspond to times of about 420sec (PERONNET and THIBAULT, 1989), 450-550sec (ALVAREZ-RAMIREZ, 2002) or 600sec (MORTON and BILLAT, 1999). By contrast, the 1500m is the frontier between the resistance and speed events (power and/or speed endurance). When we analyse the position of these events on the box-plot, we realise the low relative value of the times for the 3000m and 5000m. This tendency increases as the performance of the athletes decreases. This type of behaviour, athough it clearly exists, is less acute in the longer distance (5000m), though we have to bear in mind that this distance has been included in the official programme of the Olympic Games, the World Championships in Athletics and the continental championships since these competitions began. On the other hand, the 3000m has only been included in indoor competitions or some outdoor invitational meetings over the last few decades. This leads us to think that the all-time ranking of these two distances, particularly the 3000m, could undergo a significant change and improvement if the following variables were changed: an increase in the universe of athletes with the current training characteristics and/or incorporation of the 3000m in the programmes of the major outdoor championships. We believe that the current world records for these two distances could be improved, and that the new records would drag the other competing athletes with them to a higher level of performance. The potential record times could lie around 7:16.55 (3000m) and 12:36.55 (5000m), similar to the 5000m world record of 12:39.36 used in our analysis and Bekele's subsequent mark of 12:37.35.

The 3000m shows relatively homogeneous times with a small inter-quartile range and low dispersion, and the times show a certain tendency to approach the outliers.

The times for the 5000m are similar, but their behaviour is different, given that in this case they form a compact block around a

concentrated average, with the obvious influence of a group of specialists who powerfully drag the race towards its natural position. This suggests to us the existence of a specific specialist profile (with times of <13:00) clearly differentiated from other world-class runners (whose times range between 13:15 and 13:30). Athletes from North Africa (Morocco and Algeria) and East Africa (Kenya and Ethiopia) have played an important part in shaping the dynamics of the 5000m.

The 1500m behaves in a very different way to the two races we have just discussed. This race has two significant characteristics: first, it is a key event in athletics (its popularity giving it a greater *universe*), and second, it is located close to the border between the endurance running (>1000m), determined mainly by aerobic metabolism, and the speed events (<1000m), which rely on anaerobic metabolism.

The results obtained in the series of times used demonstrates the high average value of the times for the 1500m in relation to the tendencies found in the other events analysed. There are three aspects that might affect the position occupied by this distance: energy dependence, it's *universe* and the profile of the athlete currently running the best times in the world.

Aerobic metabolism plays a very important role at this distance, although the metabolic contribution is significantly different in the case of each athlete according to his functional profile, muscular structure and physical fitness. In this race, aerobic metabolism would appear to act as an important attractor in the organism of current world-class athletes. The anaerobic metabolism is also a determining factor, although in a different proportion. According to WARD-SMITH (1999), the full potential of the anaerobic capacity is available for conversion during extended periods of running, but other authors say that the anaerobic energy contribution declines with race duration (GOLLNICK and HERMANSEN, 1973); PERONNET and THIBAULT,1989).

According to most studies, aerobic metabolism is attributed as contributing between 60% and 90% of the total energy contribution (SPENCER et al., 1996; WEYAND et al., 1993). These figures include a wide degree of variability between individual athletes, which gives cause for thought. Clearly, part of this difference could be explained by the characteristics of the samples used in the different studies undertaken (whether they were physically very trained, quite trained or sedentary), but we need to consider other parameters as well. Experience has shown us that there are three prototypes for athletes running the 1500m: those that run this distance as well as shorter distances (800m and 1000m); those that run the 1500m well, but also perform well at longer distances (3000m and 5000m) and genuine specialists in the 1500m. This practical reality could explain some of the causes underlying this very wide range of energetic behaviour, although we should also bear in mind the possible effect of the procedures used in metabolic assessment.

Generally speaking, the main functional factors restricting performance in the 1500m could be taken as the elevated depletion of the muscular CrP, the high metabolic acidosis produced by a significant activation of the glucolitic metabolism and the insufficient capacity of the aerobic metabolism to produce enough energy. The importance of each of these aspects to the result of a race varies in each athlete, his functional profile and the type of training employed. The current world record holder at 1500m, El Guerrouj (MAR) is a particularly interesting case, because of his exceptionally good time (3:26.89). His times appear closer to the regression line (distance: 0.0064, in Table 1) than the rest of the times used in the study (up to the all-time 550th position). This led us to think that this athlete could be included in the group of runners who also run well at longer distances (2000m, 3000m and even 5000m). This opinion was confirmed when we checked his best times over 3000m (7:23.09) and 5000m (12:50.24).

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:y broke the barrier of 27 min-
sily. Initially, these times pro-
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ıathon is a particularly interest-
n here on, the scaling law, and
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he results of the half marathon
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(Figure 3) shows that half
:s do not show many outliers,
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ı60, in Table 1). This behaviour
f we bear in mind that this dis-
ıcluded in the Olympic Games, World Championships in Athletics or the continental championships. It has only recently become widely popular (in the last three decades), although the level of participation is very significant. Given the results obtained, we could posit that performances by top class athletes in the half marathon benefit from the fact that this distance falls within the range of two types of specialists (10,000m and marathon). This produces better performance and bodes well for the event's evolution.

Marathon

The marathon is clearly different from the long-distance races considered above, as top-level success calls for a highly specialised type of runner whose energy needs (and therefore training needs) are clearly differentiated from the runners of shorter distances. There is no other sufficiently developed race with similar characteristics, in terms of length, functional or physical dependence, that can be considered in this category.

From the metabolic point of view we know that races over two hours in duration significantly increase the participation of fats in the aerobic metabolism: through β-oxidation replacing the reserves of glycogen, which is the major source of energy in races lasting around an hour (for example the half marathon) (BERGSTRÖM and HULTMAN, 1967; SALTIN and LARLSSON, 1971; COSTILL et al, 1971 and 1973; SHERMAN et al, 1981; MADSEN et al, 1990; SAHLIN et al, 1990; WELTMAN, 1995; TSINTZAS et al, 1996ª; HAWLEY et al, 1997). In the marathon, the runner's energy dependence on fats is around 20%, although the importance of this substrate increases with the length or duration of the race, and can reach 60-70% in 100km races (NEWSHOLME et al, 1992; LEIBA and TERRADOS, 1996).

The change in energy dependence in races lasting 90-120 minutes could possibly be expressed in a new scaling law, which would allow us to find the decisive point between long-distance and marathon. This cut-off point could define the limits between the two

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aerobic metabolisms described above (carbohydrates and fats). However, in order to do this we would need enough information about other long-distance races (for example, 50km or 100km races). Unfortunately, this type of race is not sufficiently developed for our purposes, and potential top athletes for these races normally opt for those events that are currently more popular, such as the triathlon. The only distance in athletics that has an established competitive tradition is the 100 kilometres, but the number of participating athletes is low and there are very few genuine specialists at this distance. This fact limits the effective *universe*, gives a biased behaviour pattern over this distance and prevents us from broadening the scope of our work.

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Original article

Bioenergetic constraints on tactical decision making in middle distance running

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* Να διαβαστεί πριν από τη συγγραφή της εργασίας!!

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Abstract

Background: The highest velocity that a runner can sustain during middle distance races is defined by the intersection of the runner's individual velocity-time curve and the distance-time curve. The velocity-time curve is presumably fixed at the onset of a race; however, whereas the race distance is ostensibly fixed, the actual distance-time curve is not. That is, it is possible for a runner to run further than the race distance if he or she runs wide on bends in track races. In this instance, the point of intersection of the individual velocity-time curve and the distance-time curve will move downwards and to the right, reducing the best average velocity that can be sustained for the distance.

Methods: To illustrate this point, the race tactics used by the gold and silver medallists at 800 m and 5000 m in the Sydney Olympics were analysed. The paths taken by the runners were carefully tracked and the total distance they covered during the races and the average velocity they sustained over the distances they actually covered were calculated.

Results: In both the Olympic 800 m and 5000 m finals, for example, the winner was not the runner who ran at the highest average velocity in the race. Rather, the winners of these races were able to husband their metabolic resources to better effect by running closer to the actual race distance.

Conclusions: Race results in middle distance running events are dependent not just on the energetic potential of the runners at the start of the race and their strategy for pace allocation, but also on the effect of their tactical approach to positioning on the total distance covered in the race. Middle distance runners should be conscious of minimising the distance covered in races if they wish to optimise their performance. 1.

The major physiological factors associated with successful distance running performance include the runner's maximal oxygen uptake (VO_2MAX) and lactate threshold, the running economy (the oxygen cost of running in ml O_2/kg body mass/km), and the critical velocity. However, very little attention has been paid to the influence of race tactics on the optimal use of a runner's physiological resources and their effects on the outcome of distance races. 2. Αίτιο

The highest constant velocity that a runner can theoretically sustain without fatigue associated with an inexorably developing metabolic acidaemia can be estimated using the "critical velocity" (CV) concept.[2] The time to exhaustion at several different running velocities can be used to construct a runner's velocity-time curve (fig 1). The asymptote of this hyperbolic relation is defined as the CV (m/s), and the curvature constant (D') represents a constant distance (m) that can be covered above the CV using the currently fixed energy reserves (stored oxygen, high energy phosphates, and energy liberated through anaerobic glycolysis). The relation may therefore be described with the following equations:

$$(V - CV)t = D'$$

or

$$V = D'(1/t) + CV$$

where V is running velocity (m/s) for velocities greater than CV.

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Applied Physiology of Marathon Running

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Summary

Performance in marathon running is influenced by a variety of factors, most of which are of a physiological nature. Accordingly, the marathon runner must rely to a large extent on a high aerobic capacity. But great variations in maximal oxygen uptake ($\dot{V}O_{2\,max}$) have been observed among runners with a similar performance capacity, indicating complementary factors are of importance for performance. The oxygen cost of running or the running economy (expressed, e.g. as $\dot{V}O_{2\,15}$ at 15 km/h) as well as the fractional utilisation of $\dot{V}O_{2\,max}$ at marathon race pace ($\%\dot{V}O_{2\,Ma} \times \dot{V}O_{2\,max}^{-1}$) [where Ma = mean marathon velocity] are additional factors which are known to affect the performance capacity. Together $\dot{V}O_{2\,max}$, $\dot{V}O_{2\,15}$ and $\%\dot{V}O_{2\,Ma} \times \dot{V}O_{2\,max}^{-1}$ can almost entirely explain the variation in marathon performance. To a similar degree, these variables have also been found to explain the variations in the 'anaerobic threshold'. This factor, which is closely related to the metabolic response to increasing exercise intensities, is the single variable that has the highest predictive power for marathon performance. But a major limiting factor to marathon performance is probably the choice of fuels for the exercising muscles, which factor is related to the $\%\dot{V}O_{2\,Ma} \times \dot{V}O_{2\,max}^{-1}$. Present indications are that marathon runners, compared with normal individuals, have a higher turnover rate in fat metabolism at given high exercise intensities expressed both in absolute (m/sec) and relative ($\%\dot{V}O_{2\,max}$) terms. The selection of fat for oxidation by the muscles is important since the stores of the most efficient fuel, the carbohydrates, are limited. The large amount of endurance training done by marathon runners is probably responsible for similar metabolic adaptations, which contribute to a delayed onset of fatigue and raise the $\dot{V}O_{2Ma} \times \dot{V}O_{2max}^{-1}$. There is probably an upper limit in training kilometrage above which there are no improvements in the fractional utilisation of $\dot{V}O_{2\,max}$ at the marathon race pace. The influence of training on $\dot{V}O_{2\,max}$ and, to some extent, on the running economy appears, however, to be limited by genetic factors.

and runners in the 400m and 800m events (Svedenhag and Sjödin, 1984). Although the %$\dot{V}O_{2\,max}$ at the 4 mmol/L velocity differed significantly between sub-3-hour runners and slower runners in our unpublished data, the difference was not marked. In all, this may indicate that the rightward shift of the lactate curve relative to $\dot{V}O_{2\,max}$ may occur largely as an early response to training. The excessive amounts of training often done by marathon runners thus appear to have a relatively small effect on further shifting of the lactate curve to the right.

Training at the speed corresponding to the anaerobic threshold is widely used as a means of improving performance in marathon running (Lenzi, 1983). In view of the discussion presented above concerning the early rightward shift of the lactate curve, such a training effort would appear to be rather fruitless for a previously trained individual. However, an improvement in the anaerobic threshold velocity after threshold training in previously well-trained runners may be mostly due to effects on the running economy and the $\dot{V}O_{2\,max}$ (Sjödin et al., 1982). Evidently, there may be an intricate interplay between training and the different physiological variables determining running performance.

As was the case for %$\dot{V}O_{2\,max}$ at the marathon race pace, %$\dot{V}O_{2\,max}$ at the 4 mmol/L velocity was significantly higher in the older (sub-3-hour) runners than in the younger sub-3-hour runners (89.3 ± 0.6% *vs* 86.8 ± 0.6%). The highest value was found in the 35-year-old runner Ståhl (92.9%). This may explain, then, why the older runners were able to utilise a higher %$\dot{V}O_{2\,max}$ at the marathon race pace than the younger runners.

2.5 Fuels

2.5.1 *Energy Expenditure*

The total energy expenditure for completing the 42,195 metres of a marathon race has been calculated to amount to 9000 to 12,000 kJ (Costill, 1972; Newsholme, 1983; Wells et al., 1981). Some deviation between runners may result from individual variations in the running economy. For elite marathoners who complete the race in a faster time than 2:30, this means that the rate of energy expenditure may exceed 75 kJ/min during the race (Costill and Fox, 1969; Sjödin and Svedenhag, unpublished data). One problem for the body is to meet this huge energy demand with an adequate amount of efficient fuel.

Available fuels are carbohydrates and lipids and, to a smaller extent, proteins (Dohm et al., 1982). Endogenous fuels, such as muscle glycogen and muscle lipid stores, seem to be utilised more efficiently by the contracting muscle than exogenous energy sources such as circulating free fatty acids (FFA) and blood glucose (Felig and Wahren, 1975; Lithell et al., 1979). However, as the performance progresses and the endogenous sources become more depleted, the circulatory substrates glucose and FFA gradually become more important (Felig and Wahren, 1975; Lithell et al., 1979).

To make a fair estimate of the utilisation of different fuels by marathon runners, one must consider the high-power output (up to 85% of $\dot{V}O_{2\,max}$) that can be maintained by the elite runners throughout the race (see above). At correspondingly high exercise intensities we know that there is a greater reliance on carbohydrate than on lipids. Thus, in moderately trained subjects the rate of muscle glycogen utilisation at least above 50% of $\dot{V}O_{2\,max}$ has been found to be directly proportional to the exercise intensity (Hermansen et al., 1967).

2.5.2 *Glycogen Stores*

The mean glycogen concentration in the leg muscles has been found to be about 12 g/kg wet muscle, but there are large intraindividual variations (Hultman, 1967). Somewhat higher mean values, 17 to 18 g/kg wet muscle, have been demonstrated in endurance-trained individuals (Hermansen et al., 1967; Karlsson and Saltin, 1971). Assuming that the active muscle mass amounts to about 20kg, the total available muscle glycogen store should amount to 340 to 360g. By depleting the glycogen stores by exercise combined with a very low carbohydrate intake for 1 or 2 days and then replenishing the stores by consuming a carbohydrate-rich diet for another 2 or 3 days, the muscle glycogen stores can be more than doubled (Bergström et al., 1967). Calculations have been published which indicate that the degradation of muscle glycogen proceeds at a rate of 0.4 to 0.5 g/kg/min wet muscle tissue at exercise intensities similar to those in marathon running, i.e. 85% to 90% $\dot{V}O_{2\ max}$ (Karlsson and Saltin, 1971). Muscle glycogen consumption may be even higher after the carbohydrate loading procedure (Costill and Miller, 1980). If the muscle glycogen stores were used exclusively, these stores ought to be depleted within 40 minutes with normal stores or within 70 minutes with enlarged stores. An additional 100g glycogen may be stored in the liver and another 20g glucose is present in extracellular fluids (Newsholme, 1981). Theoretically, if all these carbohydrates could be transferred and utilised by the exercising muscles, these exogenous stores could delay carbohydrate depletion by another 15 minutes.

2.5.3 Lactate Oxidation

In addition, some extra glucose may be produced from lactate and some amino acids by gluconeogenesis in the liver (Felig and Wahren, 1975). Even though relatively low lactate values have been found after a marathon race (2.1 mmol/L, n = 6, Costill and Fox, 1969; 1.9 mmol/L, n = 6, Maron et al., 1975), higher values may occur during uphill parts of the course as the runner may then be performing at 100% of his or her $\dot{V}O_{2\ max}$ (Maron et al., 1976). Lactate can probably also be used directly in the active musculature. Thus, the alternative pathway in which lactate is oxidised is catalysed by the H-LDH isozyme (Skilleter and Kun 1972). As mentioned, relatively high activities of this isozyme have been found in the type I fibres of endurance-trained individuals (Sjödin, 1976), indicating a high capacity for lactate oxidation.

2.5.4 Glycogen Depletion and Carbohydrate Supplementation

By making similar assumptions about the delaying effect on glycogen depletion resulting from the availability of other carbohydrate sources, Locksley (1980) has calculated the total muscle glycogen depletion will occur at between 32 and 40km of the marathon race. A corresponding situation is illustrated in figure 7. Runner B obviously 'hit the wall' 7km from the finish and was thoroughly exhausted during the last 5km. By administering additional oral carbohydrate solutions during the race such a depleted condition might have at least been delayed (Coyle and Coggan, 1984). The emptying rate of the stomach is limited, however, particularly during intense exercise. Accordingly, the emptying rate is inversely related to the intensity of the exercise and the glucose concentration of the solution (Costill and Saltin, 1974). Too high a concentration of monosaccharides in the solution will produce an excessively high osmotic pressure in the gastrointestinal tract, and this will result in delayed gastric emptying and slower uptake from the intestine. This could be avoided, however, with a low concentration of the monosaccharides (glucose and fructose) or by using polysaccharides in the drinks (Daum et al., 1978).

2.5.5 Fat Metabolism

From the above discussion it is clear that the stores of carbohydrate in the body are small and will not cover the energy demands of running a marathon. As illustrated above, there is considerable evidence that carbohydrate depletion may be the main factor responsible for exhaustion during prolonged exercise. If the stores are depleted, the exercise intensity has to be reduced. However, some authors have shown that even with minimal muscle glycogen stores the exercise can still be performed at a power output of 60 to 70%, or less, of $\dot{V}O_{2\ max}$, provided that the supply of free fatty acids is adequate (Pernow and Saltin, 1971). If the supply of FFA is adequate from the beginning of exercise, this may have a sparing effect on the muscle glycogen stores. It has been demonstrated that if the FFA concentration is artificially elevated, e.g. by an intake of caffeine before exercise, a specific level of exercise can be maintained for a longer period of time (Costill et al., 1977; Hickson et al., 1977).

One of the major adaptations to endurance training is probably also related to an increased ability to oxidise fat in the active muscle tissue.

This is indicated by elevated activity levels of fat-oxidising enzymes in the skeletal muscle of endurance-trained individuals as discussed earlier (Chi et al., 1983; Essén-Gustavsson and Henriksson, 1984). Respiratory data on marathon runners have also demonstrated that more than 75% of the consumed energy could be derived from fat while running at 70% of $\dot{V}O_{2\,max}$ (Costill et al., 1979). This indicates a considerably higher turnover rate of fat metabolism than can be expected in a normal population at correspondingly high relative exercise intensities. All these metabolic adaptations may make it possible to delay the depletion of carbohydrate stores and thereby contribute to the ability of elite marathon runners to maintain a very high and constant running speed during the whole race because the most efficient fuels, the carbohydrates, will be available to the very end of the race.

2.6 Environmental and Other Factors

In addition to the physiological factors discussed above, marathon performance is dependent on several other factors. These factors are, in part, determinants of the velocity and therefore also of the %$\dot{V}O_{2\,max}$ that can be maintained during the race (see above). Thus, the physical characteristics of the marathon course (e.g. hilly or flat), the altitude of the course and whether there is a difference in altitude between the start and finish lines are obviously factors of importance to marathon performance. Other environmental factors of importance include the ambient temperature and humidity (Costill, 1972) and the wind conditions during the race. Furthermore, body fluid losses and their replacement, together with the runner's footwear and clothing (Costill and Fox, 1969), may also affect performance as well as psychological characteristics (including motivation) of the runner. The latter may be true even though marathon runners as a group have been found to score within normal limits of most psychological variables (Morgan and Costill, 1972).

The matter of body fluid losses and their replacement deserves some further notice. The bodyweight losses during a marathon may be quite large, or up to 6kg (Costill, 1972; Pugh et al., 1967). Wyndham and Strydom (1969) showed that the rectal temperature of the runners will rise when the water deficit (primarily due to perspiration) exceeds 3% of the bodyweight, even when running under cool conditions (less than 17°C). Maron et al. (1977) suggested decreased sweating as the cause of the increase in rectal temperature. The rectal temperature of marathon runners may, in fact, exceed 41°C during the latter part of a race (Costill, 1972; Maron et al., 1977; Pugh et al., 1967). Even though such high rectal temperature may not always impair performance (Maron et al., 1977), the risk is considerable (Costill, 1972). This points to the importance of fluid replacement during a marathon race in order to prevent hyperthermia, especially when the race is run under warm conditions. Even though only partial replacement of the fluid loss is possible, fluid intake has been shown to suppress the increase in rectal temperature with running time (Costill, 1972).

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LEADING ARTICLE

The Effect of Endurance Training on Parameters of Aerobic Fitness

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Abstract

Endurance exercise training results in profound adaptations of the cardiorespiratory and neuromuscular systems that enhance the delivery of oxygen from the atmosphere to the mitochondria and enable a tighter regulation of muscle metabolism. These adaptations effect an improvement in endurance performance that is manifest as a rightward shift in the 'velocity-time curve'. This shift enables athletes to exercise for longer at a given absolute exercise intensity, or to exercise at a higher exercise intensity for a given duration. There are 4 key parameters of aerobic fitness that affect the nature of the velocity-time curve that can be measured in the human athlete. These are the maximal oxygen uptake ($\dot{V}O_{2max}$), exercise economy, the lactate/ventilatory threshold and oxygen uptake kinetics. Other parameters that may help determine endurance performance, and that are related to the other 4 parameters, are the velocity at $\dot{V}O_{2max}$ (V-$\dot{V}O_{2max}$) and the maximal lactate steady state or critical power. This review considers the effect of endurance training on the key parameters of aerobic (endurance) fitness and attempts to relate these changes to the adaptations seen in the body's physiological systems with training. The importance of improvements in the aerobic fitness parameters to the enhancement of endurance performance is highlighted, as are the training methods that may be considered optimal for facilitating such improvements.

The performance of repeated bouts of exercise over a period of time causes numerous physiological changes that result in improved performance in that exercise activity. The magnitude of the training response depends on the duration of the exercise bouts, their intensity and the frequency with which they are performed,[1] along with the initial training status, genetic potential, age and gender of the individual. The specificity of the training stimulus is also important in terms of the type of training practised (endurance, strength or speed) and the exercise modality used.[2] Appropriate recovery periods are required to allow adaptation to the training load: an insufficient training stimul[illegible] nd/or too much recovery can lead to lack of p[illegible] ss or detraining,[3] while too great a trainin[illegible] nd with insufficient recovery can lead to [illegible] ng.[4]

Endurance can be defined as [illegible] to sustain a given velocity or power o[illegible] ongest possible time. Performance in [illegible] ents is therefore heavily dependant upon the aerobic resynthesis of ATP; this requires an adequate delivery of oxygen from the atmosphere to cytochrome oxidase in the mitochondrial electron transport chain and the supply of fuels in the form of carbohydrates and lipids.[5,6] Endurance can be crudely described through the generation of individual 'velocity-time curves' which relate a series of velocities (or power outputs) to the time for which these velocities or power outputs can be sustained.[7,8] Endurance training causes adaptations in the pulmonary, cardiovascular and neuromuscular systems that improve the delivery of oxygen from the atmospheric air to the mitochondria and enhance the control of metabolism within the muscle cells. These adaptations shift the velocity-time curve to the right and therefore result in improved endurance exercise performance. This review will focus on the effect of endurance training on the 4 key parameters of aerobic (endurance) fitness identified by Whipp et al.:[9] the maximal oxygen uptake ($\dot{V}O_{2max}$), exercise economy, the lactate/ventilatory threshold and oxygen uptake kinetics. For the purposes of this review, endurance exercise will be considered to be continuous events of approximately 5 to 240 minutes duration completed at around 65 to 100% of the $\dot{V}O_{2max}$. Events of shorter duration require a significant contribution from anaerobic metabolic pathways,[10] while events of longer duration may be limited by psychological, nutritional, thermoregulatory or musculoskeletal factors rather than by 'endurance fitness', *per se*.

1. Maximal Oxygen Uptake ($\dot{V}O_{2max}$)

$\dot{V}O_{2max}$, which reflects an individual's maximal rate of aerobic energy expenditure, has long been associated with success in endurance sports.[11,12] In whole-body exercise such as running, cycling and rowing, it is widely accepted that $\dot{V}O_{2max}$ is limited by the rate at which oxygen can be supplied to the muscles and not by the muscle's ability to extract oxygen from the blood it receives.[13] The $\dot{V}O_{2max}$ appears to be strongly related to the maximal cardiac output (Q_{max}). The high Q_{max} and $\dot{V}O_{2max}$ values commonly found in elite athletes are, in turn, related to very high maximal stroke volumes since maximal heart rates tend to be similar to those of sedentary individuals.[14] Following training, exercising muscle may require less blood flow for the same submaximal exercise intensity because of an increase in the arterio-venous oxygen difference.[15] The increased stroke volume resulting from increases in left ventricular size, myocardial contractility and end-diastolic volume with training, along with a decreased sensitivity to catecholamines, leads to a reduced heart rate during submaximal exercise.[16] During maximal exercise, the greater cardiac output, along with an increased extraction of oxygen by the exercising muscle, results in a greater $\dot{V}O_{2max}$.[16,17] In addition, the oxygen carrying capacity of the blood is increased following endurance training owing to an increased total blood haemoglobin content. There is also an increase in red cell 2,3-diphosphoglycerate which offsets the reduced haemoglobin concentration consequent to the relatively larger increase in plasma volume compared to red cell mass.[18] The lower [Hb] following training may be advantageous in that the reduced blood viscosity may reduce the resistance of the vasculature to blood flow.

The magnitude of the increase in $\dot{V}O_{2max}$ resulting from endurance training depends on a number of factors, notably the initial fitness status of the individual, the duration of the training programme and the intensity, duration and frequency of the individual training sessions.[1] Since most studies of endurance training have shown some increase in $\dot{V}O_{2max}$ with time, the optimal exercise volume and intensity for developing this parameter is not known. However, there is some evidence from the literature to suggest that a high intensity of training (approximately 80 to 100% of $\dot{V}O_{2max}$) may be of crucial importance provided that the minimal training volume for a particular event is covered.[1,19] In a recent study,[20] we examined the influence of 6 weeks of endurance training on parameters of aerobic fitness in 16 physical education students. Despite the relatively modest training programme (3 to 5 sessions per week of 20 to 30 minutes duration at a running speed close to the lactate threshold),

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we found that $\dot{V}O_{2max}$ increased by approximately 10% (from 47.9 ± 8.4 to 52.2 ± 2.7 ml/kg/min). Other groups[21-27] have also shown a 5 to 10% improvement in $\dot{V}O_{2max}$ with short term endurance training programmes. Hickson et al.[28] reported that $\dot{V}O_{2max}$ increased by 23% over 9 weeks of endurance training, but the majority of this increase (14%) occurred after only 3 weeks. This rapid increase in $\dot{V}O_{2max}$ and the similarly rapid reduction in submaximal exercise heart rate have been partly attributed to an early hypervolaemia which will increase stroke volume during exercise and also afford an increased tolerance to heat stress.[29,30] There is some evidence that during longer term training programmes, $\dot{V}O_{2max}$ will eventually stabilise, with subsequent improvements in performance resulting from continued improvements in submaximal factors such as exercise economy and lactate threshold.[2,31-33]

2. Exercise Economy

Exercise economy has been defined as the oxygen uptake required at a given absolute exercise intensity. There is considerable interindividual variability in the oxygen cost of submaximal exercise, even in individuals of similar aerobic fitness (defined as $\dot{V}O_{2max}$) or similar performance capability.[34-36] For example, Horowitz et al.[37] demonstrated that elite cyclists exercising at the same power output required different rates of oxygen uptake. Interestingly, the more efficient cyclists had a greater percentage of type I fibres in the vastus lateralis, suggesting that the pattern of motor unit recruitment during exercise may be important in the determination of economy. In a classic study, Conley and Krahenbuhl[34] reported that 10km race performance was closely related to running economy in a group of well-trained volunteers who had similarly high $\dot{V}O_{2max}$ values. Better exercise economy (i.e. lower $\dot{V}O_2$ for a given absolute running speed or power output) can be considered to be advantageous to endurance performance because it will result in the utilisation of a lower percentage of the $\dot{V}O_{2max}$ for any particular exercise intensity. It has been suggested that the relatively low $\dot{V}O_{2max}$ scores that have been reported in some elite endurance athletes can be compensated for by exceptional exercise economy.[38,39] Indeed, an inverse relationship between $\dot{V}O_{2max}$ and running economy has been reported in samples of well-trained runners.[40,41]

Although trained athletes are known to have better exercise economy than untrained individuals,[39] studies that have examined the effect of endurance training on exercise economy have produced equivocal results.[42-45] This may be because such training studies (typically of 6 to 12 weeks duration) are too short to produce a measurable improvement in economy, especially in individuals who are already trained. It may be speculated that good exercise economy is somehow related to the total volume of endurance training performed, since the best economy values are often found in older or more experienced athletes, or those who complete a large weekly training mileage.[33,40,42] Furthermore, athletes' most economical velocities or power outputs tend to be those at which they habitually train (unpublished data). This may indicate that athletes should train over a wide variety of speeds if they wish to lower the slope of the $\dot{V}O_2$-exercise intensity relationship. Only a few studies have tracked changes in exercise economy over a prolonged period of training.[33,40,46,47] In one such study that measured changes in a number of physiological variables over a 5-year period in an elite female distance runner,[33] it was reported that running economy improved appreciably with each year of training. For example, the $\dot{V}O_2$ at a running speed of 16.0 km/h decreased from 53.0 ml/kg/min in 1992 to 47.6 ml/kg/min in 1995. However, improvements in running economy can sometimes be observed even with short term training programmes.[26,27,48] In a recent study, we found that 6 weeks of endurance running training caused a significant improvement in running economy in 16 recreationally active individuals (fig. 1),[48] with the $\dot{V}O_2$ at a representative running speed of 12.0 km/h decreasing from approximately 39 ml/kg/min to approximately 36 ml/kg/min. Franch et al.[26] also reported that the running economy of trained volunteers could be reduced significantly following 6 weeks of high intensity distance running or long-interval training, and found that the

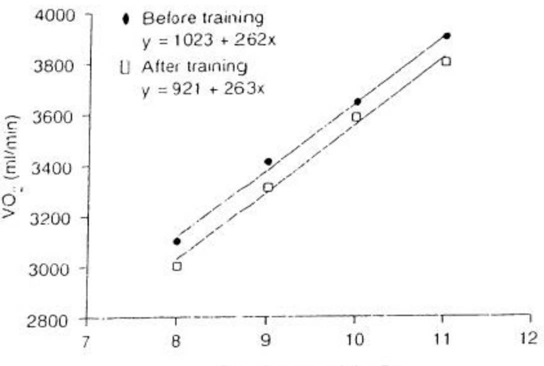

Fig. 1. The effect of 6 weeks of endurance training on submaximal oxygen uptake ($\dot{V}O_2$) [running economy]. The data represent the mean response of 16 individuals (from Jones et al.,[48] with permission).

reduction in submaximal $\dot{V}O_2$ was significantly correlated with the reduction in minute ventilation ($\dot{V}_E$).

Running economy has been associated with anthropometric (including segmental mass distribution), physiological and metabolic, and biomechanical and technical factors.[49] Improvements in exercise economy with endurance training may result from improved muscle oxidative capacity and associated changes in motor unit recruitment patterns,[50] reductions in exercise ventilation and heart rate for the same exercise intensity,[26] and improved technique.[51] These improvements may be partly offset by an increased utilisation of fat as exercise substrate following training due to the greater amount of oxygen that is required for the resynthesis of ATP from fat metabolism compared to carbohydrate metabolism. Of interest is the possibility that exercise economy is related to muscle elasticity. It has been speculated that running economy might be related to 'fluency' of movement and that it might therefore be improved by flexibility training.[52,53] However, recent observations from our laboratory suggest that the oxygen cost of running at 16.0 km/h is negatively related to lower limb flexibility (estimated with the sit-and-reach test) in 26 international-standard male distance runners, i.e. 'stiffer' runners were more economical.[54] Similar results can be found in the literature.[55,56] One explanation for these results is that stiffer muscles and tendons are better able to store elastic energy during the eccentric phase of stretch-shortening activities and that this stored energy can be released during the concentric phase of the action, thus lowering the oxygen cost of the exercise.[57] Alternatively, inflexibility in the trunk and hip may stabilise the pelvis during the stance phase and limit the requirement for stabilising muscular activity.[56]

It has been suggested that increasing maximal leg strength through resistance training may improve economy and endurance performance by reducing the proportion of the maximal force required for each contraction (e.g. pedal thrust) and hence delaying the recruitment of type II motor units.[58] However, traditional resistance training programmes which involve lifting moderate to high loads at relatively slow movement speeds have, with some exceptions,[58,59] been shown to be ineffective in improving endurance performance.[60,61] However, of great interest is a recent study which demonstrated that 'explosive strength training', involving sprinting and jumping exercises and weight training using high to maximal movement speeds and low loads (0 to 40% of the 1-repetition maximum), can improve both running economy and 5km race performance.[62] The authors suggested that the improved neuromuscular control resulting from the training could have improved running economy by allowing a tighter regulation of muscle stiffness and better utilisation of muscle elasticity. It is also possible that strength training using maximal velocity contractions may improve economy by allowing for a better recruitment of motor units or a reduced co-contraction of antagonistic muscle groups.[63] One other study has demonstrated a similar effect of explosive strength training on the economy of cross-country skiers.[64] Clearly, additional research is required to confirm and extend these findings.

3. Interaction Between $\dot{V}O_{2max}$ and Economy

The locomotory velocity associated with $\dot{V}O_{2max}$ (V-$\dot{V}O_{2max}$), which is a function of individual $\dot{V}O_{2max}$ and exercise economy characteristics and which can be calculated by solving the regression equation

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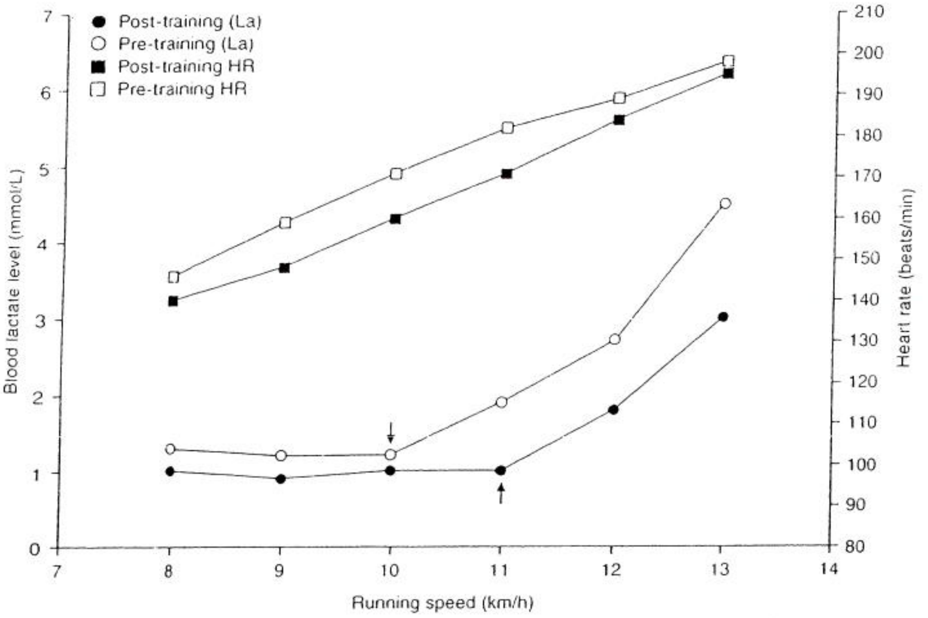
describing the relationship between $\dot{V}O_2$ and submaximal exercise intensity for $\dot{V}O_{2max}$, has been shown to be an important determinant of endurance exercise performance.[65-68] Morgan et al.[66] reported that the running speed at $\dot{V}O_{2max}$ strongly predicted 10km running performance in a group of well trained male runners with homogeneous $\dot{V}O_{2max}$ values (approximately 65 ml/kg/min). Jones and Doust[69] presented a comprehensive battery of physiological tests to 13 trained runners with a wide range of $\dot{V}O_{2max}$ values (53 to 67 ml/kg/min), and reported that V-$\dot{V}O_{2max}$ correlated more strongly with 8km running performance ($r = 0.93$) than any of the other measures, including $\dot{V}O_{2max}$ ($r = 0.69$) and running economy ($r = -0.16$). Although they are closely related, the V-$\dot{V}O_{2max}$ should not be confused with the maximal velocity reached in a fast incremental treadmill test ($\dot{V}_{max}$).[70] Although some studies have shown that the $\dot{V}_{max}$ correlates highly with endurance exercise performance,[70,71] $\dot{V}_{max}$ is influenced not just by $\dot{V}O_{2max}$ and exercise economy factors but also by anaerobic capability, muscle power and neuromuscular skill in exercising at high speeds.

Several studies have shown an increased V-$\dot{V}O_{2max}$ following endurance training. Jones[33] reported that V-$\dot{V}O_{2max}$ increased from 19.0 to 20.4 km/h over a 5-year period in an elite female distance runner. This improvement in V-$\dot{V}O_{2max}$ was the result of an improved running economy because $\dot{V}O_{2max}$ fell slightly over the same period of time. The V-$\dot{V}O_{2max}$ is similar to the velocity that can be sustained during distance running races of 3000m (approximately 8 minutes in the elite athlete),[33] and so this parameter may be especially important for success in middle-distance events. Billat et al.[27] reported that only 4 weeks of normal training caused a significant improvement in running economy and V-$\dot{V}O_{2max}$ (from 20.5 to 21.1 km/h), with no significant change in $\dot{V}O_{2max}$ (from 71.2 to 72.7 ml/kg/min), in 8 trained males. Berthoin et al.[72] reported that V-$\dot{V}O_{2max}$ was significantly improved only with high intensity training in adolescent volunteers. In another study, Jones et al.[48] found that 6 weeks of endurance training increased V-$\dot{V}O_{2max}$ from 15.3 to 16.6 km/h in 16 volunteers, with the increased V-$\dot{V}O_{2max}$ resulting from significant improvements in both $\dot{V}O_{2max}$ and running economy. The V-$\dot{V}O_{2max}$ appears to be an important and sensitive measure of endurance fitness and can be usefully measured during longitudinal work with endurance athletes.[33,66] An improvement in the V-$\dot{V}O_{2max}$ with training will mean that certain percentages of the $\dot{V}O_{2max}$ will be associated with higher speeds after training. This may be important in the improvement of endurance race performance because athletes tend to operate at quite similar percentages of $\dot{V}O_{2max}$ for a given duration of exercise.[5,6,73] However, while the V-$\dot{V}O_{2max}$ construct is practically useful, great care should be taken in its measurement. This is because $\dot{V}O_{2max}$ may be achieved during constant-load exercise over a wide range of submaximal exercise intensities above the 'critical power' because of the upward drift in oxygen uptake with time (see section 5).[74-76] Therefore, for the accurate determination of V-$\dot{V}O_{2max}$ there is a requirement both for a valid measure of $\dot{V}O_{2max}$ and for exercise economy to be measured at several moderate intensities below the lactate threshold.

It has been suggested that the V-$\dot{V}O_{2max}$ might represent an optimal training stimulus for improvements in endurance fitness.[77-81] Hill and Rowell[81] contend that training at V-$\dot{V}O_{2max}$ is important because V-$\dot{V}O_{2max}$ is the lowest speed that will elicit $\dot{V}O_{2max}$ and it is necessary to train at $\dot{V}O_{2max}$ to improve it. A concept that is closely related to the V-$\dot{V}O_{2max}$ is the time for which exercise at V-$\dot{V}O_{2max}$ can be sustained (T_{max}).[82] It has been shown that training at 100% V-$\dot{V}O_{2max}$ allows exercise at $\dot{V}O_{2max}$ to be sustained for the longest possible time (approximately 4 to 8 minutes).[82] Hill and Rowell[81] demonstrated that if interval or repetition sessions are constructed with the goal of allowing the longest possible training time at V-$\dot{V}O_{2max}$, then each repetition needed to be longer than 60% of T_{max}. Recently, it was shown that a 4-week training programme which included 2 interval training sessions per week (6 repetitions at V-$\dot{V}O_{2max}$ intensity for an exercise duration of 60 to 75% of the pre-training T_{max}) resulted in significant improvements in



. 2. The effect of 6 weeks of endurance training on blood lactate levels and heart rate response to incremental exercise in a typical
ıvidual. The vertical arrows denote the lactate threshold determined before and after training (from Carter et al.,[20] with permission).

)$_{2max}$, V-$\dot{V}O_{2max}$, T_{max} and 3000m performance
trained runners.[83] Unfortunately, this study did
t have a control group, and additional studies are
:ded to confirm the value of using V-$\dot{V}O_{2max}$ to
training intensity and T_{max} to set training dura-
n when the goal is to improve the V-$\dot{V}O_{2max}$.

4. Lactate/Ventilatory Threshold

The exercise intensity corresponding to the in-
ase in blood lactate above resting levels (lactate
:shold; LT) and the associated changes in gas
hange (ventilatory threshold; VT) are powerful
lictors of endurance performance.[35,69,84-88] Nu-
ous studies also testify to the sensitivity of the
ınd VT to endurance training (fig. 2).[20,89-93] A
ıtward shift of the LT/VT to a higher power out-
or running speed is characteristic of successful
urance training programmes.[94] This adaptation
ws a higher absolute (running speed or power
)ut) and relative (% $\dot{V}O_{2max}$) exercise intensity
e sustained without the accumulation of blood lactate after training. Endurance training is also associated with a reduction in the degree of lactacidaemia for any given absolute or relative exercise intensity. This causes the power output or running speed corresponding to arbitrary 'blood lactate reference values' such as 4 mmol/L blood lactate to increase following a period of endurance training.[20,93,95-98] Exercise above the LT is associated with a nonlinear increase in metabolic, respiratory and perceptual stress.[99,100] Furthermore, exercise above the LT is associated with more rapid fatigue, either through the effects of metabolic acidosis on contractile function[101] or through an accelerated depletion of muscle glycogen.[102] Therefore, an improvement in the LT/VT with training is a clear marker of an enhanced endurance capacity. However, it should be noted that the LT/VT is typically found at 50 to 80% $\dot{V}O_{2max}$ even in highly trained individuals, and it therefore occurs at a lower exercise intensity than is maintained by endurance athletes during most forms of endurance competition. The maximal lactate steady state (MLSS), which is

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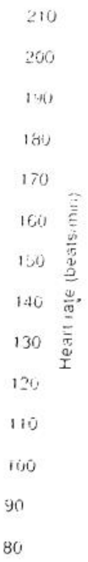

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the highest exercise intensity at which blood lactate does not accumulate over time (see section 5), may be of more importance to success in these events.

Mader[103] proposed that the precision with which training loads can be applied may be improved through individual consideration of the LT. Several authors have hypothesised that the LT represents the optimal intensity for improvement of endurance fitness.[103,104] Training at the LT should provide a high quality aerobic training stimulus without the accumulation of lactate that would compromise training duration.[105,106] Anecdotally, endurance athletes and coaches feel that training at LT through the inclusion of a regular 'threshold' or 'tempo' training session is a critical component of a balanced training programme.[107] The effect of training intensity on improvements in the LT/VT has recently been reviewed.[108] In general, it appears that training at intensities close to or slightly above the existing LT/VT is important in eliciting significant improvements in this parameter.[20,92,93,109-111] For example, it was reported that increasing training intensity through the use of fartlek training on 3 days per week,[110] or adding a 20 minute run at LT speed to the weekly training programme,[109] caused an improvement in the LT with no change in $\dot{V}O_{2max}$ in runners. Henritze et al.[92] reported that training at intensities above the LT may be even more effective for improving the LT, while Keith et al.[111] have shown that continuous training at the LT or intermittent training above and below the LT are equally effective in improving LT. Collectively, these studies indicate that exercise training at an appropriately high intensity might be most effective in stimulating improvements in LT and performance.

The reduction in blood lactate for the same absolute and relative exercise intensities following endurance training may result from a reduction in the rate of lactate production (possibly consequent to a lower rate of muscle glycogen utilisation or to speeded oxygen uptake kinetics that may increase initial O_2 availability/utilisation),[112,113] or from an increase in the ability to exchange and remove lactate from the blood.[114-116] Elite endurance athletes have a predominance of type I ('slow-twitch') muscle fibres in the trained musculature when compared to their sedentary peers.[117] This is of interest because of the strong relationship that is known to exist between the percentage of type I muscle fibres and the LT.[118-120] Endurance training causes a selective hypertrophy of the type I fibres and it is possible that a transformation of muscle fibre types from type IIb to type IIa,[23,121] and even from type IIa to type I[122,123] can eventually occur. There is also evidence that endurance training can cause an increased expression of slow myosin in type II fibres which reduces the maximal shortening speed in these fibres.[124] Conversely, detraining and micro-gravity lead to a reduction in the expression of slow myosin in muscle fibres.[125] The increased capillarity of skeletal muscle with endurance training[121,126] has the effect of increasing both the maximal muscle blood flow capacity and the surface area available for exchange of gases, substrates and metabolites between blood and muscle. The longer mean transit time for red blood cells to pass through the muscle capillary bed will increase the time available for diffusion of oxygen from the red blood cell and increase the potential for widening the arterial-venous oxygen difference during exercise.

Endurance training results in numerous adaptations within skeletal muscle that may be significant for exercise performance, including increases in sodium-potassium pump concentration,[127] lactate transport capacity[128,129] and possibly myoglobin concentration.[130] Endurance training also results in a marked increase in the oxidative capacity of skeletal muscle. This is due to an increase in the size and the number of mitochondria per unit area and an increase in the concentration of the enzymes of the Krebs cycle, electron transport chain and malate-aspartate shuttle.[23,131,132] These adaptations help maintain cellular phosphorylation potential, improve the sensitivity of respiratory control and increase the capacity for aerobic ATP resynthesis during exercise in both type I and type II muscle.[133,134] Muscle respiratory capacity is highly correlated with LT and these enzymatic adaptations may be important in allowing an athlete to exercise at a high percentage of $\dot{V}O_{2max}$ for prolonged periods.[118,119] It is possible that a greater oxidative enzyme complement in type I muscle fibres might delay the point at which the type II muscle fibres are recruited during exercise.[135] Furthermore, an increase in the oxidative potential of the type II fibres might reduce their reliance on anaerobic glycolysis for ATP production.[133] Animal studies suggest that low intensity training (approximately 50% $\dot{V}O_{2max}$) may be sufficient to maximise the increase in mitochondria in type I muscle, but that much higher intensities are needed to cause significant increases in mitochondrial volume in type II muscle.[130,136]

The greater capacity of the Krebs cycle to accept pyruvate following training may be important in reducing the production of lactate by mass action at the onset of exercise and during high intensity exercise.[137] However, the greater capillarity of trained muscle also allows for a greater uptake of free fatty acids from the blood and the increased activity of the enzymes involved in lipid metabolism increase the capacity for mitochondrial B-oxidation.[138] It has been shown that there is a reduction in the rate of glycogen depletion,[139,140] a decreased production and oxidation of blood-borne glucose[141,142] and an increased storage and rate of utilisation of intramuscular triacylglycerol following training.[143,144] The greater use of lipid during submaximal exercise, which can be documented in the lower respiratory exchange ratios found for the same absolute and relative exercise intensity following training, reduces the contribution of carbohydrate to ATP resynthesis and is therefore important in sparing muscle glycogen.[138] This adaptation, along with evidence that endurance training increases the storage of muscle glycogen,[145,146] is an important adaptation to endurance training because a depletion of muscle glycogen stores have been linked to fatigue during endurance exercise.[147]

The hormonal response to exercise appears to change rather quickly following the onset of endurance training.[141,148] For example, the catecholamine response appears to be substantially blunted for the same exercise intensity after only a few days of training.[142,148] Since adrenaline is a major effector of lactate production through its modulation of muscle glycogenolysis, this may partly account for the reduction in muscle glycogen utilisation seen with endurance training.[149] The reduced sympathetic nervous system activity may also contribute to the reduction in heart rate observed for the same exercise intensity following training.[116]

5. Oxygen Uptake Kinetics

At the onset of 'moderate' exercise (that is, exercise that is below the LT) pulmonary oxygen uptake increases mono-exponentially to achieve a new steady state within 2 to 3 minutes. For constant-intensity exercise in this domain, the oxygen deficit that is incurred at the onset of exercise may cause blood lactate to rise transiently before it returns to resting levels as exercise proceeds. On the other hand, the imposition of an exercise challenge that is just above the LT causes blood lactate to rise until it attains a steady state level that is higher than the resting concentration. In this exercise domain, pulmonary $\dot{V}O_2$ will also attain a delayed steady state but the $\dot{V}O_2$ that is achieved may be higher than would be predicted based upon the relationship between $\dot{V}O_2$ and exercise intensity for moderate exercise.[150] The MLSS can be defined as the highest running speed or power output at which blood lactate remains stable or increases only minimally ($<$ 1.0 mmol/L) between 10 and 30 minutes of exercise.[69,151] The MLSS therefore demarcates the highest exercise intensity at which a balance exists between the appearance of lactate in the blood and the removal of lactate from the blood during long term exercise, and is perhaps the 'gold standard' measure of endurance exercise capacity. In theory, the MLSS is the same as the concept of 'critical power' (CP)[74,76,152] or 'critical velocity'[153,154] that is represented by the asymptote of the hyperbolic relationship between exercise intensity and time to exhaustion. Submaximal exercise above the CP/MLSS is associated with an inexorable increase in blood lactate, pulmonary ventilation, and $\dot{V}O_2$ with time, and depending on the exercise intensity, $\dot{V}O_2$ may even rise to attain $\dot{V}O_{2max}$.[74,76,155] This 'drift' in

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$\dot{V}O_2$ during constant-load exercise to values that are greater than might be expected has been termed the $\dot{V}O_2$ slow component. While the mechanisms responsible for this apparent metabolic inefficiency during high intensity submaximal exercise are not fully understood,[155,156] exercise that elicits a $\dot{V}O_2$ slow component is poorly tolerated by volunteers.[157] Therefore, training programmes that attenuate the $\dot{V}O_2$ slow component or that extend the range of exercise intensities over which the slow component does not develop will improve endurance exercise performance.

Several studies have evaluated the effects of endurance training on $\dot{V}O_2$ kinetics during cycle exercise. In general, the steady state $\dot{V}O_2$ for the same moderate intensity exercise has not been found to change following a period of endurance training,[89,158] although the primary exponential increase in $\dot{V}O_2$ at the onset of exercise may be speeded.[158,159] In cross-sectional studies, the $\dot{V}O_2$ on-kinetic adjustment to the same absolute or relative exercise intensity has been reported to be faster in individuals with higher $\dot{V}O_{2max}$ values.[158,160] Faster $\dot{V}O_2$ kinetics at exercise onset, resulting in a more rapid attainment of the requisite steady state oxygen uptake, might be important in reducing the initial oxygen deficit and limiting the early increase in blood lactate. A speeded $\dot{V}O_2$ on-kinetic response may facilitate the rapid establishment of an intracellular environment that allows tighter metabolic control later in exercise.[161,162] Whether the primary mechanism for any speeding of the initial $\dot{V}O_2$ response to exercise is related to increased O_2 delivery to muscle or to a reduced inertia of the intracellular oxidative machinery consequent to an increased muscle mitochondrial density is debated.[159,163] Endurance training increases the CP,[164-166] and reduces the magnitude of the $\dot{V}O_2$ slow component (defined as the increase in $\dot{V}O_2$ between 3 and 6 minutes of exercise) for the same absolute power output.[164,167,168] Recent work in our laboratory has shown that 6 weeks of endurance running training results in a significant increase in the running speed at the MLSS,[20] and a significant reduction in the amplitude of the $\dot{V}O_2$ slow component (from 321 to 217 ml/min on average) for the same absolute treadmill running speed (unpublished observations; fig. 3). Although the reductions in blood lactate levels, ventilation, heart rate and plasma catecholamine levels that accompany endurance training (see section 4) might partly explain the reduced O_2 cost of heavy submaximal exercise after training, it appears that intramuscular changes and possibly alterations in motor unit recruitment patterns might be more important.[156,169] Of interest in this respect is the suggestion that the relative contribution of the $\dot{V}O_2$ slow component to the total $\dot{V}O_2$ response to heavy exercise is negatively related to aerobic fitness (as $\dot{V}O_{2max}$) and/or the proportion of type I fibres in the working muscles.[156]

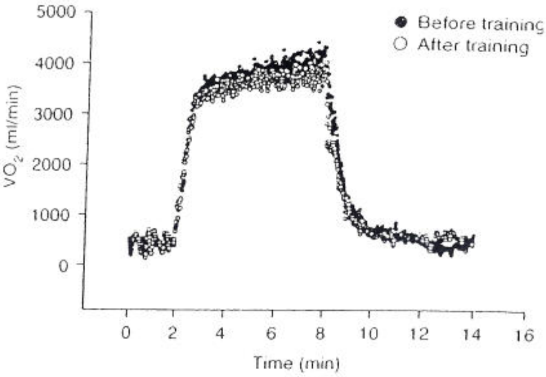

Fig. 3. The effect of 6 weeks of endurance training on the oxygen uptake response to a constant-load heavy exercise challenge in a typical individual. Note the marked reduction in the oxygen uptake ($\dot{V}O_2$) slow component (unpublished data).

6. Conclusion

Endurance exercise training results in numerous adaptations to the neuromuscular, metabolic, cardiovascular, respiratory and endocrine systems. These adaptations are reflected in improvements in the key parameters of aerobic fitness, namely the $\dot{V}O_{2max}$, exercise economy, the lactate/ventilatory threshold and the CP which will influence the oxygen uptake kinetics. An improvement in one or more of these parameters will result in an improvement in endurance exercise performance consequent to a rightward shift at various points on the velocity-time curve. The latter will allow an athlete to exercise for longer at the same exercise intensity or to sustain a higher speed for a given exercise duration. Although the aerobic parameters reviewed above are important determinants of endurance exercise performance, it should be borne in mind that competitive performance also depends upon psychological factors, race tactics and the prevailing environmental conditions. In addition, an athlete's ability to generate ATP anaerobically can be important in sprint finishes between athletes whose aerobic capabilities are similar.[170,171] Fukuba and Whipp[172] have recently suggested that an athlete's anaerobic work capacity (a derivative of the concept and computation of critical power) can determine his or her ability to initiate or respond to sections of a race that are faster than the athlete's best average velocity for the distance.

While the parameters of aerobic fitness are interrelated,[69] the specific emphasis placed on the training of each of these will depend upon an individual's personal physiological 'strengths' and 'weaknesses' (which may be assessed in the sports physiology laboratory), and the duration of the event being trained for. For example, a 3000m runner may place special importance on the development of the $\dot{V}O_{2max}$ and anaerobic capacity, while a marathon runner may focus on training to improve running economy and the running speed at lactate threshold. Presently, little is known about the most effective training practices for specifically improving the key parameters of aerobic fitness, or for altering different points on the velocity-time curve in order to effect a shift to the right of the velocity-time relationship. Exploration of the effect of various combinations of training volume, intensity and frequency on these determinants of endurance performance remains a fruitful area for future research.

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A review of the maximal oxygen uptake values necessary for different running performance levels

By Alejandro Legaz Arrese, Diego Munguía Izquierdo, Diego Moliner Urdiales

ABSTRACT

[illegible] runners exhibit high VO_2max values suggesting this helps them gain membership to the top performance cluster. Knowing the VO_2max values of groups of athletes is considered important for determining the maximum limit of performance of an athlete and an important aspect in the process of talent identification. One hundred and ninety top-class runners (137 males and 53 females) volunteered to participate in the study in which VO_2max was calculated by means of a progressive test on terdmills. Runners were classified into groups in accordance with their best performance capabilitie. Up to 1500m, an increment in VO_2max was observed and related to duration of the event. The VO_2max for elite athletes in the 3000m, 5000m, 10,000m and marathon groups did not differ significantly. Bibliographic analysis revealed small differences in VO_2max among groups with similar performance levels and significant differences among groups that differ in performance.

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Introduction

Over the past two decades, coaches and sports scientists have shown keen interest in determining those physiological characteristics that allow distance runners to perform exhaustive exercise. Specifically, the coach and scientist have been concerned with optimising performance and the prediction of competitive success[1,2]. Maximal oxygen uptake has been the physiological variable to which most attention has been paid[4-7]. Consequently, we have a great deal of information about averaged values in the different sport disciplines. However, we do not have the certainty of any study determining the values and differences of VO_2max among homogeneous groups of athletes competing over different distances and we could not find a review placing the levels neccesary for different performance levels at each distance.

The purpose of the present study was to determine the VO_2max differences in runners of both genders and to find the VO_2max values for groups of athletes competing in different distances in order to be able to examine the differences in this variable among athletes of different competitive performance levels.

Material and methods

Subject selection

A group of 137 male and 53 female runners training to compete in top-level running events was selected on the basis of their performances. The mean velocity achieved during their season's best performance had to be among among the best fifty ever in the Spanish rankings (2002). The performances were obtained after consulting the official rankings published by the Statistics Department of the Real Federación Española de Atletismo. All runners had been training for more than ten years and achieved national or international levels of competition (39 male and 17 female-trained runners had taken part in the Olympic Games).

The runners were also dichotomised into groups in accordance with their best performance capabilities[8-10]: Sprint trained (100m and 400m); middle-distance trained (800m, 1500m, 3000m and 3000m steeplechase) and long-distance trained (5000m, 10,000m and marathon) (Table 1). In each event the athletes were divided into "Class A", which comprised the half of the group with the best performances, and "Class B", which included the remaining athletes.

The criteria applied to determine the best performances of those athletes involved in several events was established by means of the corresponding performance equivalence according to the scoring tables published by the International Association of Athletics Federations (IAAF)[11]. The IAAF, using a database of performances obtained at world level, assigns a point score to each performance, enabling a comparison of different performances in different events.

Ergometric measurement

VO_2max values were determined at the National Centre of Sports Medicine in Spain. They were measured during a maximal aerobic power test on a treadmill (Jaeger Laufergotest, model L6), within the two months of the athlete's best performance. During this period, the athletes maintained their normal training programme. In the test the runners underwent a stepped protocol. The initial velocity and inclination were 8 km/h^{-1} and 1%, respectively. The velocity was increased by 2 km/h^{-1} after every 3 minute stage. From the 7th (for males) and 6th stages (for females) the velocity was increased by 1 km/h^{-1} every minute with a simultaneous increase in the slope of 2% per minute up to a maximum of 5% until the subject reached voluntary exhaustion.

The VO_2 values were measured using a Jaeger EOS-Sprint spiroergometer in conjunction with a Hellige Servomed oscilloscope. The VE was measured using a peumotachograph that was specially designed to keep linearity at high volumes. The CO_2 exhaled was measured using an infrared ray analyser and the O_2 by means of a paramagnetic system (both from Jaeger). VO_2max was chosen as the highest VO_2 value in the series of 30sec-by-30sec VO_2 values.

Bibliographic review

Specific bibliographical analysis was carried out selecting only those studies showing the VO_2max values in athletes whose performance level was clearly pointed out. For all the studies we estimated the coefficient of variance of performance (CV). In the studies in which the authors did not show enough data in order to carry out this estimation, the range of performance was indicated. If there was a study in which the authors showed the individual performance of a runner in more than one event, the athletes were included in an event according to their highest IAAF Score.

Statistical Analysis

Data were expressed as mean±SD. The coefficient of variance of performance (CV%=100xSD/mean) was calculated. A multivariate linear model was made [illegible] adjustment according to Bonferroni probabilities, using VO_2max as the dependent variable versus the type of event [illegible] independent variable. A value $p<0.05$ [illegible] considered indicative of statistical significance. The statistical analysis was performed with the Statistical Package for Social Sciences (Version 12.0).

Results

Table I shows the descriptive statistic for each distance in relation to gender.

Significant differences of VO_2max among athletes from the 100m and 400m, were only observed in the female sample ($p<0.01$). However, a more detailed analysis in male athletes showed that the better

Table 1: Descriptive statistics in highly trained male and female runners

Event	Performance	VO_2max (ml/kg⁻¹/min⁻¹)	Age (years)	N	Performance	VO2max (ml/kg⁻¹/min⁻¹)	Age (years)	N
100m	10.70 CV = 2.2%	61.9±6.5	21.4	18	12.18 CV = 1.8%	48.2± 5.6	24.9	5
400m	47.77 CV = 2.1%	62.5± 6.2	23.9	22	55.23 CV = 4.2%	56.6± 4.4	22.3	9
800m	1:50.07 CV = 2.8%	68.5± 5.0	21.7	24	2:07.13 CV = 2.0%	63.4± 6.6	22.8	7
1500m	3:42.08 CV = 3.0%	73.9± 5.7	24.2	18	4:19.65 CV = 4.2%	61.7± 5.8	24.8	9
3000m	7:45.53 CV = 0.5%	77.6± 4.4	26.9	3	9:11.61 CV = 2.0%	69.2± 5.3	21.7	6
3000m steeplechase	8:38.90 CV = 2.2%	79.9± 5.5	21.8	9				
5000m	13:45.49 CV = 4.3%	78.9± 8.5	25.1	7	15:13.88 CV = 4.5%	69.8± 11.5	26.6	2
10000m	28:58.75 CV = 3.3%	77.1± 5.6	26.1	17	33:54.77 CV = 3.1%	71.1± 8.3	24.6	5
Marathon	2:13:21 CV = 2.2%	80.1± 4.0	30.4	19	2:35:50 CV = 4.6%	73.7± 6.7	30.8	10

CV = coefficient of variation in performance

Table 2: VO_2max in male 100m and 400m runners

N	Performance	VO_2max $(ml/kg^{-1}/min^{-1})$	References
100m			
9	10.52 CV = 1.6%	57.3 ± 4	The current study "Class A" runners
18	10.7 CV = 2.2%	61.9 ± 6.5	The current study
7	11.00 CV = 1.0%	52 ± 2	12
7	11.00 CV = 5.5%	59.1 ± 2.3	13
400m			
9	45.6 CV = 1.3%	60.6 ± 3.2	14
9	45.6 CV = 1.3%	60.6 ± 3.2	14
11	46.92 CV = 1.1%	64.8 ± 4	15
11	46.97 CV = 0.8%	61.7 ± 4.6	The current study "Class A" runners
2	46.98 45.63-48.33	63.7	16
22	47.77 CV = 2.1%	62.5 ± 6.2	The current study
3	47.9 CV = 2.3%	59.7 ± 4.0	17
20	48.0 CV = 2.9%	59.5 ± 3.5	14
18	Range 44.7-52.3	61.4 ± 6.3	18
4	Range 50-53	53 ± 3	19

CV = coefficient of variation in performance

runners in the 100m (Class A, n = 9) had a lower VO_2max than the remaining athletes, 57.3 vs 66.5 $ml/kg^{-1}/min^{-1}$, respectively. Therefore, the better 100m runners showed lower VO_2max compared to the 400m runners ($p<0.001$).

The male 100m and 400m groups presented a lower VO_2max compared to middle-distance and long-distance runners ($p<0.001$). Similar results were found for the female samples. However, the significance levels were smaller due to the size of the samples.

In male 800m runners, the VO_2max was lower compared to 1500m, 3000m, 3000m steeplechase ($p<0.01$) and long-distance

Table 4: VO$_2$max in male 3000m and 3000m steeplechase runners

N	Performance	VO$_2$max (ml/kg^{-1}/min^{-1})	References
3000m			
3	7:45.53 CV = 0.5%	77.6 ± 4.4	The current study
9	7:57 CV = 2.9%	71.0 ± 5.3	[25]
5	8.10.84 CV = 2.3%	72.9 ± 4.7	[20]
3000m steeplechase			
4	8:29.15 CV = 1.3%	79.3 ± 3.4	The current study "Class A" runners
5	8:38 CV = 1.2%	72.4 ± 1.2	[6]
9	8:38.90 CV = 2.2%	79.9 ± 5.5	The current study

CV = coefficient of variation in performance

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runners ($p<0.001$). The VO$_2$max of the male 1500m runners was lower compared to 3000m runners ($p<0.05$) and marathon runners ($p<0.001$). The female 800m and 1500m runners had lower VO$_2$max values compared to marathon runners ($p<0.001$). In both genders, the marathon runners presented the higher VO$_2$max values, however the 3000m, 3000m steeplechase, 5000m, 10,000m and marathon groups did not differ significantly.

The comparison of our results with those obtained in other studies is evidenced in Tables 2 to 8. The different studies are organised downwards according to the worst athlete´s performance.

Discussion

The involvement of the aerobic metabolism in energy production progressively increases from the 100m to 1500m and 3000m events. Therefore, it will be necessary for the VO$_2$max to increase at the same rate to achieve an equivalent performance. This supposition has been confirmed in the present study. Hence, if a athlete wants to cover a distance greater to the one appropiate for her/his physiological condition with an equivalent performance (being her/his VO$_2$max inferior) or keeping the same speed as a top-level athlete in that distance, he/she would have to produce energy anaerobically from the first seconds of the event. This would cause an excessively quick accumulation of lactate in the muscle and blood and consequently the need to reduce speed drastically before finishing the competition.

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The involvement of the aerobic metabolism in energy production in the 3000m, 5000m, 10,000m and marathon does not differ significantly. Therefore, no significant differences in VO$_2$max should be expected among these athletes and, indeed, in this study, the VO$_2$max did not differ significantly between these groups.

Many researchers have attempted to explain how the variable VO$_2$max can account for a vast proportion of the variance in distance running performances. A significant relationship between VO$_2$max

Table 3: VO_2max in male 800m and 1500m runners

N	Performance	VO_2max (ml/kg^{-1}/min^{-1})	References
800m			
12	1:47.54 CV = 1.5%	68.1 ± 5.4	The current study "Class A" runners
5	1:48.99 CV = 2.9%	67.2 ± 3.5	20
14	1:49.1 CV = 1.7%	67.1 ± 3.4	14
6	Range 1:47.64-1:50.42	68.7	16
24	1:50.07 CV = 2.8%	68.5 ± 4.9	The current study
5	1:53-2:00	65 ± 2	19
7	1:59.4 CV = 0.4%	60 ± 3	12
11	2:05 CV = 3.8%	65.8 ± 1.4	13
11	2:12.6 CV = 5.5%	61.6 ± 5.1	3
1500m			
9	3:36.56 CV = 1.0%	75.1 ± 6.1	The current study "Class A" runners
5	Range 3:38.51 – 3:46.43	71.9	16
18	3:42.08 CV = 3.0%	73.9 ± 5.7	The current study
8	3:44.55 CV = 1.6%	71.5 ± 4.8	21
12	3.46.73 CV = 2.2%	72 ± 4.3	20
9	3:49.3 CV = 4.4%	71.2 ± 4.7	22
18	3:50.08 CV = 4.3%	72.2 ± 4.3	23
56	4:51 CV = 10.3%	62.5	24

CV = coefficient of variation in performance

Table 5: VO_2max in male 5000m and 10,000m runners

N	Performance	VO_2max (ml/kg^{-1}/min^{-1})	References
5000m 3	13:18.22 CV = 0.5%	82.1 ± 4.7	The current study "Class A" runners
7	13:45.49 CV = 4.3%	78.9 ± 8.5	The current study
5	13:46.45 CV = 3.8%	72.1 ± 4.6	20
6	13:58.8 13:57.1 – 14:00.4	75.3	16
8	14:04.70 CV = 3.0%	74.4 ± 4.0	14
8	14:05 CV = 0.6%	74.4 ± 1.3	6
7	14:48 CV = 1.4%	73.7 ± 1.5	13
8	14:49.00 CV = 1.7%	73.1 ± 2.5	26
12	16:07 CV = 4.0%	64.1 ± 3.9	27
14	16:48 CV = 4.8%	60.4 ± 1.4	28
10000m 9	28:17.81 CV = 1.8%	76.5 ± 5.9	The current study "Class A" runners
11	28:33 CV = 2.0%	71.5 ± 4.6	25
22	28:53.4 CV = 3.6%	75.8 ± 3.4	29
5	Range 28:36.6 – 29:21.0	78.6	16
17	28:58.75 CV = 3.3%	77.1 ± 5.6	The current study
10	31:43 CV = 5.6%	65.3 ± 4.9	30
12	32:06.00 CV = 3.1%	71.7 ± 2.8	31
10	32:17.4 CV = 3.9%	64.8 ± 2.1	32
20	32:27 CV = 3.1%	67.5 ± 3.9	33
9	33:47.13 CV = 1.5%	68.6 ± 0.7	34
21	34:06.6 CV = 5.9%	67.3 ± 5.2	35

CV = coefficient of variation in performance

Table 6: VO_2max in male marathon runners

N	Performance	VO_2max (ml/kg^{-1}/min^{-1})	References
10	2:10:56 CV = 1.3%	81.2 ± 3.9	The current study "Class A" runners
19	2:13:21 CV = 2.2%	80.1 ± 4	The current study
8	2:15	74.1	36
5	Range 2:12:07 – 2:21:04	73.86	16
5	2:17:05 CV = 1.7%	76.7 ± 0.7	37
12	2:21 < 2: 30	71.8 ± 1.2	38
4	2:23:42 CV = 4.0%	72.4 ± 2.3	14
6	2:27:23 CV = 5.8%	71.4 ± 4.2	39
13	2:29:59 CV = 6.5%	72.5 ± 3.8	5
9	2:30:42 CV = 5.4%	60.4 ± 6.5	40
10	2:32:31 CV = 5.4%	63.2 ± 2.9	40
12	2:36:37 CV = 6.2%	73.1 ± 5.2	35
16	2:37 2:30 – 3:00	65.6 ± 1.2	38
20	2:39:42 CV = 15.5%	68.1 ± 7.7	7
6	2:39:43 CV = 1.2%	70.7 ± 0.7	41
7	2:40:24 CV = 2.9%	70.0 ± 1.8	13
10	2:43:48 CV = 6.7%	68 ± 5.4	42
13	2:46:07 CV = 14.2%	61.7 ± 7.5	1
23	3:04:36 CV = 12.5%	61.9 ± 5.6	43
6	3:19:24 CV = 1.2%	60	44
7	3:24 > 3: 00	58.7 ± 1.9	38
46	3:26:00 CV = 12.9%	58.3 ± 7.3	45
25	3:26:54 CV = 17.5%	64.7 ± 9.0	45

CV = coefficient of variation in performance

Table 7: VO_2max in female middle-distance runners

N	Performance	VO_2max (ml/kg^{-1}/min^{-1})	References
1500m			
4	4:09.89 CV = 3.0%	62.2 ± 4.1	The current study "Class A" runners
9	4:19.65 CV = 4.2%	61.7 ± 5.8	The current study
6	4:20.72 CV = 5.3%	63.9 ± 4	23
8	4:29.4 CV = 4.3%	62.5 ± 3.7	22
3000m			
3	9:01.59 CV = 0.6%	66.9 ± 1.2	The current study "Class A" runners
6	9:11.61 CV = 2.0%	69.2 ± 5.3	The current study
10	9:17.93 CV = 3.7%	63.5 ± 5	46
16	10:14.96 CV = 4.7%	56.4 ± 4.4	47

CV = coefficient of variation in performance

and running performance has been found in heterogeneous groups of runners. However, different studies indicate that VO_2max is not a good predictor of performance in more homogeneous groups of runners (e.g. 50) and it has been reported that VO_2max does not relate to endurance performance within groups that are homogeneous in terms of VO_2max.

Nevertheless, the plateauing of maximal oxygen uptake in elite endurance athletes has been documented for many years in case studies only[51-54].

It cannot be argued from these data that VO_2max is unimportant. In this study, all endurance elite runners exhibited high values. The current data suggest that a high VO_2max helped each subject gain membership to this elite performance cluster. As the VO_2max values are predetermined genetically, it is unrealistic to hope for great increases due to training effects. Knowing the VO_2max values of groups of athletes on different levels of performance is considered important for determining the maximum performance limit of an athlete in relation to his/her VO_2max as well as an important point in the process of detection of sports accomplishments.

In the 100m, the lack of sufficient studies and the data obtained in our study do not allow us to reach definitive conclusions. Nevertheless we can deduce that the best athletes of this event achieve a VO_2max average < 60 ml/kg^{-1}/min^{-1}, being in accordance with data obtained from a study of athletes who achieved a performance better than 10.55 and a VO_2max of 57±6 ml/kg-1/min^{-1}. The 400m athletes with performances between 45.6 and [illegible] do not vary substantially with VO_2max

Table 8: VO_2max in female long-distance runners

N	Performance	VO_2max (ml/kg^{-1}/min^{-1})	References
5000m			
2	15:13.88 CV = 4.5%	69.8 ± 11.5	The current study
9	19:54 CV = 7.0%	52.6 ± 0.9	28
10000m			
3	33:09.60 CV = 0.6%	74.6 ± 5.7	The current study "Class A" runners
5	33:54.77 CV = 3.1%	71.1 ± 8.3	The current study
30	38:26.7 CV = 6.8%	53.5 ± 3.6	48
13	40:42.79 CV = 9.1%	59.7 ± 5.3	2
Marathon			
5	2:29:42 CV = 1.87%	75.8 ± 6.4	The current study "Class A" runners
10	2:35:50 CV = 4.6%	73.7 ± 6.7	The current study
6	2:41:51 CV = 1.2%	66.1 ± 1.4	41
9	3:07:57 CV = 6.3%	58.2 ± 4.8	5
6	3:21:48 CV = 0.9%	60	44
13	3:47	51.8 ± 3.2	49
10	4:42	45.8 ± 5	49

CV = coefficient of variation in performance

values being between 61-64 ml/kg^{-1}/min^{-1}. For those with a best performance over 48.0, the VO_2max value is slightly inferior to 60 ml/kg^{-1}/min^{-1}.

In the 800m, athletes with a best performance between 1:47.5 and 1:50.0 had a VO_2max average of 68 ml/kg^{-1}/min^{-1}. For athletes with a best performance close to or more than 2:00.0 the values are considerably lower.

The 1500m athletes with performances between 3:36.0 and 3:50.0 have VO_2max values that average between 72 and 75 ml/kg^{-1}/min^{-1}. In athletes with inferior performances, the values decrease considerably.

For the 3000m and 3000m steeplechase, due to the low number of studies, conclusions cannot be reached.

In the 5000m, athletes with a performance inferior to 13:30.0 achieve an average VO_2max value close to 80 ml/kg^{-1}/min^{-1}. For performances between 14:00 and 15:00, the values were between 73 and 75 ml/kg^{-1}/min^{-1}, disminishing considerably for performances above 16:00.

In the 10,000m, athletes with a best performance between 28:17 and 29:00 had VO_2max values between 76 and 7.8 ml/kg^{-1}/min^{-1}. For a clearly inferior performance (31:30), the average VO_2max is inferior to 70 ml/kg^{-1}/min^{-1}.

The performance level of our marathon runners was superior to those observed in the rest of the studies and the VO_2max found was clearly higher. In marathon runners with a performance between 2:16:00 and 2:30:00, the VO_2max is between 72 and 76 ml/kg^{-1}/min^{-1}. For performances of more than 2:30:00, the average VO_2max value is inferior to 70 ml/kg^{-1}/min^{-1}.

In general, we can assume that among groups of athletes with relatively small performance differences, there will not be significant differences in VO_2max (ml/kg^{-1}/min^{-1}), but there will be when groups with significant performance differences are compared.

Studies described the VO_2max (ml/kg-^{1}/min^{-1}) of different top-level athletes and the performance in competition[55,56]. These authors studied seven female middle-distance runners (four were top-level 1500m runners - avg time 4:07.9 (CV = 1.11%), one a 3000m runner - 10:03, one a 3000m and 5000m runner - 8:48, 15:22 and one a 5000m runner - 15:25). They also evaluated nine top-level long-distance runners (five 10,000m runners - avg time 32:47.2 (CV = 1.26%) and four marathon runners – avg time 2:31:17 (CV = 1.7%) and 14 "good" runners (11 of them ran their first 10,000m in an average of 38:37 with a range of 36:10 to 41:52) and 3 marathon runners whose performances were not reported. The VO_2max for middle distance runners was 68 ± 3.7 ml/kg^{-1}/min^{-1}, for long distance runners 66.4±4.5 ml/kg^{-1}/min^{-1} and for "good" runners 58.6±5.2 ml/kg^{-1}/min^{-1}. The results supplied by these authors corroborate that there are big VO_2max differences among athletes who differ significantly in their performance while, in turn, the differences among remarkable 1500m, 3000m and 5000m runners are not important when compared with long-distance athletes. The performance of the runners studied by these authors is generally slightly better than those in our study. However, their average VO_2max value is slightly lower than that of our athletes, corroborating that among athletes with a narrow scope in performance, the VO_2max is not a good performance predictor.

Similar to male athletes, in the few events with a sufficient number of studies, we found VO_2max differences only when there were significant performance differences.

Conclusions

This study has assessed the VO_2max in high-level runners and made an exhaustive bibliographic analysis with regard to the maximum limits of performance associated with VO_2max values. The results highlight the importance of evaluation of VO_2max to determine the maximum level of performance an athlete can be expected to achieve.

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The role of anaerobic ability in middle distance running performance

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Summary. The purpose of this study was to assess the relationship between anaerobic ability and middle distance running performance. Ten runners of similar performance capacities (5 km times: 16.72, SE 0.2 min) were examined during 4 weeks of controlled training. The runners performed a battery of tests each week [maximum oxygen consumption ($\dot{V}O_{2\max}$), vertical jump, and Margaria power run] and raced 5 km three times (weeks 1, 2, 4) on an indoor 200-m track (all subjects competing). Regression analysis revealed that the combination of time to exhaustion (TTE) during the $\dot{V}O_{2\max}$ test ($r^2=0.63$) and measures from the Margaria power test ($W \cdot kg^{-1}$, $r^2=0.18$; W, $r^2=0.05$) accounted for 86% of the total variance in race times ($P<0.05$). Regression analysis demonstrated that TTE was influenced by both anaerobic ability [vertical jump, power ($W \cdot kg^{-1}$) and aerobic capacity ($\dot{V}O_{2\max}$, $ml \cdot kg^{-1} \cdot min^{-1}$)]. These results indicate that the anaerobic systems influence middle distance performance in runners of similar abilities.

Key words: Power – Performance – Endurance runners

Introduction

Competitive distance runners and coaches emphasize muscular and cardiovascular endurance in their training regimens. However, in a closely clustered race, finish place may be related to the ability to generate anaerobic energy during or near the finish of the competition. Bulbulian et al. (1986) observed that anaerobic power measures accounted for a large amount of the variance in predicting 8-km performance in a homogeneous group of collegiate runners. Little additional information is available addressing the role of the anaerobic systems in distance running success. The intent of the current study was to determine if anaerobic ability was related to middle distance running performance (5 km) in a group of competitive runners with similar performance capacities.

Methods

Experimental design. Ten well-trained male distance runners (mean, SE) (age 32.0, 2.6 years; mass 62.18, 1.97 kg) participated in this study. All subjects signed a letter of informed consent after the risks and benefits of the procedures had been explained. The men selected were well-trained competitive distance runners of similar performance capabilities ($3.3-3.6\ min \cdot km^{-1}$ for 5 km) who had maintained endurance training for at least 2 years. We selected runners within this performance range since there was a reasonable number of local athletes who could participate and easily have their training monitored. Data from these subjects have been presented in a previous publication (Houmard et al. 1990).

After initial testing for maximum oxygen consumption ($\dot{V}O_{2\max}$), subjects trained for 4 weeks at their normal weekly training distance (mean, SE) (81, 5 km week^{-1}, 6 days$\cdot$week^{-1}). Based upon description of normal training (e.g. pace, number and type of intervals run) we provided each subject with a schedule detailing pace and distance. A detailed description of the training program has been described (Houmard et al. 1990). During the 4 weeks of normal training the subjects were tested weekly and performed 5-km races in weeks 1, 2, and 4. The testing and 5-km race during week 1 served to familiarize the subjects with procedures, and results were not included in the statistical analysis. Data are presented for week 2 (race 1) and week 4 (race 2) testing points.

Testing procedures. The subjects performed a battery of tests at the same time each week. Subjects reported on a Wednesday or Thursday between 0600 and 0900 hours after an overnight fast.

Margaria power and vertical jump. Subjects ran for 3 min as a warm-up, and performed six modified Margaria power runs (Costill et al. 1968). Running time was recorded to the nearest 0.001 s, with the fastest run used for data analysis. A vertical jump test was also performed (Costill 1967). A marker was placed on the iliac crest and the subject jumped adjacent to a calibrated grid. Values were obtained to the nearest 15 mm by observing a videotape of the jump in slow motion. The highest of three jumps was used in data analysis.

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$\dot{V}O_{2max}$ and time to exhaustion. The subjects performed a maximal treadmill test approximately 10-15 min after the power tests. The subjects ran submaximally for 9 min [4 min at approximately 65% (mean, SE: 65.96, 1.18%) and 5 min at approximately 85% (85.54, 1.24%) $\dot{V}O_{2max}$], after which the exercise was stopped for 30 s to obtain a blood sample for another study (Houmard et al. 1990). The subjects immediately resumed running at the 85% $\dot{V}O_{2max}$ speed, and grade was increased by 3% at 2-min intervals to voluntary exhaustion. The value for $\dot{V}O_{2max}$ was the average of the two highest 30-s oxygen consumptions. Time to exhaustion (TTE) was recorded as the time from the re-initiation of running to voluntary exhaustion. Expired gases were analyzed continuously for oxygen (O_2) (S-3A O_2 analyzer, Applied Electrochemistry - Ametek, Pittsburgh, Pa., USA), carbon dioxide (CO_2) (LB-2 Medical Gas Analyzer, Beckman, Sensor Medics, Anaheim, Calif., USA), and total volume (Parkinson Cowan dry gas meter, Vacumed, Ventura, Calif., USA), for the determination of $\dot{V}O_2$, ventilation ($\dot{V}_E$), and respiratory exchange ratio (RER). Heart rate was monitored by telemetry (AMF Quantum, Stamford, Conn., USA). Criteria for a valid $\dot{V}O_{2max}$ test (Astrand and Rodahl 1977) (RER > 1.2, plateau of heart rate and oxygen consumption) were met in all maximal tests.

Five-kilometer races. The subjects raced against each other at the 5-km distance on the Saturday of each respective week. These races were held on an indoor 200-m track with all subjects running at the same time. The runners performed similar warm-ups for 30 min before each race. Subjects were instructed to run as fast as possible using their normal pacing strategies. Elapsed times were read aloud and recorded each 400 m. Verbal motivation was provided by the experimenters. Monetary and merchandise prizes were awarded based upon performance and place.

Statistical analysis. Coefficients of variation (CV) were calculated for all the measures. Statistical comparisons were made using a repeated measures, one-way analysis of variance with the level of significance at $P<0.05$. Pearson correlation coefficients were calculated between all the measured variables with significance denoted at the $P<0.05$ level. The data were also entered into a forward inclusion and backward elimination linear regression analysis (SAS STEPWISE, SAS Users guide, 1982) to select the variables that best predicted 5-km race times and TTE. Inclusion and exclusion levels were at the 0.15 level. This type of regression analysis has been used previously in a similar study (Bulbulian et al. 1986).

Table 1. Mean (SE) of the measured variables at each testing point and their coefficient of variation (CV)

	5 km race 1	5 km race 2
Vertical jump (m)	0.40 (0.02)	0.42 (0.03)
CV	15.8	22.6
Power (W)	951.1 (35.5)	889.3 (47.3)
CV	11.8	16.8
Power ($W \cdot kg^{-1}$)	15.4 (0.6)	14.3 (0.7)
CV	1.2	1.5
$\dot{V}O_{2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	62.0 (1.3)	61.6 (1.0)
CV	6.6	5.1
Time to exhaustion (min)	5.2 (0.3)	5.5 (0.3)
CV	18.2	17.2
5-km race time (min)	16.68 (0.21)	16.77 (0.20)
CV	3.9	3.8

$\dot{V}O_{2max}$, Maximum oxygen consumption

Results

There were no significant differences ($P>0.05$) between any of the measured variables or correlation coefficients for race 1 and race 2 (Table 1). Data for both races were therefore combined for correlational analysis. Significant correlations ($P<0.05$) were observed between $\dot{V}O_{2max}$ ($ml \cdot min^{-1} \cdot kg^{-1}$) and TTE (min) ($r=0.51$), while TTE also correlated significantly with power ($W \cdot kg^{-1}$) ($r=0.45$) and vertical jump ($r=0.46$). Final 5-km run time correlated significantly with vertical jump, power ($W \cdot kg^{-1}$), $\dot{V}O_{2max}$, and TTE (Table 2).

Stepwise regression analysis revealed that TTE and measures of power from the Margaria power test (Margaria et al. 1966) accounted for a significant amount of the total variance for race 1 and race 2. The regression equations for the two races were: race 1 time = 1294.62 + 0.10 (power, W) − 17.38 (power, $W \cdot kg^{-1}$) − 24.06 (TTE, s); race 2 time = 1207.2 + 0.06 (power, W) − 8.98 (power, $W \cdot kg^{-1}$) − 23.87 (TTE, s). There were no significant differences between any of the parameters in the prediction equations between race 1 and race 2; therefore, an overall prediction equation was generated (5-km time = 1235.8 + 0.10 (power, W) − 14.31 (power, $W \cdot kg^{-1}$) − 21.39 (TTE, s). Each variable in the overall prediction equation was statistically significant; the three measures accounted for 86% of the variation in race times (Table 3); treadmill TTE accounted for the most variance (63%).

Stepwise regression analysis was also used to determine which variables had the most impact upon predicting TTE. As indicated in Table 4, $\dot{V}O_{2max}$, vertical jump, and power ($W \cdot kg^{-1}$) accounted for approximately 42% of the total variance in TTE.

Discussion

The subjects examined were well acquainted with the testing procedures and performance was determined on several occasions under controlled conditions. The major finding was that measures of anaerobic ability contributed to predicting 5-km performance.

The strength of a predictor variable in a regression equation is influenced by both the homogeneity of the

Table 2. Pearson correlation coefficients for the selected parameters and 5-km race time

	Vertical jump (m)	Power (W)	Power ($W \cdot kg^{-1}$)	$\dot{V}O_{2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	Time to exhaustion (min)
5-km Race time	−0.73***	−0.39	−0.74***	−0.60**	−0.79***

** $P<0.01$; *** $P<0.001$

Table 3. Multiple regression analysis for the selected variables and 5-km race performance

	Partial r^2	Independant contribution to increase in r^2	Multiple r^2
Time to exhaustion (min)	0.63*	$P<0.001$	0.63*
Power ($W \cdot kg^{-1}$)	0.18*	$P<0.001$	0.81*
Power (W)	0.05*	$P<0.05$	0.86*

* $P<0.05$

Table 4. Multiple regression analysis for the selected variables and treadmill time to exhaustion

	Partial r^2	Independent contribution to increase in r^2	Multiple r^2
$\dot{V}O_{2\max}$ ($ml \cdot min^{-1} \cdot kg^{-1}$)	0.26*	$P<0.05$	0.26*
Vertical jump (m)	0.12*	$P<0.05$	0.37*
Power ($W \cdot kg^{-1}$)	0.05*	$P<0.05$	0.42*

* $P<0.05$

variable and the strength of its correlation with the dependent variable (Bulbulian et al. 1986). Although $\dot{V}O_{2\max}$ achieved a significant correlation with performance, it did not enter the regression equation as a significant predictor. The CV for power ($W \cdot kg^{-1}$) was much smaller than for $\dot{V}O_{2\max}$, yet power ($W \cdot kg^{-1}$) was a significant predictor for performance. This finding suggests that the ability to exert anaerobic power was related to 5-km performance, regardless of closely clustered values. A similar conclusion was reached by Bulbulian et al. (1986) in relation to 8-km running performance.

The mechanisms associated with the differences in anaerobic ability were not apparent from the measures obtained in this study. One factor could have been between subject differences in the percentages of type IIa or IIb fast-twitch muscle fibers (Thorstensson 1977). Noakes (1988) hypothesized that faster runners possessed greater contractile properties in their skeletal muscles. Future studies should examine muscle recruitment patterns, contractility, relative enzyme activities, and muscular hypertrophy patterns in runners of similar abilities.

A standard test for $\dot{V}O_{2\max}$ involves incremental increases in speed and/or grade. A strong relationship has been observed between the peak exercise workload achieved (the highest combination of speed and/or grade achieved during the test, commonly expressed as TTE) and 5-90-km distance running performance (Noakes 1988; Scrimgeour et al. 1986; Tanaka et al. 1984). Noakes (1988) suggested that the peak achieved workload was related to anaerobic capacity, since the fastest 10-km runners also had the most powerful muscles when tested on an isokinetic cycle ergometer.

As indicated by our regression analysis, TTE was a function of both aerobic and anaerobic abilities. This finding suggests that the predictive strength of TTE lies in the integration of several components of running performance, including anaerobic ability, into one measure. Of all the measures, TTE also had the highest CV, despite the athletes possessing similar $\dot{V}O_{2\max}$ values and performance capabilities. This heterogeneity also helps explain why TTE obtained such high correlations with performance in the current and other studies (Noakes 1988; Scrimgeour et al. 1986; Tanaka et al. 1984).

Other factors such as running economy (Conley and Krahenbuhl 1980; Costill et al. 1973) and the lactate and ventilatory thresholds (Bulbulian et al. 1986; Farrell et al. 1979; Kumagai et al. 1982; Powers et al. 1983; Tanaka et al. 1984) have been associated with 5- to 10-km performance. It is possible that the addition of these variables to the regression equation could have increased predictive power. However, the results of the current study strongly suggest that measurements of anaerobic ability should be included in future examinations of distance running determinants.

In a practical application, these findings imply that middle distance runners should utilize training which develops the anaerobic systems. This would be particularly applicable to runners who have focused upon maximizing their aerobic systems, but placed little emphasis on the anaerobic systems. Middle distance events (1,500–5,000 m) are commonly performed at 90–100% $\dot{V}O_{2\max}$ (Costill 1986; Davies and Thompson 1979). These relatively high intensities suggest a substantial involvement of anaerobic energy production, particularly near the finish of the races.

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Metabolic Control and Its Importance in Sprinting and Endurance Running

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Sufficient knowledge of the mechanisms that control metabolism is now available that it can be applied to exercise. In this chapter, two extreme conditions of running are considered, sprinting and marathon running. Physiological and biochemical information about these two extremes provides a basis for discussion of the fuel supply, the limitations in each event and the possible causes of fatigue. A general account of fuel supply and the bases for exhaustion in both sprinting and marathon running is given in *Newsholme and Leech* [1983].

The Sprint

Fuels for the Sprinter

The generation of energy in the muscles of the sprinter can occur anaerobically, i.e. without the use of oxygen. In muscle, only two fuels provide energy anaerobically, creatine phosphate and glycogen. Adenosine triphosphate (ATP) can be regenerated from adenosine diphosphate (ADP) by the direct transfer of phosphate from creatine phosphate in a reaction catalyzed by the enzyme, creatine kinase, as follows:

$$\text{Creatine phosphate} + \text{ADP} \rightleftharpoons \text{creatine} + \text{ATP}. \qquad (1)$$

Glycogen, which is a store of glucose within the muscle, is converted by the process known as glycolysis to lactate which regenerates 3 ATP molecules for every glucose molecule used.

$$\text{Glucose-in-glycogen}' + 3\ \text{ADP} \rightarrow 2\text{-lactate}^- + 3\ \text{ATP} + 2\text{H}^+. \qquad (2)$$

This process generates about 10-fold less ATP than complete oxidation of glucose to carbon dioxide and water, but the capacity of the process is high in type IIA and type IIB fibers so that the rate of glycolysis can provide all the energy required by the muscles of the sprinter; indeed, the power output of the sprinter is severalfold greater than that of the endurance runner.

Sprinting utilizes about 3 μmol ATP/g active muscle/s. It demands the utilization of either 1 μmol (or 0.4 mg) of glucose from glycogen or 3 μmol creatine phosphate/s [*Newsholme*, 1980a]. Laboratory experiments demonstrate that sprinting utilizes, at most, 15 μmol creatine phosphate/g muscle (the total store is 18 μmol). This would provide energy for 5 s of sprinting, which supports the conclusions of previous work based on lactate production. It is likely that, for the first 2–3 s of the sprint, creatine phosphate provides most of the energy for regeneration of ATP but then glycolysis gradually takes over, so that by 5 s the latter process provides almost all the energy.

The concentration of glucose as glycogen in human muscle is approximately 80 μmol/g and is probably somewhat higher than this in the muscle of elite sprinters. This could provide, in theory, 240 μmol ATP, which is sufficient energy for 80 s of sprinting. But maximum power output (i.e. that achieved in the 100-meter sprint) cannot be maintained for 80 s. In other words the power output is reduced as the duration of the race increases above 100 m. Laboratory experiments demonstrate that fatigue occurs in sprinting-type activity when less than half the total glycogen store has been used. Of importance for understanding the metabolic basis of fatigue is the observation that the exhaustion occurs when the lactate concentration in the muscle approaches about 30 m*M*. However, it is not the lactate per se that is responsible for fatigue but the accumulation of hydrogen ions (H^+) within the cell. Hydrogen ions are formed together with the lactate during glycolysis (see above). The concentration of hydrogen ions is usually measured as the pH, which is the negative logarithm of hydrogen ion concentration. As the hydrogen ion concentration increases, the pH decreases. The pH inside the muscle cell is 7.0 at rest; it decreases to 6.4 or even lower during sprinting to exhaustion.

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How the increase in the hydrogen ion concentration causes fatigue is not known, but it may interfere with the link between the nervous stimulation of the muscle and contraction (i.e. the excitation-contraction coupling process). Calcium ions are known to be intimately involved in this link within the muscle, so that it would not be too surprising if high concentration of hydrogen ions (H^+) interfered with the biochemical action of calci-

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um ions within the muscle. An alternative explanation is that a decrease in pH leads to inhibition of phosphofructokinase (PFK, via potentiation of the ATP inhibition) and this decreases the rate of ATP formation. This will lead to a decrease in the ATP/ADP concentration ratio and, therefore, a decrease in kinetic efficiency of energy transfer. In addition, it is possible that a decrease in the ATP/ADP concentration ratio could be the signal for inhibition of contractile activity just as it is the signal for stimulation of phosphofructokinase.

Although direct measurements on pH changes in muscle during sprinting are not available, the author considers that the increase in hydrogen ion concentration is not a limitation in the 100-meter sprint; the ability to control *precisely* the rate of glycolysis may be the major metabolic limitation over this distance (see below). However, in the 200-meter and especially the 400-meter sprint (and of course, longer distances) the process of glycolysis will proceed for a sufficient time to cause an accumulation of lactate and hence hydrogen ions. The time of exhaustion will depend upon how much of the glycolytic end-products can be fully oxidized to carbon dioxide and water and how much buffering capacity is present in the muscles of these sprinters to slow the rate of decrease in the muscle pH.

Substrate Cycling in the Control of Glycolysis in Sprinters

The rate of glycolysis (glycogen conversion to lactate) in resting muscle is about 0.05 μmol/min/g muscle. It increases to a maximum of 50–60 μmol/min/g muscle during sprinting. How is this enormous increase in rate achieved?

A key reaction in glycolysis, the phosphorylation of fructose 6-phosphate, is catalyzed by the enzyme PFK, which plays an important role in the control of the rate of glycolysis. Contraction results in an increase in the rate of conversion of ATP to ADP which changes their concentrations such that the ATP/ADP concentration ratio decreases. It is the change in this ratio that is largely responsible for providing feedback control between the rate of ATP utilization and the activity of PFK and hence the rate of glycolysis. However, maintenance of the ATP/ADP concentration ratio near to normal is required for kinetic efficiency so that large changes in the concentrations of these energy nucleotides cannot occur. Consequently, a small change in the ATP/ADP concentration ratio must produce the enormous increase in the catalytic activity of PFK during sprinting. This can be achieved *only* if the regulatory system is *very* sensitive, so that small changes in the concentrations of these regulators produce a large response in the rate of enzyme-catalyzed reaction. This high sensitivity is achieved by the presence of a further enzyme, fructose bisphosphatase (FBPase) which catalyzes the reverse reaction to that of PFK, i.e. dephosphorylation of fructose bisphosphate: the simultaneous activities of the two enzymes produce a cyclic flux from fructose 6-phosphate to fructose bisphosphate which is known as a substrate cycle. Such cycles provide high sensitivity only if the rate of cycling compared to the net flux through the pathway is high. The response of the cycling and glycolytic systems to the race is seen as follows.

When the sprinter is resting in the changing room prior to the race, the activities of both PFK and FBPase are thought to be very low. When the sprinter is on his blocks waiting for the gun, the stress hormones, adrenaline and noradrenaline, cause a stimulation of the catalytic activities of both enzymes, so that the rate of cycling is high. But, since the muscles are not mechanically active, the energy demand is small and hence the glycolytic flux is very low. In other words, the flux through the PFK reaction is almost 'balanced' by the flux through the reverse reaction (FBPase) so that the *net* flux is low. This condition provides the high sensitivity; only a small change in the ATP/ADP concentration ratio is needed to produce an enormous increase in the *net* flux. This change occurs, of course, when the gun is fired and the race begins [*Newsholme*, 1980b].

Elite sprinters probably have a high capacity for cycling and it is predicted that the changes in stress hormones increase cycling rates close to the theoretical maximum, when required; i.e. when the sprinter is on the blocks waiting for the gun during a competitive race. Although such predictions are very difficult to test in man, experiments with isolated rat muscles show that the stress hormones increase the rate of the fructose 6-phosphate/fructose bisphosphate cycle. Similarly, the substrate cycle between glucose and glucose 6-phosphate is increased markedly upon flight in the insect.

The Marathon

The major fuels for muscle during the marathon are glucose plus fatty acids obtained from the bloodstream and glycogen obtained from within the muscle. The important limitations in the use of these fuels will be discussed below. From this it will be shown that these fuels should not be indiscriminately used but that the rate of utilization of one fuel should be controlled not only in relation to the energy demand by the muscle but also in relation to the rates of utilization of the other fuels [*Newsholme and Leech*, 1983].

Fuels for the Marathon Runner

Use of Blood-Borne Glucose. An elite marathon runner expends energy at a rate of about 84 $\text{kJ} \cdot \text{min}^{-1}$ during the race. Since 1 g glucose produces 16 kJ energy on complete oxidation, the runner would use about 5 g glucose/min. Since the total quantity of glucose in the extracellular fluid is about 10 g, glucose must be released into the bloodstream to prevent serious hypoglycemia. This glucose is released from the liver. Experiments with both man and other animals demonstrate that liver glycogen is depleted during sustained exercise. Since the total hepatic store of glucose is only 100 g this would suffice for about 20 min. This represents a rate of glucose utilization of about 1.0 $\mu\text{mol} \cdot \text{min}^{-1} \cdot \text{g}^{-1}$ muscle. Although the maximum activity of hexokinase has not been measured in muscles of elite marathon runners, it is about 1.0 $\mu\text{mol} \cdot \text{min}^{-1} \cdot \text{g}^{-1}$ in muscle of fit normal subjects. This suggests that the marathon runner could support the energy demands of muscle from utilization of blood glucose alone, but only for a limited period.

Use of Muscle Glycogen. In sustained exercise muscle glycogen is depleted gradually. Volunteers were exercised on a bicycle ergometer at such an intensity that they became exhausted after about 100 min. Glycogen was assayed in biopsy samples of muscle taken during the exercise period; glycogen depletion occurred over the entire exercise period and exhaustion occurred when the stores were depleted. From the glycogen content of human muscle, it can be calculated that, if the total muscle glycogen could be used, it would provide energy for about 70 min of marathon running.

Use of Blood-Borne Fatty Acids as a Fuel. The largest fuel reserve in the body is triacylglycerol (fat) which, in theory, could ensure fuel supply for perhaps 70 h or more of marathon running. Triacylglycerol is stored in adipose tissue which is distributed diffusely throughout the body; for example, under the skin, around the major organs and in the peritoneal cavity. It is released from adipose tissue as long chain fatty acids which are transported via the bloodstream to the muscle where they are taken up and oxidized to carbon dioxide and water. The blood concentration of fatty acids increases during sustained exercise by 3- to 6-fold and may reach a concentration of about 2 m*M*. A concentration of 2 m*M* reflects the maximal capacity of the high affinity binding sites for fatty acids on albumin. Higher concentrations will increase the free concentration of fatty acids but this will lead to the formation of micelles which are known to be dangerous. They damage cell membranes, increase the rate of aggregation of platelets, cause inhibition of enzymes and, in hypoxic conditions, increase the risk of cardiac arrhythmias.

Despite the fact that fatty acids are known to be used by muscle in prolonged exercise, there is evidence that their rate of oxidation cannot provide sufficient energy for the muscles [for references, see *Newsholme*, 1981]. (1) If carbohydrate stores of the body are depleted by feeding subjects a high fat diet prior to exercise, a given level of exercise produces exhaustion considerably more quickly than for subjects on a normal diet or a high carbohydrate diet. (2) If the carbohydrate store in the muscle is elevated, a given level of exercise can be maintained for a longer period of time. (3) If the fatty acid concentration in the blood is artificially elevated prior to exercise, a given level of exercise can be maintained for a longer period of time. (4) In ultradistance runners, studied during a 24-hour run, the energy expenditure gradually declined from 87.5% of the maximum rate of oxygen consumption after 1 h to 44.4% after 24 h. It seems likely that, during this run, the availability of carbohydrate was progressively reduced so that fatty acid eventually became the only available fuel. This would suggest that fatty acid oxidation alone can provide *about* 50% of the maximum aerobic power output. (5) *Cerretelli* [personal communication] has investigated the $\dot{V}_{O_{2max}}$ of a patient with muscle 6-phosphofructokinase deficiency. The rate of glucose oxidation would be minimal in this patient so that fatty acid oxidation would provide most if not all of the energy. *Cerretelli* found that the $\dot{V}_{O_{2max}}$ is approximately 60% of what would be expected from other physiological characteristics of the patient.

Glucose/Fatty Acid Cycle in Prolonged Exercise

The increased concentration of fatty acids in the bloodstream during prolonged exercise increases their rate of oxidation by muscle which decreases the rate of utilization and oxidation of both glucose and muscle glycogen. The mechanism of this regulation by fatty acids is as follows. Fatty acid oxidation in muscle raises the intracellular concentrations of the important allosteric regulators of glycolysis and pyruvate oxidation, acetyl-CoA, citrate and glucose 6-phosphate. An increase in the acetyl-CoA/

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CoA concentration ratio will inhibit pyruvate dehydrogenase and markedly reduce carbohydrate oxidation; an increase in the concentration of citrate will inhibit 6-phosphofructokinase and reduce the rate of glycolysis. This latter effect will raise the concentration of glucose 6-phosphate which inhibits both hexokinase and glycogen phosphorylase resulting in a reduction in the rates of glucose utilization and glycogen degradation.

It should be noted that, although fatty acid oxidation reduces the rate of glycolysis and pyruvate oxidation, this does not imply that the rates of glycolysis and pyruvate oxidation are inhibited but they are less than they would be if there was no fatty acid oxidation. Furthermore, the mechanism of regulation of glycolysis is such that if the intensity of exercise is increased, and there is no compensatory change in the rate of fatty acid oxidation, the rate of glycolysis will increase.

Metabolic Basis of Fatigue in Endurance Exercise

It would appear, from considerations outlined above, that for the marathon run and indeed for all other track events that depend upon aerobic metabolism, the rates of oxidation of both the blood-borne fuels (fatty acids and glucose) cannot provide energy at a sufficient rate to meet the demands of the muscle. Hence muscle glycogen must be used to supplement the blood-borne fuels and fatigue will occur when it is depleted. * 505

These metabolic considerations lead to the view that the marathon runner should run at such a rate than his glycogen stores in the muscle are depleted just as the race is completed. If the race is completed with glycogen remaining in the muscle, the athlete could have run faster; if all the muscle glycogen was used prior to completion of the race, then the athlete would depend solely on fatty acid oxidation, and the power output would fall by perhaps 50%. In the marathon runner this would be considered to be fatigue.

Triglyceride/Fatty Acid Substrate Cycle and Regulation of Fatty Acid Mobilization

Since the rate of fatty acid oxidation depends in part upon the blood concentration, the control of the rate of mobilization is of considerable importance in providing a sufficient concentration to maintain a high rate of oxidation in muscle. Changes in the levels of the hormones, insulin, and catecholamines during exercise are important in increasing the rate of fatty acid mobilization.

In adipose tissue, the process of lipolysis occurs simultaneously with that of esterification, so that triglyceride is broken down to fatty acids, which are re-activated and re-esterified to form triglyceride. Thus, a substrate cycle between triglyceride and fatty acid is present in adipose tissue. It is suggested that one role of this substrate cycle is to provide a sensitive control mechanism for fatty acid mobilization. Thus, changes in blood levels of lipolytic and/or antilipolytic hormones and other lipolytic regulators could ensure that the rate of fatty acid mobilization is the same as that utilized by the muscle so that exercise causes neither an excessive increase in the fatty acid concentration, which could be dangerous, nor too small an increase which would permit glucose to be utilized and result in hypoglycemia. There is now some evidence in experimental animals that the catecholamines both in vitro and in vivo increase the rate of the triglyceride/fatty acid cycle [*Brooks* et al., 1982]. Endurance training may increase the capacity of the triglyceride-fatty acid substrate cycle in adipose tissue so that an increase in the cycling/flux ratio could easily be produced to provide a control mechanism sensitive to small changes in the concentrations of hormones and other regulators.

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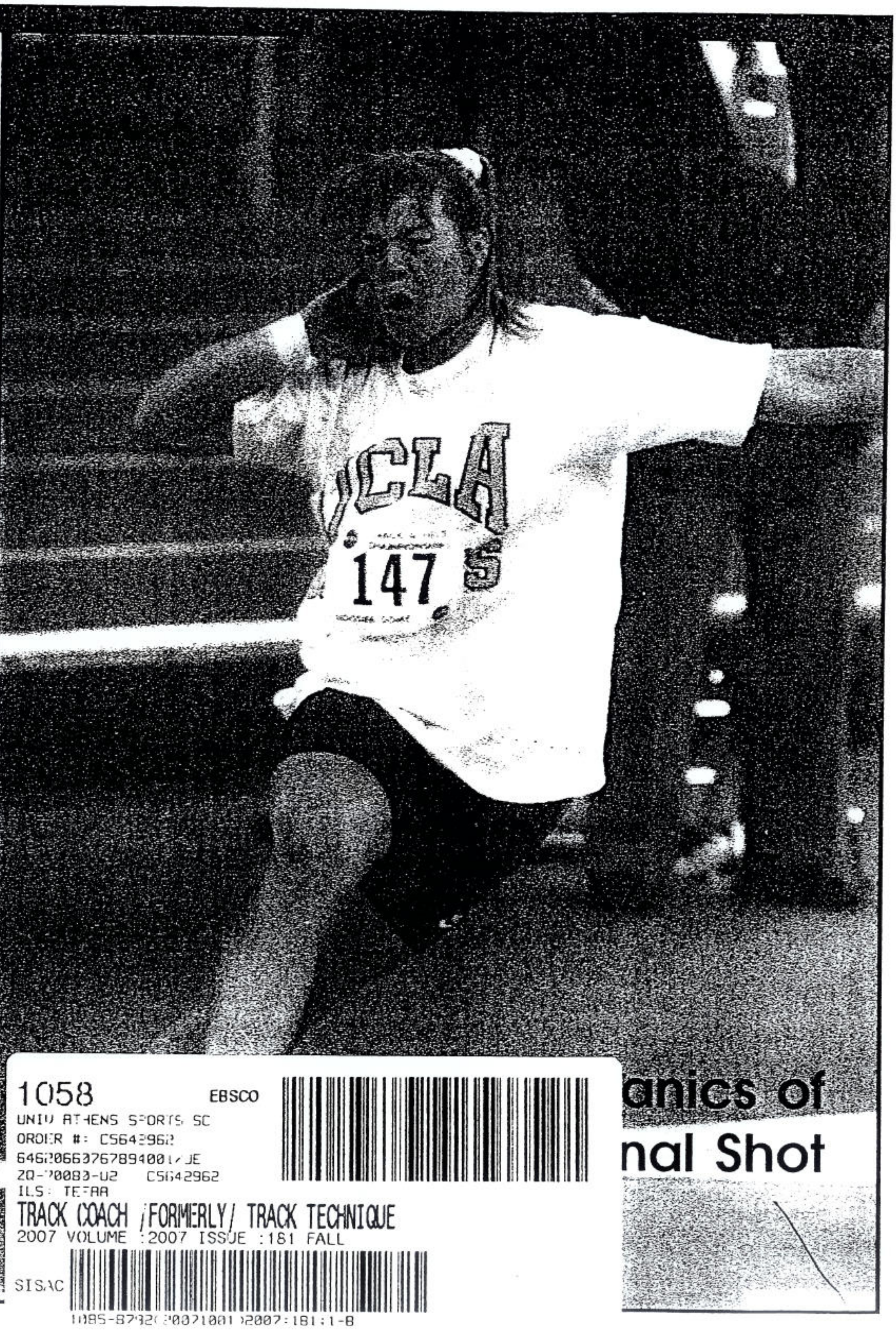
CONTENTS

FALL 2007

181



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The Three Players Of Distance Running

An In-Depth Look at Lactate Threshold

This is the second in a series of three articles by exercise physiologist/coach Jason Karp on "The Three Players of Distance Running." This one explains Lactate Threshold and its significance for endurance running. The final article will discuss running economy.

Lactic acid was first discovered in 1780 in sour milk. In our bodies, it is produced in a metabolic pathway called glycolysis, a series of nine chemical reactions that breaks down glucose to provide energy (ATP) for muscle contraction. Pyruvate, the final product of glycolysis, has two fates: (1) conversion to Acetyl-Coenzyme A and entry into the Citric Acid Cycle (Krebs Cycle) or (2) conversion to lactic acid.

The lactic acid conversion occurs when oxygen is not supplied fast enough to meet the needs of the muscle cells, as has been known since the 1920s, when Nobel Prize winners A.V. Hill and Otto Meyerhof discovered that lactic acid is produced during fatiguing muscle contractions in the absence of oxygen. When lactic acid is produced at the pH of our body fluids, it immediately releases a proton and thus exists as the molecule lactate rather than as its acid form.

Since the time of Hill's and Meyerhof's groundbreaking finding, lactic acid has been the exercising community's scapegoat for fatigue. But there has never been any experimental evidence that has shown a cause-and-effect relationship between lactate production and fatigue.

Although it has been widely accepted by the scientific community for a long time that lactate is innocuous and is not the cause of fatigue or muscle burning during intense exercise, lactate still takes the blame and still is regarded by runners as the enemy. No physiologist has ever burnt himself when taking a blood sample from a subject containing a high blood lactate concentration. Indeed, not only does lactate not cause fatigue, its production in muscle is vital during intense exercise, as it serves a number of roles.

Lactate production maintains the ratio of certain biochemical molecules, supporting the continued ability of glycolysis to keep working. Lactate is also used as ① a fuel by the heart, is used by the liver to make new glucose by a ② process called gluconeogenesis, and is converted back into glycogen (the ③ stored form of carbohydrate) by a reversal of the chemical reactions of glycolysis. Both the new glucose and glycogen are then themselves used as fuels by muscles so high-intensity exercise can continue.

By Jason R. Karp, M.S.

FALL, 2007

LACTATE'S THRESHOLD RESPONSE

At slow speeds, lactate is removed from the muscles as quickly as it is produced. At faster speeds, there is a greater reliance on anaerobic glycolysis for energy, and aerobic metabolism (Krebs Cycle and electron transport chain) can't keep up with the production of pyruvate from glycolysis. Pyruvate is thus converted into lactate and lactate removal starts lagging behind lactate production. The lactate threshold is the fastest pace above which lactate production begins to exceed its removal, with lactate concentration beginning to increase exponentially.

Think of a bucket with a hole in it that sits out in the rain. When it's drizzling, the water filling the bucket empties through the hole. But when it's pouring, water fills the bucket faster than it empties through the hole, and water accumulates in the bucket.

To take the analogy further, there is an intensity of rainfall at which the amount of water emptying the bucket is just enough to keep up with the amount of water entering the bucket so that the water does not overflow. If the rainfall is heavy enough, the bucket will overflow. The point at which lactate quickly accumulates—the overflowing bucket—is an important marker in physiology, and is called the lactate threshold. The intensity of rainfall that is needed to overflow the bucket is therefore determined by the size of the hole in the bucket.

The lactate threshold demarcates the transition between exercise that is almost purely aerobic and exercise that includes significant oxygen-independent (anaerobic) metabolism. (All running speeds have an anaerobic contribution, although when running slower than lactate threshold pace, that contribution is negligible.) Therefore, the lactate threshold represents the fastest speed your athletes can sustain aerobically.

The lactate threshold also signifies a change in fuel use. At running speeds slower than lactate threshold pace, your athletes use a combination of fat and carbohydrates for fuel. As running speed increases, the contribution from fat decreases and the contribution from carbohydrates increases. At speeds faster than the lactate threshold, your athletes use only carbohydrates (blood glucose and muscle glycogen).

There are many terms that have been used to describe the lactate threshold, including anaerobic threshold, individual anaerobic threshold, ventilatory threshold, onset of blood lactate accumulation, lactate breakpoint, and maximal lactate steady state. In a previous issue of *Track Coach*, I proposed the term "acidosis threshold," since it is the acidosis that we're really interested in rather than lactate; the accumulation of lactate is only a reflection of the state of acidosis.

All of these terms describe similar phenomena that are interrelated. Because the term "anaerobic" literally means "no oxygen," the term "anaerobic threshold" is not often used any longer since the occurrence of the anaerobic threshold does not signify a lack of oxygen. After all, how can a muscle be anaerobic at submaximal intensities?

HOW IS THE LACTATE THRESHOLD MEASURED?

The lactate threshold is typically measured during a VO_2max test, with blood samples taken from a finger prick or from a catheter placed into a vein in the arm. The lactate threshold is defined as the speed (or VO_2) at which the blood lactate concentration begins to increase exponentially (Figure 1). In lieu of taking blood samples during the test, the ventilatory threshold,

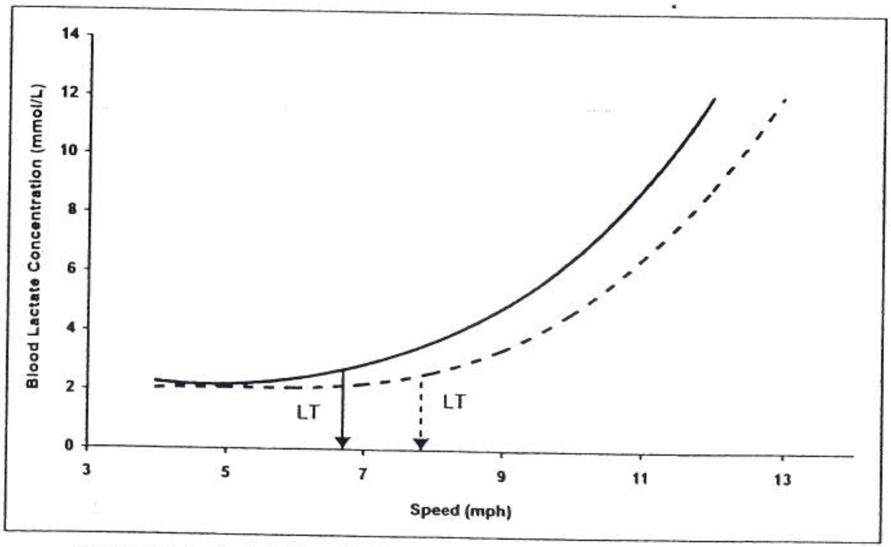

Figure 1: The lactate threshold is the speed at which the blood lactate concentration begins to increase rapidly. A shift in the lactate curve to the right, depicted by the dotted curve, represents an increase in the lactate threshold (because it now occurs at a faster speed) and an improvement in endurance.

which is determined from changes in ventilation and respiratory gas samples, is often used to indicate the lactate threshold since there is a close relationship between the two thresholds—as the speed increases, the greater reliance on oxygen-independent metabolism increases the amount of carbon dioxide that is produced, which stimulates ventilation to expire the carbon dioxide.

Alternatively, the lactate threshold can be measured with a series of steady-state runs at increasing speeds, with blood samples taken at regular intervals during each run. At the slower speeds, lactate will increase slightly and plateau. When lactate threshold pace is reached, however, lactate keeps increasing rather than leveling off.

Lactate is measured in millimoles of lactate per liter of blood (mmol/L). The lactate threshold can be reported as a speed or pace or as a percentage of VO_2max. The higher the percentage the lactate threshold occurs in relation to VO_2max, the better the athlete's endurance.

Knowing your athletes' VO_2max is not be enough to determine their fitness. For example, two runners may have similar VO_2max values but differ in their lactate thresholds. If Runner A and Runner B both have a VO_2max of 60 ml/kg/min, but Runner A's lactate threshold is 70%
sos and Runner B's lactate threshold is 80% of VO_2max, Runner B can sustain a higher intensity and will beat Runner A.

Also, two runners may have different VO_2max values but perform similarly due to differences in their lactate thresholds. If Runner X has a VO_2max of 60 ml/kg/min and a lactate threshold that is 67% of her VO_2max and Runner Y has a VO_2max of 50 ml/kg/min and a lactate threshold that is 80% of her VO_2max, both Runner X and Runner Y will be able to sustain a similar intensity, assuming their running economy is equal (67% of 60 = 40 ml/kg/min vs. 80% of 50 = 40 ml/kg/min).

LACTATE THRESHOLD TRAINING AND PERFORMANCE

From the time of the classic study published in *Medicine and Science in Sports and Exercise* in 1979 by some of the most prominent names in exercise physiology (Farrell, Wilmore, Coyle, Billing, and Costill), research has shown that the lactate threshold is the best physiological predictor of distance running performance. The longer the race your athletes are training for, the more important it is to improve their lactate thresholds because the closer the race pace will be to their lactate threshold pace and the more important it becomes to be able to hold a hard pace for an extended time.

So, for the marathon and half-marathon, the lactate threshold should be the focus of their training. The keys to success for the longer distance races are (1) getting your athletes' lactate threshold pace as fast as they can and (2) being able to run as close to their lactate threshold pace as possible for as long as possible.

The lactate threshold is more responsive than VO_2max to training. While VO_2max plateaus after a few years of high-intensity training, the lactate threshold can still increase, improving your athletes' performances. Training the lactate threshold increases the speed at which lactate accumulates and acidosis occurs, enabling your athletes to run at a higher percentage of VO_2max for a longer time.

Increasing their lactate threshold pace allows your athletes to run faster before they fatigue because it allows them to run faster before oxygen-independent metabolism begins to play a significant role. The benefit to being able to run aerobically at 5:30 pace compared to 6:00 pace is obvious.

You can target the lactate threshold by having your athletes run at or near their lactate threshold pace. Research has shown that runners who do specific lactate threshold workouts have a significantly greater improvement in their ability to hold a hard pace compared to those who train with only long or short intervals.

One of the major advantages to lactate threshold training is that the intensity represents the fastest pace at which your athletes can train without excessive fatigue. That's because the workouts remain aerobic. Lactate threshold training is the best aerobic bang for your buck.

WHAT PACE SHOULD YOUR ATHLETES RUN LACTATE THRESHOLD WORKOUTS?

As a coach, I've noticed that the most difficult type of workout for athletes to run at the correct pace are lactate threshold workouts. Many runners, especially those who are inexperienced with these workouts, have a difficult time holding back the pace and finding their fastest sustainable aerobic pace.

Lactate threshold pace is about 10 to 15 seconds per mile slower than 5K race pace (or about 10K race pace) for slower runners (slower than about 40 minutes for 10K). If using a heart rate (HR) monitor, the pace is about 75 to 80% max HR. For highly trained and elite runners, lactate threshold pace is about 25 to 30 seconds per mile slower than 5K race pace (or about 15 to 20 seconds per mile slower than 10K race pace) and corresponds to about 85 to 90% max HR. The pace should feel "comfortably hard."

It seems that many runners and coaches miss the nuances of the lactate threshold when prescribing training paces for workouts. Every time I read a magazine or mainstream book about running, I read that lactate threshold pace is 25 to 30 seconds per mile slower than 5K race pace, 15 to 20 seconds per mile slower than 10K race pace, and between 10-mile and half-marathon race pace.

However, these guidelines are only true for very good runners. The better your athletes' endurance, the longer they can hold their lactate threshold pace and the better they are at sustaining any fraction of their lactate threshold pace.

In other words, if a 15-minute 5K runner can run 30 seconds per mile faster than lactate threshold pace (which equals 110% of lactate threshold pace) for those 15 minutes, certainly a 25-minute 5K runner is not also going to be able to run 30 seconds per mile faster than lactate threshold pace (which equals 106% of lactate threshold pace) for 25 minutes, 10 minutes (and 66%) longer than the good runner.

Someone who runs a 10K in 50 minutes is likely running slower than his/her lactate threshold pace for a 10K, not 20 seconds per mile faster. And someone who runs a half-marathon in 1 hour and 45 minutes is certainly not running anywhere near lactate threshold pace. What matters is how long it takes to run the distance, not the distance itself.

TYPES OF LACTATE THRESHOLD WORKOUTS

I typically use four types of lactate threshold workouts with my athletes: (1) continuous runs at lactate threshold pace, starting at about three miles (15 to 20 minutes) and increasing up to seven to eight miles (about 45 minutes) for marathoners; (2) intervals run at lactate threshold pace with short rest periods, such as 4 x 1 mile at lactate threshold pace with 1:00 rest or 8 x 1,000 meters at lactate threshold pace with 1:00 rest; (3)

(Continued on page 5793)

Table 1: Sample Lactate Threshold (LT) Training Program

Mesocycle #1	**LT Workout #1**	**LT Workout #2**
Week 1	3 x 1 mile @ LT pace w/1:00 rest	
Week 2	3 miles @ LT pace	
Week 3	4 x 1 mile @ LT pace w/1:00 rest	
Week 4 (Recovery Week)	3 x 1 mile @ LT pace w/1:00 rest	
Mesocycle #2	**LT Workout #1**	**LT Workout #2**
Week 5	4 x 1 mile @ LT pace w/1:00 rest	
Week 6	2 x 2 miles @ LT pace w/2:00 rest or 4 miles @ LT pace	
Week 7	5 x 1 mile @ LT pace w/1:00 rest	
Week 8 (Recovery Week)	3 x 1 mile @ LT pace w/1:00 rest	
Mesocycle #3	**LT Workout #1**	**LT Workout #2**
Week 9	5 x 1 mile @ LT pace w/1:00 rest	4 miles @ LT pace
Week 10	2 sets of 3 x 1,000 meters @ 5 to 10 seconds per mile faster than LT pace w/:45 rest & 2:00 rest between sets	4 miles @ LT pace
Week 11	2 sets of 4 x 1,000 meters @ 5 to 10 seconds per mile faster than LT pace w/:45 rest & 2:00 rest between sets	5 miles @ LT pace
Week 12 (Recovery Week)	3 x 1 mile @ LT pace w/1:00 rest	

Include a warm-up and cool-down before and after each workout and fill in the other days of the week with runs to meet mileage goals.

running coaching. Especially in distance running, physiological principles must be considered and systematically implemented to achieve optimum results. This should all be accomplished within a performance plan of an effective distance running coach.

CONCLUSION

The most effective coaches are masters of all aspects of the coaching process. Each coach may accomplish these aspects in their own way. A distance running coach cannot rest on past success any more than a runner can. NCAA D-I and II coaches face a turnover in athletes every four to five years. These coaches must continually accommodate and adapt for each new runner to become and remain effective. The most effective NCAA D-I and II distance running coaches, then, are the ones who year after year demonstrate individual athlete improvement based upon individual athlete goals, ability levels, environmental factors and circumstance. Only the names and faces change; the results do not.

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AN IN-DEPTH LOOK AT LACTATE THRESHOLD

Continued from page 5785

shorter intervals run at slightly faster than lactate threshold pace with very short rest periods, such as 2 sets of 4 x 1,000 meters at 5 to 10 seconds per mile faster than lactate threshold pace with 45 seconds rest and 2:00 rest between sets; and (4) medium-long distance runs with a portion run at lactate threshold pace, such as 12 to 16 miles with the last 2 to 4 miles at lactate threshold pace or 2 miles + 3 miles at lactate threshold pace + 6 miles + 3 miles at lactate threshold pace (I only use these latter workouts for marathoners).

As your athletes progress, increase the training load by having them spend more time at lactate threshold pace rather than by running faster. You can do this by increasing the volume of a single workout or by adding a second lactate threshold workout each week. Only increase the pace of the workouts once your athletes' races have shown that they are indeed faster. See Table 1 for a sample training program.

So if you want your runners to perform at the highest level they can, train their lactate thresholds. Not only will they set new personal records, they'll have holes in their buckets big enough to rival a black hole.

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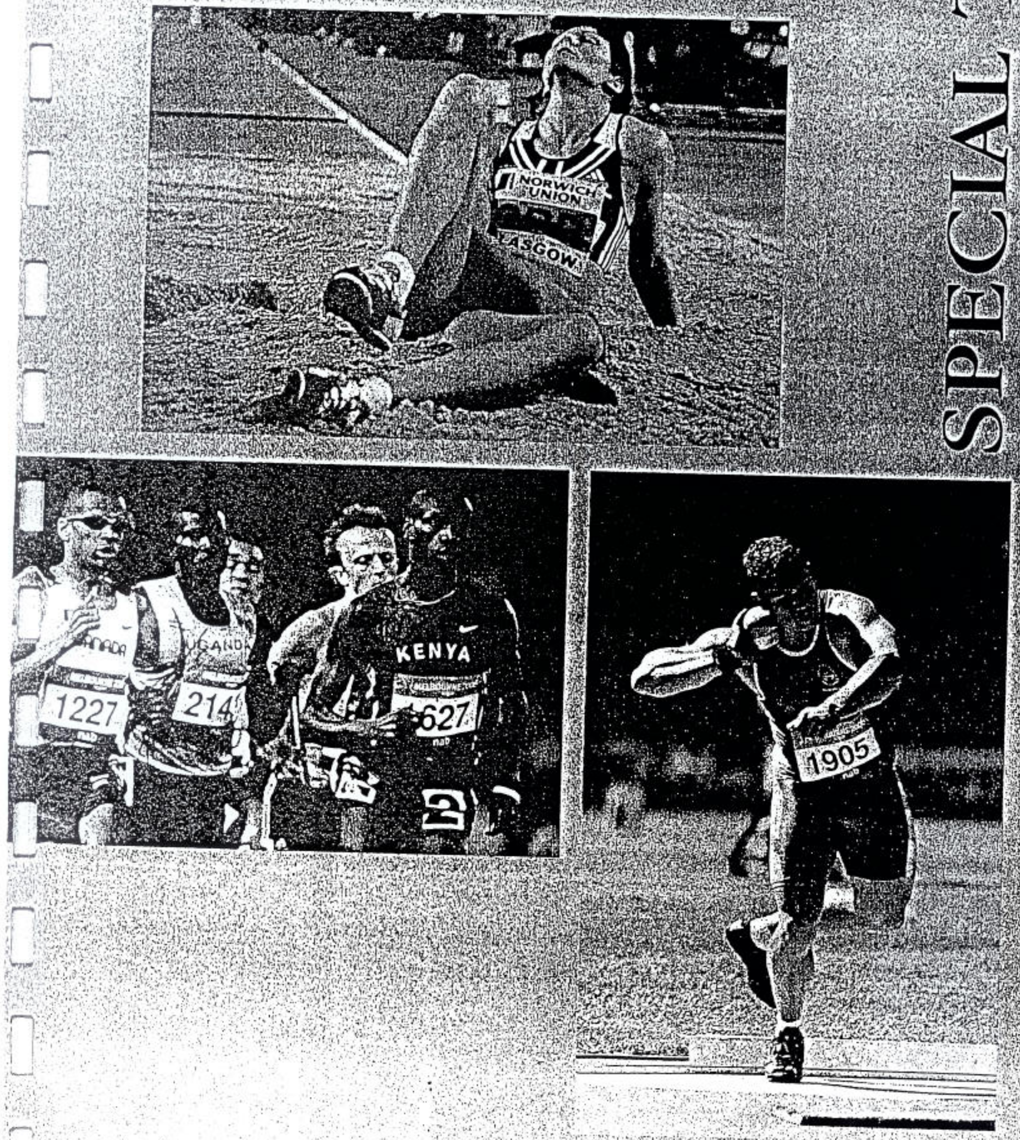
SPECIAL TOPIC



Προβολη

It is not lactic acid's fault

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By Guy Thibault, François Péronnet

ABSTRACT

Lactic acid and lactate are widely believed to be the cause of fatigue, cramps and soreness in athletes. The authors take issue with this orthodoxy, citing a number of recent studies to support their view. They point out that it is possible to observe muscle fatigue while the lactic acid concentration in the muscle remains low and observe an absence of fatigue when the lactic acid concentration in the muscle is high. They argue that in many situations performance does not depend on the ability of the runner to produce less lactic acid, as many people think, but in the ability to produce more. They also question the existence of the anaerobic threshold – the point in exercise intensity beyond which the source energy moves from an aerobic metabolism to a combination of aerobic and anaerobic metabolisms - arguing that current scientific knowledge does not support its existence. If an anaerobic threshold really does exist, they say, it does not have all the uses people currently ascribe to it.

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> *'There's nothing so useless as a bad theory.'*
>
> Leonid Brezhnev

Introduction

You feel the pain as soon as you push yourself hard. Your muscles and your stomach hurt, not to mention your ego. And it stands to reason that if you feel pain, something has to take the blame for it. In the world of endurance sport, including running, it is claimed that lactic acid is the cause of all pain. You have cramps or stiffness? Lactic acid is the culprit. And while we're there, why not blame lactic acid for overuse injuries, overtraining, baldness, the decline in moral standards and continental drift?

The widely accepted belief that lactic acid is the source of all ills is still supported by some of those sports scientists who are not up to date or who have not had the courage to confess the truth to athletes, simply because they fear going against popular opinion.

Let's start with a fact: in high intensity exercise muscles produce lactic acid, which appears in the blood in the form of a salt that we call 'lactate'. If, however, we study the details of how energy is produced in the muscle during efforts of varying intensities, we find that lactate is not responsible for the ills that some think it is.

A simple but ill-defined theory

To blame lactic acid for muscular fatigue satisfies the simplistic logic that commands us to find a reason for every problem. And when we've gone as far as blaming something for a *particular* problem, why not accuse it of being liable for as many problems as possible? This approach offers many advantages. For one, we can avoid having to figure out the cause of each problem. For those who do not want to bother pondering on the process of fatigue, lactic acid is the perfect scapegoat. Nevertheless, reality is more complex than that.

In truth, the concept of a muscular fatigue does not exist; we should rather speak of muscular *fatigues*. Despite the fact that the outward signs of these fatigues may be the same (they make continued effort impossible) the fatigue felt by a 400m runner is not the same as that felt by a marathoner, which in turn is not the same as that felt by a body builder or a mountain-bike specialist, and so on. It would be naïve to think that lactic acid is the only villain responsible for these varied forms of muscular fatigue.

We find that between the brain's neurons (which send out the motor commands) and the muscles' myofilaments (which carry out these commands) there are several links in the information transmission chain that allows for power output. Any of these links can fall short in its task and so block the continuance of muscle contraction and exercise. Thus, these links appear on the long list of possible suspects in the development of the different types of fatigue. This list might, in some cases, include lactic acid. However, it is undoubtedly not the sole or even the main culprit.

Many research studies have shown that lactic acid is, in the end, only marginally responsible for muscular fatigue. As some of these arguments are quite complex, they will not be discussed here; we will only highlight that the most recent reviews on the subject all point to the conclusion that "The disturbance of the balance of the skeletal muscle acid base is not as critical a factor as is sometimes suggested" (FITTS, 1996; JONES et al., 2003; PÉRONNET and MORTON, 1994; PÉRONNET and THIBAULT, 2005, ROGBERGS et al., 2004; SCHWANE et al., 1983).

Myth 1: muscular cramps are caused by the presence of lactic acid in the muscle

A cramp is not the result of the accumulation of lactic acid. Of course, one can observe the occurrence of cramps at high lactate concentrations, but muscle lactate can be elevated, even towering, without cramps occurring. This is the case with the 400m race, where all the runners finish with a blood lactate concentration that is 20 to 25 times higher than that of the resting level, but where cramps are rare. On the contrary, some people suffer from cramps while sleeping, when the blood lactate concentration, as well as the effort level, is low.

In most cases, cramps occur during strenuous efforts of long duration, as in a very long training session. In such conditions, the lactate concentration is perhaps clearly higher than at rest, but far below the maximal levels observed during very intense but brief efforts. Therefore, one cannot blame the accumulation of lactic acid for the occurrence of cramps, which is unquestionably due to a hyper-excitability of muscular tissue or of the nerves that innervate it (SCHWELLNUSS et al., 2004).

One can also take into account the case of people with McArdle's disease. They cannot produce or accumulate lactic acid. However, they still suffer from cramps, a further argument confirming that lactic acid is not related to the occurrence of cramps.

Table 1: Effects of isometric exercise

	Immediately after an isometric exercise	Two minutes after an isometric exercise
Degree of muscle acidity	Very high	High
Fatigue	Very high	Very low
Strength	Weak	Normal

The most convincing argument in this debate is that on the one hand it is possible to observe muscle fatigue while the lactic acid concentration in the muscle *remains low* and, on the other hand, observe an absence of fatigue when the lactic acid concentration in the muscle is *high*. For example, at the end of a 100km race, a particularly demanding event, the fatigue level is quite high but the blood lactate concentration is not much higher than in the resting state. Moreover, people who suffer from McArdle's disease are incapable of producing (and thus of accumulating) lactic acid and are very prone to suffering from muscular fatigue. Thus, muscular fatigue can be accompanied by a *very low* lactic acid level, or even with *no* lactic acid at all.

On the other hand, if one performs an exhausting isometric effort with the quadriceps (e.g. the 'chair exercise', with the back leaning against the wall), fatigue will tend to reduce strength temporarily. However, this fatigue rapidly fades and goes away almost entirely after a two-minute period of recuperation: after this period, the muscle can once again produce the initial power. When observing the degree of acidity in the muscles, we see that it has increased considerably during the isometric contraction, which might support the hypothesis that asserts lactic acid is responsible for fatigue. However, during the recuperation period, the degree of acidity in the muscles only returns to normal rather slowly. Hence, two minutes after completion of the exercise, the degree of acidity remains very high but since

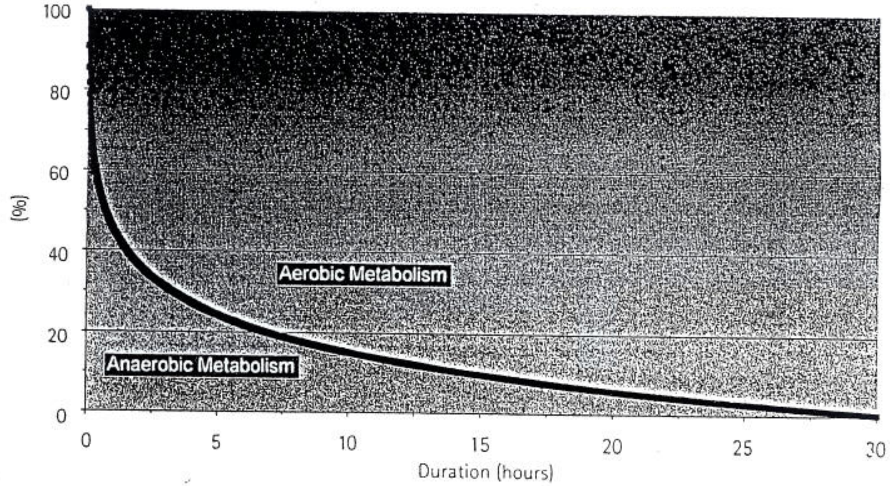

Figure 1: Percentage of energy generated by aerobic metabolism and by anaerobic metabolism, in relation to the duration of maximal efforts, supposing that each test is carried out from start to finish at a constant intensity (as is generally the case in athletics races run on a track or flat course).

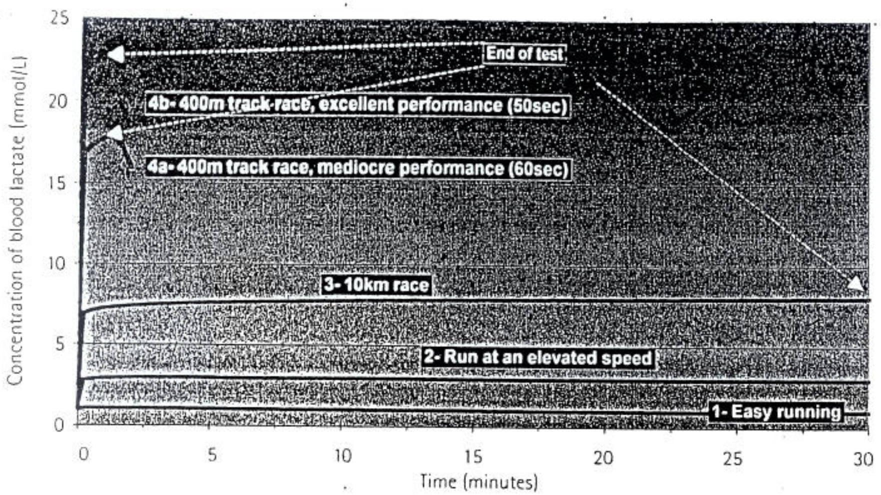

Figure 2: Schematic representation of the production of the blood lactate concentration during efforts of varying relative intensities.

the muscle can once again produce its initial force, the fatigue is obviously gone (see Table 1). For this reason, it is difficult to embrace the idea that the increase in lactic acid in the muscle causes fatigue, since a high degree of acidity *without* fatigue can be observed.

Myth 2: the presence of lactic acid in the muscle causes muscle stiffness and soreness

Delayed onset muscle soreness (DOMS) is the pain that appears a day or two after an unfamiliar intense effort. This type of pain occurs mainly when the exercise entails eccentric muscle contractions, namely contractions during which the muscles contract while lengthening themselves (e.g. absorbing the shock of a falling weight). These muscular pains have nothing to do with the presence of lactic acid in the muscles.

Sometimes lactic acid is accompanied by soreness, but it is also possible to get lactic acid without soreness and vice versa. Laboratory studies provide evidence to confirm this. In one study, the subjects had to run two interval tests (9 x 5 minutes at 7.5mph, with 2 minute recovery periods), first on the flat and then on a 10% descent. The flat run (higher concentration of lactate) did not generate soreness. In contrast, the day after the downhill run (lower concentration of lactate) the subjects suffered severe soreness (SCHWANE et al., 1983).

This is well known to people who run on hilly courses: it is neither the flat stretches nor the climbs that cause stiffness, but the downhill stretches, which call for a much larger number of eccentric contractions. These cause more damage to the musculature because the number of muscle fibres solicited to produce a contraction of a specific tension is 4 to 8 times as great for an eccentric contraction as opposed to a concentric contraction. The tension to which each fibre is subjected is therefore far greater, and this is what causes the micro-traumas and the ensuing inflammation. This is a smart demonstration that lactic acid has nothing to do with muscle soreness.

To summarise: the diverse types of fatigue experienced by runners depend on a mixture of causes, depending on the type of effort; but nothing proves that lactic acid or lactate is the sole cause, nor even one of the major causes of any of these forms of fatigue.

Table 2: Advantages and disadvantages of anaerobic and aerobic energy production

Process	Advantages	Disadvantages
Anaerobic glycolysis	Energy produced at an elevated rhythm	Limited amount of total energy produced
Aerobic	High volume of total energy produced	Energy produced at a low rhythm (depends on VO_2max)

Which is better: producing more or less lactate?

Some believe that the more lactate you produce, the less effective you are. In reality, it is exactly the opposite. In numerous track and field events, if you produce more lactic acid, it is a sign that you are working at a higher intensity and therefore running at a higher speed.

In relatively violent efforts, like the 400m, 800m or 1500m, an important part of the energy used in muscular contraction comes from 'anaerobic glycolysis'. In this process, muscle cells produce the energy necessary for contraction through the degradation (-lysis) of glucose (glyco-), without using oxygen (anaerobic: *without* oxygen). If we compare it to aerobic (*with* oxygen) processes of energy production, anaerobic glycolysis, which always accompanies the release of lactic acid, has both advantages and drawbacks (see Table 2). Hence, in sprint and middle-distance events, where the quantity of energy produced during each second is very high, an especially large part of the energy is supplied by anaerobic glycolysis. In longer events, where the total quantity of energy deployed is increased, an extremely important part of the energy comes from the aerobic process (Figure 1).

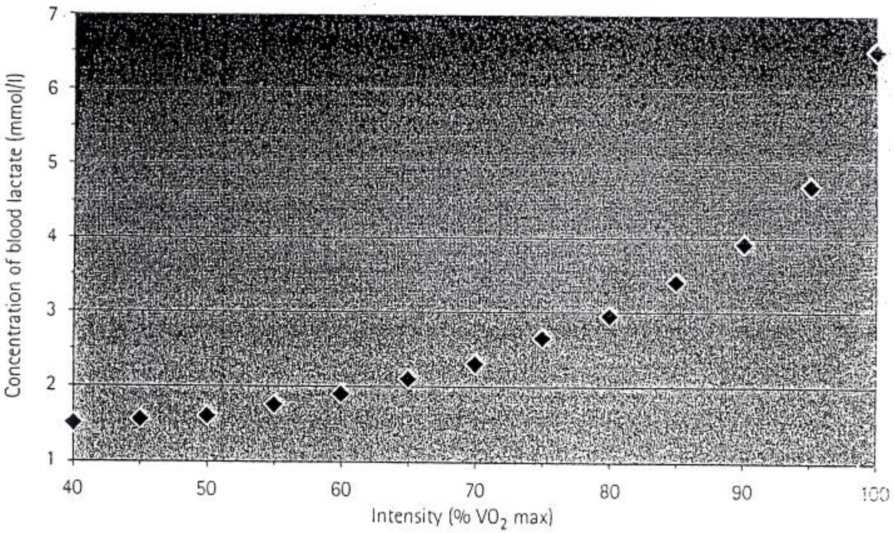

Figure 3: Lactate variations during the course of a maximal progressive treadmill test. Believers will see here a threshold, which a thorough examination does not confirm: it is simply a parabola without a deflection point (PÉRONNET and MORTON, 1994).

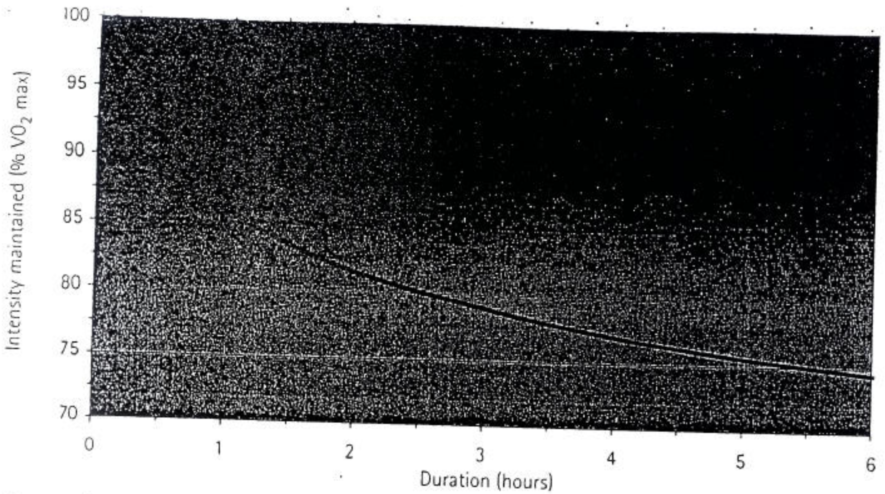

Figure 4: If runners are subjected to a series of maximal tests of different lengths, you find that the intensity attained reduces in proportion to the duration of the test: 100% of VO_2max for 7 minutes, 90% for 30 minutes, 80% for 2 1/2 hours, and so on. If the anaerobic threshold had the significance it is granted, this reduction would show a deflection with regard to the intensity corresponding to this famous threshold (PÉRONNET and THIBAULT, 1989).

Consequently, one should not be surprised that athletes engaging in brief, intense exercises produce a lot of lactate and that, as a result, the more they produce the better they perform. Thus (and as shown in Figure 2), the blood lactate concentration, which is about 1 mmol/l in the resting state, increases to about 18 mmol/l at the end of a 400m race for average runners, and up to 23 mmol/l for elite athletes. Therefore, in short efforts (10 seconds to 10 minutes), athletes who produce a lot of lactate, and thereby supply their muscles with much anaerobic energy, will tend to be those that succeed.

To believe or not to believe ...: in the anaerobic threshold

There are those who have no doubt in the existence of the anaerobic threshold; that somewhere between the intensity of a leisurely jog and the most frantic sprint there is a point beyond which you go from aerobic metabolism to a combination of aerobic and anaerobic metabolisms. This convenient and attractive theory has many devotees at present. Popular magazines frequently cite it, implying that its existence is something that is generally agreed upon. Indeed, during a high intensity run for several minutes, you sometimes feel that it would require great courage to increase your speed by even the smallest amount.

However, current scientific knowledge refutes the anaerobic threshold theory. Presenting the details here would be tedious, but we highlight the following points:

- There is no power threshold below which a muscle does not produce lactate. A muscle constantly produces lactate, even from the lowest work level, and a muscle produces lactate even when the supply of oxygen is adequate.
- During a ramp test (such as the ones carried out in the laboratory in which the runner must run at a regularly increasing intensity until exhaustion), the blood lactate concentration never appears as a threshold, as some people argue. The curve obtained shows no deflection (Figure 3). To see one, a very fertile imagination is required. It is true that many sports scientists (whose fame is somewhat inferior to the revenues they obtain from the tests they conduct) unscrupulously possess such an imagination but, in reality, the shape of this curve is most likely the result of a delay in the appearance of the lactate in the blood (PÉRONNET and MORTON, 1994).

For a given running intensity (for example, at 150 heart beats per minute), the lactate concentration decreases from the effect of following a good training programme. But this is not related to the anaerobic threshold: the reason behind this is definitely the fact that training improves the precision of metabolic control.

If an anaerobic threshold existed and if it had the physiological importance we now give it in sporting groups (transition aerobic-anaerobic), the relation between running intensity and critical time (the period during which a runner can sustain a given intensity) would not produce such an even curve (Figure 4) and there would be a deflection (PÉRONNET and THIBAULT, 1989).

If it were as demanding as believers think it is to exercise at an intensity above the anaerobic threshold, athletes could not perform at an intensity above that corresponding to the anaerobic threshold – which is what virtually all runners with the least motivation do over the classic distances such as 5km and 10km.

Measuring something that does not exist: what a challenge!

Moreover, finding the best way to identify this famous anaerobic threshold triggers some puzzlement. We have gathered a list of twenty or so ways: complex, subjective, dubious and harebrained. In this last category sits the famous Conconi test, valued by athletes but sternly criticised by scientists. These varied methods, simply because they are so different from one another, generate measures of the anaerobic threshold that are far too widely spread to be convincing. Indeed, one can see a relatively good correlation between, on the one hand, speed at the so called 'anaerobic threshold', and on the other hand, performance, for instance, in a 10,000m race. However, that can be explained: the speed that the runner can sustain at the anaerobic threshold (established by one means or another) depends on the maximal oxygen consumption (VO_2max) more than on any other factor. The higher the VO_2max, the better the performance, regardless of the event, as long as it lasts more than a few minutes.

Conclusion: not guilty

Lactic acid and lactate are not the cause of fatigue, cramps or muscle soreness. Performance in sprint and middle distance races depends on the ability of the runner to produce more, not less lactic acid. And if an anaerobic threshold exists, it definitely does not have all the uses people apply to it.

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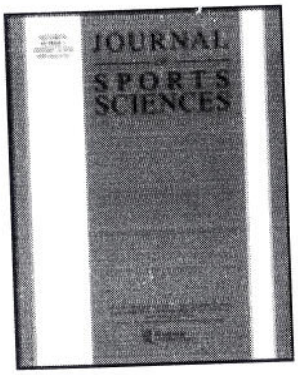

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Pacing in Olympic track races: Competitive tactics versus best performance strategy

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Pacing in Olympic track races: Competitive tactics versus best performance strategy

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Abstract

The purpose of this study was to describe pacing strategies in the 800 to 10,000-m Olympic finals. We asked 1) if Olympic finals differed from World Records, 2) how variable the pace was, 3) whether runners faced catastrophic events, and 4) for the winning strategy.

Publically available data from the Beijing 2008 Olympic Games gathered by four transponder antennae under the 400-m track were analysed to extract descriptors of pacing strategies. Individual pacing patterns of 133 finalists were visualised using speed by distance plots.

Six of eight plots differed from the patterns reported for World Records. The coefficient of running speed variation was 3.6–11.4%. In the long distance finals, runners varied their pace every 100 m by a mean 1.6–2.7%. Runners who were 'dropped' from the field achieved a stable running speed and displayed an endspurt. Top contenders used variable pacing strategies to separate themselves from the field. All races were decided during the final lap.

Olympic track finalists employ pacing strategies which are different from World Record patterns. The observed micro- and macro-variations of pace may have implications for training programmes. Dropping off the pace of the leading group is an active step, and the result of interactive psychophysiological decision making.

Keywords: *athletic performance, competitive behaviour, running, track and field, physical endurance*

Introduction

Pacing strategy is an important determinant of success in sports competitions (Abbiss & Laursen, 2008; Foster, Schrager, Snyder, & Thompson, 1994; Tucker & Noakes, 2009). Athletes have to distribute their ability to provide for muscular adenosine triphosphate (ATP) generation while maintaining an adequate reserve (Swart et al., 2009a, 2009b) such that the athlete neither runs out of energy and faces catastrophic physiological failure before the finish, nor has excess energetic reserves at the end of the competition. This is probably a learned pattern, or a pacing template, based on extensive experience gained during training and previous competitions (Foster et al., 2009, 2012; Micklewright, Papadopoulou, Swart, & Noakes, 2010).

In long-distance running events, most of the literature on pacing is either on World Record performances (Tucker, Lambert, & Noakes, 2006) or on sub-elite-standard runners running at their own best pace (Abbiss & Laursen, 2008; Faulkner, Parfitt, & Eston, 2008; Lima-Silva et al., 2009). The dominant 'best race' strategy in 800-m middle-distance running is thought to be a small but progressive slowing (Tucker et al., 2006). In 1.5–10-km track races, the best race strategy has been described as even pacing with an endspurt (Tucker et al., 2006).

However, in high-standard competitions, the finishing place is a more important outcome than finishing time. Top runners might run with a slower than ideal pace with varied tactics, and variations in pace can vary with the overall pace of the race. Also, less accomplished runners can feel forced to stay with the leading group at a pace markedly faster than their best performance. This increases the risk of premature excessive fatigue that could result in a decisive and progressive decrease in pace.

Unfortunately, there are few data on ways in which races at world-class championships are actually contested. Split times have been available only for 400-m segments, so the temporal resolution of

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ΣΜΙΡΝΙΩΤΥ

pacing data has been inadequate to reveal the behaviour of athletes during competition.

Timing data from the 2008 Olympiad have now become publically available (www.iaaf.org) with a resolution of 100 m, which allows an examination of how world-standard races are contested. With the availability of this unique data set, we addressed several basic questions:

1. Do the pacing strategies in middle- and long-distance track events (800–10,000 m) at Olympic finals differ from World Record pacing?
2. How 'constant' is running speed during the middle portions of long-distance events? Do the traditionally used 400-m split times represent the same variation in running speed as 100-m splits?
3. Is there evidence of a 'catastrophic event' in runners who drop off the leading group in the 5- or 10-km races? Do these runners run at a progressively slower pace throughout the event, or do they simply decrease their pace to a more individually appropriate level and then display a normal pacing pattern?
4. What is the winning strategy of the medallists over non-medallists (places 4–8) and finalists (places 9+)? Is the winning strategy among medallists dependent on forcing the following runners to 'drop back' during the event or on a better endspurt?

Methods

Split times from the men's and women's 800-m, 1500-m, 5-km and 10-km finals from the 2008 Beijing Olympic Games, which are publically available on the website of the International Association of Athletics Federations (IAAF) (www.iaaf.org) were analysed. In Beijing, the IAAF used a new system provided by Swiss Timing Sportservice GmbH (Leipzig, Germany). The system comprises a transponder antennae under the 400-m track at 0 m, 100 m, 200 m and 300 m, and ID chips on the inside of each athlete's front bib. When athletes pass over the transponder, their ID is read from the chip and their time registered to the nearest tenth of a second. In the women's 5-km final, one of the timing markers did not function. Accordingly, 100-m data were calculated based on the measured 200-m time for this segment, with the two adjacent 100-m segments assumed to be at the same pace.

Analysis was completed in four ways. First, individual plots of speed by distance allowed visual comparison of the pattern of pacing for each individual runner with the recent World Record as published in the IAAF book of world records (International Amateur Athletic Federation, 2007). Also, the relative speed of the second versus the first half of the race was calculated in medallists (places 1–3), non-medallists (places 4–8), and finalists (places 9+) and compared with recent World Records to indicate whether the overall pacing pattern was positive, even, or negative. Second, intra-individual coefficients of variation of running speed were calculated based on 100-m, 400-m and 1000-m split times as applicable, and compared to recent World Records. Also, the absolute value of the individual relative change in pace for every 100 m was calculated to improve the sensitivity of pace variation. Furthermore, plots of the mean speed of all finalists were compared at resolutions of 100 m versus 400 m. Third, in the long-distance races, the largest decrease of speed between any two 100-m segments in the second half of the race was calculated for medallists, finalists (places 4+) and runners who slowed down (>3% decrease of speed in the second half of the race) to detect possible catastrophic events. In the same groups, running speed in the last lap was reported normalised to the speed in the last quarter to compare runners' reserves for an endspurt. Fourth, individual data were collapsed into groups of medallists, non-medallists, and finalists to allow visualisation of the pacing pattern in competitively meaningful groups of runners, and speed-by-distance plots of the three medallists were constructed.

Because these data represent unique observations, the analysis was fundamentally descriptive, and no conventional statistical analyses were used.

Results

All of the events were won in a time within 4% of the World Record, except the women's 5 km, which was run in a particularly tactical manner. Bronze medallists were within 2% of the race winner, and in all races except the women's 10 km, the last finisher was within 10% of the winner (Table I).

Plots of running speed versus distance show that in all races except the women's 800 m and 10 km, the individual patterns of speed in Olympic finals differed from the World Record (Figures 1 and 2). The overall pacing patterns (1st versus 2nd half) were also different (Table II). In the 5- and 10-km races, runners who were 'dropped' from the field appeared to achieve a stable running speed, and increased their speed on the last 400 m.

Runners varied their speed every 100 m by a mean 1.6–2.7%, even in fast races or after they had been dropped off. Coefficients of variation in running speed were higher based on 100-m rather than 400-m split times, and for most runners higher in the Olympic finals than in World Records (Table III). Plotting mean running speed based on 100-m splits yielded additional information on the pacing pattern

Table I. Performance times in Beijing Olympic finals.

Race	Number of Finishers	Winning Time	Winning Time (% vs. World Record)	Bronze Medal Time (% vs. Winning Time)	Last Finisher Time (% vs. Winning Time)
M 800 m	8	1:44.65	103.5	100.2	102.4
W 800 m	8	1:54.87	101.4	101.6	106.8
M 1500 m	12	3:32.94	103.4	100.6	103.3
W 1500 m	12	4:00.23	104.2	100.6	102.9
M 5 km	14	12:57.82	102.7	101.1	107.4
W 5 km	15	15:41.40	110.6	100.3	109.1
M 10 km	35	27:01.17	102.8	100.2	108.9
W 10 km	29	29:54.66	101.3	101.5	111.3

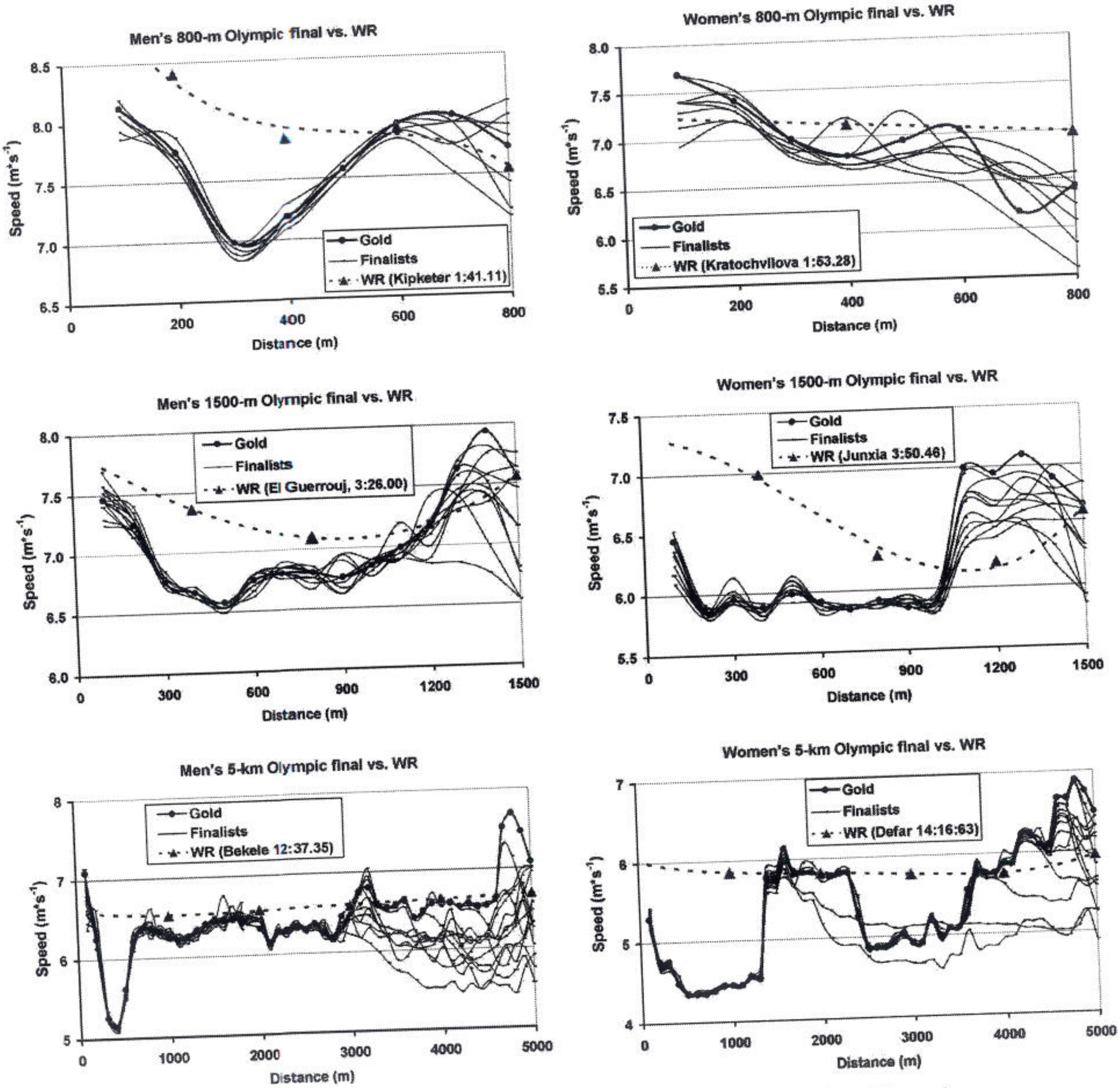

Figure 1. Pacing strategy of Olympic 800- to 5000-m finalists compared with the world record.

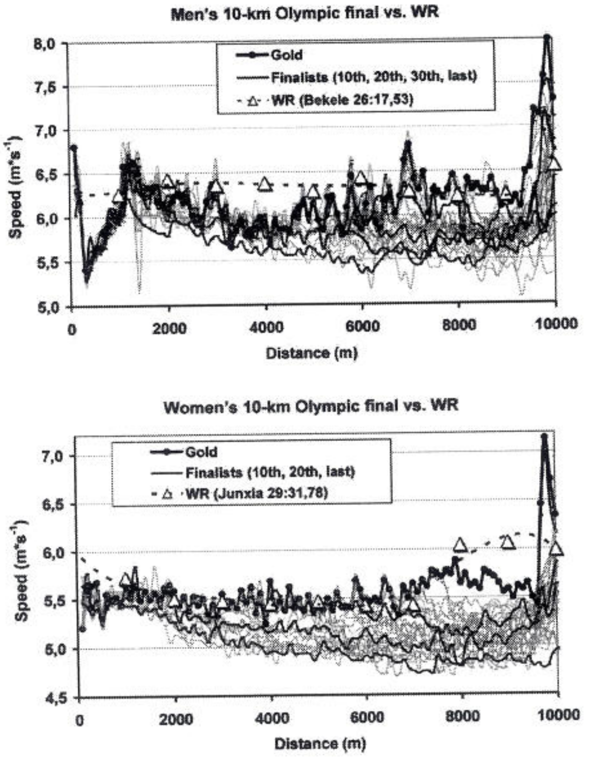

Figure 2. Pacing strategy of Olympic 10-km finalists compared with the world record.

Table II. Mean relative speed in the second versus the first half of the race in world records (WR) achieved 1983–2008, and in the 2008 Beijing Olympic finals.

	Speed in the 2^nd^ half of the race (%)			
		Olympic finals		
Race	WRs	Medallists	Non-medallists	Finalists
M 800 m	93.9	104.2	103.4	–
W 800 m	98.1	93.3	91.8	–
M 1500 m	102.3	104.3	103.3	101.2
W 1500 m	95.7	109.0	107.6	104.9
M 5 km	101.3	105.7	101.6	97.8
W 5 km	100.0	110.3	109.6	106.3
M 10 km	100.6	104.3	103.4	97.9
W 10 km	102.3	101.9	98.5	95.1

over plots based on the traditional 400-m splits (Figure 3).

Throughout the long-distance races, runners who slowed down in the second half of the race did not decrease their pace more suddenly than medallists and finalists (Table IV). They also displayed an increase of speed during the last lap, albeit smaller than the other finalists (Table IV).

The pacing pattern used by medallists to reduce the size of the field differed from race to race (Figures 4–7, top), but medallists were consistently faster during the endspurt than other finalists (Table IV). In the 1.5-, 5- and 10-km finals, the race amongst the medallists was decided on the last 400 m by differences in the endspurt (Figures 4–7, bottom).

Discussion

The current study used high-resolution data gathered in 800- to 10,000-m Olympic track finals to understand pacing in competition where placing is more important than time.

Olympic pacing versus World Record strategy

Except in the women's 10 km, pace in the Olympic finals was less in the opening segment and more variable than the World Record pace. In six of eight finals, pacing did not fit the pattern characteristic of 800-m (positive pacing) and of 1.5- to 10-km (even pacing) World Record performances, respectively (Tucker et al., 2006). The pacing pattern did not systematically vary by distance. De Koning et al. (2011) showed that athletes use different pacing strategies in different disciplines (swimming, running, speed skating) to solve the same problem (comparable finishing times). Our data show that in world-class championships, runners used different pacing strategies even in the same discipline and over the same distance.

Constant speed of running

Constant running speed in middle- and long-distance events does not occur and traditional reporting of 400-m lap splits does not represent the 'true' degree of variation in high-standard finals. Runners usually develop the ability to change speed by using established stochastic training models (fartlek, interval training). Based on our findings, coaches should introduce training models that involve frequent, but small changes in pace.

'Microvariation' seen in Olympic finals represents the complex regulation necessary to balance runners' efforts to keep their pace at the desired level despite growing fatigue, while avoiding a physiologically catastrophic event. For runners performing 10-km races in 42 minutes, Billat, Wesfreid, Kapfer, Koralsztein, and Meyer (2006) reported a similar phenomenon. The coefficient of variation (CV) of 10-m-running speed was 8.7 ± 2.1%. Billat et al. (2006) suggested that pace variations are an intentional strategy to minimise the physiological strain during severe exercise.

Lap splits in World Record performances suggest smooth and slow transitions of speed. It remains to

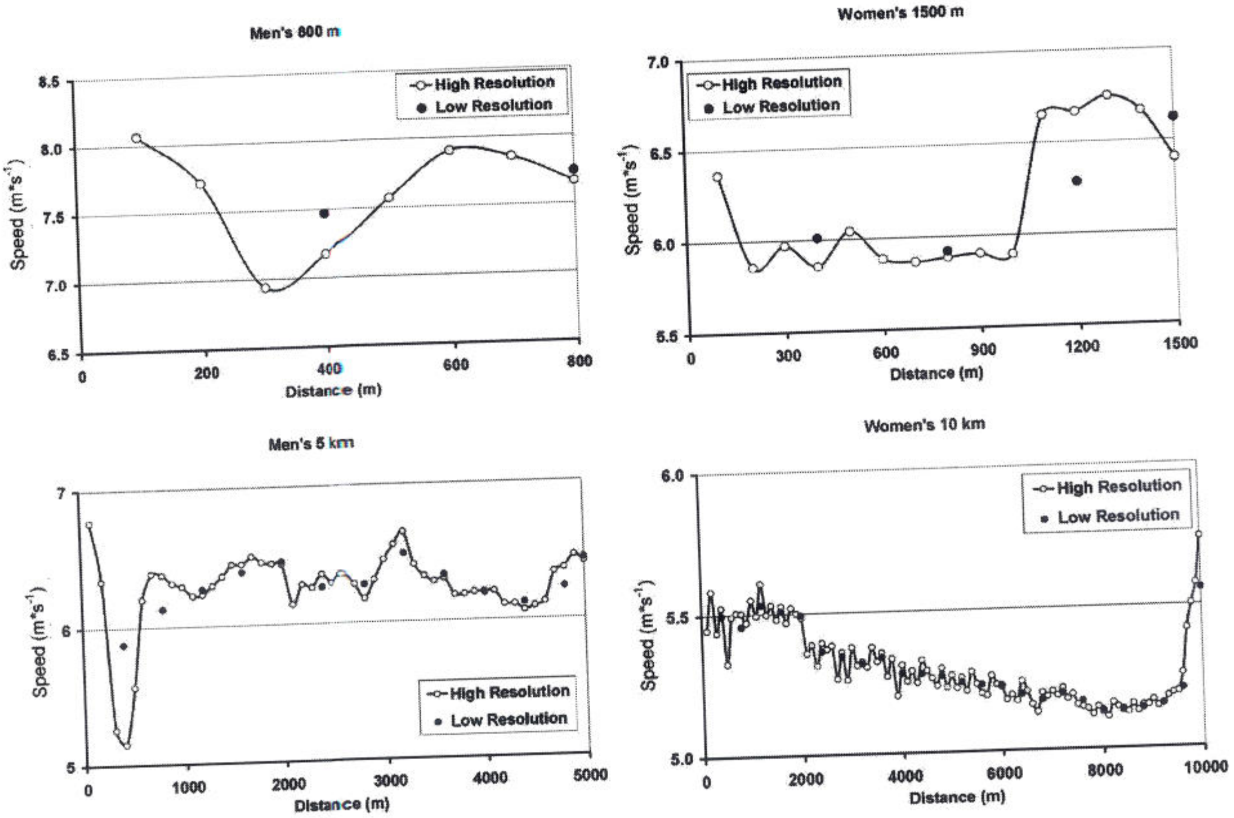

Figure 3. Mean speed of Olympic track finalists at resolutions of 100 m versus 400 m.

Table III. Coefficient of intra-individual variation of running speed during world records (WR) between 1983 and 2008 based on 400-m (800 m, 1500 m) or 1000-m split times (5 km, 10 km) and during Beijing Olympic finals 2008 based on 1000-m, 400-m and 100-m split times (mean, range).

	Coefficient of variation (%)			
		Olympic finals		
Race	WR 400 m/ 1000 m	1000 m	400 m	100 m
M 800 m	4.5 (3.5–6.4)	–	2.5 (0.3–4.2)	5.3 (4.6–5.9)
W 800 m	3.7	–	5.0 (2.6–6.6)	6.2 (3.6–8.1)
M 1500 m	2.9 (2.1–3.8)	–	4.1 (1.8–6.1)	4.9 (3.1–6.3)
W 1500 m	5.5	–	5.1 (2.9–7.0)	6.1 (4.6–7.9)
M 5 km	1.7 (0.5–3.1)	3.2 (1.9–5.6)	4.0 (2.7–5.7)	5.5 (4.7–6.8)
W 5 km	2.5 (1.5–4.0)	9.8 (5.6–12.2)	11.1 (6.7–13.5)	11.4* (7.5–13.5)
M 10 km	1.5 (0.9–2.2)	3.2 (1.5–5.0)	3.6 (1.7–5.1)	4.4 (2.4–6.4)
W 10 km	2.7 (1.5–4.7)	3.1 (1.2–4.9)	3.4 (1.8–5.0)	3.6 (2.1–5.4)

M, Men; W, Women; *Due to the malfunction of one timing marker in the women's 5-km race, interpolation was used to calculate 100-m split data, resulting in an underestimation of the variation of running speed.

be determined whether in World Records or personal best races, runners also vary their pace every 100 m to the degree seen in Olympic finals.

Catastrophic events

Most research into pacing has occurred under controlled or simulated conditions, whereas competition in the field often forces a variable pacing strategy on the athlete for various reasons. One is to counteract changing external conditions like wind and environmental temperature (Swain, 1997). Another is the requirement of competition, when catching up on a gap is difficult. At the speed typically seen in 5- or 10-km races, shielding by another competitor one metre ahead can reduce the

Table IV. Largest speed reduction throughout the race, and endspurt speed of medallists, finalists and runners who slowed down in the Beijing long-distance events (mean; range).

	Medallists			Finalists			Slowed down[1]		
	N	Largest % slow-down[2]	Endspurt speed[3] [%]	*N*	Largest % slow-down	Endspurt speed [%]	*N*	Largest % slow-down	Endspurt speed [%]
M 5 km	3	4.4 (3.3–6.0)	103.6 (99.4–108.6)	10	4.3 (1.9–6.7)	102.1 (94.4–107.6)	1	3.7	101.5
W 5 km	3	9.6 (9.5–9.7)	107.1 (105.7–108.7)	12	8.7 (3.0–11.7)	101.4 (96.2–105.4)	0	–	–
M 10 km	3	8.5 (8.2–8.9)	116.1 (113.6–118.9)	22	6.1 (2.3–11.2)	108.6 (102.4–114.4)	10	4.0 (2.8–6.1)	105.3 (94.5–114.3)
W 10 km	3	3.8 (3.7–4.0)	113.4 (108.3–117.7)	10	3.4 (2.6–4.9)	108.7 (106.1–111.5)	16	3.5 (1.9–7.1)	106.0 (100.2–111.8)

[1] Runners with a 3% decrease of speed in the second half of the race were defined as runners who had slowed down.

[2] Largest decrease of speed observed in any 100-m segment versus the previous 100 m, excluding the first half of the race and the last 400 m.

[3] Last 400 m versus fourth quarter of the race.

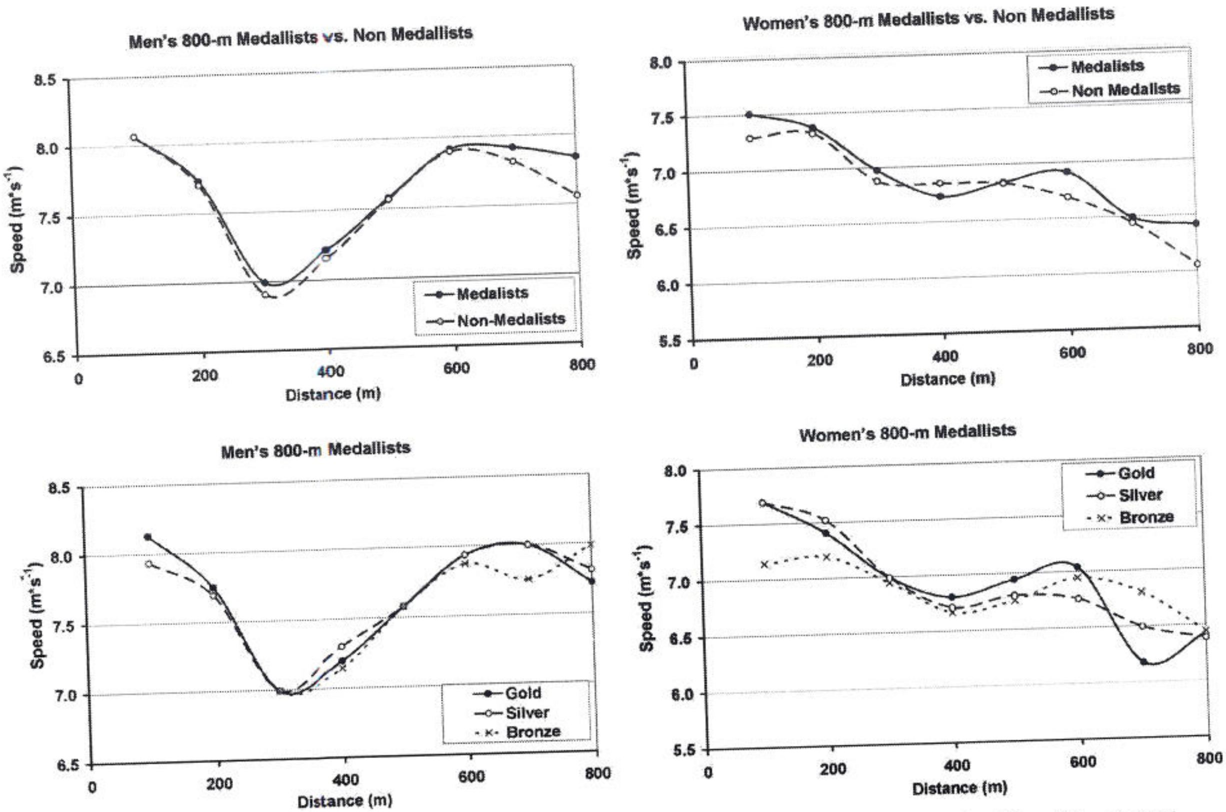

Figure 4. Mean speed of medallists and finalists (top) and individual speed of medallists (bottom) in the 800-m Olympic final.

total energetic cost of running by 6.5% (Pugh, 1971), or decrease lap times by one second (Davies, 1980). In the initial stage of a race, athletes often do not self-select their pace, but rather precisely adjust to the speed enforced by the current group leaders. Olympic finals provide an opportunity for 'catastrophic events' (a massive and progressive reduction in speed) to occur. However, runners tend to fall off the pace of the leading group in a controlled fashion and achieve a stable running speed. The mid-race attenuation of pace and accompanying effort in lesser runners does not constitute a catastrophic event, but an active step to prevent such an event while maintaining the overall pacing strategy. This clearly supports the importance of interactive psychophysiological decision making described in the pacing literature (Swart et al., 2009a, 2009b).

Olympic finalists seem to tolerate running the initial kilometre up to 8% faster than their mean pace without becoming overly fatigued (that is, dropping out of the race). Some of these athletes might consider incorporating positively paced running sessions into their training regime to prepare for fast championship races.

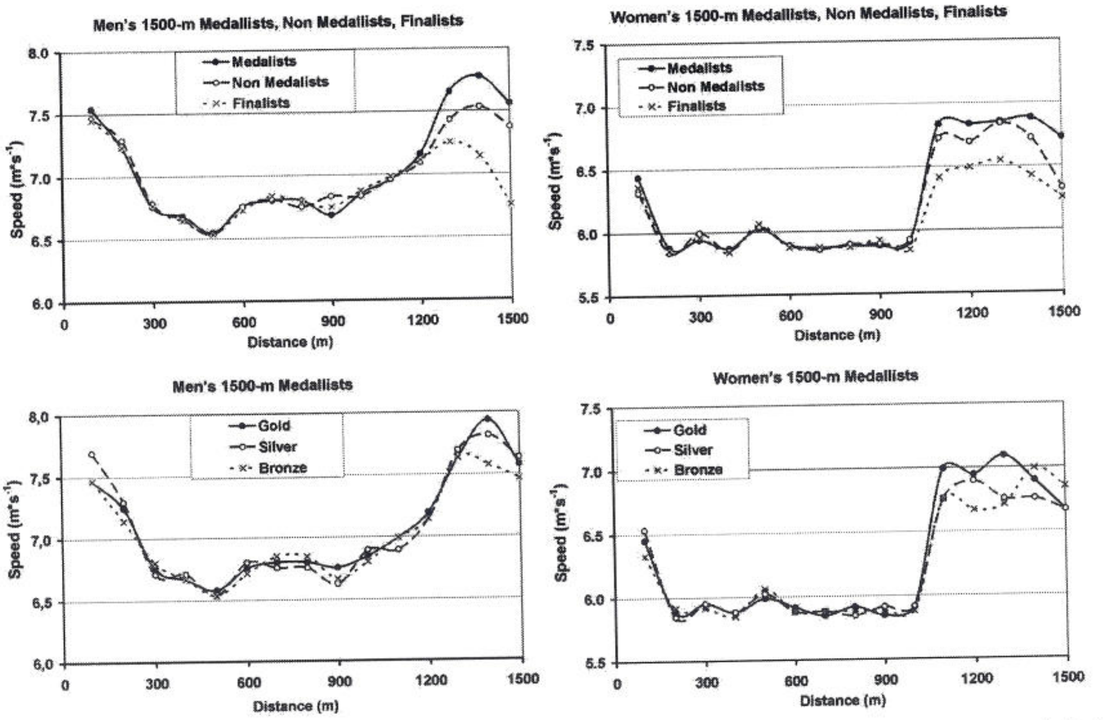

Figure 5. Mean speed of medallists and finalists (top) and individual speed of medallists (bottom) in the 1500-m Olympic final.

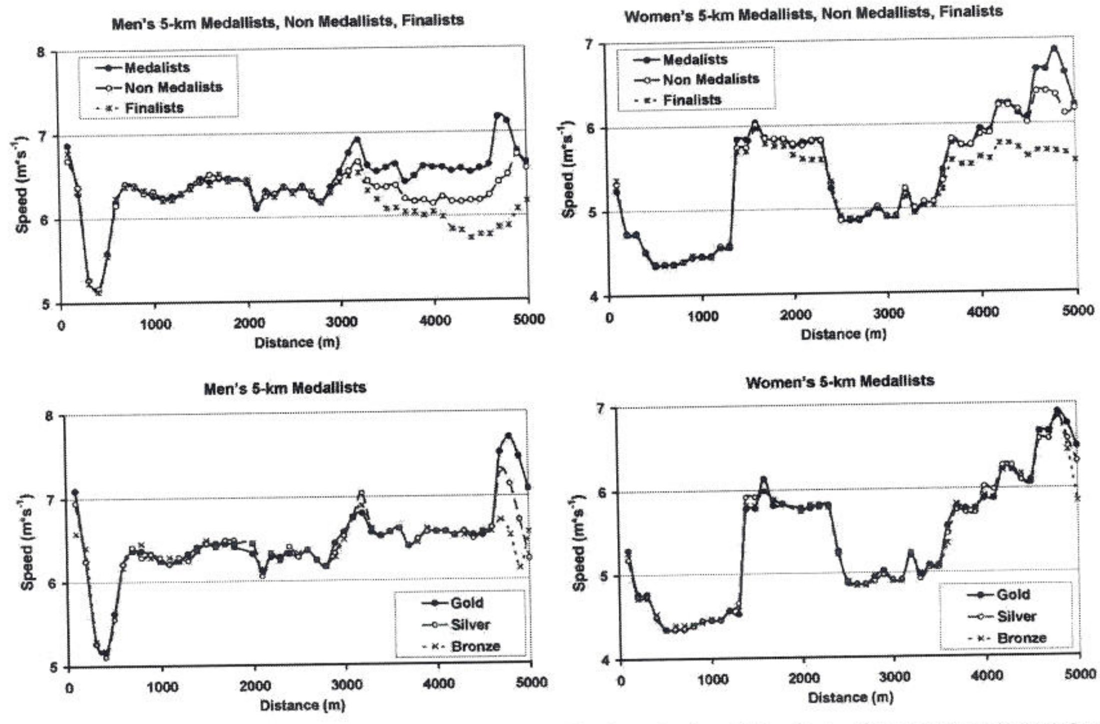

Figure 6. Mean speed of medallists and finalists (top) and individual speed of medallists (bottom) in the 5-km Olympic final.

Winning strategy

The strategy used by medallists to separate themselves from the field varies. Top contenders use either a continuously high speed (men's and women's 10 km), a 'break away' in the middle of the event by increasing the pace (at 3 km in the men's 5 km), or a long endspurt after a gradual increase in speed at the end of the race (women's

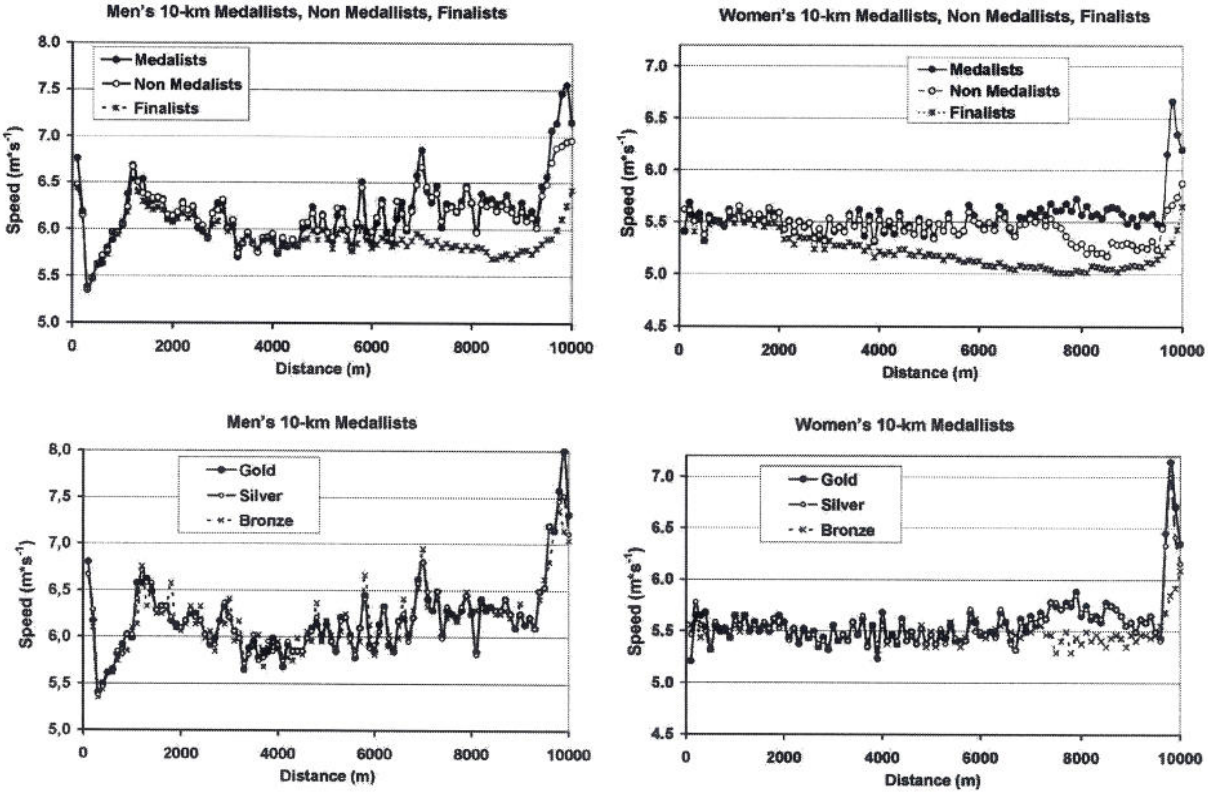

Figure 7. Mean speed of medallists and finalists (top) and individual speed of medallists (bottom) in the 10-km Olympic final.

5 km). Although the athlete may initially envision an overall pacing strategy (creating a template out of experience, expected duration and physiological input) (Foster et al., 2012; Micklewright et al., 2010; Tucker, 2009), this strategy appears to be continuously modified in response to changes in both internal and external factors, among which are tactical considerations. Tactics represent dynamic decisions that can hinder the best possible competitive performance, but conversely, improve the competitive outcome (e.g., a mid-race surge to win the race in less than a personal best time). This tactical nature of races is particularly seen in the slowest race, the women's 5 km.

Amongst the medallists, race outcomes were close, reflecting the high standard of competition. The 1.5- to 10-km finals were decided by differences in the endspurt, with peak speed typically achieved early during the last 400 m. To win a gold medal in the long-distance races, women and men athletes must achieve 6.9–7.1 $m{\cdot}s^{-1}$ and 7.7–8.0 $m{\cdot}s^{-1}$, respectively, which also needs to be considered when designing training programmes.

Conclusion

Olympic track finalists use pacing strategies different from those in World Record or personal-best races. Races are highly stochastic, even if they are run at an overall even pace. Also, microvariation in running speed is higher than previously assumed. Dropping off the pace of the leading group is not a catastrophic event, but an active, controlled step designed to prevent such an event. While top contenders use variable pacing strategies to separate themselves from the field, the Gold medal is typically won by the endspurt on the last 400 m. Training programmes that address these specific requirements of high-standard championships should include intervals, microvariation runs, positive-pacing training and speed training.

Competing interests

No competing interests.

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