

Current perspectives on performance improvement in the marathon: From universalisation to training optimisation

By Véronique Billat

Since 1984, the world's best performances in the men's and women's marathon have improved by 2% and 4% respectively, prompting questions about how much faster athletes will be able to run the race and what sorts of training they will use to achieve better performances. The author starts with a description of the phenomena of the marathon and points out that the universalisation of long-distance running, including greater participation by women, has been an important factor in performance development as it increases the likelihood that athletes with ideal physical characteristics will be identified and brought into the event. Noting that this will remain true in the future, she then focuses on two areas that seem to hold the most promise for coaching marathoners: 1) optimisation of training through better understanding of the energetic factors related to performance and 2) optimisation of training and racing strategies through better knowledge of the effects of speed variation and physiological strain. In this extensive review of the literature, the latest thinking on ultimate performance predictions, oxygen uptake, utilisation of oxygen, qualitative training, critical velocity, critical power, pace regulation and psychological coping strategies is examined and key conclusions are drawn.

ABSTRACT

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Introduction

The last two decades have seen improved performances in long-distance running and especially the marathon. Since 1985, the year after the women's marathon was introduced to the Olympic programme at the Games in Los Angeles, the best recorded time (the IAAF officially began using the appellation "World Record" for the marathon, half-marathon, 25km, 15km and 10km in 2004; prior to that only "world bests" were recognised) has improved by six minutes or 4% in females (2:21:06 to 2:15:25) and three minutes or 2% in males (2:07:12 to 2:04:55). For both genders, 70% of the all-time 1000 best performances have been set in the last 20 years.

But what of the future? Will records and performance levels in the marathon continue to develop at the same rate or

will they level off? What factors or techniques will lead to future improvements? And is there a limit to how far the records can go?

For a start, we know that the three biological prerequisites for success in the marathon are: 1) high aerobic power, which is expressed as VO_2max (the maximum volume of oxygen the body can use), 2) the ability to use a high fraction of VO_2max for long periods (i.e. for hours), which is expressed as F and 3) a low energy cost running at marathon pace^{1, 2, 3, 5}.

JOYNER⁶ in an excellent review of the physiological limiting factors in distance running underlined that the banned practices of “blood doping” and the use of EPO (erythropoietin) may have contributed to recent improvements in performances by increasing the maximal oxygen uptake at the lactate threshold, which is related with endurance⁴.

Leaving this aside, three of the most obvious sources for performance improvement in athletic events are better talent identification, better training and better competition strategies. The purpose of this paper is to provide a review of recent literature associated with long-distance running in an attempt to identify trends or factors that may contribute to the future development of performance, particularly in the marathon. The focus will be on three areas that seem to hold the most promise: 1) improved identification of talented individuals through the universalisation of long-distance running, 2) optimisation of training through better understanding of the energetic factors related to performance in the marathon and 3) optimisation of training and racing strategies through better knowledge of the effects of speed variation and physiological strain.

The universalisation of long-distance running

Marathon geography

The last two decades have seen an increase in the popularity of long-distance running

and in the number of places around the world where the sport is practised seriously. One of the appeals of this activity is in the nature of road races, such as the marathon, in which amateur athletes of all performance levels can participate alongside top-class performers. To get some idea of how many are doing so and the size of the long-distance running movement, we can start by looking on the websites of the London, New York and Paris marathons. These show that each of these races has had more than 500,000 individual finishers over the last 20 years. And further investigation shows that dozens of other city marathons around the world, from Amsterdam to Berlin to Boston to Chicago to Fukuoka to Stockholm, can claim a great percentage of that figure.

If we look at Japan, for example, we see that a national passion has developed for marathon racing and the Ekiden (a relay race splitting the marathon into variable distances between 5 and 12 km, which is seen as a good initiation for young runners). The marathon is just behind Sumo in public popularity but it is still in front of soccer (remember that this is a country that has recently hosted the Football World Cup). It is likely that there are cultural aspects (and not only the way of living) involved, which are largely beyond the scope of this review. Regardless, it is clear that being an elite marathon runner is of great prestige in Japan. The situation has led to large numbers of sub-2:20:00 performances by Japanese men every year (for example, 102 and 143 in 1984 and 1999 respectively) and a very high level performance density by Japanese women (11 athletes ran the distance in less than 2:25:00 in 2003).

In the United States, the estimated number of marathon finishers per year grew by 67% in the 1990s (260,000 in 1990 to 435,000 in 1999). Ironically, although many thousands in the US train for marathons or run regularly, the weight of that country's marathon runners on the international scene has fallen and we have seen a substantial reduction in the number of US marathoners at the top level, the reasons for which remain unclear⁸.

As the sport has become known in more of the world, the map of top-level marathoning has shifted from the USA and Europe towards East Africa. In their first involvement in international marathon running at the Olympic Games of Melbourne in 1956, no East African athlete finished in the top ten places⁷ but they learned very quickly and four years later Abebe Bikila of Ethiopia won in Rome with a world best time of 2:15:16. Indeed, at the time of writing Kenyan and Ethiopian runners had achieved 43% and 10% respectively of the world's best performances.

One of the major modifications to the sport since Bikila's victory came in 1982 when the IAAF (International Association of Athletics Federations) made it legal to receive payments for races. Successful runners can now make a living by running in a small number of lucrative big-city marathons. In 2003, for example, the four best male and female runners each participated in two top-level marathons at four- to six-month intervals (spring and autumn), which is comparable with a normal elite racing programme in 1983 when the first World Championships in Athletics were held (sub-elite runners tend to compete in more races in order to accumulate the small allowances on offer with the downside that they have less and less time for training and recovery). It should be noted that the many of the best marathon runners do not participate in the Olympic Games or World Championships in Athletics. However, as underlined by RADFORD⁹, it is not only a matter of money, it is also about self-respect. It is now possible, with the money and other rewards that go with it, to believe that long-distance running is extremely serious and to see it as a profession. In Europe as in the US, running has become a way for some individuals to achieve a better position in life and we see that many elite marathon runners in these countries come from recent immigration (second or third generation North Africans) or strategic naturalisation. In the case of Kenya, running is a popular career choice and athletes are attracted to participate in well-organised training camps.

The universalisation of long-distance running and particularly marathon running

increases the likelihood that individuals with good combinations of the physiological variables influencing marathon performance will come into the sport. It would seem that this process has had an effect already and as it continues, it will be an important factor in future performance development.

Women in the marathon

Opportunities in long-distance running are also open to women and some have been liberated thanks to the sport and its economic rewards. The 1984 addition of the marathon to the Olympic programme is seen as a major milestone in the development of women's sport (Joan Benoit (USA) won that race in the excellent time of 2:24:52, which remains the 119th best performance twenty years later). Since then, more and more women have taken up long-distance running as a serious pursuit. In 1984, 1% of all marathon finishers were women while in 2003 that figure had risen to 15%. This feminisation of the marathon has taken place alongside and contributed to the universalisation of the event.

The facts that women only started participating in the marathon seriously in the late sixties and that the programme for elite athletes was not complete until 1984 explain the faster rate of improvement of the women's record relative to the men's record. The current best time by a woman, 2:15:25 by Paula Radcliffe (GBR) in 2003, is 7.8% slower than men's record of 2:04:55 by Paul Tergat (KEN), also in 2003 (note that Radcliffe's time is just nine seconds slower than Bikila's then world best time in Rome 1960). Radcliffe has run her three best marathons below 2:18:00, a performance consistency that compares with the sub-2:06 three-race averages achieved by Tergat and former record-holder Khalid Khan-nouchi (USA) (performance consistencies for all three are significantly better than reported in well-trained athletes by 2.5%¹²).

Regardless of Radcliffe's spectacular achievements, women will not be outrunning men in the marathon or any other distance on the athletics programme. Some time ago, two

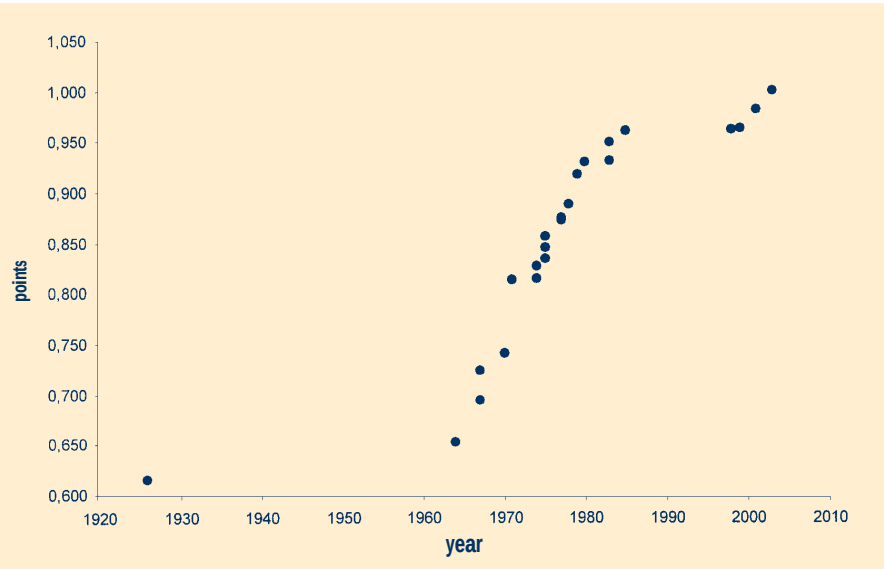


Figure 1: Development of the women's world best performance (World Record after 2004) in the marathon according to the IAAF scoring table

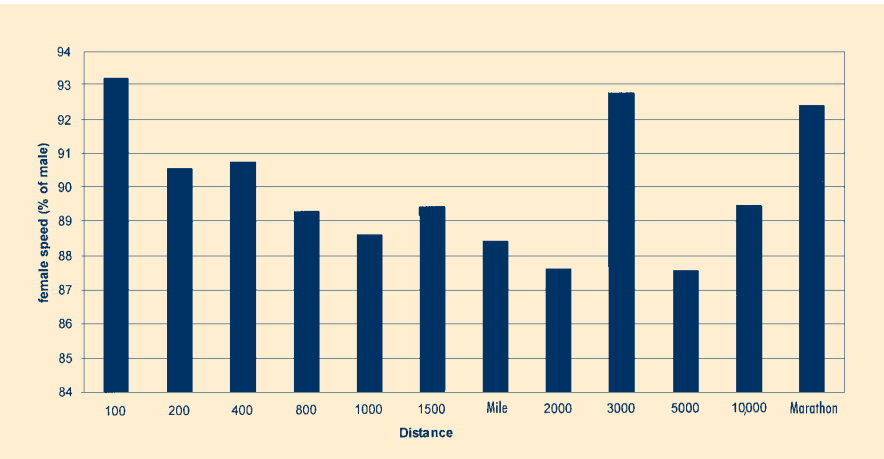


Figure 2: Comparison of the speed of women's world records to men's world records over standard race distances

physiologists¹³ predicted in *Nature* magazine that women would run faster than men in the marathon by 1998. Through the extrapolation of the progression in average running velocity versus historical time, they calculated that a woman would eventually complete the event in a time of 2:01:59. However, what they omitted from their consideration was the

late start of women in the sport. Moreover, we can now see that female performances have started to plateau (Figure 1). Marathon performances have certainly improved very quickly during the last 20 years (Figure 3) but women have not approached the predicted time and are not outrunning men over the marathon or any distance (Figure 2).

When she achieved her best time, Radcliffe beat the existing women's record (her own) by nearly two minutes. The best performance by the second fastest woman marathoner (2:18:47 by Catherine N'dereba (KEN) in 2001) is 10% slower than the second fastest man (2:04:56 Sammy Korir (KEN) in 2003). There are only two women who have run in a range of 2.5% of the best performance (< 2:18:47) compared to 112 men (< 2:08:38). Moreover, four women among the five best all-time best performers (2 Kenyans, 1 Chinese and 1 Japanese) hold 40 of the 900 all-time best performances (almost 5%). This phenomenon is not observed in males, even if

Tergat and Khannouchi hold five of the top eight all-time performances between them. Women have now achieved more than 900 marathon performances of less than 2:29:45, however the 900th best performance for men is 2:10:27.

The difference in performance levels between the genders reflects the difference in the maximal oxygen uptake. Women will always run slower (as for shorter distances) mainly because of their lower value of $VO_2\text{max}$ (-13% when expressed by kg of body mass and -7% when expressed by kg of lean

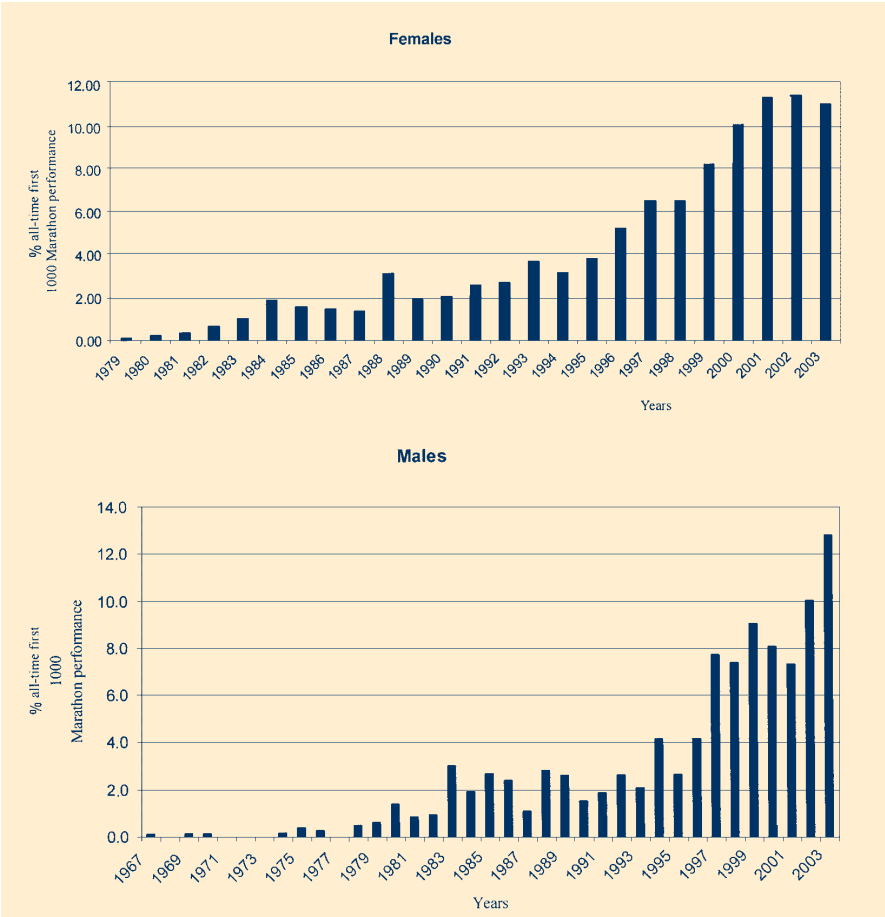


Figure 3: Percentage of all-time top 1000 marathon performance by year for males and females

body mass). The difference in $\text{VO}_{2\text{max}}$ comes not only from the greater fat mass, but also from a lower value of oxygen transport due to a lower cardiac index (cardiac output divided by the body surface area) and haemoglobin mass. Increase in maximal oxygen uptake, therefore, would seem to be both a key and ultimately the limiting factor for improving marathon performance by women¹¹.

It should also be noted that while world records in athletics provide a measurement of physical as well as physiological human performance, socio-cultural factors also play a role and may influence the lower number of top-level performers and performances by female athletes relative to their male counterparts. So, for women, there is still great room for improvement due to universalisation, which, as stated above, will increase the possibility of finding the main variables influencing the marathon performance in the same person.

Sources of future elite performers

We can observe that many female records in many athletics events have progressed roughly twice as quickly as men's records during the last twenty years. As in the marathon, this is certainly true in the 100m, thanks to the 10.49 in 1988 by Florence Griffith Joyner (USA). However, in middle-distance running, performances have improved less than in the marathon (+0.4% and +3.4% in the 1500m and 5000m respectively) with more improvement by males over 1500m (+2.2%) and much more over 5000m (+7.9%). The middle-distance events are mentioned because many believe that the pool of middle-distance runners will provide a major source of top marathon performers in the future. Radcliffe is a case in point as her personal bests over 3000m, 5000m and 10,000m of 8:22, 14:31, 30:01 respectively are each a world class performance in their own right. And then we have Haile Gebreselassie (ETH), who set 5000 and 10,000m world records of 12:37.35 and 26:22.75 in 1998 (although countryman Kenenisa Bekele has since broken both records). Gebreselassie ran his first marathon in 2002 in London, where he finished in

2:06:35, the 17th all-time best performance, and declared that he did not drink during the marathon. This shows promising potential if he decided to repeat the experience with the appropriate drink^{14,15}. But, coming back to the point, if 1) the thesis is true and 2) women's middle-distance performances really are stabilising, expectations for future improvement in the women's marathon must be tempered accordingly.

In contrast, the men's marathon at the 2000 Olympic Games in Sydney was won by Gezahgne Abera, yet another Ethiopian runner, whose credentials at the middle distances are less well known. A recent study¹⁶ on the demographic characteristics of elite Ethiopian endurance runners reported that they have a distinct environmental background in terms of geographical distribution, ethnicity and having travelled farther to school, often by running. Is it possible that the received wisdom about middle-distance runners coming to dominate the marathon is only partially true? BILLAT et al.¹⁰ demonstrated that two different training methods (high-speed v. low-speed training) induced radically different physiological characteristics even in the same group of Kenyan runners (the Kissi). Perhaps future performances will come from this combination of top-level middle-distance runners who lean toward the marathon and unknown runners from the right environmental and training backgrounds who try their luck directly with the marathon.

Energetic aspects and optimisation of training

How fast can they go?

What are the limits for marathon performance? To answer to this question, we can examine the possibilities for performance improvement from an energetic point of view, which is not, of course, the only possible approach.

Di PRAMPERO³ showed that marathon running speed (vMarathon expressed in m/min⁻¹)

can be predicted by three factors as shown in Equation 1:

$$v_{\text{Marathon}} = F \text{ VO}_2\text{max} / \text{Cr} \quad (1)$$

where Cr is the energy cost of running measured by the oxygen cost of running ($\text{ml/kg}^{-1}/\text{km}^{-1}$, the energetic equivalent of oxygen being 21 kJoules for 1 litre of oxygen consumed at a rate of expiratory ratio = 0.96), VO_2max ($\text{ml/kg}^{-1}/\text{min}^{-1}$) is the subject's maximal oxygen consumption and F is the fraction of VO_2max that can be sustained throughout the race ($F < 1$).

Using this equation, the fastest predicted time for the marathon is 1:48:36 in men (compare to Tergat's record of 2:04:55 set in 2003, i.e. a difference of 13%) and 2:00:00 in women (compare to Radcliffe's record of 2:15:25, i.e. a difference of +11%). These predictions are in accordance with those of PÉRONNET and THIBAULT¹⁷, who predicted an ultimate marathon best performance of 1:48:25, and higher than those of JOYNER et al.¹⁸, who limited the VO_2max value to 84 $\text{ml/kg}^{-1}/\text{min}^{-1}$ and the lactate threshold to 85% of VO_2max combined with a gross energy cost of running of 199.6 $\text{mlO}_2/\text{kg}^{-1}/\text{km}^{-1}$ (i.e. a VO_2 of 71 $\text{ml/kg}^{-1}/\text{min}^{-1}$ at a speed of 21.46 km/h^{-1})^{19,20}. In 1989, JOYNER et al predicted the record would be 2:05:23 in the year 2000 (at that point, Belayneh Dinsamo (ETH) held the world best at 2:06:50).

The calculations are based on a hypothetical male marathon runner with the best values for VO_2max , F and Cr collected in real marathon conditions on the road using portable gas analysers²¹. This ideal athlete has a VO_2max of 84 $\text{ml/kg}^{-1}/\text{min}^{-1}$ and his $F = 90\%$ VO_2max ¹⁸.

Finding the most promising factor

The fractional utilisation of VO_2max , or F value, is closely related to the time taken rather than the distance: the faster the runner, the higher the fraction of VO_2max can be sustained²². COSTILL and FOX²³ estimated an F value of 0.75 for the winner of the 1968

Boston Marathon running at 17.8 km/h^{-1} (2:22:00). This fraction is perhaps underestimated with regard to values reported for similar marathon performance: 82% in a time of 2:31:00²⁴ or a similar fraction in slower marathon times. Indeed, di PRAMPERO et al.³ and BRUCKNER et al.²⁵ have reported F values of 0.73 in three-hour marathon runners. Females and males with similar marathon performances (2:40:00) were found to have similar F values²⁶ and this finding was repeated in a comparison of slower runners of both sexes (3:19:00)²⁷.

Furthermore, when we compare elite marathoners ($< 2:11:00$ men, 2:31:00 women) with sub-elite (2:11:00-2:16:00 and 2:31:00-2:38:00, respectively) the difference in performance is explained by VO_2max value²¹. The sub-elite group has a high fractional VO_2max utilisation during the marathon (factor F) but this does not compensate for a lower VO_2max compared to the elite group. Hence, the approach to marathon training over the last 20 years considers VO_2max as the major factor for performance²⁸. This is after having focused on F and the energy cost of running since the famous data on Derek Clayton (AUS), who achieved a world best of 2:08:33 in 1969 with a VO_2max of 70 $\text{ml/kg}^{-1}/\text{min}^{-1}$ and COSTILL et al.²⁹ showed that this performance was due in part to a very high F value (0.86). We can calculate that this implies a gross energy cost of running of 183 $\text{ml/kg}^{-1}/\text{km}^{-1}$, which is rather exceptionally low.

In 1985, SJÖDIN and SVEDENHAG¹ reported a similar case involving Kjell-Erik Stål (SWE), who ran 2:10:38 in 1983 with a VO_2max equal to only 67 $\text{ml/kg}^{-1}/\text{min}^{-1}$. We can calculate (using Equation 1 above) that this performance is possible for a similar low Cr value (0.183 $\text{ml/kg}^{-1}/\text{m}^{-1}$) with F equal to 0.88. However, the data was obtained from treadmill measurements and we know that oxygen uptake (L/min^{-1}) is increased by 0.002 v^3 (v is the velocity in m/s^{-1}) on the road due to the aerodynamic element of the energy cost of running³⁰.

We must consider allometric law when we want to compare marathon runners of different weights and heights. Indeed, oxygen uptake is not a power 1 function of the mass but rather 0.75^{31,32}. Smaller and lighter runners have a higher VO_2max and a high oxygen cost of running. That is why when comparing subjects of different weights, C and VO_2max must be expressed by $\text{kg}^{-0.75}$ of body mass^{31, 33, 34} and that was the case for comparing the energy cost of running in male and female marathon runners¹⁰. But this does not modify the F value since Cr and VO_2max can have the same scaling factors. Therefore, we can estimate that for Clayton this could have given an additional value of 327 $\text{ml}/\text{min}^{-1}$, i.e. + 7% (for his weight of 73.5 kg). Consequently, for the same speed with an increased value of Cr due to the addition of the aerodynamic part, the fractional utilisation of VO_2max during a marathon would be equal to 92.2%. This looks to be high but it fits with real data collected from a group of elite marathon runners used to training at the maximal lactate steady state velocity (MLSSv) rather than with interval training eliciting VO_2max ¹⁰. It is also in accordance with the data reported by JOYNER¹⁸ and just below (93-94%) that reported by HELGERUD et al.²⁷ and MADER³⁵.

This factor F has been reported to be the major difference between black and white runners during a treadmill marathon^{36,37}. The authors concluded that the only physiological difference that might account for the superior performance in their group of black runners matched for their best standard marathon time (2:45:00) was an ability to run at a higher percentage of VO_2max during the marathon (76 ± 8 vs. 68 ± 5 %). However, this was a rather low F value due to the fact that the runners ran 2 km/h^{-1} below their marathon speed (14.2 v. 16.9 km/h^{-1}) and the fact that this is another type of exercise closer to the crossover point (the velocity or work rate at which energy derived from oxidation of CHO-based fuels predominates over energy derived from lipids at 50% of VO_2max) than to the maximal lactate steady-state³⁸.

F represents the athlete's endurance (i.e. an ability to sustain a high fraction of VO_2max for a given time) and can be quantified by the Endurance Index proposed by PÉRONNET and THIBAUT³⁹, which is the loss of the fractional utilisation of VO_2max with the exercise duration. The time of the x axis is expressed in a natural logarithm of the seconds since these authors consider that the relationship between the speed and duration of exercise is an exponential function (while others prefer a hyperbolic function, which allows the calculation of the critical velocity concept that is the vertical asymptote of the relationship between speed and time⁴⁰). They demonstrated that this endurance index was correlated with the ventilatory threshold in marathon runners. For instance, Carlos Lopes (POR), who ran a then world best of 2:07:11 in 1985, had a very high Endurance Index of -3.65 ³⁹.

The controversy could come from the fact that all these papers consider a constant speed rather than variable pace as the independent variable and hence assume a constant metabolic work rate. However, marathons, as we shall see in the next section, are run not at the same average pace but with a coefficient of variation of 5%, similar to what we see in middle-distance running⁴² (this also being the case in the 1 hour cycling world record⁴³) (see Figure 2). MARON et al.⁴¹, in a study that measured the oxygen uptake during a hilly marathon, demonstrated that F was between 68 to 100% of VO_2max .

The ideal marathon runner would have a low gross energy cost of running = 0.195 $\text{ml}/\text{kg}^{-1}/\text{m}^{-1}$ (including energy spent at rest). This gross energy cost of running is the same as for the 1968 Boston marathon winner as reported by COSTILL and FOX²³: 191.6 $\text{mlO}_2/\text{kg}^{-1}/\text{km}^{-1}$ (i.e. a VO_2max of 56.8 $\text{ml}/\text{kg}^{-1}/\text{min}^{-1}$ at a speed of 17.8 km/h^{-1}).

According to Equation 1³, the average velocity of the best possible marathon performance is:

$$v_{\text{Marathon}} (\text{m}/\text{min}^{-1}) = 0.90 \times 84/0.195 = 387.69 \text{ m}/\text{min}^{-1} \text{ i.e. } 23.26 \text{ km}/\text{h}^{-1} \quad (2)$$

The high value of VO_2max ($84 \text{ ml/kg}^{-1}/\text{min}^{-1}$) on which this prediction is based was measured on a flat road course by European record holder Antonio Pinto (POR) four weeks before he achieved his best time of 2:06:36 in the 2000 London Marathon. This predicted running velocity of 23.26 km/h^{-1} is currently the speed at which top 10km races are run.

The situation is the same for women runners. Indeed, we can analyse Paul Radcliffe's record 2:15:25 (i.e. a velocity of 5.1932 m/s^{-1} or $311.59 \text{ m/min}^{-1}$). In this race, she ran at 86.9% of the velocity of her 3000m best (8:22.20, in July 2002, i.e. at an average speed of 358.4 m/min^{-1}). Given that over a 3000m race, the fractional utilisation of VO_2max equals 1 in elite runners, it may possible to estimate Radcliffe's VO_2max ($73.5 \text{ ml/kg}^{-1}/\text{min}^{-1}$) for a value of the energy cost of running currently reported in high-level women marathon runners ($0.205 \text{ ml/kg}^{-1}/\text{m}^{-1}$). This value of VO_2max has also been recently been measured on the track in elite women middle-distance runners from Kenya. The equation of Radcliffe's best performance is as follows:

$$v\text{Marathon} (\text{m/min}^{-1}) = 311.592 \text{ m/min}^{-1} \quad (3)$$

$$311.592 \text{ m/min}^{-1} = 0.869 (F) \times 73.5 (\text{VO}_2\text{max}) / 0.205 (\text{Cr}) \quad (4)$$

This means that in order to further improve the best marathon performance, one may increase VO_2max and F and or decrease Cr. Training allows this, even in elite and already well-trained athletes. If the best value measured in one female runner is met, the marathon can be run in 2 hours as shown in equations 5 and 6:

$$v\text{Marathon} (\text{m/min}^{-1}) = 0.90 (F) \times 76 (\text{VO}_2\text{max}) / 0.195 (\text{Cr}) \quad (5)$$

$$v\text{Marathon} (\text{m/min}^{-1}) = 350.07 \text{ m/min}^{-1} \quad (6)$$

As noted above, it has been demonstrated that performance in the marathon is related to VO_2max in elite men marathon runners and not to F or Cr. The ability to run fast for a

short period (or distance) has also been reported as being a performance determinant in long-distance running by NOAKES (cited in BILLAT et al. 2001¹⁰). In addition, speed over 1000m measured after a 10km run at $v\text{Marathon}$ has been reported as a good predictor of marathon performance in elite male marathoners ($< 2:11:00$). The high correlation could be because the runners are still able to maintain the recoil characteristics of the muscles for a stretch load even in a fatigued condition¹⁰. The association between flexibility and running economy has been reported in sub-elite male distance runners. The results suggest that inflexibility in certain areas of the musculoskeletal system may enhance running economy by increasing storage and return of elastic energy and minimising the need for muscle-stabilising activity⁴⁴.

Our study of top male and female marathon runners also showed that no single factor was related to performance in elite women marathon runners ($< 2:31:00$). However, we do not know if all the three factors that contribute to marathon performance are exclusively independent variables¹⁰. Indeed, LUCIA et al.⁴⁵ reported that in world-class cyclists there was an inverse relationship between VO_2max and economy as previously found in runners^{46, 47}. We do not know, for example, whether physiological characteristics associated with a high VO_2max tend to co-express with characteristics towards a reduction of energy cost of running. What has been proved is that the changes in the best performance times in human locomotion (including running) brought about by changes of the energy cost alone account for 45-55% of the changes obtained when all variables (Cr, VO_2max and anaerobic stores) are changed by the same amount (2.5 to 10%)⁴⁸.

The trend in training

We also know that increasing the intensity of training toward VO_2max , or the qualitative approach, is the newest trend for marathon training¹⁰. Indeed, regular training at velocities above $v\text{Marathon}$, seem to

characterise elite marathoners. Compared to with the sub-elite runners (< 2:11:00 v. 2:11:01-2:16:00), the elite marathoners studied ran more total weekly kilometres (more than 200km per week) as well as more kilometres at or above v10,000m (more than 20km per week). However, the relative distribution of running intensity in training between elite and sub-elite runners was actually identical. For example, the previously mentioned Carlos Lopes (POR) was also an excellent 10,000m runner. In addition to a high weekly total distance (200km to 240km), he was known to perform two “speed” workouts per week (for example 15 x 400m at the v3000m and 6 x 2000m at v10,000m) almost all of the year. Current European marathon record holder Antonio Pinto (POR) has personal bests of 3:38 for 1500m, 7:38 for 3000m, and 13:02 for 5000m). As with Lopes, these good middle-distance performances by a marathon specialist are approached and maintained with regular training at velocities well above vMarathon (at VO₂max i.e. 120% of vMarathon)¹⁰. From the training of elite marathoners we can consider that high-velocity training seems to allow enhance-

ment of VO₂max and elicits high levels of force and brief ground-contact times, which can in part replace strength training. However, future of elite-level marathon training is certain to include strength training at least twice per week. Further study is needed in this area to determine the optimal programme.

The endurance of a marathoner, i.e. his/her ability to sustain a high percentage of VO₂max over the marathon distance (F factor), is determined by the maximum running velocity that can be maintained with a stable (steady state) blood lactate level. This particular velocity is known as MLSSv (maximum lactate steady state velocity)⁴⁹. Above MLSSv carbohydrates (glucose and glycogen) are increasingly utilised for energy rather than lipids. This, of course, means that running at this speed subjects the athlete to the risk of hypoglycaemia during a marathon. It has recently been demonstrated that training at MLSSv enhances the time until exhaustion at MLSSv. Indeed, a recent study⁴⁹ on improving endurance (F factor) showed that six weeks of twice-weekly sessions at MLSSv improved the level of MLSSv

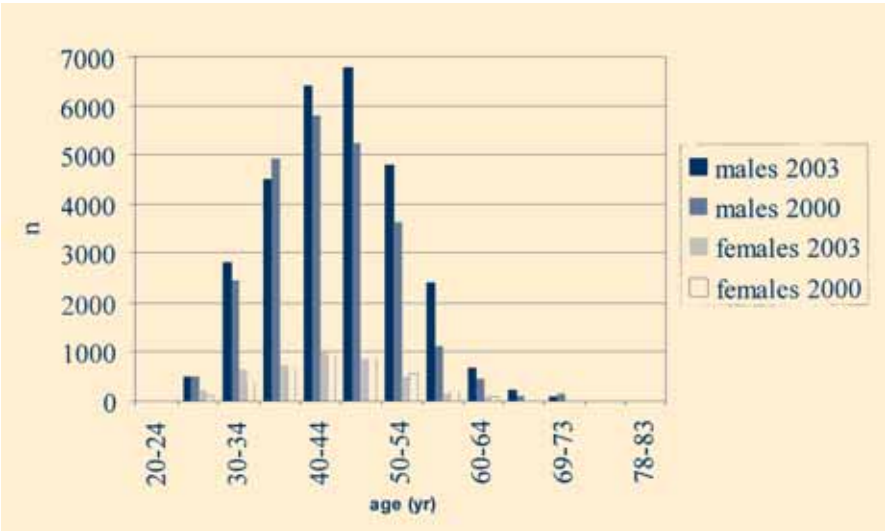


Figure 4: Number of participants in the Paris Marathon in 2000 and 2003 (Note that females represent 14% of the starters and finishers and only 15% of the participants fail to finish the race)

and VO_2max and greatly increased the time to exhaustion at MLSSv from 40 to 60 minutes (+ 50%). For this reason, we recommend starting the first half of the marathon at no more than 95% of MLSSv.

Although running time at MLSSv increased, the percentage of CHO oxidation at MLSSv did not change due to training. Indeed, before and after training, CHO yielded 80% of the energy in an endurance run at MLSSv. Perhaps it is that even highly trained humans can not sustain a greater rate of CHO oxidation because the prerequisite glycolytic flux inevitably results in metabolic acidosis. This means that training increases lactate clearance so that higher glycolytic and oxidative fluxes can be sustained. Therefore, the goal of training should be to increase oxygen uptake to incorporate more CHO without acidosis. To be a good marathon runner, it is more important to have a high VO_2max and a high MLSSv rather than a high F value of a low VO_2max ⁵⁰. Therefore, the new way of training for the marathon is to enhance VO_2max and the rapidity of kinetics during metabolic transitions, which has been reported to be related to performance^{50,51,52,53,54}.

However, recent data collected on veteran (45+ year old) long-distance runners, who constitute most of the population of the marathon runners (Figure 4), must be confirmed and compared with those obtained in other groups according to age, gender, level of performance and habits for intensity of training, especially at velocities faster than MLSSv, which are widely used by elite male and female marathon runners⁵⁵.

Pacing aspects and optimising training

New Technology

As with longer races on the road, athletes in the middle-distance races on the track may spontaneously choose to modulate their pace during the race to avoid becoming over fatigued before reaching the finishing line⁶⁰. These races are performed with free rather than constant pace running and an athlete in any event lasting more than two minutes has the opportunity to use energy available from the phosphagen and glycolysis in a flexible manner⁶¹.

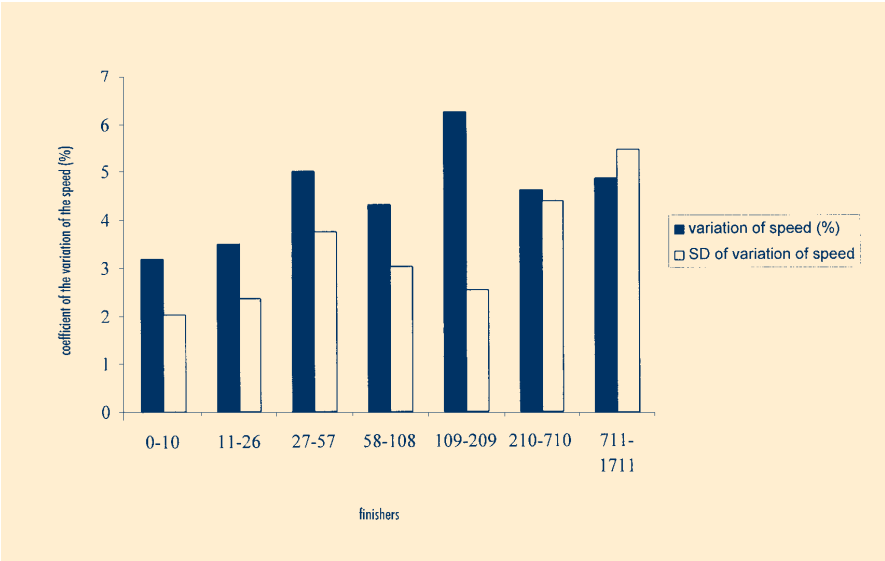


Figure 5: Coefficient of speed variation for the top finishers in the 2003 Paris Marathon

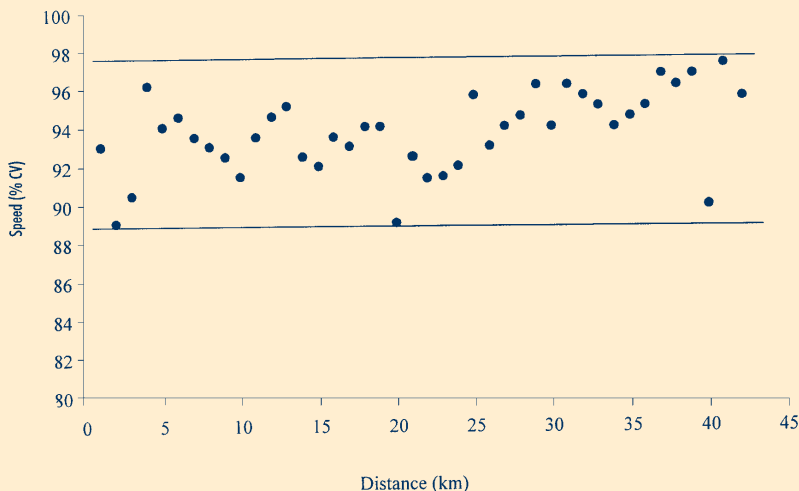


Figure 6: Speed (expressed as a percentage of Critical Velocity – CV) during the men's world World Record marathon (Paul Tergat, 2:04:55 in 2003)

Examination of the pacing shows that the coefficient of speed variation in the records by Tergat (2:04:55) and Radcliffe (2:15:25) was 2.2% and 3.5% respectively. This speed variability during the race is of same order as those during the last three world records in each of the middle-distance events (1500m, 3000m, 5000m and 10,000m). Indeed, it can be observed that the range of the coefficient of variation of velocity is 1% to 5%⁴². However, while both Tergat and Radcliffe had rather small pace variations on a scale of one kilometre, Tergat had four speed-waves of 10km with a 5% variation between the trough and the crest (Figure 6). For Radcliffe we can distinguish two big waves of 21km with a speed variation of 7% (Figure 7).

The coefficient of speed variation for the 27,397 and 28,870 finishers in the Paris Marathon in 2000 and 2003 respectively (from over 32,000 starters in 2000 and 34,400 starters in 2003) was examined. The variation was 4.3 ± 2.4 and 4.64 ± 3.4 % for the first 30 male and female runners (Figure 5). The race winners had a speed variation that was two times less than the average (2.1%

and 1.5% for the male and female winners respectively in 2000 and 1.3% and 1.1% respectively in 2003). Females had the same race pattern and finished the race in the same proportions as males i.e. 85.6% and 83.9% in 2000 and 2003.

Since 2000, the race has included designated pacers who are meant to run at an even tempo for performances of 3:00:00, 3:15:00, 3:30:00, 3:45:00, 4:00:00, 4:15:00, and 4:30:00. However, the runners who finished in these times (± 2 min) were not more regular than the others in the race. This indicates that it is very difficult to run a marathon at a constant speed. Moreover, it is not sure that this is the best way for improving one's personal best. Further research going deeper into the issue of optimisation of running pace is required^{59,62,63}.

In a review on pacing strategy and athletic performance, FOSTER et al.⁶⁴ point out that since the initial study by ROBINSON et al.⁶⁵ of a 1200m run, there have been few systematic investigations to determine how various pacing strategies might influence the outcome of competitive performances. The studies that have been conducted were true pac-

ing studies^{60,64,66,67} or controlled stochastic investigations^{68,69}. Moreover, for technological reasons, very few studies conducted to date have measured physiological responses during a marathon.

It would seem, however, that a promising source for future improvements in marathon training will be a more detailed understanding of speed variations in the race and the associated physiological stress. New technology, including portable gas exchange analysers and GPS systems^{56, 57, 58, 59}, now allows us to accurately determine running velocity and to make physiological measurements at any point during a marathon. Rather than focusing on average pace provided by intermediate times from the global performance, we can explore more subtle variations and relate them to the level of the runner. This information will aid in the design and implementation of training programmes that aim to optimise the metabolic production of ATP (Adenosine Tri-Phosphate). It will also make it possible to better characterise the specificity of marathon speed as it relates to critical speed, the concept of which we will consider below.

Critical Velocity

One of the more interesting areas of study related to pacing is that of critical speed or critical velocity (CV). In locomotion sports, performance is defined as the time taken to cover a given distance. The relationship between distance and time (in seconds) to cover this distance (in metres) is a regression line⁷¹. Therefore, the slope of this regression is velocity (in metres per second). This latter is the CV (or critical power when the distance is replaced by work in Joules) (see reviews^{40,72}). CV has been shown to be the highest constant work rate that can be sustained without VO₂ blood lactate and H⁺ inexorably increasing towards maximal attainable levels. Theoretically, CV represents the fastest running speed that can be maintained indefinitely⁷³. It presumably represents an inherent characteristic of the aerobic energy supply system. The concept of CV has been very well analysed by di PRAMPERO⁷⁰ and a review of the model time in human endurance models has been addressed in Sports Medicine⁴⁰.

The determination of an athlete's CV is very easy and does not require any device, only the personal bests over racing distances between

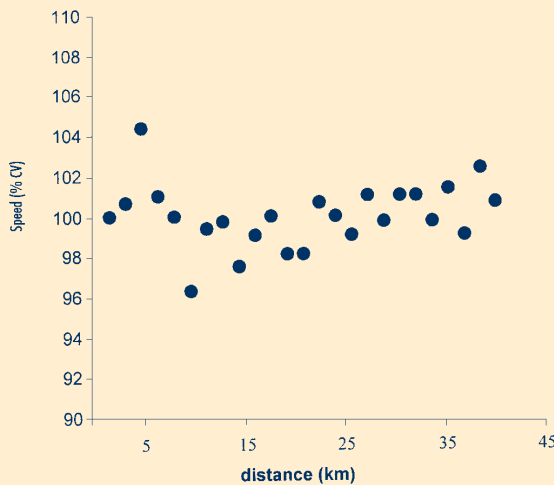


Figure 7: Speed (expressed as a percentage of Critical Velocity – CV) during the women's world World Record marathon (Paula Radcliffe, 2:15:25 in 2003)

1500m and 21,100m. Time to exhaustion (time limit) is modelled using the 2-parameter critical power model^{80,81}:

$$t = AWC / (P - CP) \quad (7)$$

or

$$(P - CP)t = AWC \quad (8)$$

where t is the time to exhaustion at the power output P ; AWC is the anaerobic work capacity (joules), taken as the total amount of energy that can be derived from the complete depletion of the anaerobic stores (phosphagens and glycolysis resulting in net lactate production) and oxygen stores. CP is the critical power (watts) representing the boundary between the power outputs that, theoretically, could be sustained indefinitely, and those, for which exhaustion occurs in a finite time.

Although the critical power test has been regarded as providing a reliable measure of the maximal fatigueless rate of work⁸² it has also come under criticism. In fact, CP can only be sustained for about 30 minutes^{73,83,84,85}. Consequently, MORTON⁸⁶ proposed a 3-parameter critical power (or, as shown below, critical velocity in the case of running) model. For this model he extended equation 8 allowing a non-zero asymptote at $t = k$ to produce equation 9 (adapted from MORTON⁸⁶):

$$(V - CV)(t + k) = AWC \quad (9)$$

or

$$t = [AWC / (V - CV)] - k \quad (10)$$

where k is a negative constant which has the dimension of time.

Thus, for $t = k = AWC / (V_{max} - CV)$. Equation 10 becomes equation 11, which introduces the third parameter of the critical power model, V_{max} (maximal velocity), in addition to the CV and the AWC. This becomes:

$$t = AWC / (P - CV) - AWC / (V_{max} - CV) \quad (11)$$

In practice, CV over-predicts the running velocity that can be maintained indefinitely and typically subjects are only able to maintain a running pace at a speed equal to CV for less than 40 minutes while at the same time inducing a blood lactate concentration of 7-9 mM^{73,74,75,76}. CV is well correlated with performances in the half marathon and marathon^{77,78} and this means that the performances achieved in shorter events (3-60 minutes) used for determining CV⁴⁰ are in line with performances at longer distances, which is not surprising for long-distance runners. Marathon pace is about 10% of the MLSSv, which is itself on average 10-12% below the CV determined with the linear 2-parameter model^{75,78,79}. Even if the CV is determined with the non-linear 3-parameter model, the marathon is run below this speed. Hence, fatigue in the marathon race does not match the metabolic model of fatigue as proposed by FUKUBA⁴⁰. This is probably because the anaerobic work capacity is not exhausted at the end of the marathon (the average blood lactate concentration collected from elite marathon runners equals 5 ± 2 mM²¹).

The critical velocity, determined from the 3-parameter critical power model, better reflects the capacity for prolonged exercise than the critical velocity calculated with the 2-parameter model^{87,88,89}. However, if we apply both models to Tergat, we get the more or less the same CV value (6.02 m/s^{-1} and 6.06 m/s^{-1} with the 2- and 3-parameter models respectively). Only ADC is completely different, the 3-parameter model giving a much greater value (424m vs. 260m in the 2- and 3-parameter models respectively), which conforms with previous studies^{40,86}.

The MLSSv is probably closer to the critical power determined with the 3- rather than the 2-parameter model and the marathon speed is below the maximal lactate steady state and therefore the CV. It would be interesting to experimentally assess this point at a different level of performance. MLSSv and the onset of blood lactate accumulation are correlated and close (for MLSSv) to the critical

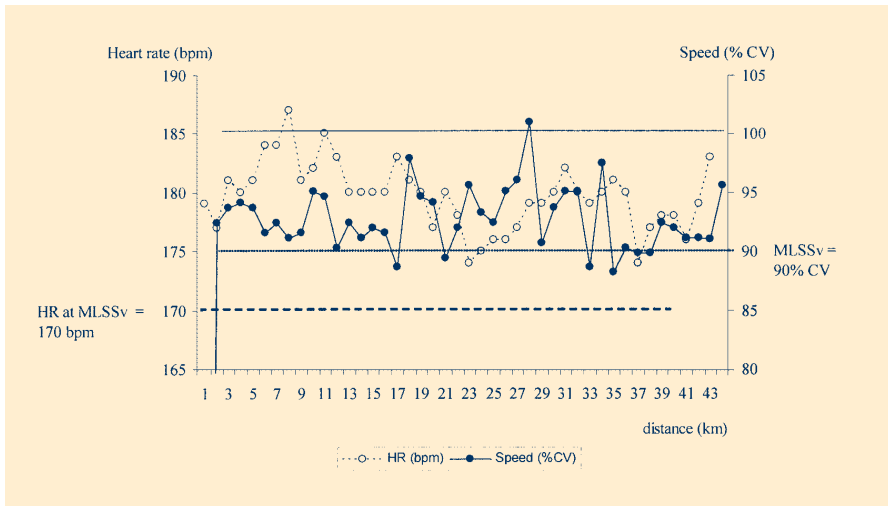


Figure 8: Comparison of heart rate and critical velocity in the marathon

speeds^{90,91,92,93} calculated from MONOD and SCHERRER's⁶⁷ model this being recently confirmed by SMITH et al.⁷⁹ (Figure 8, personal data).

Critical Power and Mechanics

There is also the concept of local critical power as an index of local endurance⁹⁴ that could play a major role in the last 10km of a marathon, particularly in the increase of the extension of the knee at foot-strike and the maximal angle in the non-support phase and the decrease in the mean stride length observed in the last 30 minutes of the race (-8.4%)⁹⁵. Even if the specific critical power alteration after a marathon has not been studied, the leg extensor strength (maximal peak torque) and work capacity (i.e. the total work accumulated for 50 maximal contractions at 3.2 rad/s⁻¹) have been shown to decrease by 15-20 minutes and until three and seven days respectively after a marathon performed at personal best times (2:43:48±2:12) in groups training (30 minutes at 50-60% of VO₂max) and not training the week following the race⁹⁶. An increase in the energy cost of running at the end of the marathon²⁵ and at two hours and two days and seven days after a marathon or

duathlon^{97,98} or even after a 90 minutes of running at 80% of VO₂max⁹⁹ has been clearly reported. Even if these changes in energy cost of running are not correlated with mechanics^{97,100}, the increase of the energy cost of running could be an indicator of the neuromuscular fatigue^{101, 102}.

Indeed, DAVIES and THOMPSON¹⁰³ reported an increase of the energy cost of running in the last 30 minutes of the constant pace prolonged exercise of 4:00 hours (67 to 73% of VO₂max) in an ultra-marathon. No study has yet attempted to link this increase in the energy cost of running and the critical power in the knee extensors and quadriceps. NICOL et al.¹⁰³ found a 30-35% lower integrated electromyography activity in the vastus lateralis and vastus medialis during maximal isometric contraction after a marathon. Similar results were found after a 85km ski race¹⁰⁴ and recently this was reported to be due to central fatigue after a 65km race¹⁰⁵. Reduced neuromuscular activity and force generation during prolonged cycling (100km at stochastic pace) has also been reported to show that neuromuscular activity in peripheral skeletal muscles falls in parallel with a reduction in power output during exercise.

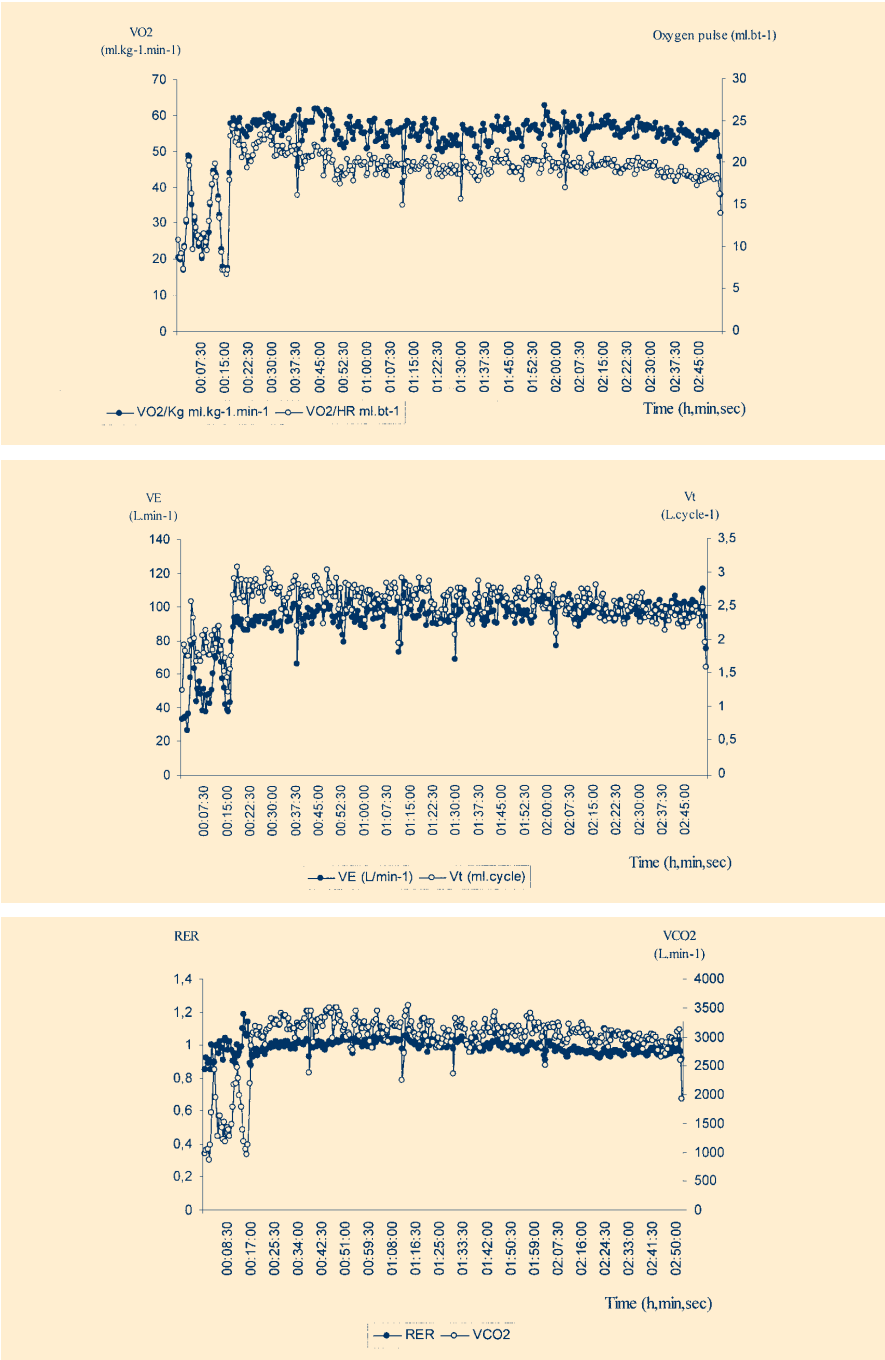


Figure 9 (a, b, c): Key indicator values during a 2:50:00 marathon

These changes occurred when less than 20% of available muscles were recruited, which, according to the authors, may suggest the presence of a so-called “central governor” that reduces the active muscle recruited during prolonged exercise¹⁰⁶. When motor units have to achieve a task that is no longer within the scope of less powerful units, there is a general conflict between efficiency and power output¹⁰⁷. This increase in the energy cost of running has been reported to be associated with the time at which runners become noticeably less coordinated and use more arm, shoulder, and torso movements in their running action.

If a clear relationship between biomechanics and the increase in the energy cost of running has been established, it would be interesting to search for a possible contribution of the ventilatory cost. CHEVROLET et al.¹⁰⁸ demonstrated a high correlation between the decrease in aspiratory force and leg muscle force two and a half hours after a marathon (3:09:00). MARON et al.⁴¹ found that during a marathon the minute-ventilation could be maintained at values as high as 80 L/min⁻¹ in some runners. This is confirmed by an average value of ventilation of more than 100 L/min⁻¹ in a direct measurement we made with a breath-by-breath portable analyser (K4b²)⁵⁷ weighting 800g and set near the centre of mass on a runner who finished the 2000 Paris Marathon in 2:50:00 (as opposed to a 2:35:00 personal best) (BILLAT et al., 2000, unpublished data) (Figure 9 a,b and c).

We can observe that in the marathon, ventilation increases throughout the race and that the oxygen pulse decreases due to the oxygen uptake (VO₂) steady-state with an increase in heart rate (Figure 9 a,b,c). Fatigue and ensuing exhaustion will occur if any contributing physiological system functions above its critical power. During exercise, many different tissue systems must increase their metabolic demand. Hence, WALSH⁵² proposed with a convincing demonstration that each tissue system, such as cardiac, respiratory and leg muscles, has its own critical power.

Cardiac muscle has the greatest critical power relative to its maximum power because it has the shortest diffusion distances. Respiratory muscle also has a substantially higher relative critical power than leg muscle. The higher relative critical powers of cardiac and respiratory muscle are due in part to the homeostatic functions these tissues provide.

Pace Regulation

Pace is regulated according to the rate of perception of exhaustion (RPE), which is the integration of all the pain at the brain level. We still do not know how this spontaneously regulates the pace during a race when runners do not follow a time schedule or heart rate targets. What we do know is that the drop in speed during a marathon has also been reported to be associated with the drop in carbohydrate utilisation, unchanging free fatty acid utilisation and a fall in blood glucose¹⁰⁹. These are accompanied by three major physiological effects: hypoglycemia, hyperthermia and vascular hypovolemia¹¹⁰.

Marathoners ingesting carbohydrate (1 L per hour with 6% of carbohydrate) have been reported to be able to run at a higher intensity while reporting a insignificant difference in RPE during a competitive race, especially in the last 10km of the race (16.8±0.3 v. 16.1±0.3, P = 0.06), compared with those using placebo beverage¹¹¹ (performance was not significantly different between the two groups- 4:19:00 in the carbohydrate group vs. 4:28:00 in the placebo group). Furthermore, heart rate was significantly higher in the carbohydrate group (78.7±1.0% v. 84.6±0.7% of HR max) in the last 10km with no difference in the plasma volume change (-0.22% v. -0.19% in the carbohydrate vs. control group). The heart rate showed less variation between the two groups (82.0±0.6% v. 84.2±0.6% of HR max) in the first 30km. The heart rate of the placebo group decreased with the speed in the final 10km. The weight loss was more pronounced in the control group (-1.6±0.02 kg v. -1.2±0.2 kg in the control vs. carbohydrate group, P < 0.01). The authors concluded

ed that in marathon running, where speed varies from point to point in the race, factors other than carbohydrate energy substrate availability apparently play an important role in mediating the perceived intensity of exertion.

However, the fact that speed regulation was free decreased the possibility to have a great difference of the RPE between the two groups. NOAKES et al.¹¹² consider that the brain command to decrease the speed of the runners of the placebo group was to spare the more delicate heart by leading to a reduction in the oxygen demands of the heart, thereby protecting it from damage caused by oxygen starvation. They have developed a model proposing the existence of a “governor” that monitors the state of oxygenation of the heart and perhaps other organs such as the brain and diaphragm. They predict that the very best athletes will be those with the highest maximum rates of coronary blood flow, perhaps because they have larger coronary blood vessels with a greater capacity to dilate during exercise and the most economical hearts and muscles with the greatest contractility and elasticity. The governor in their brains may also allow their heart to continue contracting with lower oxygen concentrations in the cardiac muscle. Indeed, HASKELL et al.¹¹³ showed that highly trained endurance runners have large epicardial coronary arteries. Left ventricular mass index ($\text{g}\cdot\text{m}^{-2}$) was significantly greater in runners and their dilating capacity was positively correlated with VO_2max .

This central governor would not necessarily have an anatomical locus and may just be of a functional nature. It would receive signals from various systems related to the current exercise and integrate these inputs to provide an output towards the cortex forcing the decision to stop the effort if the total input went beyond a given threshold. For instance, during heavy exercise, signals from the legs, ventilation, heart and brain would all provide input to the central governor, eventually leading to the cessation of effort¹¹⁴. However, this threshold is not

known and could be the integration of several thresholds (this recalls concept of organ critical power proposed by WALSH mentioned above). The researcher who discovers this mathematical function according to the length and exercise intensity will be awarded at least a Nobel Prize in Science of Sport and Exercise.

Another study has reported that the self-selected speed of running in recreational long distance runners elicited RPE, HR and blood lactate values not significantly different from a constant speed run at the speed of the lactate threshold¹¹⁵. However, the velocity of the self-selected speed and the average heart rate during the race showed significantly lower variances than v_4 mM and the corresponding HR. This suggests that, besides the need for avoiding blood lactate accumulation, other factors must be involved in the choice of running speed. The authors’ hypothesis on the determinants of the self-selected running speed is that the freely chosen running speed correlates with the minima of the functions relating the speed with the energy cost and the mechanical power at speeds ranging from 9 to 16 $\text{km}\cdot\text{h}^{-1}$ ¹¹⁵.

However, a clear relationship between shock attenuation and stride length during running at different velocities has been recently established^{116,117}. Further studies are needed to know how the decrease in speed and stride length at the end of a marathon, even if selection of stride length remains spontaneous, could decrease the shock attenuation, which is the process of absorbing impact energy and reducing the amplitude of the shock wave. Indeed, shock attenuation is related to lower-extremity geometry and compliance at impact and these factors are directly related to stride length.

In the Paris Marathon, where we asked a runner to run at the same pace (16 $\text{km}\cdot\text{h}^{-1}$) for 2:30:00 wearing a K4b², we saw that oxygen uptake stayed at a steady state (55 $\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) while the heart rate increased throughout the race, the oxygen pulse

decrease by 4% and the tidal volume decreased by 6%. All the frequencies (respiratory and heart rate) increased in order to maintain output (ventilatory and oxygen uptake) (Figure 9 a, b, c). This could argue in favour of the theory of the proper critical power of the organs¹⁵², which limits speed and could be in accordance with NOAKES' theory on the brain's role in self-regulation of pace. As underlined by KAYSER¹¹⁴, any voluntary exercise starts and ends in the brain. He states that exercise involves the contraction of muscle tissue through an increase in spatial and temporal recruitment of motor units. Similarly the exercise ends with a de-recruitment of motor units. Both are the results of modulation of descending motor command. A conscious decision is necessary to start a voluntary effort and even though it is not clear what forces the de-recruitment of motor units, "the end of effort is again volitional and a (forced) conscious decision precedes it"¹¹⁴. During a marathon, there is a moment at which the pain becomes more intense than is tolerable.

Coping Strategies

The self-regulation of pace seems to be successful, since most runners (85%) finished the Paris Marathon in an average time of 3:56:05 $\pm$ 39:35 in 2000 and 3:47:11 $\pm$ 29:31 in 2003. The performance of the 1000th was also similar in 2000 and 2003 (2:55:03 in 2000 and 2:55:06 in 2003) for an average value of (2:45:00 $\pm$ 14:47 in 2000 and 2:45:01 $\pm$ 11:16 in 2003). This is a remarkable performance density, which is probably similar to what can be observed in other large city marathons around the world. To endure the physical suffering involved, the motivation must be at a great level yet, amazingly, this aspect of marathon performance remains poorly documented.

It has been demonstrated that elite middle- and long-distance runners manage pain using associative coping strategies, where the athlete focuses on internal sensations such as body awareness, muscular tension, and racing strategy (as opposed to a dis-

associative coping strategies, where the runner focuses on non-internal sensations such as listening to music¹¹⁸). Indeed, MORGAN and POLLOCK¹¹⁹ reported that elite distance runners used predominantly associative coping thought processes while running, whereas non-elite runners tended to use dis-associative coping thought processes. They concluded that more experienced runners were more likely to use associative coping strategies in order to endure long-distance runs, whereas less experienced runners were more likely to dissociate the discomfort. Twenty years later it was proved that the pace of the run may determine which coping strategy is used¹¹⁸ and as running intensity increases runners become more associative rather than dis-associative and use the running intensity to monitor their body rather than external variables.

Conclusion

The future of long-distance running is symbolic for the future of sport since it is one of the rare events where amateur and elite athletes compete together from the same start line and it is a sport that is becoming more and more universal. For this article, we have reviewed the literature relating to the most promising avenues for continued performance development in the marathon. It is our hope that the discussion presented will contribute to improvements in training methodology and performance levels for elite runners and to increased physical and mental health for all athletes in the sport.

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References

Please contact the author for specific questions regarding the references for this article.