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Review

Physiology of Marathon: A Narrative Review of Runners' Profile and Predictors of Performance

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Abstract: Marathon sports events and those who participate in them have grown over the last years, reflecting notably an augmentation of women and master runners' participation. The aim of the present narrative review was to briefly present the results of studies on anthropometric, physiological, and training characteristics, as well as predictors of performance, in marathon runners. It was observed that performance was better in runners with a small body weight, body mass index, body fat percentage, and rate of endomorphy. Regarding physiology, an increased maximal oxygen uptake, anaerobic threshold, and improved running economy could result in a faster race time. The training variables that could predict performance involved weekly training volume (distance) and intensity (running speed), as well as history of training (years). A combination of these three broad categories of characteristics may offer an approximate estimation of the race speed considering that other aspects (e.g., nutrition, biomechanics, and motivation) influence race performance, too. In summary, the findings of the present study provided an overview of the anthropometric, physiological, and training characteristics associated with marathon race times; thus, optimization of any of these characteristics would be expected to improve the race time.

Keywords: age; exercise intensity; long-distance running; maximal oxygen uptake; running economy; sex

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1. Introduction

The term "marathon" may refer either to a phenomenon of extreme length or a running race of 42.2 km or a geographic location in Greece [1]. The first marathon race was performed in the first modern Olympic Games (Athens 1896) and the Boston Marathon started one year later [1]. During the 128 years since that period, this race distance has grown in popularity, with an increased number of annual races and participants, especially concerning women and master runners [2–4]. Not surprisingly, marathon running has attracted an increased scientific interest covering a wide range of topics from physiology and biomechanics to psychology and sociology, resulting in a large body of literature requiring reviews to systematize the knowledge resulting from original studies [5–8].

Recently, several aspects of marathon running—such as personality [5], participation trends [6], use of non-steroidal anti-inflammatory drugs [7], impact of running on intervertebral discs [8], sleep [9], nutrition [10], the risk of cardiovascular disease [11], and myocardial injury [12]—have been reviewed. On the other hand, a bibliometric analysis of the literature on marathon running during the last 15 years (2009–2023) highlighted the physiology of runners as the first research hotspot [13]. Nevertheless, no comprehensive review has been ever conducted on physiological aspects. Therefore, the aim of the present narrative review was to briefly present the results of studies on anthropometric, physiological, and training characteristics, as well as predictors of performance, in marathon runners. For the purpose of this study, the Scopus database was searched on 27 June 2024 using the syntax "marathon AND (training OR anthropometric OR physiological OR predictors)" in

the title of candidate articles, resulting in 241 entries. Then, the literature of the selected articles was hand-searched for additional literature. It should be noted that although it was not necessary to report the search approach considering the narrative type of the present review, we thought that it might be helpful to provide details about the applied criteria leading to the selection of the original studies. Furthermore, a summary of the abbreviations used in this text was provided to help readers less familiar with this topic (Table 1).

Table 1. Abbreviations and definitions of terms.

Abbreviation	Term
BIA	Bio-impedance analysis
HR	Heart rate
HRmax	Maximal heart rate
Lamax	Maximal lactate
RE	Running economy
SKF	Skinfold thickness
VEmax	Maximal minute ventilation
VO_2	Oxygen uptake
VO_2 max	Maximal oxygen uptake
vVO_2 max	Velocity at maximal oxygen uptake

2. Anthropometry

Anthropometry has been referred to as the evaluation of the human body using surface dimensional measurements [14]. The information about the anthropometric profile of marathon runners has been based on studies that (a) profiled high-performance runners such as Kenyans [15], (b) compared marathon runners of different performance levels according to either the personal best time or the race time on a particular race [16–19], or (c) marathon runners with runners of shorter distances [20], half-marathon [21] and ultramarathon runners [22], triathletes [23], track-and-field athletes [24], other sports [25], university students [26], and sedentary adults [27]. Most of these studies used laboratory or field measurements; however, it was possible to collect data (e.g., height, body weight, and body mass index, BMI) using questionnaires from a large number of runners [17]. Considering the validity of self-reported anthropometric characteristics in recreational marathon runners, self-reported values overestimated their height by 0.44 cm and underestimated their actual body mass by 0.65 kg and their actual BMI by 0.35 $kg \cdot m^{-2}$ [17]. Moreover, women underestimated body mass values more than men, and it was noticed that the differences between self-reported and actual values in the abovementioned study were smaller than those observed in non-athletes, indicating a relatively good self-perception of their physique [17].

The anthropometric assessment concerned not only the height and weight, but also other noninvasive quantitative measurements of the body such as somatotype and skinfold thickness (SKF), which is a measure of fatness and an approach to estimating body fat percentage (BF) [15,18,28]. Since BF could be estimated by different methods in marathon runners, a comparison of two assessment methods of BF (SKF versus bioimpedance analysis, BIA) was conducted in female and male marathon runners [28]. A very large correlation was found between the two assessment methods, where SKF provided a higher score than BIA by 3.9% in men and a similar score in women. Furthermore, both methods showed a positive correlation with age, i.e., a higher BF was observed in the older age. It should be mentioned that the commonly used measures of anthropometry were BMI and BF.

With regards to the profile of high-performance runners, male Kenyan marathon runners (best race time 2:07:16 h:min:s) had an average age of 27.7 years, height of 171 cm, body weight of 58 kg, training volume of 200 km weekly, BF score of 8.9%, and somatotype consisting of endomorphy 1.5, mesomorphy 1.6, and ectomorphy 3.9 [15]. About the variation of body weight by performance level, it has been observed in fast (marathon race time <3:24 h:min) and slow runners (>3:24 h:min) that fast runners were lighter than slow

runners by 4.9 kg and had a lower BMI by 2.5 kg·m^{-2} [18]. In addition, the difference in SKF by performance level has also been shown in female professional marathon runners (international, personal best <2:34 h:min; national, 2:34–2:45 h:min; and average level 2:45–3:19 h:min), where iliac crest SKF was smaller in the international than the national group, and all skinfolds were smaller in these groups than in the average level group [19]. In recreational female and male marathon runners (age 40.1 and 44.3 years, respectively), the abdominal SKF was the largest in both sexes, whereas the smallest was the biceps and chins, respectively [29]. Interestingly, this research reported that the slowest runners had comparatively more fat in the arms and trunk.

In female and male marathon runners (~50 km weekly training load), the smallest SKF in women was the chin, and in men, it was the biceps [29]. A comparison of 10 anatomical sites identified the triceps as the SKF with the largest sex difference. The fastest runners had less SKF in the arms and trunk. Elsewhere, female marathon runners were categorized into three performance groups based on their marathon race time [16]. These three groups did not differ in height, bone widths, circumferences, and body weight. The body weight and BF of all runners were lower than sedentary women. The fastest runners had lower BF (especially triceps SKF) and were more ectomorphic and less endomorphic than the slower ones. In addition, comparative research conducted on male novice ($\leq$3 finishes in marathon races) and experienced (>4 finishes) runners [30] showed that the experienced runners were faster and had lower abdominal and iliac crest SKF and BF.

Compared with runners of shorter distances, marathon runners had the smallest SKF; in addition, BF was related to performance only in marathon runners [20]. These findings were partially attributed to the increased fat metabolism in training and racing in marathon runners. Compared with half-marathon runners, marathon runners were lighter and had thinner arms and thighs, a smaller sum of SKF thickness, lower BF and FFM, with more years of sports experience and a higher weekly training volume and training time [21]. Furthermore, the marathon race time had half of its variance explained by BF and speed in running during training. Compared to 100 km ultramarathon runners, marathon runners had smaller calf circumference, larger pectoral, axilla, and suprailiac SKF, and had fewer hours and shorter distances in weekly training, which was at a faster speed [22]. In marathon runners, race time was related to BF and speed in running during training. Furthermore, in comparison to track-and-field athletes, it was supported that long-distance runners such as marathon runners had relatively low muscle and fat mass [24]. In this context, marathon runners should not have increased muscle mass since this would lead to increased energy demands to deform and overcome the inertial load (first law of Newton) [31].

Compared to triathletes, male marathon runners did not differ for BF [23]. An estimation of BF based on SKF in male national-level marathon runners showed a score of 7.5%, which was 5% smaller than that of age-matched university students [26]. A comparative study examined differences between marathon runners and sedentary adults [27]. Marathon runners had a smaller body weight, BMI, arm and forearm circumference, and skinfold thickness, as well as increased BIA ratios and phase angle for the whole body. A comparison of international-level male athletes in 26 Olympic events found that marathon runners were among the athletes with the smallest BF (6.4%) [25]. Marathon runners had less fat mass and fat-free mass than swimmers [32]. In summary, with a few exceptions, the literature indicated that the fast runners were lighter and had less BF than their slower counterparts. The abovementioned studies highlighted the role of anthropometric characteristics in marathon runners. Based on this body of literature, coaches and sports scientists should develop specific programs to optimize these characteristics.

3. Physiological Characteristics

Studies on marathon runners' physiological characteristics have focused so far more on aerobic capacity-related parameters, such as maximal oxygen uptake (VO_2 max) [33–39] and less on neuromuscular fitness, such as flexibility and anaerobic performance [30,40]. It should be noted that VO_2 max refers to the maximal capacity of the O_2 transport system

from the air to the mitochondria limited by the cardiovascular, respiratory, and muscle systems [41]. Marathon runners have been characterized by a high VO_2 max; e.g., a case study of two marathon runners showed a VO_2 max of about 61 mL·min^{-1}.kg^{-1}, maximal minute ventilation (VEmax), 100 L·min^{-1}, HRmax 188 bpm [38]. A case study reported for a master runner (age 59 years; race time at this age, 2:30:15 h:min:s) showed HRmax 165 bpm, VEmax 115 L·min^{-1}, maximal lactate concentration 5.7 mmol·L^{-1}, and VO_2 max 65.4 mL·kg^{-1}·min^{-1}, and running economy (RE) at his race pace of 210 mL·kg^{-1}·min^{-1}, with VO_2 corresponding to 91% of his VO_2 max [42].

Considering the increased participation of women in marathon races during the last years, a few studies examined sex differences in physiological characteristics [15,43–45]. The VO_2 max in female and male marathon runners (age 20–30 years) of the same level (race time 3:20 h:min) was similar (~60 mL.min^{-1}·kg^{-1}) [45]. In the same study, women and men of the same performance level did not differ in anaerobic threshold (83% of VO_2 max or 89% of HRmax), whereas RE in women was worse (i.e., higher VO_2 at a given submaximal speed). It should be noted that the anaerobic threshold (other relevant terms included lactate threshold, the onset of blood lactate accumulation, and heart deflection point) referred to one's ability to sustain a high fractional utilization of VO_2 max [46].

In another study, a comparison between national-level female and male marathon runners showed that men had a higher VO_2 max than women [43]. Furthermore, at given running speeds, men had better RE using less oxygen. Elsewhere, female and male runners were examined for aerobic capacity, and it was shown that both VO_2 max and submaximal VO_2 were higher in men than in women [44].

The VO_2 max (68.5 versus 74.1 mL.min^{-1}.kg^{-1}) and the energy cost of running (0.182 versus 0.192 mL O_2·kg^{-1}·m^{-1}) in male marathon runners were lower than in 5–10 km runners [36]. In another research, male marathon runners (best race time 2:12:04 h:min:s) did not differ in submaximal scores (VO_2, heart rate (HR), and lactate), VO_2 max, or HRmax, but had smaller velocity at VO_2 max (vVO_2 max) than 3 km steeplechase runners [35]. Marathon runners were compared with university and school student runners and had a lower resting HR and a higher resting VO_2 [34]. Furthermore, Kenyans were examined together with European marathon runners, and no difference was observed in VO_2 max, vVO_2 max, and energy cost of running [39].

With regards to neuromuscular fitness, observational research on cycle ergometer all-out short-term tests showed a worse performance in marathon runners than in sprinters, indicating differences in anaerobic power, endurance, and power athletes [40]. Moreover, moderate scores of neuromuscular fitness were observed in female marathon runners (age 40 years, personal best race time 4:34 h:min), considering the standards of the non-athlete population [47]. Furthermore, the younger runners performed better in jumping and maximal power cycle ergometer tests than the older runners, and the slowest performed better in the sit-and-reach test, a measure of flexibility. In summary, not surprisingly, most of the studies on physiological characteristics investigated aerobic capacity parameters, mostly VO_2 max, anaerobic threshold, and RE, suggesting that good scores in these characteristics were associated with a fast marathon race time.

4. Training

Exercise training has been typically described in terms of intensity, frequency, duration, and mode [48]. Outcome measures of exercise intervention in marathon runners have included BF, fat-free mass, VO_2 max, anaerobic threshold, RE, perceived fitness, rate of perceived exertion, and maximal isometric force of knee extension [49–55] (Table 2).

Table 2. Training characteristics of marathon runners.

Study	*n*	Sex	Age (Years)	Performance Level	Intervention	Outcome
[49]	51	F and M	21	Novice	15 wks consisting of training either 4 ds·wk^{-1} (G4) or 6 ds·wk^{-1} (G6); 20% less volume in G4 than in G6	BF and HRmax decreased; FFM and VO_2 max increased in both groups; no difference between groups
[50]	22	F and M	40	Recreational	8 wks consisting of either endurance running (E, 276 mins·wk^{-1}) or endurance and strength training (ES, 360 min·wk^{-1})	Maximal isometric force of knee extension increased only in ES; VO_2 max and anaerobic threshold increased in all participants
[51]	9	M	44	Recreational	3 wks of detraining and 4 wks of retraining	VO_2 max decreased during detraining and increased during retraining; BF did not change
[52]	16	F and M	38	Recreational	16 wks of training	Ventilator threshold speeds and running economy improved
[53]	8	F and M	34	Competitive	12–13 wks of training	BF decreased and VO_2 max increased
[54]	7	M	21–42	Competitive	1 wk pre- and 2 wks post-marathon race; 30 min treadmill run (individualized constant speed) was monitored	In treadmill run, HR and VE did not change, whereas RPE increased and VO_2 decreased in post-race period
[55]	21	M	35–50	Novice	30 wks	VO_2 max and anaerobic threshold improved at 15 wks compared to baseline, and did not change at 30 wks compared to 15 wks

n = sample size, F = female, M = male, wk(s) = week(s), d(s) = day(s), BF = body fat percentage, HRmax = maximal heart rate, FFM = fat-free mass, VO_2 max = maximal oxygen uptake, HR = heart rate, VE = minute ventilation, RPE = rate of perceived exertion.

In female and male marathon runners (age 38 years), a 16-week training program increased perceived fitness and anaerobic threshold and improved RE [52]. In another study, female and male marathon runners (age 34 years, personal best race time <3:30 h:min) were tested at 10 weeks and 1.5 weeks pre-race [53], and it was observed that BF decreased by 2% and VO_2 max increased by 12.3 $mL \cdot min^{-1} \cdot kg^{-1}$.

Furthermore, sedentary female and male adults (age 34 years, race time 4:13 h:min) participated in a training program to run a marathon and were tested for physical activity using accelerometers pre- and post-race [56]. During this period, sedentary behavior did not change, whereas physical activity was lower at one-month post-race than two months pre-race. The effect of a 30-week marathon training program in sedentary male adults was examined in a study with measurements of VO_2 max on a cycle ergometer at baseline, week 15, and week 30 [55]. The cardiorespiratory fitness parameters (VO_2 max and anaerobic threshold) improved at week 15 and did not change at week 30. VO_2 max and submaximal VO_2 did not change in male marathon runners during four weeks pre-race and one-week post-race [37]. In 39-year-old marathon runners, VO_2 max was higher in the more trained ($\geq$100 km per week, 59 $mL.min^{-1}.kg^{-1}$) than in the less trained runners (<100 km per week; 50 $mL \cdot min^{-1} \cdot kg^{-1}$) [33].

A study examined the effects of three weeks of detraining and four weeks of retraining in male marathon runners [51]. VO_2 max decreased during the detraining and increased during retraining, whereas BF did not change. Elsewhere, a 15-week training program was tested in novice marathon runners in groups practicing either four or six days weekly [49]. Both groups applied the same exercise intensity, but the first one had less training volume. Both groups reduced BF and increased both VO_2 max and fat-free mass; however, these changes were independent of whether the runners practiced training four or six days weekly. Regarding exercise intensity, the speed of running during training in high-performance level marathon runners was identified at 85% of VO_2 max [57]. In the context of the preparation for a marathon race, runners applied either only endurance or combined endurance/strength 8-week training [50]. The maximal isometric force of knee extension improved only in the combined training, whereas both groups improved similarly in both VO_2 max and submaximal performances.

Scientific interest has been focused not only on the effect of training on marathon performance, but also on the influence of single or multiple marathon races on training parameters [54,58–61]. Exercise testing including 30 min constant speed running on a treadmill was conducted in runners one-week pre-marathon race and one- and two weeks post-race [54] in research where RPE increased in the first week post-race and VO_2 was lower in the second week post-race compared to pre-race scores. A case study of a female runner (age 54 years, VO_2 max 53 $mL \cdot kg^{-1} \cdot min^{-1}$) examined physiological responses to running 10 consecutive marathons in 10 days on a treadmill at a constant pace corresponding to 60% of VO_2 max [58]. During this period, weight decreased by 2.6 kg, BF by 3.1%, and muscle mass by 0.4 kg, due to a total energy deficit of 12,700 kcal. Elsewhere, a research paper analyzed the impact of seven marathon races within a week on female and male runners (age 42.6 years, average race time 4:44 h:min), with measurements pre-race, post-first, post-fourth, and post-seventh race [59]. Although body weight decreased, plasma volume, fluid, and electrolyte balance did not change post-race, suggesting that the decrease in body weight did not correspond to changes in the hydration status.

Furthermore, a case study of a master runner completing 51 marathon races in consecutive days was examined. Fat mass and mean race HR decreased during this period [60]. A blood and urine analysis showed no muscle damage or renal dysfunction. A multi-stage run consisting of seven marathon races in corresponding consecutive days was analyzed [61]. A small elevation of muscle damage markers, liver cell damage markers, and inflammatory markers were noticed post-race. Fat mass decreased and fat-free mass increased post-race, whereas body weight did not change. In summary, training programs lasting 8–30 weeks improved body composition and VO_2 max, showing a clear interplay among training, anthropometry, and physiology.

5. Predictors

The profile of anthropometric, physiological, and training characteristics has been described in the previous three sections of this review. The present section shows how these characteristics might predict race performance in marathon runners, where race performance refers either to race time or average race (running) speed. Since the knowledge of predictors of performance has had large theoretical and practical value for scientists and coaches working with marathon runners, respectively, many studies have focused on this topic [62,63]. A review of 21 studies on marathons concluded that VO_2 max, vVO_2 max, training intensity and load, and BF were the best predictors of marathon running performance [62]. It has been observed that marathon runners with a similar race time had a large variation of VO_2 max, suggesting that other factors (e.g., RE and anaerobic threshold) may play a crucial role in race performance [64]. In the same study, the anaerobic threshold was reported to be the best predictor of marathon race time.

Race speed (km/h) in the Athens Authentic Marathon 2017 could be predicted using the formula "8.804 + 0.111 × VO_2 max + 0.029 × weekly training distance in km −0.218 × BMI" [65]. In a study that examined VO_2 max, anaerobic threshold, race time in various long distances, and marathon race time could be predicted by race time in 10 km or a half-marathon [63]. The findings of Noakes et al. [63] indicated the role of performance in distances other than marathon distances, with an affinity for marathon races, considering that marathon runners competed not only to their target distance, but also to 10 km, half-marathon, and ultramarathon races.

Regarding the methodological approach of the relevant literature, the selection of candidate predictors should be highlighted during the interpretation of the findings. For instance, in male recreational runners (age 41 years, race time in the Madrid Marathon 226 min), age, running experience, number of marathon races finished, mean kilometers run weekly in the last three months, and previous personal best time in a 10 km, a half marathon, a marathon, Ruffier test, and whole-body isometric force test were considered as potential predictors of race time in the particular marathon [66]. Their best prediction model included BF, HR change during recovery from the Ruffier test, and HM personal record. The predictors of performance might vary by age; it has been observed that predictors of race time in master runners were VO_2 max, diastolic blood pressure, age, and training volume, whereas, in younger runners, this included height, resting HR, systolic blood pressure, and VO_2 max, with VO_2 max being the best predictor in both age groups [67]. In another study of female marathon runners (4:11 h:min), the marathon race time in min could be predicted by using the formula "184.4 + 5.0 × (circumference calf in cm) − 11.9 × (speed during training in km·h^{-1})" [68], and was related with body weight, BMI, thigh and calf circumference, front thigh and medial calf SKF, weekly training volume (km), and number of weekly sessions.

In female (2:34:53 h:min:s) and male marathon runners (2:12:04 h:min:s), predictors of race time were subscapular SKF, serum ferritin, and the sum of six SKF. In female runners, marathon race time was related to lactate at 10 km.h^{-1}, left ventricular telodiastolic diameter, and lactate at 22 km.h^{-1} [69]. In male runners, marathon race time was related to the percentage of slow twitch fibers, VO_2 max, RE, VO_2, and treadmill speed at the onset of plasma lactate accumulation [70]. From these parameters, the prediction model of race time included only the onset of plasma lactate accumulation (OPLA). In addition, the runners paced the race by 5 m.min^{-1} faster than the treadmill speed at OPLA. In female and male marathon runners, the personal record in this race (4:02:53 h:min:s) could be predicted from BF and the right ventricular end-diastolic area [71]. In this study, other correlates of race time were the maximum minute ventilation indexed to body surface area, hemoglobin concentration, and hemoglobin mass.

In marathon runners, the running velocity corresponding to the onset of blood lactate accumulation could be closely predicted by the weekly training volume [72]. In addition, it could be closely predicted by the enzyme activities of lactate dehydrogenase, phospho-fructokinase, and citrate synthase. In male marathon runners (best record 2:15–4:54 h:min),

the best predictors of race time included CPK, age, training volume, SKF, and cortisol [73]. In summary, a combination of anthropometric, physiological, and training characteristics may offer an approximate estimation of race speed, considering that other aspects (e.g., nutrition, biomechanics, and motivation) influence race performance, too.

6. Conclusions

In summary, the present review highlighted the role of anthropometric (body weight, BMI, BF, and somatotype), physiological (VO_2 max, anaerobic threshold, and running economy), and training characteristics (training volume, intensity, and experience) for marathon performance. These findings have large practical applications considering the number of runners and professionals (e.g., coaches, sports scientists, nutritionists, physiotherapists, physicians, and psychologists) involved in marathon training. Since most of the existing literature has examined men of middle age, future studies need to focus on women and less-studied age groups such as underage and elderly runners.

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