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INVITED COMMENTARY

Contemporary Nutrition Approaches to Optimize Elite Marathon Performance

Trent Stellingwerff

The professionalization of any sport must include an appreciation for how and where nutrition can positively affect training adaptation and/or competition performance. Furthermore, there is an ever-increasing importance of nutrition in sports that feature very high training volumes and are of a long enough duration that both glycogen and fluid balance can limit performance. Indeed, modern marathon training programs and racing satisfy these criteria and are uniquely suited to benefit from nutritional interventions. Given that muscle glycogen is limiting during a 2-h marathon, optimizing carbohydrate (CHO) intake and delivery is of maximal importance. Furthermore, the last 60 y of marathon performance have seen lighter and smaller marathoners, which enhances running economy and heat dissipation and increases CHO delivery per kg body mass. Finally, periodically training under conditions of low CHO availability (eg, low muscle glycogen) or periods of mild fluid restriction may actually further enhance the adaptive responses to training. Accordingly, this commentary highlights these key nutrition and hydration interventions that have emerged over the last several years and explores how they may assist in world-class marathon performance.

Keywords*:* carbohydrate, running, training, periodization

Since 2008, the men's marathon has entered an unprecedented era of performance. In 1999, the marathon world record stood at 2:05:42. In 13 years this time has now been bettered 40 times, with 36 of those times since 2008 and 37 of the record-breaking athletes coming from either Kenya or Ethiopia. The world record currently stands at 2:03:38 by Kenya's Patrick Makau Musyoki. Although the women's marathon has shown progress too, it has been more linear, and its world record has stagnated since 2003, with some suggesting that women have not had the same socioeconomic opportunities to pursue professional running as their male counterparts.[1] It has been argued that this explosion of marathon performance is due to a "perfect storm" of circumstances such as physiology, anthropometrics, biomechanics, training advances, environmental factors, and socioeconomic influences.[1,2] These outstanding marathon performances have ignited the debate on the limits of human endurance, as highlighted by a recent scientific article titled "The Two-Hour Marathon: Who and When?"[3] and the numerous published countercommentaries on various potential intervening factors.[4]

However, beyond these factors, an appreciation of a modernized approach to nutritional physiology and periodization needs to also be considered. In fact, there is an ever-increasing importance of nutrition during prolonged endurance events[5] and throughout periods of very high training loads. Thus, given the duration of the marathon (>2 h) and the fact that elite marathoners routinely train 220 to 280 km/wk,[6,7] the marathon is an event uniquely suited to benefit from nutritional interventions. Therefore, the aim of this commentary is to highlight some of the contemporary acute (Figure 1) and chronic (Table 1) nutrition and hydration interventions that have both scientifically and anecdotally emerged over the last several years and explore how they may assist in world-class marathon performance.

Chronic Nutrition and Training Interactions Allowing for Optimal Training Adaptations

Table 1 highlights the chronic training adaptations that can be affected by nutrition and hydration to optimize endurance physiological adaptations. Beyond the typical endurance-athlete preparation, which features large amounts of aerobic training[6–8] to drive expression and proliferation of mitochondria, enzymes, transporters, and capillaries, this section focuses on the emerging thesis that carbohydrate (CHO) cycling and periodic low-CHO training may further optimize these adaptations.

Despite recommendations to always attempt to train in glycogen-compensated states, recent data suggest that periodically decreasing CHO availability may further enhance endurance-training adaptations.[9] Lowering CHO availability can be achieved by either training with low endogenous glycogen availability[10,11] or training with

The author is with the Canadian Sport Institute–Pacific, Victoria, BC, Canada.

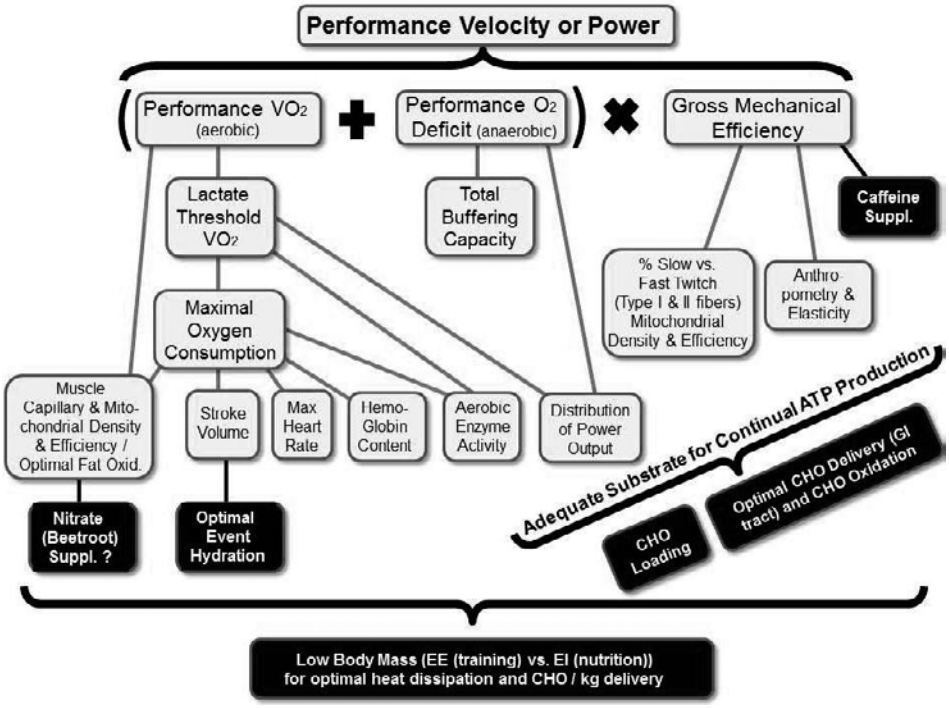

Figure 1 — Schematic framework of acute physiological and nutritional determinates of marathon performance (adapted from Joyner and Coyle[30]). Abbreviations: VO_2, oxygen uptake; CHO, carbohydrate; GI, gastrointestinal; EE, energy expenditure; EI, energy intake.

Table 1 Outline of Chronic Training Adaptations That Can Be Affected by Nutrition or Hydration Interventions to Optimize Marathon-Specific Physiological Adaptations

Desired physiological adaptation	Type of training or environmental intervention	Potential nutrition or hydration intervention
↑ muscle glycogen contents.	Large volumes of upper aerobic power training (eg, fartleks, tempos).	↑ CHO cycling via periodically training under low CHO availability and acute prerace CHO loading.
↑ or maintain healthy hemoglobin content for optimal O_2-carrying capacity.	Minimize inflammatory responses by large volumes of aerobic training at intensities below lactate threshold; potentially use hypoxic environments to increase natural RBC production.	Optimal dietary iron and vitamin B_{12} intake.
↑ PV leading to ↑ SV and VO_{2max} and heat acclimation.	Periodic VO_{2max} training sessions (large durations of high quality of training intensity at or near HR_{max}); training in a heat-stress environment.	Targeting mild to moderate dehydration during heat-stress training and ingestion of protein after heat-stress training?
↑ buffering capacity or ↑ lactate or ventilatory threshold.	High-intensity anaerobic training to increase anaerobic capacity and lactate tolerance.	Chronic beta-alanine supplementation.
↑ aerobic or mitochondrial genes, enzymes, transporters.	Large volumes of upper aerobic power training (eg, fartleks, tempos) and lactate-threshold training.	Periodically training under low CHO availability and potentially L-carnitine supplementation?
↑ intestinal CHO-transporter density and/or function.	Marathon race-pace-specific training in target marathon weather conditions to mimic race-specific GI blood shunting and GI stress.	↑ exercise-specific CHO fueling and overall dietary CHO intake over a several-week period?
↑ overall training load in a volume-dependent sport via optimized nutritional recovery practices.		
↑ ratio of power to body mass to improve running economy via long-term management of energy expenditure vs energy intake.		

Abbreviations: CHO, carbohydrate; O_2, oxygen; RBC, red blood cell; PV, plasma volume; SV, stroke volume; VO_{2max}, maximal oxygen consumption; HR_{max}, maximal heart rate; GI, gastrointestinal. Question mark indicates that more research is needed to fully validate initial findings.

low exogenous CHO availability (overnight-fasted training[12]). The seminal paper in this area, by Hansen et al,[10] reported increased endurance adaptation and performance in untrained men when half of the training sessions (5 d/wk over 10 wk) were undertaken in a muscle-glycogen-depleted state (training twice per day, so the second training bout was glycogen depleted), as compared with 100% of training conducted in a glycogen-loaded state. Several follow-up studies have confirmed these enhanced endurance-training-induced muscle adaptations with periodic low CHO availability, but without a further enhanced performance outcome compared with normal training group.[11] Several follow-up studies have also confirmed enhanced training adaptations with low-energy-availability training (either low muscle glycogen or low exogenous CHO availability via overnight-fasted training), but not necessarily with performance changes. Some of the proposed mechanisms included elevations in resting muscle glycogen content, increased maximal activity of several key β-oxidation pathway enzymes, elevated skeletal-muscle fatty-acid protein transporters, and higher rates of whole-body fat oxidation (for review, see Burke[9]). Nevertheless, it is difficult to extrapolate the results of short-term laboratory training studies (~10–25 sessions) to the real world of marathon running, where elite athletes are looking for only marginal improvements in performance over years of training (eg, elite marathon runners will undertake 550–650 training sessions per year[6,7]).

Intriguingly, anecdotal reports indicate that East African runners undertake some training in a glycogen-depleted or fasted, water-only state (Hilary Stellingwerff, personal observations, Ethiopian training camp, November 2008). However, whether this low-CHO training is purposeful or an indirect product of programs with a high training frequency (resulting in a lack of time for glycogen resynthesis) remains to be elucidated. Despite the fact that this type of low-CHO-availability training is both physiologically and psychologically challenging, these scientific and anecdotal reports suggest that elitely adapted athletes may need to periodically undertake low-CHO-availability training to fully maximize endurance-training responses. Accordingly, a recent case-study publication examined individualized low-CHO-availability training interventions incorporated into 3 elite marathoners' training programs.[6] During the general preparation training phase each marathoner was encouraged to increase the frequency, duration, and quality of these low-CHO-availability sessions as they better tolerated and adapted (up to ~2–3 sessions/wk). Subsequently, there was a purposeful decline in these training sessions during the taper and an increased frequency of utilizing CHO sports drinks during this final phase. Although this case study was descriptive in nature, all training and nutrition interventions together resulted in the athletes improving their marathon race times from 2:16:53 to 2:11:23, 2:15:15 to 2:12:39, and a debut at 2:16:17. Nevertheless, it also remains to be elucidated what low-CHO-availability approaches (low-glycogen training vs overnight-fasted training vs. low-glycogen recovery periods, eg, overnight) will ultimately provide the best stimulus for adaptation while minimizing the likely deleterious effects of delayed recovery, decreased training quality, and increased immune-system stress.

Acute Nutritional Determinants of Marathon Performance

Figure 1 outlines a framework of acute physiological and nutritional determinants of endurance performance. Although caffeine[13] and nitrate[14] supplementation and CHO loading[15] have all been shown to potentially affect endurance-based performance, this review focuses on novel research to optimize CHO delivery and oxidation during racing to enhance performance.

Fuel Utilization During Elite Marathon Running

Given that elite marathoners routinely run 220 to 280 km/wk,[6,7] with a large percentage of this volume as aerobic training,[6] they are highly adapted for utilizing lipids via oxidative phosphorylation. However, elite marathon race pace tends to elicit ~80% to 90% of maximal oxygen consumption (VO_{2max}), which has led some to hypothesize that, coupled with exogenous CHO intake (ie, sports drinks), these athletes could potentially complete the entire marathon using only CHO as fuel.[16] To my knowledge there are no published data showing CHO-utilization rates of world-class marathon runners at race pace. However, subelite marathon runners (~2 h 45 min) had respiratory-exchange ratios of .95 to .97 during the last half of an overnight-fasted treadmill marathon with just water provision,[17] indicating an ~96% dependence on CHO as a fuel. So contrary to the widely held belief that marathon runners primarily use fat as a fuel, carbohydrate-derived energy stores and exogenous CHO supplementation are actually of paramount importance to elite marathon performance. Nevertheless, respiratory-exchange-ratio data in elite marathon runners, who are uniquely adapted for optimal fat oxidation, have yet to be published to confirm this hypothesis.

Impact of Optimal CHO Delivery on Marathon Performance

Given that elite marathon running is nearly 100% CHO-dependent,[17] it is important to appreciate the fuel limitations in endogenous muscle glycogen and, thus, the importance of exogenous CHO fueling. Therefore, in endurance events lasting longer than approximately 90 minutes, a highly efficient gastrointestinal (GI) absorptive and subsequent CHO-oxidation (CHO_{oxid}) capacity, with a low overall body mass, is also a fundamental determinant contributing to modern world-class endurance performance.

It appears that the rate-limiting step to exogenous CHO_{oxid} is at the level of the GI tract due to the intestinal CHO-transport mechanisms, specifically the sodium glucose transport protein-1 (SGLT 1) transporter for glucose and the GLUT-5 transporter for fructose.[18] Research led primarily by Jeukendrup and coworkers has shown that the combined intake of glucose and fructose sports drinks results in 30% to 50% higher CHO_{oxid} and, during prolonged exercise, enhanced performance (for review, see Jeukendrup[18]). It is also thought that having a high CHO_{oxid} efficiency of supplemented CHO beverages should reduce the accumulation of CHO in the GI tract and reduce the potential for GI distress during exercise.[19] It is important to note that even minor GI distress is associated with negative endurance-performance outcomes.[20] Research has shown a highly variable response in individual CHO_{oxid} and GI tolerance.[18,21] Supporting this is a between-subjects coefficient of variation of measurement for CHO_{oxid} of ~15% to 20% in well-controlled studies conducted under similar conditions in similar subjects (for review, see Jeukendrup[18]). In addition, recent evidence suggests that these CHO transporters appear to be trainable, so athletes who repeatedly expose their transporters to high CHO intakes can potentially up-regulate CHO_{oxid}.[22,23] Conversely, we have found a highly significant correlation between endurance athletes who have a history of GI problems during exercise and measured GI problems during competition,[21,24] with about 15% to 20% of endurance athletes having a chronic history of GI problems. Taken together, it appears that there is a large diversity of CHO_{oxid} and GI responses and that each endurance athlete will have a unique "sweet spot" where he or she is able to absorb and oxidize a maximum amount of CHO and fluids to improve endurance performance versus too much fluids and CHO, which will cause GI distress and decrease performance. In support of this, a recent 51-subject CHO dose-response study using a cycling intervention showed a curvilinear performance response, with a 4.7% improvement in time-trial performance at a CHO intake rate of 78 g/h.[25] However, there was large individual variability in the optimal intake, as the 95% confidence intervals suggested uncertainty in the optimum of ~68 to 88 g/h CHO. This individual variability is reflected in a recently published elite-marathon nutrition and training case study showing a self-selected range from 49 to 77g/h CHO in 3 elite marathoners during sub-2:12 marathon efforts.[6]

Low Body Mass's Positive Effects on Heat Dissipation and CHO Delivery

Heat production during a marathon can increase 10-fold, so there certainly appears to be a distinct physiological advantage for an athlete to have a low ratio of body mass (BM) to surface area to reduce thermoregulatory strain caused by the elevated metabolic heat production during prolonged endurance exercise.[26] "Larger" marathon runners have the option to target races that take place in cooler conditions (except for major championships), but the requirement and ability to absorb and oxidize fuel (CHO) is completely weather independent. It is interesting that there has been a small and consistent decline in the BMs of the marathon world-record holders over the last 60 years (Figure 2).

Recent data summarized from 7 individual studies (N = 63), from the same laboratory and under similar conditions, demonstrated no correlation between BM and CHO_{oxid}.[18] In other words, some of the lightest subjects (~60 kg) had the same ability to absorb and oxidize exogenous CHO as some of the heaviest subjects (>90 kg). This suggests that it appears to be the quality and quantity of CHO transporters, not the length of the GI tract, that ultimately dictates exogenous CHO delivery and oxidation. Thus, it is important to note, based on Jeukendrup's data where subjects of differing BMs were able to oxidize CHO to a maximum of ~1g/min,[18] that a 70-kg runner is only able to absorb and oxidize ~0.0143 g CHO/min/kg BM, while a 54-kg runner is able to absorb and oxidize ~30% more per kilogram BM (~0.0185 g/min/kg). Theoretically, this results in a much smaller shortfall of required CHO energy for lighter versus heavier marathon runners. In fact, theoretical calculations support the premise[16] that small marathon runners who are muscle- and liver-glycogen loaded and using an aggressive exogenous-CHO-supplementation protocol may in fact be able to complete the entire marathon on nearly 100% CHO-derived energy.

Summary

World-class marathon performance depends on a multitude of physiological, anthropometrical, biomechanical, training, and environmental factors and socioeconomic influences.[1,2] However, both acute and chronic nutritional interventions will also play an important role in pushing marathon performance ever closer to that 2-hour barrier. Whether by evolutionary design, through purposeful training and dietary practices, or merely by chance, many East African athletes may already be predisposed to practicing some of the ideal nutritional interventions highlighted in this commentary. For example, East African runners naturally have ideal body masses and anthropometrics (light body masses; Figure 2). Furthermore, despite high carbohydrate intake,[27] given their incredible training volumes of 220 to 280 km/wk[7] (sometimes up to 3 sessions/d) they must inherently undertake a certain amount of training in moderate to low muscle-glycogen states. Recently, more athletes and coaches are also appreciating the performance enhancement that can be gained from ideal race-day fluid and CHO consumption, certainly supported by recent literature.[6,25,28] In fact, the great Haile Gebrselassie "only" ran 2:06:35 for third place in his first serious marathon attempt (2002 London Marathon). However, it was later reported in an article titled "Geb Runs Out of Gas" that he had never used CHO sports drinks in training or competition and,

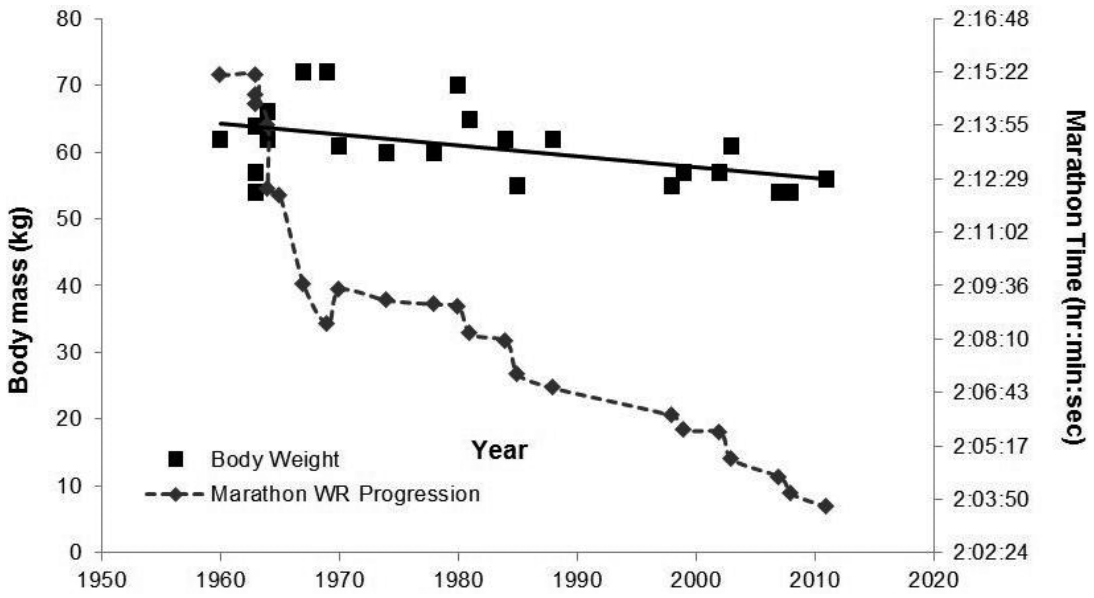

Figure 2 — Relationship between body mass and marathon world-record times from 1960 to 2012.

therefore, only consumed water in that race.[29] Conversely, Gebrselassie, at only 54 kg, consumed ~60 to 70 g/h CHO in ~1000 mL/h fluids (Asker Jeukendrup, personal communication, November 2010) during his 2008 Berlin Marathon world record (2:03:59)—a 2% improvement in performance.

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