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Invited Review Article

The race within a race: Together on the marathon starting line but miles apart in the experience☆

Louise M. Burke [a], Jamie Whitfield [a], John A. Hawley [a,b,*]

[a] Exercise and Nutrition Research Program, Mary MacKillop Institute for Health Research, Australian Catholic University, Melbourne, Victoria, 3000, Australia
[b] Department of Sport and Exercise Sciences, Manchester Metropolitan University Institute of Sport, Manchester, United Kingdom

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ABSTRACT

Every four years the world's best athletes come together to compete in the Olympic games, electrifying audiences with incredible feats of speed, strength, endurance and skill as personal best performances and new records are set. However, the exceptional talent that underpin such performances is incomprehensible to most casual observers who often cannot appreciate how unique these athletes are. In this regard, endurance running, specifically the marathon, a 42.195 km foot race, provides one of the few occasions in sport outside of Olympic, world and national competitions, that permits sport scientists and fans alike to directly compare differences in the physiology between recreational and elite competitors. While these individuals may all cover the same distance, on the same course, on the same day – their experience and the physiological and psychological demands placed upon them are vastly different. There is, in effect, a "race within a race". In the current review we highlight the superior physiology of the elite endurance athlete, emphasizing the gap between elite competitors and well-trained, but less genetically endowed athletes. We draw attention to a range of inconsistencies in how current sports science practices are understood, implemented, and communicated in terms of the elite and not-so-elite endurance athlete.

1. Introduction

The performances of elite athletes entertain and enthrall us. Every four years we watch and admire the world's best athletes competing in the 30 plus sports that make up the Olympic Games, witnessing phenomenal feats of speed, strength, endurance and skill as personal best performances and new records are set and surpassed. But how do the performances of these elite athletes keep improving? Changes in the culture of many sports have afforded more opportunities to a greater number of athletes, especially females, enabling them to train full-time and receive medical and sport science support to assist in attaining their athletic goals. Commercial enterprise has also played a role in driving select elite endeavors in which "barriers" to performance have been tackled as science-driven, top-down projects. A recent example has been the successful attempt for a male to run the marathon distance (42.195 km) in under 2 h (the INEOS 1:59 project, preceded by Nike's "Breaking 2″ marathon project). Technological breakthroughs in equipment design and the application of wearable devices have also ushered in a new area of data acquisition and analyses underpinning advances in training and performance in several sports. However, for the average recreational athlete, the so-called "weekend warrior", the performances of a select few genetically endowed individuals are inconceivable and for the most part, unattainable. In this regard, endurance running, specifically the marathon, offers a unique opportunity in modern-day sporting events whereby males and females, young and old, can line up in the same race as Olympic and world champions. As such, the marathon provides one of the few occasions in sport that allows sport scientists to directly compare and contrast the differences in the underlying physiology between well-trained recreational and world-class elite competitors.

There are currently more than 800 marathons organized globally annually, but only six of these are afforded the title of a "World Marathon Major", these being the Berlin, Boston, Chicago, London, New York and Tokyo marathons. The popularity of these events can be gauged by the fact that a "world record" 840,318 people have applied to run the 2025 London marathon [1]. Such appeal may be due to the ease of access to train for running compared to equipment-intensive sports such as

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* Corresponding author. Exercise and Nutrition Research Program, Mary MacKillop Institute for Health Research, Australian Catholic University, Melbourne, Victoria, 3000, Australia.

E-mail address: john.hawley@acu.edu.au (J.A. Hawley).

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cycling and triathlon. While we typically dissect the prerequisites for success in sporting events such as the marathon from a single perspective (i.e., the physiology of the elite runners), the nuances within each event are considerable. For example, on September 27th, 2015, and despite his insoles detaching from his shoes during the race, 30-year-old Kenyan Eliud Kipchoge won the Berlin marathon in 2:04, a personal best (PB) for him at the time. In the same event, one of the authors (LMB, female and 56 y at the time) also ran a PB of 3:26:04 to place within the top five women in the 55–59 age group. Meanwhile official race results reveal that a 30-year-old male completed the race in 6:26:59, while a female age-group contemporary crossed the line almost 90 min ahead of him in 4:59:37. Each of these athletes completed the same race, on the same course, on the same day, under similar weather conditions (although the majority of runners spent considerably longer than 2 h out on the course). These "marathon majors" are unusual in allowing this event scenario to occur. Nevertheless, we argue that each of these runners was competing in an entirely different race in terms of absolute and relative physiological demands, race support, tactics, and personal aspirations and motivations. There was, in effect, a "race within a race".

In this review, we discuss a range of themes related to the generation and application of sports science to endurance athletes. Using the marathon as an exemplar, we provide commentary on some contemporary themes on how sports science is understood, practiced, and communicated in terms of the top end and tailgaters in endurance sport. Topics include a recent attempt to provide objective labels for the elite and lesser caliber athletes in sport, and to describe the physiology of the very best endurance athletes. Differences in the training approaches of elite versus less successful marathon runners are characterized, and the possibility of a greater widening of the performance gap between the groups is raised. Despite this disparity, we contend that both the science and the commercial world conflate the needs of the two groups without recognizing several issues. We provide evidence, from the domain of sports nutrition, that few elite athletes have contributed to the studies on which the many position stands and expert recommendations for nutritional strategies are made. Furthermore, there is evidence that some strategies may have a different degree of effectiveness in elite athletes, and that the physiological needs of lower caliber athletes may not actually justify the use of others. Finally, although the actual practices of some elite athletes have been described, we will explore the notion that these should not be used as proof of efficacy without opportunity to investigate cause and effect.

2. Who is elite?

The world of the elite athlete is dominated by extreme precision in outcomes; millimeters in a marathon and single decisions over a six-month season can separate glory from despair. By contrast, the term "elite athlete" is one of the most imprecise and ill-defined themes in the larger world, with considerable variation in how it is used even within the sports science literature [2]. Indeed, across several subdisciplines in sports science, researchers have identified the absence of a standardized taxonomy to describe athlete caliber or training status [2–5]. For example, a survey of sports psychology literature targeting "elite" or "expert" participants, published between 2010 and 2013, found eight different ways of defining such athletes within 91 papers, ranging from Olympic champions to regional level competitors with as little as two years of experience in their sport [4]. Terms such as "trained," "highly trained," and "well-trained" also seem to be highly subjective, with considerable range around training load, training history, and training intent [2–5]. To address the challenges created by such heterogeneity, a single system to define an athlete's status was proposed, based on standardized metrics around five criteria: 1) highest performance standard, 2) level of success, 3) years of experience, 4) competitiveness of the sport within the athlete's country, and 5) global competitiveness of the sport [4]. However, quantitative approaches to these metrics cannot always account for nuances between sports.

We have contributed to an international and multi-disciplinary effort, across sporting disciplines, to develop a tiered framework that can be implemented both prospectively (i.e., as part of study participant recruitment) and retrospectively (i.e., during systematic reviews and/or meta-analyses) to classify the caliber and training status of participants [2]. It includes quantitative metrics around performance standards and training characteristics, with allowances for the nuances of different sports, and without the need for extensive physiological or skills-based testing. Furthermore, it considers the proportion of the world's population that might be eligible for each of the six tiers, as well as strategies to manage variations in performance levels or training commitment within the same athlete. This framework is summarized in Table 1. Other valuable features of the project include commentary of design features that should be included in methodological descriptions of participants or study features, examples of its specific implementation in various sports, and guidelines for researchers to apply the system retrospectively in audits of the current literature [2,6]. In the case of the specific focus of this review, Tier 5 marathon runners are defined as having a personal best performance within 2% of world record/leading performances, while Tier 4 athletes are within 7% of world record/-leading performances. Based on the world records at the time of writing (2:00:35 and 2:11:53), this equates to personal best performances (h:mm:ss) equal to or faster than 2:03:00 (Tier 5 men) and 2:14:31 (Tier 5 women), and 2:09:01 (Tier 4 men) and 2:21:07 (Tier 4 women).

3. Champion physiology

The physiological factors that interact to determine endurance performance capacity have been comprehensively discussed elsewhere [10–14], and here we provide only a synopsis of those characteristics. For the most part, these commentaries have focused on "whole-body" measures, with limited investigation into the skeletal muscle properties that underpin such outcomes. Part of the reason for this is that elite athletes are somewhat reluctant to undergo invasive procedures such as tissue (muscle and blood) sampling in the name of science. In this regard, the landmark gathering of elite male long-distance runners published in the Annals of the New York Academy of Sciences [15] stands as the perhaps the only investigation to date that has comprehensively explored the physiological, biochemical, medical, psychological and biomechanical aspects of elite versus "good" distance runners. A decade later, Pate and colleagues [16,17] gathered a group of elite female distance runners (marathon time 2:35 or faster) to undertake a testing regimen focused on whole-body measures of cardiorespiratory fitness, similar in scope to the recent investigation of Jones and colleagues [12] who studied a cohort of the world's best male distance runners as part of Nike's "Breaking 2″ marathon project (no muscle sampling was undertaken in either of these latter studies).

From the results of these and other investigations, a central premise that underpins elite marathon performance is the highest rate of aerobic metabolism that can be sustained for the duration of a race, the upper limit of which is established by the athletes maximum O_2 uptake ($\dot{V}O_{2max}$). Champion male endurance-trained athletes may exhibit $\dot{V}O_{2max}$ values 2-fold greater than recreationally-trained runners, but while a high $\dot{V}O_{2max}$ (>70 and > 60 mL/kg/min for males and females, respectively) is a prerequisite for successful endurance performance [15,18], marathons are run at speeds below $\dot{V}O_{2max}$, with the highest proportion of $\dot{V}O_{2max}$ sustainable for the duration of the race termed "fractional utilization" of $\dot{V}O_{2max}$ [19]. The world's top marathon runners can sustain higher rates of fractional utilization without incurring significant increases in blood lactate concentrations (a proxy marker for glycolytic stress and disturbances in cellular homeostasis). Increases in muscle and blood lactate concentration typically occur at ~60–65% of $\dot{V}O_{2max}$ in well-trained recreational runners but at 85–90% of $\dot{V}O_{2max}$ in elite marathon runners [12,20]. While the main determinants for the high $\dot{V}O_{2max}$ values of elite endurance athletes are related to oxygen

Table 1
The McKay Tiering system for classifying athletes based on performance and training characteristics (adapted from Ref. [2], where additional data to support system is provided).

Tier	Criteria for Classification	Comments about involvement in sports science research
Tier 5: World Class *< 0.00006% of the global population*	• Olympic and/or world medalists. • World record holders and athletes achieving within 2% of world record performance and/or world leading performance. • Top 3–20 in world rankings and/or top 3–10 at an Olympics/World Championships (i.e., finalists in their event), with this number determined based on size and depth of competition in the event. • Top players within top teams (teams which medal or are in the most competitive leagues) or athletes achieving individual accolades (i.e., most valuable player, player of the year). • Maximal, or nearly maximal training, within the given sports norms. • Exceptional skill level achieved (i.e., running biomechanics, ball skills, acquired decision making components).	• Rarity of these individuals makes involvement in cohort studies highly unusual. • Most common research design involves case studies yielding valuable information about the top-end of athletic performance
Tier 4: Elite/International Level *~0.0025% of the global population*	• Competing at the international level (individuals, or team sport athletes on a national team). • Team sport athletes competing in international leagues/ tournaments. • Top 4–300 in world rankings, with this number dependent on size and depth of competition in the event. • Achievement of within ~7% of world record performance and/or world leading performance. • NCAA Division I athletes. • Maximal, or nearly maximal training, within the given sports norms, with intention to complete at top-level competition. • Highly proficient in skills required to perform sport (i.e., biomechanics, ball skills, acquired decision making components).	• Challenging to involve in cohort studies due to their smaller numbers and availability. • Specialized research projects involving such individuals can provide particularly valuable insights and outcomes with high ecological validity • Majority are a part of the registered or national testing pools defined by World Anti-Doping Agency
Tier 3: Highly Trained/National Level (Provincial/State or Academy Programs) *~0.014% of the global population*	• Competing at the national level. • Team sport athletes competing in national and/or state leagues/ tournaments. • Achievement of within ~20% of world record performance and/or world leading performance. • NCAA Division II and III athletes. • Completing structured and periodized training and developing towards (within 20%) of maximal or nearly maximal norms within the given sport. • Developing proficiency in skills required to perform sport (i.e., biomechanics, ball skills, acquired decision making components).	• Expected to provide reliable measures of performance in familiar tasks • Suited to both laboratory and field-based research • May represent the "sweet spot" in sports science research due to relatively larger numbers and general availability, and balance between opportunities to collect mechanistic data and reliable performance outcomes. • Often happy to participate in studies using invasive measurements or requiring larger time commitment • Some may be in pools for drug testing
Tier 2: Trained/Developmental *~12–19% of the global population*	• Local level representation. • Regularly training ~3 times per week. • Identify with a specific sport. • Training with a purpose to compete. • Limited skill development.	• Represent most of the available population of trained individuals and well suited for trials requiring large cohort to achieve statistical power. • When involved in performance-based studies, sensitive laboratory-based tests of known typical error should be chosen and with inclusion of familiarization trials for participants
Tier 1: Recreationally Active *~35–42% of the global population*	• Meet World Health Organization minimum activity guidelines: adults aged 18–64 years old completing at least 150–300 min moderate intensity activity or 75–150 min of vigorous intensity activity a week, plus muscle strengthening activities two or more days a week [3]. • May participate in multiple sports/forms of activity.	• Can contribute to sports science literature by forming suitable control groups in cross-sectional/observational studies of athletes • Can be participants in mechanistic studies, which involve pharmacokinetic, dose-response and proof-of-concept investigations. • Inclusion in investigations of sports performance is inappropriate due to the poor reliability of performance measures and lack of key characteristics of athletes in higher tiers.
Tier 0: Sedentary/inactive *~46% of the global population*	• Do not meet minimum activity guidelines. • Occasional and/or incidental physical activity (e.g., walking to work, household activities).	• Should not be involved in studies even as a control group since inactivity may be considered "a disease" [7–9]

transport capacity [13], the higher "lactate threshold" in champion marathon runners is also associated with improved buffering capacity [21,22,23] and training-induced increases in skeletal muscle oxidative capacity [21,24,25,26]. Indeed, citrate synthase activity is increased 1.5 fold in elite athletes compared to well-trained individuals performing ~9–10 h of training per week [25].

With regard to skeletal muscle morphology, work by Costill and colleagues [15,27] determined the fiber composition from the gastrocnemius muscle of 14 elite male long distance runners (including 1972 Olympic marathon champion, Frank Shorter), 18 good (but not world-class) male long distance runners, and 19 untrained men. The elite runners had an average of 80 % slow twitch (type I) muscle fibers, compared to 62 % in the good and 57 % in the untrained men, with the values found for several of the elite runners being the highest observed in human muscle (>92 % slow twitch). A similar study was performed in elite middle and long--distance female runners, with marathon runners exhibiting ~80 % type I fibers compared to ~60 % in recreational female runners [24]. However, muscle fiber type does not necessarily discriminate between elite and non-elite performance: two runners in the work by Costill and colleagues [15,27] with similar best times for the marathon (2:18) had 50 % versus 98 % slow twitch fibers. A high proportion of slow twitch fibers probably underpins the large variability in running economy (the cost of locomotion, measured in mL O_2/kg/km), which can differ by as much as 40% between elite and untrained runners [12,28–32].

Running economy is also heavily influenced by anthropometric variables (Fig. 1), including body shape, size and composition [12,20,30,33–40]. Indeed, it is estimated that ~80% of the metabolic cost of running is driven by the need to support body mass and move forward [41]. Elite runners therefore tend to have a low body mass index (BMI) and body fat percentage compared to recreational runners when assessed via skin-folds [12,20,36–38] or dual-energy X-ray absorptiometry [35,40]. There have also been a series of studies performed primarily amongst Kenyan runners exploring differences in lower limb architecture in an attempt to elucidate what impact this may have on running economy and whether it can help explain their dominance over most distance events [42]. Kenyan athletes display long shanks with thinner calf muscles, and longer Achilles tendons and Achilles moment arm [36,43–45]. This anthropometric phenotype may increase ankle-joint stiffness thereby reducing the oxygen cost of locomotion [44]. Similarly, it was noted that the flexibility (assessed via sit-and-reach test) of a former world-record holder in the marathon declined over the course of her career, which may have led to a stiffer muscle tendon-structure and greater energy storage and return during the stretch-shortening cycle [29]. There was also a drastic improvement in running economy in this athlete, with the oxygen cost of running at 16 km/h decreasing from 205 mL/kg/km to 165 mL/kg/km over a ~14 year period [29]. Higher leg stiffness will also result in a reduction in ground contact time [45] thereby improving running economy due to decreased time for braking force to act on the forward motion of the body [46]. This is consistent with findings of reduced ground contact time in both male and female Kenyan runners [47,48].

More recently, research has focused on the inclusion of physiological resilience/durability as an overarching fourth pillar or dimension to the physiological framework for determining endurance performance [50]. As originally noted by Joyner [49], $\dot{V}O_2$ drifts upwards during long distance races, representing changes in muscle recruitment and substrate utilization patterns [71–74] Placing this pillar at the top of the physiological framework (Fig. 1), highlights that factors such as $\dot{V}O_2$, lactate threshold, and running economy are not static or fixed – rather they are impacted by prior exercise and can deteriorate during a prolonged bout of exercise such as the marathon. Amongst well-trained marathon runners (personal bests ranging from 2:12–3:00), the percentage of self-reported threshold pace held during the marathon declined from ~92% at the start of the race to ~89% in the final ~4 km, with this drop-off beginning ~28 km into the race [75]. This was associated with a reciprocal increase from ~86 to 90% of heart rate max, indicating a decoupling of internal to external work (i.e., a greater heart rate for a given speed) that progressed throughout the race. Notably, there was substantial variability in these measures, suggesting there is considerable inter-athlete differences for this metric. While the durability or physiological resilience amongst elite/world-class runners has not been reported, there is some evidence that such variability is related to training status. Recent work by Unhjem [76] demonstrated that active adults (Tier 1) exhibited a greater increase in $\dot{V}O_2$ during a 1 h run at 70% $\dot{V}O_{2max}$ compared to trained runners (Tier 2–3), resulting in a greater increase in the relative intensity of exercise across the bout. Consistent with this finding, an analysis of more than 82,000 recreational runners found faster marathon performances in individuals who had a lower ratio of internal to external work decoupling (<10%) across the race than those with higher rates (>2%) [77].

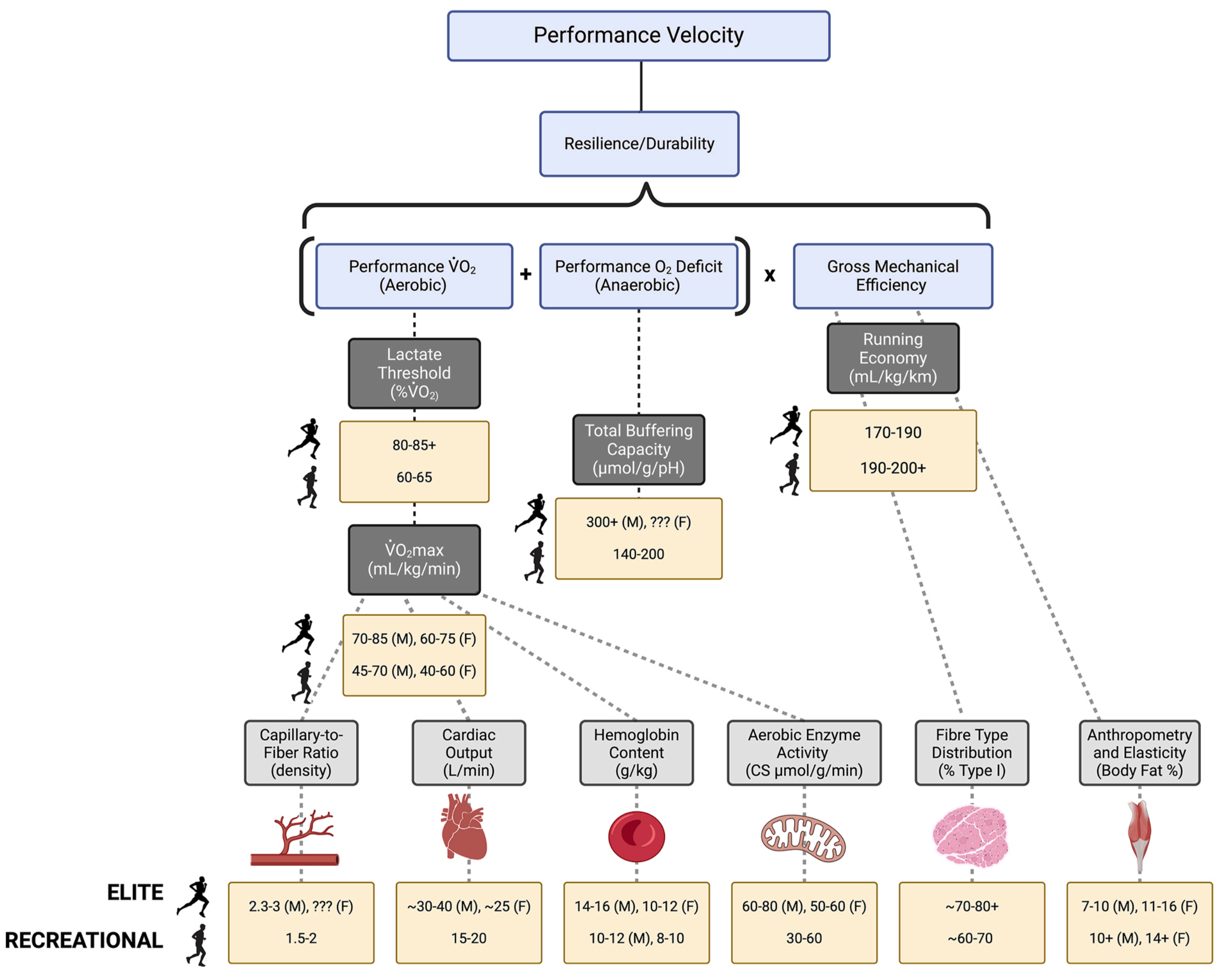

Fig. 1. A proposed framework underpinning marathon running performance. Here we have attempted to highlight the range of physiological norms that have been reported in both elite and recreational distance runners, and place them in the context of the framework originally proposed by Joyner [49] and adapted by Jones [50]. Where data exists, we have separated findings in males (M) and females (F), noting that running economy (mechanical efficiency) and lactate threshold do not typically differ between elite male and female runners [51–54]. Moreover, there is considerable overlap in many variables amongst recreational athletes of both sexes given the high levels of variability in this cohort. Definitions: $\dot{V}O_{2max}$, maximum aerobic capacity; CS, citrate synthase activity. Figure created with BioRender.com. References: lactate threshold, [12,30,33,34,55]; $\dot{V}O_{2max}$, [12,15,18,27,29]; buffering capacity, [22,23,30]; running economy, [12,28–31]; capillary density, [56,57,55,58–60]; cardiac output, [61–65]; hemoglobin content, [35,66–69]; enzyme activity [21,25,26,59], fibre type, [15,27,59,70]; anthropometrics, [12,29,33–40].

4. Training comparisons across marathon cohorts

Training adaptations are the cumulation of repeated and multiple acute bouts of exercise completed over a prolonged period (i.e., months to years). The molecular and cellular events mediating adaptation processes in skeletal muscle in response to exercise have been reviewed previously, including discussion of the molecular bases underpinning heterogeneous responses to endurance training [78], and are directly associated with the prevailing physiological inputs (i.e., the intensity, duration, and frequency) of the sessions performed. Coaches will manipulate these variables in the short- (micro- and mesocycle) and long- (macrocycle) term as part of an overall training plan targeting peak performance at key races. However the optimal training intensity distribution for successful endurance performance is a hotly debated issue (see Refs. [79,80]). Briefly, the two most prominent models are a "polarized" approach, where ~80% of all training is completed at low intensity (often described as Zone 1 in a 3-zone distribution model, <2 mM lactate), with the remainder undertaken at a high intensity (Zone 3, above the lactate turn point (LT2)) and as little as possible completed in between or a "pyramidal" model where there is a descending volume of training completed from Zone 1, to Zone 2 and Zone 3 such that ~80% of training is completed at low intensity (Zone 1, <2 mM) and the remaining 20% distributed between Zones 2 and 3 [81].

While there is an extensive body of work that has investigated various training models and intensity distributions, much of this describes how elite athletes are already training [29,34,82–85]. Indeed, best practices for achieving new limits in human athletic performance, including advances in training techniques, rarely originate with science [86]. World class endurance runners typically have been training and competing for up to ten years, with international athletes running ~160–220 km/week during preparatory phases [84]. Such high volumes are achieved through a high frequency of training (i.e., 2–3 sessions per day) as well as the inclusion of prolonged, submaximal endurance runs, the majority of which is performed at low intensity. Such volumes of low intensity training appear necessary to facilitate peripheral adaptations including mitochondrial biogenesis [87] (see Fig. 1). For example, training data collected from two-time Olympic gold medallist and former marathon World Record holder Eliud Kipchoge reveals training volumes of 200–220 km/week during his general preparation phase, with over 80% of the total volume performed at "low intensity" (Zone 1–2 of a 7-zone scale, ≤1.0–2.0 mM blood lactate, 60–82% of maximal heart rate), that equates to a pace of 03:50 (mm:ss) or slower (<75% of marathon pace) [84].

Analysis of pooled results from multiple studies with large sample sizes including recreational athletes have attempted to uncover the dose-response relationship between training characteristics and subsequent marathon performance. A meta-regression analysis including 87 studies consisting of 8845 runners (25% female) [88] found significant correlations between finishing time and multiple training parameters (average weekly running distance, number of weekly runs, maximum running distance per week, number of runs longer than 32 km, running hours per week, and average running pace during training), suggesting an increase in any single parameter would yield an improvement in finishing time [88]. In theory, the univariate results of this study could be used to guide an athlete or coach to develop a program. For example, this model predicts an athlete aiming to run a marathon in 3 h (180 min) would need to run 7–8 times per week for a total of ~107 km at an average pace equivalent to ~77% of their marathon pace (05:42 mm:ss). This model is consistent with published data on recreational marathoners with finishing times of 2:30–3:00 for the marathon, that revealed a mean training volume of 92 ± 32 km/week, undertaken at an average intensity of 77% of their marathon race pace [89]. Similarly, quantitative assessment of 92 publicly available training plans targeted to recreational runners (>3:00 marathon finishing times) showed that high-volume plans averaged ~108 km/week, with a pyramidal intensity distribution that had 67% of all completed training in Zone 2 (73–80% of max heart rate) [90].

These findings emphasize that runners across a range of abilities train (or are encouraged to train) in a similar manner to their elite counterparts, albeit with a lower number of runs per week and total weekly volume. However, it is unclear if this represents best practice or is simply based upon tradition, with the underlying assumption that how elite athletes train is optimal. Unfortunately, the nature of training and competition means it is difficult to determine if an alternate program or training method would achieve a different outcome in a randomized controlled trial, so it remains unclear whether individuals become elite because they train to a certain plan or program, or because of their unique physical traits and physiological adaptations accrued over many years.

5. The widening gap between elite and non-elite

In late 2016, Nike announced the Breaking2 project - a commercially backed, science driven attempt to support a male to run the marathon distance in under 2 h. They organized a team of three elite runners who prepared specifically for a private, unsanctioned race held in May 2017 on a Formula One racetrack in Italy. Although this attempt fell just 25 s short of breaking the 2-h mark, Eliud Kipchoge crossed the finish line well within the existing world record of 2:02:57. Fast forward to October 2019, for the INEOS 1:59 Challenge; another staged attempt held on a 2.4 km looped course on the streets of Vienna. Kipchoge, shielded by a V-shaped arrangement of pacemakers guided by pacing lasers projected onto the road, and supported by an optimized nutrition plan and bespoke running shoes, was able to sustain an average speed of 21.2 km/h and finish in 1:59:40:2. While neither of these events were eligible for an official world record as the lead runners were paced by a roster of interchangeable pacemakers, they signaled the start of a new era of distance running performance. Indeed more than a third of the improvements in the marathon records from the last 30 years (over 2 min for men and 3 min for women) has occurred since the initial Breaking2 attempt [91]. These improvements are largely due to technological improvements including carbon-plated "super shoes", which became commercially available in 2017 [92,93] and have been a source of much debate [94,95]. Laboratory trials have demonstrated that the unique combination of a carbon plate embedded in thick foam material can improve running economy, a key determinant of marathon running performance (Fig. 1), by ~4% [96–98]. This has also resulted in increasingly difficult minimum standards for elite athletes to qualify for major championships such as the Olympic Games. For example, in order to qualify for the Rio Olympics in 2016, an athlete needed to run faster than 2:29:50 (females) or 2:12:50 (males) [99] – a time surpassed by only 126 women and 259 men globally that year [100,101]. In contrast, 238 women and 393 men have ran faster than the old 2016 standard in the first 5 months of 2024 alone [102,103]. Indeed, in the last decade the average time for the top 300 athletes in the world has improved by ~2% for men (from 2:09:45 ± 0:02:04, to 2:07:22 ± 0:01:38 [h:mm:ss]) and ~4% for women (from 2:30:55 ± 0:03:46 to 2:24:53 ± 0:03:08), culminating in new world records for both men and women in 2023 (Fig. 2).

Juxtapose the progression of these world-class athletes with that of non-elite, recreational athletes in the same event. A decade ago, there were 1,298,725 marathon finishers worldwide (0.17% of the global human population), with an average finish time of 4:29:53 (4:21 for men and 4:49 for women). But despite the popularity of big city marathons, which have a limited number of entries and are massively oversubscribed, the average finish time is now some 40 min slower than it was in 1986 despite a plethora of technological breakthroughs [104,105]. Indeed, the average time for a "Six Star Finisher" (i.e., someone who has successfully completed all six World Major Marathons) is 4:02:53 at an average age of 51 [106,107]. For context – the current minimum qualifying time for the Boston Marathon in this age bracket is 3:25:00 for men, and 3:55:00 for women [108].

The disparity in performance between the elite and recreational runner highlights the unique "race within a race" nature of the marathon. As highlighted above – the inherent differences in physiological characteristics between an elite athlete and a well-trained recreational athlete (see Fig. 1) will dictate the absolute and relative intensity that they can compete at. This also has unique implications on the nutritional strategies an athlete may employ. For example – we suggest that to be considered an elite marathoner (Tier 4 or above), an athlete must be within ~7% of the world-record/world-leading performance in that event (2:09:01 for males and 2:21.07 for females), or within the top 300 global rankings (2:10:50 and 2:32:01) [2]. The average marathon runner is therefore running for considerably longer (i.e., 80–85+ min) at a much lower absolute and relative intensity, to finish the same race.

Despite the clear differences between these populations, lay media is often quick to extrapolate training and nutrition patterns from one group to the other. For example, much has been made of the training paces of athletes such as Eliud Kipchoge, highlighting the relatively "easy" pace of some of his training runs. However, what is often lost in translation is that these easy runs form only a part of an overall training program. For Kipchoge, this often includes running in excess of 200 km per week, on dirt roads in the Kenyan highlands 2,500m above sea level [109] – a program scarcely imaginable to a recreational athlete. In the case of nutrition, substantial differences have been identified in the food choices, meal schedules and macronutrient distributions in the diets of East African runners compared with Western dietary practices [110–113]. These include limited food variety, very high carbohydrate intakes both in absolute amounts (g/kg BM) and as a proportion of energy intake, and a reliance on plant food sources [111,113,114]. Daily energy intake is distributed over a small number of meals, with prolonged moderate-to fast-paced morning runs being undertaken before breakfast and with minimal or no intake of fluids or energy [112,114]. Meanwhile, meals are consumed soon after training sessions and high–intensity track sessions are completed as a mid-morning workout after breakfast [110–114]. Although it is unlikely that recreational athletes will have interest in adopting East African dietary practices *per se,* some principles such as the periodization of carbohydrate availability around training sessions are topical [115], and merit further comment. It is also worth noting that, against a background of minimal use of dietary supplements [116], elite East African athletes have been targeted for the use and marketing of new sports foods (drinks and gels), designed to increase the consumption and muscle delivery of carbohydrate during endurance sports [117,118].

6. Do elite athletes really have an evidence base for their sports science practices?

Many international sporting organizations have released expert statements or guidelines for recommended practices for athlete health and preparation. Here, the example of sports nutrition will be presented, since this has been the topic of a substantial number of consensus statements by working groups including the International Olympic Committee [119–122], World Athletics [123], World Aquatics [124], International Federation of Association Football [125], and Union of European Football Associations [126]. In some cases, these statements have been specifically addressed to "high performance" [121] or "elite" [126] athlete populations. On this basis, it could be expected that recommendations are drawn from literature in which such populations have been participants, since this is a fundamental principle about the generalizability of research [127]. This is not always the case!

Our group has undertaken systematic audits of the literature from which such sports nutrition guidelines have been derived [128–131]. Although these were primarily motivated to gauge the underrepresentation of female participants across different themes in sports science research, the application of a standardized auditing tool also provides insight into the involvement of elite athletes as research participants, via the retrospective use of the McKay tiering system [2] to classify study cohorts. Fig. 3 summarizes the results of a secondary analysis of these audits to focus on the involvement of Tier 4 and Tier 5 athletes in the investigation of some key themes in sports nutrition: evidence-based performance supplements [128] identified by the Australian Institute of Sport's Supplement Framework [132], strategies to acutely manipulate carbohydrate availability around exercise sessions [130] and chronic strategies of manipulating carbohydrate availability in the athlete's training diet [131].

In the case of the performance supplements, a total of 1867 investigations from studies published up until 2021 were included in the audit, with only 81 (~4%) of these being undertaken on athletes identified as elite and world class, representing a total of 1272 individual participants. A further breakdown of these studies identifies that 61 of the studies involved male only (n = 43) or mixed sex (n = 18) participants, with only 13 studies involving female only participants, and seven setting up a male versus female comparison [128]. Therefore, information on specific responses or needs of elite female athletes is particularly scarce for developing recommendations for their use of performance supplements. Within the 937 investigations of acute strategies for manipulating carbohydrate intake [130], only 21 (~2%) involved observations on athletes identified as Tier 4 (with no Tier 5). Meanwhile, the 281 investigations of chronic studies of carbohydrate

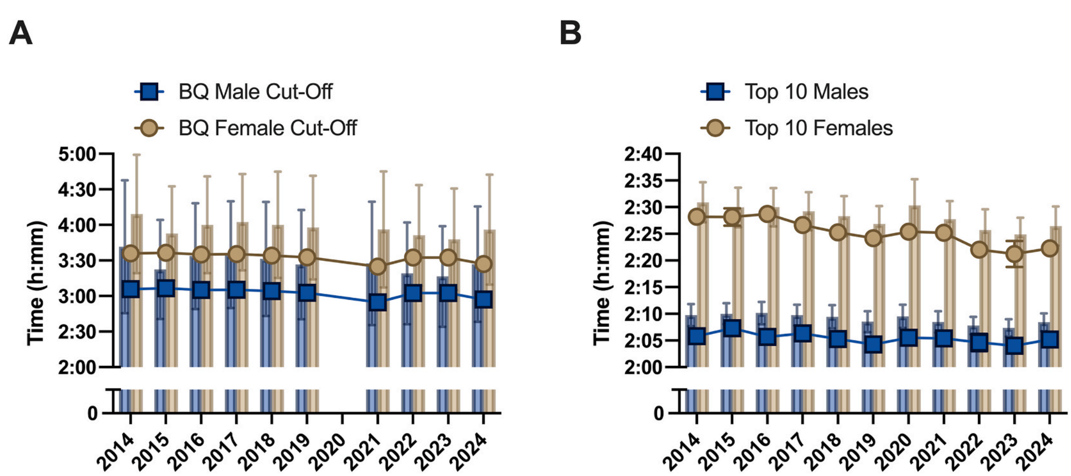

Fig. 2. Progression of marathon performance captured from the Boston Marathon (A) in comparison to global elite athlete rankings (B) over time. The Boston Marathon represents the highlight of many amateur athletes' athletic careers due to its stature as one of the oldest and perhaps the most prestigious marathons in the world. It is also unique amongst World Major Marathons for requiring a qualifying time "standard" which makes it useful for indexing changes in recreational runner performance. Pictured in panel A are the average finishing times of male and female athletes aged 18–39 in the Boston marathon (bars) in comparison to the calculated average qualifying time for 18–34 and 35–39 age brackets minus the "cut off time" below the standard required for an athlete to be accepted that year. Panel B highlights the change in the average performance time for the top 300 athletes in the World Athletics rankings (bars) in comparison to the average time for the top 10 individuals. All data are presented as mean ± SEM.

manipulations fared better, including 27 (~10%) observations involving elite and world class athletes [131], most of which have come from our research group. Collectively, these audits demonstrate the gap that exists between evidence collected in elite athletes and the consensus statements published from sport governing bodies on their behalf. Moreover, studies which involve elite female athletes are scarce, with no studies of themes within chronic manipulation of carbohydrate in the training diet, and a total of four studies across themes of acute carbohydrate manipulation (two female only, and two male versus female comparisons). Fig. 3 visualizes the variability, but overall scarcity, of the participation of elite athletes within investigations of these key themes of sports nutrition, despite the apparent confidence with which guidelines for evidence-based practice are provided. To circumvent the limitations of the lack of studies of elite athletes in the underpinning literature, it is critical to include applied scientists/practitioners, coaches, and athletes themselves, as collaborators and co-authors of these guidelines [133,134] to better represent what is occurring at "the coal face" of high performance sport.

7. The hidden world of sports science support for elite sports

Although elite athletes are under-represented in the sports science literature, this does not mean that their efforts are not supported by sports scientists. Indeed, many national teams and professional sporting organizations employ applied sports scientists, who implement a parallel universe of both traditional and case-study style research to identify new training and nutrition interventions that continue to push the performance envelope. Some but not all this research is published; deterrents to publication and wider dissemination of such information include the desire to maintain a competitive advantage, the lack of an academic incentive for sports scientists who are sport-based, and the different features of real-world methodologies that may not be considered robust by traditional sports scientists (e.g., low sample sizes, metrics gained in the field rather than the laboratory, lack of control groups). Nevertheless, there is a growing overlap between the sports-centered and traditional academic due to models such as the embedding of doctoral programs with academic institutions as well as sponsorships by sports science industry partners (e.g., the Gatorade Sport Science Institute, Science in Sport etc.).

Furthermore, journals such as the *International Journal of Sports Physiology and Performance* and *International Journal of Sport Nutrition and Exercise Metabolism* have created a home for applied sports science and even within the traditional literature, published data on elite athletes is often rewarded by large citation and Altmetric scores. The data collected from the Breaking2 project for example [12], has been cited 89 times with an Altmetric score of 1,128, and has been shared by 114 news outlets as well as hundreds of posts across multiple social media networks. Meanwhile, our first study of the ketogenic low-carbohydrate high fat diet in Tier 4–5 race walkers [135] has been cited 270 times, with an Altmetric score of 969, which includes nearly 1400 mentions on X (Twitter) to a readership of 4.4 million. This highlights the considerable impact, interest and translation these publications have generated both within and outside of traditional academic settings. Other key themes that have transcended outside of academia into common forums for athletes at a range of levels include novel training strategies (e.g., polarized training [79,80], the "Norwegian threshold model" [136], etc.), incorporation of heat and/or altitude training [137], recovery strategies (e.g., ice baths [138]) and ultra-high carbohydrate intakes during endurance exercise [139]. However, at present it is uncertain how many of these techniques are taken up by non-elite athletes, or are actually suitable in terms of cost, logistics and application to their physiological limitations.

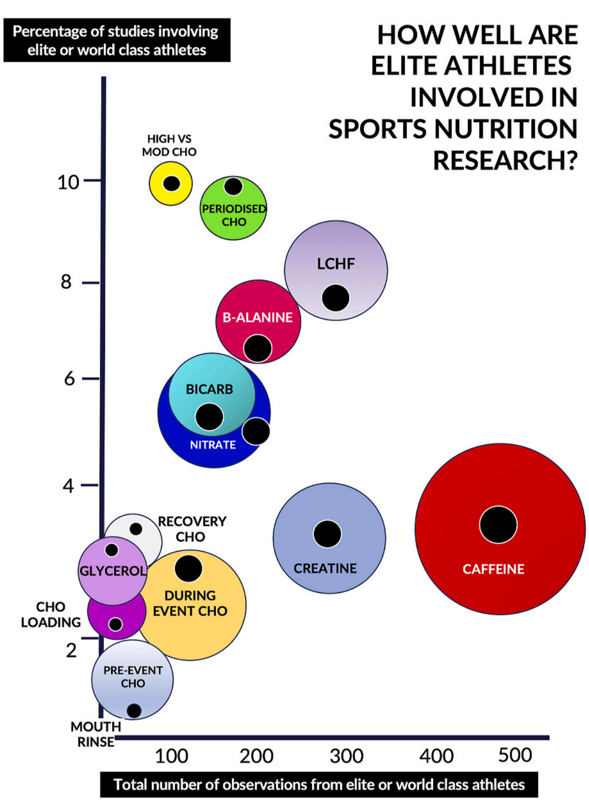

Fig. 3. Graphical representation of elite athletes (Tier 4 and Tier 5 athletes according to McKay system [2]) participation within studies of key themes in sports nutrition, in absolute numbers and as a percentage of the total number of studies. Size of the colored balls represent the total number of studies on each theme, while the size of the black balls represents the number of these studies which have included elite athletes. Data derived from systematic audits of sports nutrition literature [128–130].

8. Evidence that some sports science interventions may be less effective in elite athletes

Periodically, scenarios have developed in which strategies shown to enhance performance in studies of recreational and "trained" individuals (Tier 1–3 athletes) are suspected of having little or less efficacy in highly trained (Tier 3–5) athletes. Hypothetically, differences could occur if the strategy addresses a physiological/biochemical limitation that is not seen in the elite athlete due to genetic characteristics that have been self-selecting for their sporting prowess or the conditioning effects of their training history. Alternatively, differences in the characteristics of the competitive events undertaken by trained versus elite competitors may call for different strategies. Of course, differences in the apparent efficacy of a performance strategy may be an artifact of the literature; studies that fail to show benefits in elite athletes may suffer from methodological flaws that prevent real benefits from being exposed or detected. Table 2 illustrates two strategies involving sports nutrition in which the caliber of the athlete has been investigated as a systematic factor in determining their value to performance outcomes. This table demonstrates a process by which the elite athlete might consider the available information in deciding about their investment in various sports science strategies.

9. Evidence that sport science interventions may be irrelevant for recreational athletes

The flip side of the previous scenario is also true; some strategies and sports science interventions targeted at elite athletes are not useful for recreational level athletes. Tapering before a marathon for example, may be less relevant for a recreational runner who trains five sessions or less per week. Similarly, the risk of hyponatremia (water intoxication) is higher in slower runners than their elite counterparts when they consume fluid intakes that are suited to the high sweat rates of elite competitors [166,167]. Another topical example is the interest in protocols and products that allow endurance athletes to consume very high rates of carbohydrate intake during prolonged (>3 h) endurance events. Feeding protocols of up to 120 g/h of carbohydrate are now described in the scientific literature [139] and elite athlete practice [168]. This "carbolution" is enabled by commercial sports foods and drinks, based on combinations of carbohydrate sources with diverse intestinal transport mechanisms [169], and special hydrogel encapsulation that increases gastric emptying and muscle carbohydrate delivery [170]. As previously described, elite athletes are known to achieve high absolute and relative rates of energy production and rates of carbohydrate oxidation which may be enhanced by the availability of substantial amounts of exogenous carbohydrate. Meanwhile, recreational athletes have little need for such aggressive fuel support due to the lower energy turnover and absolute energy requirements of their event. Ironically, such products rely on use by recreational athletes to achieve commercial viability. Use of specialized sports products and equipment by recreational athletes (even if unnecessary) may be justified if it supports a market for verifiable uses and/or encourages community involvement in sport and exercise. Nevertheless, the recreational athlete should be aware of the unnecessary expense and the potential for side effects (e.g., gastrointestinal upsets from excessive intake of carbohydrate) when they misunderstand the difference in the physiological bases of their efforts. Therefore, there is a reciprocal need for appreciation of the true basis of sports performance.

10. Summary

Whether elite athletes follow or lead successful sports science practices is currently unknown and is arguably, a moot point. Although there are isolated studies of *some* practices of *some* of the world's best marathon runners, this information has not been systematically captured or extended to all champion level athletes. Furthermore, there is no evidence of cause and effect, and the frailties of the current literature, at least as has been examined in relation to sports nutrition, include the lack of

Table 2
Considerations for the elite athlete in considering the specific evidence base for the value of sports science strategies.

Discussion point	*Example 1: Periodization of training with low carbohydrate availability into training program*	*Example 2: Nitrate supplementation*
Explanation of the hypothesized benefit The physiological/mechanistic basis of the nutrition strategy should be understood so that special features related to the elite athlete can be isolated. These may arise from unique characteristics of the elite athlete or features of their specialized execution of training or competition.	Undertaking endurance exercise with low glycogen stores or prolonging its post-exercise restoration may upregulate or amplify the signaling cascades that underpin mitochondrial biogenesis and increased capacity for muscle fat oxidation [115]. A thoughtful combination of training and dietary sequences, which integrates high quality sessions with high carbohydrate availability, delayed refueling ("sleep low") and low-moderate intensity sessions undertaken with low carbohydrate availability may enhance the overall training outcomes, leading to enhanced performance [115].	Acute supplementation with inorganic nitrate may increase the formation of nitric oxide (NO) via the nitrate-nitrite-NO pathway that commences with the reduction of nitrate in the mouth by commensal bacteria in the oral microbiome [140]. NO may enhance sports performance by reducing the oxygen cost of exercise [141,142] or via direct effects on muscle contractility [143–145].
Hypothesis to explain possible differences in elite athletes In addition to individual- or event-derived differences (see above), elite competitors may already be close to their training/performance ceiling, making any potential changes harder to detect because of the smaller magnitude.	The high volume and intensity of training sessions, and the experience-derived sequencing of these sessions within the programs of most elite endurance athletes may already create strategic fluctuations in muscle glycogen [146,147]. Therefore, elite athletes may already achieve periodized carbohydrate availability without special dietary strategies. Finally, the imposition of low carbohydrate availability strategies on high volume training may cause additional fatigue that requires a specific taper before performance outcomes are evident.	A thoughtful point: counterpoint activity has been undertaken to consider the relevance of nitrate supplementation to elite athletes [148–150]. Elite endurance athletes may have greater percentage of Type I muscle fibers, greater muscle capillarization and adaptation (which reduces the development of hypoxia and metabolic acidosis), and a more developed pathway to produce NO from arginine; these conditions may reduce the benefit of an enhanced activity of the nitrate-nitrite-NO pathway [151].
Evidence that elite/highly trained athletes have different responses from recreational athletes. A summary of the literature may detect apparent differences in the response of athletes of different caliber/training volume. Greater interest is focused on studies that directly compare the responses of elite versus recreational athletes, or meta-analyses that can identify factors that contribute to performance benefits. Ideally, some of these studies will measure characteristics that provide a mechanism to explain different outcomes.	Studies of Tier 2–3 endurance athletes have shown that those who undertook strategic periodization of carbohydrate availability over a one week [152] or three week [153] training block achieved greater performance outcomes compared to groups training undertaken with sustained high carbohydrate availability. Meanwhile, studies in Tier 3–5 athletes have failed to show a superior performance outcome with periodized versus sustained high CHO availability [135,154,155].	According to a study of nitrate supplementation in athletes of different calibers [156] "individual aerobic fitness level affects the ergogenic benefits induced by dietary nitrate supplementation. The optimal nitrate loading regimen required to elevate plasma nitrate and to enhance performance in elite athletes is different from that of low-fit subjects and requires further studies". In addition, a meta-analysis of nitrate supplementation studies found that the benefits were only significantly observed in active individuals and recreational athletes [157]. Several studies in Tier 3–5 cohorts have failed to find a benefit of nitrate supplementation [158–160].
Alternative explanation for apparent differences between lesser trained/lower caliber athletes and high-performance athletes Aspects of the literature should be examined to identify whether studies were undertaken with a methodology that was likely to allow any real benefits to be detected. Type 2 errors are common in small sample sized studies, which are typical of sports nutrition interventions, especially in elite athletes.	There are very few studies of periodized versus sustained high carbohydrate availability on training adaptation and performance outcomes, because of the difficulty of undertaking chronic training-nutrition studies.	Many studies within the nitrate supplementation literature have failed to use adequate/optimal dosing protocols or focused on a performance protocol that was highly variable, or unlikely to be affected by NO availability [161]. Therefore, some studies involving high performance athletes may not have been able to adequately test the efficacy of nitrate supplementation.
Decisions for the elite athlete: should they use the strategy? Pros and cons of using the strategy should be examined. Studies that are more suited to the elite athlete, with optimal protocols, might be given more prominence in decision making. An individual case study approach (involving the specific athlete and controlled observation of special training sessions or lower-level competition) could be implemented to confirm the benefit of the strategy and any fine-tuning that may promote benefits.	The elite endurance athlete should assess their current training and nutrition strategies to identify how well these appear to match fueling practices to the goals of each session. In some cases, they will find that "trial and error", or daily logistics/cultural considerations have created sequences that already achieve periodization goals. Disadvantages to overemphasis of low carbohydrate availability strategies, include fatigue and an increased risk of illness and injury [122,162]. Athletes typically change the emphasis of their training-nutrition strategies across the course of the season, with deliberate integration of some low carbohydrate availability strategies in the base phase, and greater emphasis on fueling support for high-quality sessions, particularly during immediate preparation for competition [163,164].	There are few side-effects from nitrate supplementation other than pink stools or urine following the intake of beetroot juice. Some studies [165] and individuals within investigations involving Tier 3–5 athletes [158], show benefits of nitrate supplementation with specific events and dosing protocols. High performance athletes/events in which a higher dose/pre-loading protocol is used, and performance involves shorter, higher-intensity exercise that creates greater hypoxic and acidic stress, and the relatively greater involvement of type II muscle fibers or small muscle groups might be targeted [140]. The elite athlete should experiment with their use of nitrate supplementation in scenarios that have a plausible chance of gaining a benefit, and make an individualized decision [150].

representation of elite athletes in the studies that underpin "evidence-based" guidelines, and the presence of findings that some interventions have different effects on elite vs lesser trained individuals.

While only a tiny fraction (<0.1%) of the world's population will ever compete at the Olympics, we contend that understanding and studying the physiology of elite athletes is important. Looking "under the hood" of these uniquely endowed individuals highlights the capacity of the human being and provides insight into what can be achieved through optimized training and nutrition practices. Over 30 years ago Joyner wrote a provocative paper in which he modeled the "limiting" factors in human endurance performance for the marathon, on the basis of various combinations of previously reported values of $\dot{V}O_{2max}$, lactate threshold, and running economy in elite distance runners [49]. The fastest time for the marathon predicted by Joyner was 1:57:58 in a hypothetical subject with a $\dot{V}O_2$max of 84 mL/kg/min, a lactate threshold occurring at 85% of $\dot{V}O_{2max}$, and exceptional running economy [49]. While this time may have seemed impossible as recently as 10 years ago, the recent global improvements in running times for both men and women has made this time a real possibility. Indeed, substituting data collected from the Breaking2 athletes into this model yields a theoretical time of 1:55.05 [12,50]. And while the symmetry of a 2 h marathon naturally captures the imagination in a manner similar to when Sir Roger Bannister broke the "impossible" 4 min barrier for the mile, it is worth noting that the estimated female equivalent (~2:10 [171]) is also on the horizon, or may have even already been achieved [172]. With additional advances in technology, nutrition, and the extremes of physiology – it may perhaps be wiser to ask not how likely it is for us to see such performances, but rather when.

CRediT authorship contribution statement

Louise M. Burke: Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **Jamie Whitfield:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **John A. Hawley:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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