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## VIEWPOINT

# Commentaries on Viewpoint: Physiology and fast marathons

### COMMENTARY ON VIEWPOINT: PHYSIOLOGY AND FAST MARATHONS

TO THE EDITOR: An essential addition to the Viewpoint of Joyner et al. (3) is to consider how the pacing strategies of word record (WR) holders have changed in the last decades (1). As such, from 1967 to 1988, athletes used to start off faster than the goal speed needed to break the WR, and due to these unsustainable initial speeds, they displayed significant speed losses in the second half of the race. However, since 1988, it seems that the pacing strategy has moved from a positive to a negative profile, with athletes speeding up from the 25th km to the finish line (1). The trend toward smaller pace variations between 5-km sections in recent WRs also suggests that a more stable pacing, with an average speed almost equal for the whole race, may be the pacing goal for future WR seekers. One way of ensuring such a stable pace is a careful selection of the course profile. For example, for the "Breaking2" attempt, Nike looked for a course as flat as possible (Monza, Italy), and in the subsequent Ineos 1:59 Challenge, Kipchoge ran on a flat course with only 2.4 m of elevation change. Within the conventional WR eligible races, Berlin, one of the most likely candidates in terms of potential venues for future WR attempts (2), is relatively flat (starts at an elevation of 38 m above sea level and never exceeds 53 m), and has a net downhill profile over the final 15 km.

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### BETTER ENGAGEMENT DURING FAST MARATHONS

TO THE EDITOR: We would like to comment on the Viewpoint by Joyner et al. (3). Research has outlined that elite marathon runners possess excellent running economy among other well-known physiological and biomechanical determinants (2). Not only is whole body dynamic exercise metabolically costly, but neural processing effort, requiring the brain's limited metabolic resources, continually occurs during prolonged exercise (4), notably for self-paced exercise like running a marathon. Under the umbrella of energy saving, executive functioning capacity resting on goal-oriented behavior may also explain differences in endurance performance even at top levels. First, executive function may be predictive of endurance performance (1): faster runners would have better inhibitory control, not only over motor responses but also over interfering, distracting information. Further, the elite athletes through deliberate practice over the years may have developed the ability to execute their patterns free of much frontal cortex participation. Neuroimaging studies corroborate this idea, as prefrontal cortex activity is seen to decrease in elite Kenyan runners (5). Second, effective pacing involving cognitive control and decision-making process is crucial to endurance performance. As highlighted (2), optimal pacing was an important factor in the exhibition event to break the 2-h barrier. Given that marathon might be seen as an effortful cognitive task that places high demands on several brain areas related to emotional, motivational, interoception, and executive processing, pacing assistance would be valuable in reaching an automatic mode to divert resources effortlessly and when needed. Thus, we can assume that this strategic conservation of mental effort resources through pacing aid may lead to hypofrontality phenomenon (4) and the so-called neural efficiency.

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### PHYSIOLOGY AND FAST MARATHONS: "THE PROPULSIVE AND MUSCULAR EFFICIENCY," KEYSTONES OF RUNNING PERFORMANCE

TO THE EDITOR: Joyner et al. (5) in their Viewpoint left no stone unturned in their search for determinants of Kipchoge's world record. However, they poorly defined the "mechanical efficiency," which should be clarified since it is a key parameter of running performance.

The minimum, inevitable, work that Kipchoge et al. did to cross the finish line is given by the external frictional drag times the 42.195 km. The overall efficiency can thus be expressed as the ratio between this minimum work and the chemical energy transformed by the muscles (2). It can be also defined as the product of the "muscular efficiency," indicating the ability to transform chemical energy into muscle work, and the "propulsive efficiency," indicating the ability to utilize the muscle work to move the body against the wind resistance.

While Kipchoge's recent performance may be partly explained by lower drag due to his body shape and drafting, the recent improvements of running performances are certainly closely related to an enhancement of muscular efficiency. For instance, trained subjects can exploit better the dynamic coupling between segments to save mechanical energy than untrained (1). Additionally, smaller muscle-tendons (and shoes!) hysteresis in athletes (3) reduces the imbalance between energy dissipation and generation, a major determinant of the running cost (4).

Scientific contributions on fatigue resistance, muscle strengthening, and training intensity have potentially led to biochemical and neuromechanical adaptations, improving efficiency. Even a small enhancement of the role played by elasticity may especially impact long-distance performances, by reducing muscular fatigue over a huge number of steps.

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## NEUROMUSCULAR FUNCTION: THE POWER BEHIND FAST MARATHONS

TO THE EDITOR: I appreciate the physiologically informed discussion presented in the Viewpoint by Joyner et al. (3), highlighting the potential mechanisms underpinning the recent marathon performances by Eliud Kipchoge and Brigid Kosgei. The authors note that at the elite level maximal oxygen uptake of endurance athletes is likely similar to that which was reported in the 1960s (4); therefore, other factors beyond improved cardiac output and arteriovenous oxygen difference must be considered. Taken together with the lack of data demonstrating higher lactate thresholds in elite runners compared with the 1960s, it is most plausible that Kipchoge and Kosgei achieved greater improvements in running economy (RE). Although the authors provide a biomechanical perspective for differences in RE, I believe the potential training-related neuromuscular adaptations (e.g., force, velocity, and power) and the subsequent effect on RE have been underappreciated in this discussion.

For example, Kipchoge regularly performs tempo runs consisting of interspersed high-speed sprinting and jogging (3). Explosive exercise training of this nature has been shown to improve neuromuscular characteristics and RE (1, 2) in absence of changes in maximal oxygen capacity (1). This may be due to increased muscle stiffness or motor unit coordination and/or recruitment resulting in *1*) greater storage and utilization of elastic energy, *2*) reduced ground contact time, and *3*) reduced energy expenditure (1, 2). Collectively, these neuromuscular adaptations would allow endurance runners to run at a greater relative peak power output and/or reduce rate of muscle fatigue (1, 2, 5). Thus, it is pertinent that differences in neuromuscular attributes are considered in this discussion.

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## TIME-DEPENDENT PHYSIOLOGICAL CHANGES—THE MISSING PIECE OF THE MARATHON PUZZLE?

TO THE EDITOR: While the Viewpoint by Joyner et al. (3) superbly summarizes key factors underlying marathon running physiology and potential reasons for recent records surge, the inherently dynamic physiological nature of marathon running might have been understated. To comprehensively interpret marathon performance, one also needs to consider the time-dependent physiological alterations during both the actual marathon run and the preceding training. In particular, the average elite marathon running velocities can be explained by regression calculations using "static" values of maximal oxygen uptake, lactate threshold (LT) and running economy (RE) (2). However, given the dynamic nature of long-distance running, the contribution of these determinants to subsequent physiological responses and actual running performance significantly varies and cannot be precisely predicted by static values modeling. The variation can relate to both the relative contribution/importance of each factor and the duration-related dynamic differences. Indeed, LT can be altered due to potential glycogen-depletion-related reduction in lactate production while RE is known to decrease as a function of running duration (4). Training also represents a complex dynamical system comprised of numerous fluctuating determinants (i.e., intensity/duration/frequency, hypoxic/heat training, tapering) further complicated by the distinct individual (5) and daily (1) variability in training-induced responses. It, thus, seems crucial to constantly monitor the corresponding training-related physiological fluctuations. Given our currently scarce understanding, further exploration of time-dependent dynamics of physiological determinants during both the marathon running and training seems warranted. It will provide important insight into the often omitted "dynamic" aspect of the marathon performance puzzle and, ultimately, limits of marathon running.


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## FAST MARATHON PHYSIOLOGY: THE ROLE OF CARDIAC TROPONINS

TO THE EDITOR: Marathons are a showcase of exquisite physical prowess as well as a remarkable opportunity for physiological discovery. Joyner et al. (1) in their Viewpoint "Physiology and fast marathons" analyze the factors that have led to the recent improvements in the marathon and 1,500-m run world records. They conclude that reductions in time come from the interplay between biological ability, intensive training programs, and modern techniques such as drafting and pacing. Moreover, better shoes, optimized tracks, and carbohydrate feeding could have also played a role by increasing running efficiency. Parallel to these advances, there is a strong body of evidence suggesting that cardiac troponin (cTn) levels rise as a consequence of running a marathon, specially in young male runners (2, 3).

Troponin, a heterotrimeric protein complex that regulates muscle contraction, is a valuable biomarker in cardiology, used to define acute myocardial infarction or AMI (4). However, the prognostic significance of cTn elevation in the setting of a marathon is controversial (5). From a physiological viewpoint and returning to the topic of marathons, it would be interesting to evaluate if the magnitude of troponin rise is altered with the presence or absence of the novel running techniques (i.e., drifting, pacing, specialized shoes, improved tracks, and carbohydrate feeding). This is a unique opportunity to study the release of cTn triggered by exercise and could inform whether the release of troponins is a modifiable phenomenon. Thus marathons are more than ever a valuable method for the advancement of cardiovascular research and could potentially provide the much-needed answers for the clinical dilemma around cardiac troponins and endurance running.


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## PREDICTING FAST MARATHON PERFORMANCES WITH ADVANCING AGE

TO THE EDITOR: Over the last three decades, the improvement in the marathon world record (WR) has been ~4–5% for elite runners (1). During the same time period, marathon performances of the best master runners have improved at a much greater rate, especially for the older age groups (> 60 yr old) (2, 3). When changes in marathon world record performances are considered with advancing age, the decline in performance is ~10% per decade. For example, the marathon WR for a 60-yr-old male is 02:36:30, which represents a running velocity 22% slower than that of the world's fastest time, set by Eliud Kipchoge (age 34 yr old). However, this trend of age-related decline in marathon performance is based on WRs that belong to different runners and thus induces bias in the analysis. Previous studies showed that the age-related decline could be limited to 5–7% per decade at least until 60 yr of age for the same well-trained individual (4). Imagine therefore that Kipchoge remains competitive until 60 yr old. If so, we could predict a 6% decline in velocity per decade which would result in a marathon time of 02:18:15 at 60 yr old i.e., 18 min faster than the current WR for a 60-yr-old. This simulation suggests that marathon WRs in master categories will probably continue to improve in the future if ex-elite runners preserve their motivation to compete as they age. These super master runners will therefore offer valuable information about how lifelong endurance exercise can counteract the age-related decline in integrative physiological function (3, 5).


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## PHYSIOLOGY AND FAST MARATHONS—FUTURE IMPROVEMENTS THROUGH BRAIN STIMULATION?

TO THE EDITOR: In their Viewpoint, Joyner et al. (1) describe the physiological underpinnings of maximal oxygen consumption ($\dot{V}O_{2max}$), lactate threshold, and running economy in light of the recent improvements in marathon world records. Rightfully, the authors point to advancements in footwear design and even the psychological benefits of pacing when reviewing determinants of running economy. While adequate, it is apparent that most recent improvements in running economy are of peripheral or environmental origin, potentially approaching a point of diminishing returns apart from further technological progression. Although less work exploited central nervous system (CNS) circuitry, central fatigue (CF) is known to influence endurance performance (3), suggesting a putative role for the CNS in marathon outcomes. Transcranial magnetic stimulation (TMS) and the more portable direct-current stimulation (tDCS) (2) are two noninvasive brain stimulation techniques that can alter corticospinal excitability, and thus provide a theoretical alternative to reduce the energetic cost of running. As the performance-enhancing benefits of tDCS/rTMS remain inconclusive, better targeting strategies and repeated, instead of single-session, studies are needed. Although consecutive sessions of brain stimulation warrant careful monitoring, refined stimulation parameters and insight from neuroimaging modalities, such as positron emission tomography (PET) using the glucose analog fluorodeoxyglucose, could provide intriguing information about whole body energetic costs (i.e., glucose uptake of brain and active skeletal muscle) during running (4). If brain stimulation effectively modulates supplementary motor area-, dorsolateral prefrontal-, or primary motor cortex activity, similar improvements in perceived effort (5) as during pacing are plausible, presenting a framework for future endurance performance improvements.

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## IS PHYSIOLOGY OF FAST MARATHONS THE SAME FOR ALL AGE GROUPS?

TO THE EDITOR: In their Viewpoint, Joyner and colleagues (1) provided a comprehensive overview of the physiological basis of fast marathon focusing on the physiology of the fastest runners independently of age. Considering the age of peak performance in marathon and the increased number of master runners participating in marathon races during the last decades (4), the physiological mechanisms reported by Joyner et al. (1) should be verified in master runners, i.e., those older than 40 yr old (2). It was acknowledged that physiological characteristics related to race time (maximal oxygen uptake, anaerobic threshold, and running economy) declined with age (2). Nevertheless, the older fast age groups—despite their slower race time compared with younger fast age groups—paced similarly as their younger counterparts (3). The ability of fast master runners to pace similarly as fast younger runners might be attributed to nonphysiological aspects. For instance, fast master runners might be considered as more "selected" runners compared with their younger counterparts considering the decreasing rates of participation in marathon races with age (3, 4). In addition, fast master runners accumulated a long sport experience, e.g., number of finished marathon races and training volume, which might offset the decline of physiological characteristics with age. Nowadays, master marathon runners compete at a high level, and considering their specific characteristics and increasing number, future research should examine the physiological characteristics of fast master marathon runners.

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**PHYSIOLOGY AND FAST MARATHONS: AN INTEGRATIVE APPROACH**

TO THE EDITOR: Joyner et al. (4) have presented an elegant discussion on the physiological factors that may have contributed to the improvement in marathon performance in recent years. The authors outlined classic physiological traits associated with endurance performance, such as the maximum oxygen consumption ($\dot{V}O_{2max}$), lactate threshold, and running economy [RE (4)]. Unfortunately, there are multiple combinations by which these aforementioned physiological traits result in a similar marathon performance [e.g., a modest $\dot{V}O_{2max}$ and outstanding RE (4)]. A better approach to understand the physiology of fast marathons may be derived from the maximal intensity at which a steady state can be achieved. The relationship between speed and the duration until task failure is hyperbolic, and its asymptote termed critical speed (CS). Jones et al. (2) argued that CS is the "gold standard" to determine the maximal metabolic steady state. Furthermore, CS seems to be an excellent predictor of endurance performance (5). Indeed, Jones and Vanhatalo (3) reported that a group of elite athletes, on average, completed their fastest marathon at ~96% of their CS. Critical power, the cycling analog of CS, has been shown to decline with prolonged exercise (1), which may explain the fractional utilization of CS in the marathon. Further research should investigate whether data from elite athletes (3) are applicable to other populations (e.g., recreational athletes). In summary, marathon performance requires steady-state exercise, and CS has been proposed as the "gold standard" to assess maximal metabolic steady state. Therefore, CS offers an integrative approach of the physiological factors underpinning marathon performance.

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**PHYSIOLOGY AND FAST MARATHONS: LESSONS FROM MASTERS ATHLETES**

TO THE EDITOR: In their Viewpoint, Joyner et al. (2) proposed that a convergence of factors (physiology, training, technology, and logistics) may explain the recent swift improvement in marathon times. While we agree on the importance of these factors and we acknowledge previous research in elite marathon runners, we believe that masters athletes can add to the discussion for reaching fast marathons. The analysis of recent exceptional performances in masters runners (2:27:52 and 2:54:23 at 59 and 70 yr of age, respectively) reveals a common characteristic among these athletes, which is a very high fraction (91–93%) of $\dot{V}O_{2max}$ at marathon pace (4, 5). In comparison, elite runners generally sustain 80–85% $\dot{V}O_{2max}$ on the marathon with a quite similar running economy (1, 2). These data show new limits to human physiological capacities during endurance exercise and raise questions about the determinants of performance in the marathon. We may first wonder if the best marathon runners could sustain >90% $\dot{V}O_{2max}$ on the marathon, and by how much the current record could be improved. We may also wonder if the higher fractional utilization of $\dot{V}O_{2max}$ observed in masters could derive from the reduction of $\dot{V}O_{2max}$ with aging or could result from specific long-term training adaptation. Finally, it reopens the debate about the optimization of training for the marathon; should the fractional utilization of $\dot{V}O_{2max}$ become a priority with advancing age? Within this context, masters athletes require the continued attention of exercise physiologists, and a better knowledge of their training practices could be valuable for improving performance after 40 yr of age (3).

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**MARATHON RECORD BREAKERS: IS IT IN THE GENES?**

TO THE EDITOR: As discussed in the Viewpoint by Joyner et al. (2), the combination of outstanding values in major physiological determinants of marathon performance, along with the latest technological advances, has contributed to the recent progression in marathon world records. Interestingly, most of the best marathon times have been obtained by Kenyan or Ethiopian runners, which reinforces the common believe that these athletes might also have the right genetic pool. However, limited evidence is currently available on the influence that genetics exert on athletic performance (1), which may be due to the multifactorial nature of the latter.

A recent systematic review including 10,442 participants, of whom 2,984 were elite marathoners, identified 16 single-nucleotide polymorphisms associated with marathon performance (3). There is, however, a lack of replication studies of most of these genes, and thus it is not possible to identify yet the optimum genotype for endurance running performance (1, 3). Further, about half of world-class endurance athletes do not possess the supposedly "optimum" genetic pool (5), which suggests that having the right genetics might favor but not determine the odds of achieving elite-level performance, possibly due to the key influence of epigenetics.

Although genetics are commonly considered an important factor to break the 2-h marathon barrier, we still do not possess any genetic tool to identify those runners with greater chances of achieving this feat (4). Future multicenter research involving whole genome sequencing, especially in top level marathoners, is needed to identify the performance-enhancing polymorphisms that would allow athletes to break the limits of human performance.

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### STRENGTH TRAINING AS AN ERGOGENIC TOOL TO ENHANCE RUNNING ECONOMY AND ELITE MARATHON RUNNING PERFORMANCE

TO THE EDITOR: The Viewpoint by Joyner and colleagues (4) provides an eloquent summary of the physiological characteristics required for elite marathon running. Practically, the training insights of the world's best marathon runner are also useful for applied practitioners in helping to understand the preparation required to reach this level.

Although we appreciate that the focus of the section entitled "TRAINING" in Joyner and colleagues (4) was intended to be running-related, we feel it is important to highlight the value of strength training as a strategy to enhance running economy (RE) and performance (1). This is particularly important for highly trained distance runners, who possess similar maximal oxygen uptake values, but display considerable variation in how much oxygen it costs to run at a given speed (2). Given the small margins of improvement that are possible using conventional running training methods at the elite level, we contend that an appropriately designed and periodized routine of strength training is likely to offer a potent stimulus to the neuromuscular system that enhances RE and marathon performance.

The mechanisms that underpin an improvement in RE following a period of strength training remain to be fully elucidated. It has previously been shown that greater muscular strength endurance confers a fatigue-resistant effect resulting in smaller decrements to RE following intensive running (3). Although further work is required to confirm whether a relationship exists between strength qualities and deteriorations in RE during prolonged running, we speculate that improvements in marathon running performance are possible via this mechanism.

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### IS ALTITUDE TRAINING ONE OF THE KEY FACTORS IN FAST MARATHONS?

TO THE EDITOR: In a recent Viewpoint, Joyner et al. (2) discussed the main factors responsible for the larger performance enhancement in marathon (4–5%) than for the 1,500-m run (1–2%) over the last 30 years. Their section on TRAINING (2) reports some interesting novel data with historical comparison. In our view, the most important difference between the current training methods and those of the 1950s is the importance of altitude training. To our knowledge (4), most—if not all—elite marathon runners used altitude training. The diversity of these methods has been enlarged in the last 10 years (4). The total volume of training spent in altitude has been increased in many endurance sports over the last 30 years (1), and Joyner et al. (2) reported that "Kipchoge often trains in excess of 200 km/wk at high altitude." In fact, altitude training is now integrated into the winter preparation program (1) and not only used as a precompetition peaking strategy, as 20–30 years ago (1). Among the beneficial effects of this "extended" altitude training, an enhanced running economy has been shown (5). Since this latter represents one of the main determinants of endurance exercise performance in elite (2) and master marathon runners (3), altitude training may be directly (increased hemoglobin mass) or indirectly (improved running economy) considered as one of the training key factors in fast marathons.

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## CRITICAL SPEED: A GOOD ALTERNATIVE FOR TRAINING PRESCRIPTION, PERFORMANCE PREDICTION, AND TRAINING QUANTIFICATION IN MARATHON RUNNERS

TO THE EDITOR: The main determinants of performance during the marathon are *1*) maximal oxygen uptake ($\dot{V}O_{2max}$), *2*) ability to sustain high percentages of $\dot{V}O_{2max}$ during long periods of time, and *3*) running economy (RE) (3). The fractional use of $\dot{V}O_{2max}$ is related to the ability to sustain high workloads before lactate begins to accumulate in the blood, i.e., the so-called lactate threshold (LT) (3). Another important concept is the critical speed (CS) considered the boundary between fatigue and performance during endurance exercises (4). Typically, LT occurs at 75–90% $\dot{V}O_{2max}$ (1) while CS occurs at higher absolute and relative intensities (2). Thus, physiologically, LT demarcates the transition between moderate- and heavy-intensity domains while CS demarcates the transition between heavy- and severe-intensity domains (1). Consequently, workloads above CS promote an increase in oxygen consumption, blood lactate accumulation, and a worsening in RE, causing a decrease in performance. In a literature review, Jones and Vanhatalo (2) showed that elite long-distance runners complete the marathon distance, on average, at 96 ± 2% of their CS. In this way, considering that currently, CS is the main landmark for separating the physiological limit at which physiological homeostasis can be maintained during prolonged exercises (1), we believe that CS can be an attractive tool to guide the prescription of training intensity, as well as the race-pace strategy for the marathon. Furthermore, future studies should verify CS as a method to quantify the training intensity distribution, similar to other studies that used blood lactate accumulation as a reference (5).

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## PHYSIOLOGY AND FAST MARATHONS: CURRENTLY, CAN TECHNOLOGY BE CONSIDERED THE MAIN VARIABLE OF THIS PERFORMANCE?

TO THE EDITOR: We would like to comment on the recent Viewpoint by Joyner et al. (2). Recently, the search for breaking two hours in the men's marathon has increased the discussion of what to do to achieve this goal (1–3). Determination and prediction factors of endurance performance such as maximal oxygen consumption ($\dot{V}O_{2max}$), velocity corresponding to $\dot{V}O_{2max}$ sustained for the maximal time, running economy, and anaerobic threshold are elucidated by the literature (2). As much as the combination of neural (4), metabolic, and mechanical mechanisms (5) are the main adaptations for performance, technology must also be added in this process. The evolution of running shoes and their relationship with performance are based mainly on sports biomechanics. Models that combine high midsoles, rigid carbon fiber plates, and low weight have been used even by athletes sponsored by other sports brands. Foams are highly compliant and resilient, cushioning, storing and returning energy in mechanical response. Carbon plates, on the other hand, can increase longitudinal flexural stiffness (1), providing modifications in the lever systems and consequently a possible improvement of the stretch-shortening cycle. For these reasons, World Athletics banned the use of a shoes prototype that had already been used in street competitions, further increasing the possible mechanisms related to shoes technology. Thus, in the current scenario, can technology be considered the main variable in fast marathons? We suggest vigorous discussions and studies on the topic.

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## POPULARITY PRESERVES PHYSIOLOGY

TO THE EDITOR: In their Viewoint, Joyner et al. (2) explain the recent advancement of the marathon world record by acknowledging the synergistic influence of training advancements, technology, nutrition, and optimal physiology. Omitted from the discussion, however, is the recent popularization of the marathon. The rising popularity of the marathon represents increased opportunity to race, to win, and to make running a financially viable occupation. As a result, the draw of the marathon has increased, and more runners have devoted their efforts towards this distance (3). Popularization of the marathon would also cause some top athletes to migrate from the track to pursue the luster of the roads. That this has occurred is perhaps most intriguing when one remembers that Eliud Kipchoge was once a 5,000-m track world champion. Additionally, the newfound opportunity afforded by the popularity of the marathon has undoubtedly prolonged the running careers of a number of athletes who otherwise may have retired following successful stints on the track. Some highly trained, aging athletes can maintain $\dot{V}O_{2max}$, lactate threshold, and running economy into their mid to late 30s (1), and the marathon has benefited from having runners continue to compete during these years. For example, world leading times have come from 35-yr-old Haile Gebrselassie (2:03:59), 37-yr-old Kenenisa Bekele (2:01:41), and even 34-yr-old Eliud Kipchoge (1:59:40). In conclusion, the rising popularity of the marathon has attracted a greater talent pool and has preserved the career of top-tier athletes whose elite physiology remains conducive to world class performance.

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## PHYSIOLOGY AND FAST MARATHONS: THE IMPORTANCE OF CEREBRAL DEMAND AND OXYGENATION

TO THE EDITOR: With interest we read the Viewpoint by Joyner et al. (2) addressing the physiology of fast marathons. In addition to the prerequisite of a high $\dot{V}O_{2max}$, the ability to sustain a high % of $\dot{V}O_{2max}$, and excellent running economy (2), we consider a role for cerebral oxygenation. A reduction in cerebral oxygenation has been implicated in the development of central fatigue as a limitation for exercise performance (4). Among elite Kenyan (Kalenjin) runners (mean half-marathon time 62.2 ± 1.0 min), the top performers in a 5-km trial are those who best maintain their cerebral oxygenation (3). Although a reduced ventilatory drive during exercise would attenuate reduction in $Pa_{CO_2}$ and in turn cerebral blood flow and oxygenation, Hansen et al. (1) found, by clamping $P_{ET_{CO_2}}$ during high-intensity exercise (~90% $\dot{V}O_{2max}$), that despite preventing the hyperventilation-induced reduction in $Pa_{CO_2}$ and the concomitant decrease in cerebral flow velocity, cerebral oxygenation was reduced at exhaustion. We take reduction in cerebral oxygenation to indicate that during maximal exercise the cerebral demand exceeds the $O_2$ delivery even under conditions of maintained cerebral blood flow (1), suggesting that not only $O_2$ delivery but also the magnitude of cerebral $O_2$ demand is important for exercise tolerance. It may be that Kenyan runners due to both excellent genetically endowed mechanical efficiency (2) and training (5) are better in attenuating the cerebral $O_2$ demand for running and thus maintain cerebral oxygenation that contributes to the astonishing middle- and long-distance performances in this population (2).

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## INTERPERSONAL SYNCHRONIZATION IN PACING STRATEGIES AND LOCOMOTOR-RESPIRATORY AND CARDIAC COUPLING AS POTENTIAL FACTORS INFLUENCING MARATHON RUNNING PERFORMANCE

TO THE EDITOR: The physiological mechanisms determining endurance exercise performance have been studied mainly regarding various organismic subsystems and influencing factors. We want to emphasize that endurance performance is multifactorial and has to be considered holistically regarding interactions between the organism and the environment. In their Viewpoint, Joyner et al. (3) offer physiologically informed discussion about why marathon times have fallen so dramatically in the last decade. We would like to add a new aspect to the discussion that will address the increased implementation of pacing groups with multiple pacers in the majority of international marathon races and the influence of interpersonal synchronization on the running rhythm. Drafting behind another runner during a marathon provides substantial metabolic benefits (2), and besides running at a steady pace and drafting, running in a group can have additional effects. It has been shown that synchronization occurs preferably during side-by-side running (4) and that interpersonal synchronization can optimize running economy and performance (1). Furthermore, synchronization in step frequency comes along with additional synchronization of other physiological parameters such as breathing frequency, stated as locomotor-respiratory coupling and could have benefits for the entrainment between cardiac and locomotor rhythms (5). For interpersonal synchronization to occur, similar leg length, stride length, and step frequencies between two or a group of runners are prerequisite (4).Taking advantage of spontaneous interpersonal movement synchronization might be an important factor when optimizing pacing strategies. Further research is necessary to provide recommendations for specific pacing strategies to take advantage of interpersonal synchronization to enhance endurance performance.

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## PHYSIOLOGY AND FAST MARATHONS: THE ROLE OF BIOLOGICAL AGE

TO THE EDITOR: Biological age is a key factor contributing to fast marathon performance; however, the optimal age is unknown. At the time of their respective world record performances, Eluid Kipchoge was 33.8 yr old whereas Brigid Kosgei was only 25.6 yr old. As presented by Joyner and colleagues (3) in their Viewpoint, determinants of marathon performance include $\dot{V}O_{2max}$, "lactate threshold," and running economy. Although $\dot{V}O_{2max}$ declines on average by 1% per year after ~25 yr of age (1), this decline can be blunted among elite athletes who maintain high levels of training (5). Potential age-related declines in "lactate threshold" are likely secondary to reductions in $\dot{V}O_{2max}$ (4); thus, the optimal age for marathon performance is primarily a trade-off between $\dot{V}O_{2max}$ and running economy. Laboratory data from Paula Radcliffe, the previous world record holder for the women's marathon, demonstrate a 15% improvement in running economy and no change in $\dot{V}O_{2max}$ from age 18 until 29 yr when she set the marathon world record (2).

Together, these laboratory and performance data suggest there is a broad range of optimal age for marathon performance over nearly one decade of life, influenced by an age-dependent trade-off between $\dot{V}O_{2max}$ and running economy. Although personal best performances by Kipchoge and Kosgei have incrementally improved, likely reflecting progressive improvements in running economy, how much longer will these record-setting athletes maintain an optimal physiology to perform fast marathons? The approximately decade-long optimal age for fast marathon performances may be dwindling for Kipchoge and just beginning for Kosgei.

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## COMMENTARY ON VIEWPOINT: PHYSIOLOGY AND FAST MARATHONS

TO THE EDITOR: Joyner et al. (3) in their Viewpoint raised a relevant discussion regarding elite marathoners' main performance determinants. Notwithstanding its solid background, some methodological and conceptual questions may arise. We agree on identification of the lactate threshold (LT) and running economy (RE) as the most decisive physiological variables to paramount marathon performances. However, LT hardly represents the ability to sustain high intensities before lactate starts to accumulate in blood (3) or the metabolic rate above which lactate first rises above baseline during incremental exercise (1–2 mmol/L) (1), but the ability to exercise as fast as possible without losing body homeostasis. Running fast for long periods without increasing significantly muscular acidosis does not mean that lactatemia could not rise, as well established in the maximal lactate steady state methodology (2). Thus, the LT might not happen at 80–85% of $\dot{V}O_{2max}$ but higher particularly in elite athletes with a very well-developed aerobic capacity [as hypothesized by Joyner et al. (3) and observed by us for high level runners, cyclists, rowers, and swimmers]. Second, we consider that not only submaximal intensities should be used when assessing RE (3), but also all the steps of an incremental protocol to exhaustion should be included. Furthermore, both aerobic and anaerobic contributions should be considered. In fact, if a step protocol is interrupted before the last steps and only $\dot{V}O_2$ values are computed, RE could be overestimated (5). Last, we find it misleading to consider LT and RE as exclusively physiological markers since exercise metabolic effects are closely dependent on biomechanical/coordinative patterns (4).

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## LONG DISTANCE CAPACITIES OF AMERINDIANS

TO THE EDITOR: Joyner et al. (4) analyze the main factors contributing to the improvement in marathon races emphasizing $\dot{V}O_{2max}$, lactate threshold, and running economy (RE). We consider it important to foreground the role of high altitude. There is evidence that four weeks of training periods at simulated 2,000–3,100 m can decrease the $\dot{V}O_2$ for a given velocity (5). Also, there are interesting investigations not only in African but also in Amerindian athletes. The latter living between 2,000 m and more than 4,000 m of altitude are not such good marathon runners as East-Africans, but successful on longer distances. Interestingly they do not train only on mountain planes but also on steep ascents. The last Tour de France winner Egan Bernal living near Bogotá/Colombia may climb from 500 m to 3,000 m during one training unit (2). Similarly, the Tarahumara tribe in Northern Mexico live and train alternately between 800 and 2,400 m of altitude. They usually do not win Marathon races but are excellent runners on mountainous distances between 60 and 700 km. Unfortunately, only a few investigations on the physiological basis have been performed (e.g., 1, 3). The body shape with long slender legs is similar to that of Kenyans; together with light sandals and a stiff foot arch, this helps to save energy. Running downhill (usually half of the distances in Tarahumara competitions) costs very little energy.

The main causes for the successful distance running in both Kenyans and Tarahumara are therefore probably physique and conditioning beginning already in early childhood.

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## COMMENTARY OF VIEWPOINT: PHYSIOLOGY OF FAST MARATHONS

TO THE EDITOR: The recent Viewpoint by Joyner et al. (2) provides an excellent take on the converging factors that led to recent men's and women's marathon world records set by Eliud Kipchoge and Brigid Kosgei, respectively. However, there may be an additional performance-related factor yet to converge— age. Eliud Kipchoge was just shy of 35 yr old when he broke the 2-h mark during an exhibition marathon in 2019. This is ~4–8 yr older than the age most elite male marathoners achieve personal best performances (1, 3, 4). Conversely, Brigid Kosgei was only 25 yr old during her record run in the 2019 Chicago Marathon, ~2–4 yr younger than the reported age for peak performance in high-level female marathoners (1, 3). These results call into question whether *1*) there is a narrow, universal age for peak marathon performance; and *2*) if so, is it older or younger than currently reported peak performance ages? If younger athletes are best suited to the marathon, then future records may be set by those, like Kosgei, who debut at a young age. Or perhaps performance will converge around an older age as Kipchoge demonstrates that years of intensive training can lead to fitness gains at relatively older ages. Therefore, it will be interesting to see whether record-setting marathons continue to occur across a wide age range or if age converges and the marathon begins to be dominated by athletes of a specific age (older or younger) that differs from the reported age of peak performance.

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#### COMMENTARY ON VIEWPOINT: PHYSIOLOGY AND FAST MARATHONS

TO THE EDITOR: The Viewpoint by Joyner and colleagues (4) is timely with the recent marathon world records. Properly measuring the key physiological determinate running economy (RE) in a laboratory setting deserves commentary. First, it is now understood that the relationship between $\dot{V}O_2$ and velocity is not linear but curvilinear. Importantly, this means when RE is expressed as a cost-of-transport (COT) or the amount of oxygen or energy required to run a given distance (ml $O_2 \cdot kg^{-1} \cdot km^{-1}$), COT is U-shaped across velocity (1). Because RE is not constant across velocity, RE should be evaluated at a velocity near "lactate threshold" to understand marathon performance. Second, the practice of measuring RE at one particular incline (e.g., 1%) to simulate air resistance during treadmill running (3) has shortcomings. Aerodynamic force increases with running velocity. Thus, a single incline is only accurate for one running velocity. Furthermore, during running, the leg muscles and tendons function in series to store and return mechanical energy similar to springs. Treadmill inclines change the biomechanical determinants of energy return which influences RE (5). Air resistance should be considered only when trying to understand performance by accounting for the athlete's exposed surface area and running velocity. Last, treadmill decks vary considerably in stiffness. More compliant surfaces increase leg stiffness, resulting in greater energy return which reduces the metabolic cost of running (2). Compliant treadmills in series with compliant running shoes can misinform the effects of RE during overground performance. Using stiff treadmills is obligatory to understand how technological advancements influence RE and performance.

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#### COMMENTARY ON VIEWPOINT: PHYSIOLOGY AND FAST MARATHONS

TO THE EDITOR: Joyner et al. (3) posited that improvements in running economy (RE) have facilitated the recent rapid progression in marathon world records (WR). Here, I consider if improvements in RE can account for the historical progression in marathon times. RE (ml $O_2 \cdot kg^{-1} \cdot km^{-1}$) increases at faster running speeds but fair comparisons between measurements made at different speeds are possible if RE is converted based on Kipp et al. (4) to a standard speed (i.e., 16 km/h). In 1930 (WR 2:29:01.8), Dill et al. (1) determined that Clarence DeMar (2:34:48 marathoner and 7-time Boston marathon winner) had gross RE of 182 ml $O_2 \cdot kg^{-1} \cdot km^{-1}$ at 11.28 km/h which, converted to 16 km/h, equates to ~193 ml $O_2 \cdot kg^{-1} \cdot km^{-1}$. In 2006 (WR 2:04:55), Lucia et al. (5) discovered that Zersenay Tadese (2:08:46 marathoner) had unprecedented RE, averaging 153 ml $O_2 \cdot kg^{-1} \cdot km^{-1}$ while running at 17–21 km/h up a 1% inclined treadmill which, converted to level running at 16 km/h, is ~142 ml $O_2 \cdot kg^{-1} \cdot km^{-1}$. In 2018 (WR 2:02:57), Hoogkamer et al. (2) found that exceptional new racing shoes facilitated an average RE of 181 ml $O_2 \cdot kg^{-1} \cdot km^{-1}$ at 16 km/h in sub-elite runners, many of whom had run marathons faster than DeMar's best. Over the past 90 years, the marathon WR has decreased ~19% and RE of elite runners by ~26%. RE values that were once rare are now commonplace. In 2020 (WR 2:01:39), I anxiously await public disclosure of RE and other physiological data for the athletes who have recently run record times wearing exceptional shoes.

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## AGE GROUPERS ALSO RUN FAST MARATHONS!

TO THE EDITOR: First, we would like to commend the authors of the Viewpoint (2) for publishing this comprehensive summary of important factors for running fast marathons and the intent to advance this area of research.

Despite the recent performances achieved by elite runners, we believe age-group runners should receive similar research attention, since age-groupers of both sexes achieve remarkably fast marathon results with less financial and/or infrastructural support.

In contrast to the few elite runners running <2:05 h, the growing number of subelite runners in numerous marathon events represents a very interesting population to study the mechanisms and processes of breaking personal performance boundaries such as “sub 3” or “sub 4.”

Joyner et al. (2) offer a “physiologically informed discussion about why marathon times have fallen so dramatically recently” building on evidence of the last years. Unfortunately, few analyses about the annual rate of increase in marathon performance of sub-elite runners are available. In this regard only few analyses about the performance declines in (fe)male age-group winners exist (3).

Besides the physiological foundations and training, the influence of data-guided training prescription with new technology [e.g., wearable sensors with “intelligent” biofeedback (1)], running equipment, and logistics are of great interest for recreational runners. Subelite runners often behave as elite runners, but do not have the time or efficient infrastructure for, e.g., recovery and medical treatments. Therefore, we believe it is essential to understand subelite athletes’ responses of both sexes to exercise (4) to identify personalized strategies to achieve individual fast marathons.

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## PHYSIOLOGY AND FAST MARATHONS: MORE DETAILED CHARACTERIZATION OF TRAINING AND CAREFUL MONITORING ARE NECESSARY TO IMPROVE OUR UNDERSTANDING OF LONG-TERM ADAPTATIONS

TO THE EDITOR: First, we would like to commend the authors of the Viewpoint (2) for this comprehensive summary of factors of importance for running fast marathons. Then, we would like to comment on their discussion of fast marathon physiology (2).

We follow closely the debate concerning *1*) footwear designed to improve marathon performance; and *2*) nonofficial optimization of the course arrangement, ambient conditions, including headwind, individualized starting times, possibilities for hydration, pacing, etc., that influence running performance.

Although marathon performance has improved more than middle-distance running (4–5% versus 1–2%), does this reflect optimization of such factors and/or improvements in long-term preparation for fast marathons during the last 30 years? Descriptions of long-, middle- and short-term preparation by current elite marathon runners (1, 2) lack comprehensive analysis of macro- and mesocycles of exercise intensity, volume, frequency, and sequence and individual monitoring and control of internal and external loads.

Our understanding, in particular, of the distribution of training intensity (5) and technology-assisted monitoring among elite athletes has improved (3), and researchers should describe in detail the preparation for and monitoring of fast marathons. This will advance our knowledge concerning intra-individual variations in the fundamental determinants of fast marathons (i.e., maximal oxygen uptake, running economy, etc.). This reporting should provide a holistic overview (4) of the distribution of training intensity and volume, frequency of sessions, recovery procedures, the type and characteristics of strength training, environmental conditions (heat and altitude) and potential nutritional strategies associated with the different macro- and mesocycles and tapering utilized by elite male and female marathon runners.

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## RECENT IMPROVEMENTS IN MARATHON TIMES ARE NOT PHYSIOLOGICAL

TO THE EDITOR: October 2019 saw Eliud Kipchoge run the marathon distance unofficially in under 2 h, and Brigid Kosgei break Paula Radcliffe's 16 yr-old marathon record both in carbon fiber plate (CFP) shoes. Current men's and women's world records in the half- and full-marathon have all been broken by Nike athletes in CFP shoes, raising concerns that the introduction of this technology leads to a distinct nonphysiological advantage to Nike-sponsored athletes. For example, Javier Guerra chose to break his Adidas contract to use a Nike CFP shoe and qualified for Tokyo 2020.

Laboratory studies have shown improved running economy (RE) with CFP shoes (3). Unpublished data from our laboratory shows a 2.3% improvement in a female runner wearing CFP shoes during three 10-km trials (39:08 ± 00:29 min:s) compared with three 10-km trials wearing her preferred non-CFP shoes (40:03 ± 00:20 min:s). In another unpublished study from our laboratory, we tested an East African athlete (a current World Record holder) running on a treadmill at 21 km/h, and a CFP shoe elicited a 2.6% improvement in RE compared with his preferred non-CFP shoe. The recently released Nike Alphafly shoe has been suggested to improve RE by more than 5% and potentially, the men's marathon by 5:30 (min:s) (4), which is comparable to the performance benefit of doping with erythropoietin (1, 2). Recent improvements in marathon world records are not physiological as implied in the Viewpoint of Joyner et al. (5) but rather technological. Current rules are therefore no longer fit for purpose, requiring revision to safeguard the integrity of sport.

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## COMMENTARY ON VIEWPOINT: PHYSIOLOGY AND FAST MARATHONS

TO THE EDITOR: In the recent Viewpoint of Joyner et al. (3), the authors showed evidence and hypothesized several mechanisms associated with fast marathons. Of note, Joyner et al. (3) stated that much of the success of the current men and women marathon world record holders is related to running economy (RE). Further, Joyner et al. (3) stated that it is unclear how trainable RE is; however, it has been shown that RE could be improved after plyometric jump training (PJT), a common training method among athletes, and since the 2000 scientific publications on PJT have increased 25-fold compared with any previous period, including studies with endurance runners (4). Indeed, PJT has demonstrated a significant improvement of RE and time-trial performance in recreational runners (1). Of note, in the aforementioned study (1), PJT was demonstrated to be of value for endurance athletes performing after an acute exposure to high altitude. One mechanism associated with improved RE may be related to the neural control of the lower-limb muscle and their mechanical properties, including enhanced lower-limb reactivity (e.g., reduced foot contact time while running) and foot-arch stiffness (2). Therefore, although we agree with Joyner et al. (3) that RE is key for successful marathon runners, evidence shows that adequate training methods, such as PJT, could be of value to improve RE, and, therefore, running times. In summary, in recent years, the improvements of performance in marathoners noted by Joyner et al. (3) may be related to improved training methods (i.e., PJT), leading toward improvements in RE, probably associated with enhanced lower-limb reactivity and stiffness, and thus better running times (2, 5).

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## BRAIN PHYSIOLOGY AND FAST MARATHONS

TO THE EDITOR: Accumulating evidence indicates that the brain can play a role to determine endurance performance, in addition to the classical aerobic parameters that are discussed in Joyner et al. (2). For instance, induction of positive expectations regarding an intervention can improve endurance performance of well-trained runners without modifying maximal oxygen consumption, lactate threshold, and running economy (5). Moreover, application of transcranial direct current stimulation on the left dorsolateral prefrontal cortex enhanced Stroop task performance (i.e., a measure of inhibitory control) at rest, as well as reduced perceived effort and improved endurance performance in healthy individuals (1). Such findings are possibly explained by a complex brain regulation of endurance performance. Signals derived from the brain itself (e.g., corollary discharges) and the periphery (e.g., muscle afferents) are involved in the formation of exercise-related sensations (e.g., pain, dyspnea, thermal discomfort, perceived effort) (4). Thus, the ability to cope with such sensations, which is known as inhibitory control, likely contributes to determine endurance performance. In this sense, professional cyclists have been shown to present better inhibitory control at rest as compared with recreational cyclist (3). However, few studies have investigated the brain regulation of endurance performance in elite athletes. Therefore, many questions remain unanswered. For example, does inhibitory control during exercise indeed play a role in performance regulation? Do African runners present better inhibitory control than other runners? Is it possible to improve elite runners' inhibitory control to further improve performance? Thus, better understanding and manipulation of brain physiology may give an extra push to elite marathoners to continue improving their marks.

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## COMMENTARY ON VIEWPOINT: PHYSIOLOGY AND FAST MARATHONS

TO THE EDITOR: With great interest I read the recent Viewpoint by Joyner and colleagues (3). From a sociological perspective, the general disdain for Eliud Kipchoge's efforts to break, and actually breaking, the 2 h barrier is unwarranted. Indeed, it seems governing bodies, and the rules they impose, are a "moving goal post" dependent upon the technology du jour. Physiologically, potent aerobic prowess, expressed as a high maximal oxygen consumption ($\dot{V}O_{2max}$), is the foundation for such sub-2 h performance (3). As human aerobic capacity seems to have plateaued, increasingly it is other factors such as running economy, nutrition (2), and sports science that are likely the premier targets. The physiological underpinnings of such great running economy have yet to be elucidated, although factors such as skeletal muscle expression of sarco(endo)plasmic reticulum $Ca^{2+}$-ATPase (SERCA) and isoform (1), or changes in musculotendinous stiffening (5), are potential candidates. Although altitude is mentioned in the context of $\dot{V}O_{2max}$, it is also interesting to note that altitude exposure can also influence running economy (4), perhaps mediated at least in part through SERCA expression. Although in a discussion of a viewpoint in physiology it is perhaps heretical to evoke psychology, nonetheless the role of factors such as analytical ability, resiliency, self-confidence, and vast ability to adequately cope with pressure cannot be understated in producing such high levels of human performance. Although genetics is unlikely to reveal a singular explanation (3), epigenetics, integrative physiology, and transdisciplinary approaches may provide a unifying hypothesis for such human running performance.

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**NOW AFOOT: ENGINEERED RUNNING ECONOMY**

TO THE EDITOR: Drs. Joyner, Hunter, Lucia, and Jones deserve commendation for their timely, concise consideration of endurance running performance in terms of bodily energy supply and demand (3). Supply limits are imposed by the maximal rates at which oxygen is converted into chemical energy ($O_2$/time). Demand is set by how economically the running muscles convert the energy available into speed ($O_2$/distance). As they note, the supply limits of current and former marathon champions seem similar.

Rather, racing records have fallen markedly since 2016 because innovative shoe technology has reduced the energy demands of running. The critical advance has been incorporating lightweight, compliant materials with superior energy return (1). The conspicuously thick, yet light midsoles of the new shoes appear to economize running as tuned tracks have (4, 5). Both allow the substrate beneath the runner to yield after touchdown before recoiling to elevate the body later in the step. Satisfying relatively more of the step-cycle lift requirements via passive, elastic recoil requires relatively less of energy burning muscles.

Consequently, early models (1) reduced the energy demands of treadmill running by 4.0%, translating into 3.5% faster estimated racing velocities, and >4-min reductions in marathon times, per both Hoogkamer et al. and Joyner's analyses (2). Undoubtedly, the newer, thicker models reduce energy demands and marathon race times by greater margins.

The agreement between scientific evidence and recent race-time reductions marks a technological watershed for endurance running. Performances set largely by physical capabilities in the past are now dependent on athlete-equipment interactions.

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**PSYCHOPHYSIOLOGY OF FAST MARATHONS**

TO THE EDITOR: Joyner et al. (1) proposed a physiologically founded perspective arguing that $\dot{V}O_{2max}$, lactate threshold (LT), and running economy (and training specificities and technology) likely explain why marathon time has largely fallen recently. We propose a more psychophysiologically oriented discussion, as the prefrontal cortex (PFC) plays a role in the exercise capacity regulation (2–4) when integrating afferents from the periphery into emotionally relevant messages such as pleasure/displeasure (3). In addition to connections to premotor cortex areas to regulate the motor output, the PFC is further connected to amygdala and takes part in body interoceptive representations of a variety of physiological conditions. The PFC inhibits the amygdala-mediated negative sensations; thus a decline in PFC oxygenation (i.e., deactivation) may reveal an impaired capacity to deal with aversive sensations during exercise (2, 3). In this regard, PFC oxygenation declines from LT intensities, even to baseline levels (2), so that a PFC deoxygenation from the LT can suggest a pleasure/displeasure turn point indicating a closeness to exercise disengagement and exhaustion (5). In contrast to recreational athletes with $\dot{V}O_{2max}$ ~57.5 $ml \cdot kg^{-1} \cdot min^{-1}$ (2), elite Kenyan runners with $\dot{V}O_{2max}$ ~71.9 $ml \cdot kg^{-1} \cdot min^{-1}$ (4) showed no decline in PFC oxygenation (after an initial increase) during maximal self-paced exercise. In theory, the preserved PFC oxygenation allowed them to perform maximally, having a greater resilience to tolerate aversive sensations. Romantically, this may have allowed them to exercise resisting a "dream-to-nightmare turn point". Surprisingly, were the "showcase" runners of the marathon records Kenyan? The understanding of elite athletes may require a psychophysiological model.

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## RUNNING ECONOMY UNDER THE MICROSCOPE

TO THE EDITOR: We read with great interest the Viewpoint proposed by Joyner et al. (3) and would like to comment on the potential factors that may influence running economy and may have led to the recent improvements in marathon performance. First, it is striking that despite its importance in determining running economy, mitochondrial efficiency (P/O) ratio is unknown in elite athletes. Some reports suggest that mitochondrial efficiency can be improved to a greater extent by training twice per day versus once per day (1). Indeed, elite marathon runners often train twice or even thrice daily. Second, single muscle fiber size and contractile function (strength, speed, and power) can be improved with strength or plyometric training (5), which has gained popularity among athletes. Specifically, muscle fiber distribution, myosin heavy chain composition, and titin isoforms have been linked to running economy (4). In addition, it is likely that an interaction exists between muscle-tendon contractile properties, and the improvements in running economy from modern running shoes (2). It is apparent that variability exists in the metabolic benefits that can be obtained by using these modern marathon racing shoes (2), but it is not known how much more economical these shoes are for Kipchoge and Kosgei, specifically. Future research would need to determine whether those benefits are reduced or amplified in individual elite athletes due to specific contractile properties or modifications of lower limb biomechanics.

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## PHYSIOLOGY AND FAST MARATHONS: IT'S ABOUT TIME!

TO THE EDITOR: The Viewpoint by Joyner and colleagues (4) on the physiology of fast marathons comes at a timely crossroads in athletics. The authors discuss the physiological limitations pertaining to two of the primary aerobic performance outcome factors, $\dot{V}O_{2max}$ and lactate threshold. While athletes like Eliud Kipchoge and Brigid Kosgei are arguably near the limits of these physiological parameters, the athletic world has been remarkably naïve regarding technological considerations to improve running economy (RE), until very recently. Improvements in RE via footwear have been claimed by athletic companies for quite some time. In 1980, claims of 2.85% improvement in RE were demonstrated with an air cushion in the midsole of marathon shoes versus still-utilized ethylene-vinyl acetate (EVA) foams (2). The minimalist footwear trend also distracted the running media, which were hypersensitized to data supporting the improvement of RE with reductions in shoe mass (1). Eventually, the ergogenic effects of cushioning outweighed the once-prevailing thoughts (5), and the search for novel lightweight foams with high rebound had begun. With new applications of polyether block amide (PEBA) foam with carbon fiber plates reported to exhibit resilience of up to 87% (3), it was only a matter of time before athletic performances caught up to the polymer science. Still, there remains a gap in the true effect of high-cushion, high-energy return marathon shoes. Studies typically measure running economy in short-duration circumstances; while these data are useful, it may underestimate the true improvements in running economy over the late stages of the marathon distance.

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### TECHNOLOGICAL AND STRATEGIC INFLUENCES ON RUNNING ECONOMY ACCOUNT FOR THE OUTSIZED IMPROVEMENT IN MARATHON RECORD TIMES

TO THE EDITOR: Joyner et al. (3) suggest improvements in running economy (RE) as the most likely physiological mechanism behind the rapid improvement in marathon world records compared with other endurance disciplines. Interestingly, removing the recent record performances from Kipchoge and Kosgei brings the men's and women's marathon record improvement to 3.06% and 4.03%, respectively, since 1989—more in line with the 5-km and 10-km record improvements. Thus, it appears that recent technological and strategic advances in two marathon-specific factors specifically affecting RE—shoes and drafting—can account for most, if not all, of the relatively larger marathon improvement.

In 2017, Nike developed a shoe with a carbon-fiber plate in the midsole that enhances compliance and returns more mechanical energy with each step. Hoogkamer et al. (1) demonstrated the shoes improve RE by ~4% in the laboratory, translating to a 2–3% improvement in marathon performance time (2). Although the shoes have less of a benefit with wind resistance, much is mitigated by wind-blocking pacers running in a flying-V formation at modern marathon competitions. Running just 1 m behind another runner can reduce air resistance by up to 93%, which at a speed of 6 m/s (close to Kipchoge's average speed of 5.78 m/s) can boost RE by up to 6% (4). These interventions together would be far above the smallest worthwhile change in RE of 2.2–2.6% (5). Considering Kipchoge and Kosgei's record times were a respective 1.06% and 1.00% improvement from the previous records, it is quite plausible the shoes and drafting made majority contributions.

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