REVIEW

Swifter, higher, stronger: What's on the menu?

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The exploits of elite athletes delight, frustrate, and confound us as they strive to reach their physiological, psychological, and biomechanical limits. We dissect nutritional approaches to optimal performance, showcasing the contribution of modern sports science to gold medals and world titles. Despite an enduring belief in a single, superior "athletic diet," diversity in sports nutrition practices among successful athletes arises from the specificity of the metabolic demands of different sports and the periodization of training and competition goals. Pragmatic implementation of nutrition strategies in real-world scenarios and the prioritization of important strategies when nutrition themes are in conflict add to this variation. Lastly, differences in athlete practices both promote and reflect areas of controversy and disagreement among sports nutrition experts.

Ancient Olympians manipulated their diets according to prevailing beliefs, with Pythagoras being credited (probably incorrectly) for introducing athletes to meat and protein-rich foods in place of traditional figs, cereals, and cheese (*1*). Meanwhile, modern-day athletes are bombarded with social media "warriors" who evangelize vegan, Paleo, and low-carb "keto" diets for peak performance. In contrast to the battle over the perfect menu, contemporary sports nutrition embraces diversity in dietary practices, underpinning the demands of training and competition with the philosophies of specificity, periodization, and personalization (*2*).

The metabolic demands of elite sport are complex, with events lasting from seconds (jumps, throws, and lifts) to several weeks (Grand Tour cycling races). Performance outcomes culminate from deliberate, sport-specific training aimed at maximizing adaptations toward the fulfilment of individual genetic potential (*3*). Although some elite athletes benefit from systematic, science-driven advice on training adaptation and competition performance, others use trial-and-error approaches under the guidance of experienced coaches, leaving scientists to explain post hoc how diet might have contributed to their performance peaks (*3*).

Solving the fuel crisis

Energy for competitive sports is provided by transforming chemical energy (intramuscular glycogen and lipids) into mechanical energy (contraction), with adenosine triphosphate (ATP) being the metabolic intermediary (*4*). Because intramuscular ATP stores are small, exercise-associated increases in ATP turnover within active myocytes (up to 100 times the resting turnover rate) pose a major energetic challenge. Metabolic pathways for resynthesizing ATP are rapidly activated during short-term (<30-s) sprints, primarily through substrate-level phosphorylation: phosphocreatine (PCr) breakdown and the conversion of muscle glycogen to lactate. However, as ATP production becomes unable to match rates of utilization, a range of metabolic by-products accumulates. Some of these, such as hydrogen ions, appear to exert negative feedback on the pathways that produce them to prevent further disruption to homeostasis, whereas others, including adenosine monophosphate (AMP) and organic phosphate, stimulate energy sensors, such as the 5′-AMP–activated protein kinase, to maintain cellular homeostasis by regulating anabolic and catabolic pathways, thereby ensuring a balance between energy supply and demand.

Sporting activities lasting several minutes to several hours and performed either as a steady state (e.g., marathon running) or with intermittent high-intensity bursts (e.g., team sports) are fueled principally by the oxidation of intramuscular glycogen and, to a lesser extent, lipids, whereas the mobilization of extramuscular substrates [plasma glucose from the liver and gut and free fatty acids (FFAs) released from adipocytes] becomes more important as exercise duration increases. Training enhances the metabolic flexibility of the myocyte, enhancing the size of substrate pools and the capacity to rapidly switch between carbohydrate (CHO)– and fat-based fuels to meet the demands of the working muscles.

The location- or fiber-specific depletion of muscle glycogen stores is often associated with fatigue, and since the introduction of the percutaneous needle biopsy technique to exercise science in the 1960s (*5*), numerous investigations have examined strategies to promote the storage of glycogen before or between exercise bouts. The key factor in the synthesis of this macromolecule is the quantity of dietary CHO consumed (*6*), but because maximal hourly synthesis rates are equivalent to ~5% of the size of normalized stores, athletes need to plan adequate time as well as sufficient CHO intake to increase

Box 1. Move over, muscle: The brain's the boss!

The brain and CNS are implicit in skilled tasks and events requiring concentration and decision-making. Only recently, however, have we recognized their role in the performance of even simple locomotor events, including strategies around pacing. A century ago, Bainbridge wrote, "There appear, however, to be two types of fatigue, one arising entirely within the central nervous system, the other in which fatigue of the muscles themselves is superadded to that of the nervous system" (*71*). Despite this early insight, sports nutrition has evolved with a bias toward studying peripheral mechanisms of fatigue and their role in performance, possibly because of the opportunities provided by available research tools (*72*). Exceptions are noted; hypoglycemia has long been recognized as a cause of fatigue during endurance sports (*73*), and brain astrocytes are now known to have labile glycogen stores (*74*). Furthermore, we now explain the ergogenic benefits of caffeine through central roles (reduced perception of effort and increased neural recruitment of muscle fibers) rather than a metabolic origin (muscle glycogen sparing because of increased availability and oxidation of plasma FFAs) (*75*).

An intriguing theme in modern sports nutrition involves the CNS and nutrients that can enhance performance without even being absorbed (*76*). This interest emerged from the recognition that exogenous CHO intake could improve ~1-hour cycling time trial performance, even though muscle substrate (glycogen) availability is not rate limiting for this event (*76*). The same performance benefits were detected when the mouth was simply rinsed with a glucose or maltodextrin solution (*77*), exposing receptors in the oral cavity to CHO and stimulating reward centers in the brain to increase pace or work output (*78*). The "oral sensing" benefits of CHO have been shown to be robust and repeatable when undertaken throughout an event, offering new performance nutrition strategies and a different range of targeted sports (*76*). Although this science is still in its infancy, evidence shows benefits of oral sensing from other tastants (e.g., fluid and caffeine), and effects have been reported for menthol (perception of cooling), quinine [activation of the autonomic nervous system and/or corticomotor excitability for brief events (*79*)], and capsaicin, acetic acid, cinnamaldehyde, and other plant chemicals that are known transient receptor potential channel activators and may prevent exercise-associated muscle cramps (*80*).

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glycogen to levels commensurate with the demands of the upcoming session (*6*). Factors reducing the efficiency of glycogen synthesis from a given CHO intake include muscle damage and inadequate energy intake, whereas other factors (training status, the severity of glycogen depletion, intake within the hours following strenuous exercise, and co-ingestion of protein) can increase synthesis rates or absolute stores (*6*). The resting glycogen concentrations in endurance-trained muscle are higher than those in sedentary individuals; furthermore, glycogen supercompensation ("CHO loading") can be achieved in trained muscle with as little as 24 to 48 hours of reduced activity and high intakes of CHO [10 to 12 g per kilogram of body mass (BM) per 24 hours] (*6*). For at least 50 years, such techniques have been used by athletes to enhance their performance in endurance events in which glycogen depletion would otherwise occur (*7*).

Of course, the fuel demands of many sports exceed muscle glycogen storage capacity or the athlete's opportunity to replete endogenous stores between events. Exogenous CHO (CHO consumed in the hours before and/or throughout exercise) maintains euglycemia by "sparing" hepatic glucose production (*8*), with blood glucose making an increasing contribution to rates of muscle CHO oxidation as glycogen stores become depleted (*9*). Strong evidence suggests that performance in a range of sports and exercise scenarios is enhanced by consuming CHO during exercise, with intakes targeted to the muscle's need to supplement its diminishing glycogen reserves [30 to 60 g/hour in endurance events of up to 2 to 3 hours duration and 60 to 90 g/hour in ultra-endurance events lasting 8 to 10 hours (*10*)]. Intestinal CHO absorption is likely the rate-limiting step in the oxidation of ingested CHO (*11*). However, to some extent this can be overcome by "training the gut": increasing CHO intake in the diet and during exercise to increase tolerance and the activity of sodium-dependent glucose transporter SGLT-1 (*12*, *13*). The use of glucose-fructose mixtures that utilize different gut transporters can also increase total intestinal absorption and rates of muscle oxidation of ingested CHO (*14*).

The relatively large lipid stores in even the leanest of athletes have, understandably, intrigued sports scientists as a potential source of fuel for prolonged aerobic exercise. However, whereas CHO oxidation is closely geared to the energetic demands of the working muscles, no mechanisms exist for closely regulating the availability and metabolism of FFAs to the prevailing energy expenditure. Short-term strategies [overnight fasting or low-CHO, high-fat (LCHF) eating] have proven unsuccessful in enhancing performance, despite increasing FFA availability: The small increase in FFA oxidation is insufficient to replace the contribution of CHO after near depletion of liver and muscle CHO stores (*15*). An alternative strategy (*16*) to potentially boost the use of both substrate pools involves exposure (5 days) to LCHF (60 to 70% fat) diets to promote muscle retooling to enhance FFA transport and utilization, followed with restoration of endogenous and exogenous CHO availability (24 hours of high-CHO diet and CHO intake before and during exercise). Despite substantial increases in rates of fat oxidation after such protocols, benefits to endurance performance have been, at best, limited to specific scenarios or individuals (*17*).

More notably, the observed reduction in the utilization of CHO during submaximal exercise ("glycogen sparing"), initially thought to be advantageous in preserving this fuel for later oxidation, was discovered to be impaired CHO oxidation, caused by reduced muscle glycogenolysis and the down-regulation of flux through the citric acid cycle secondary to reduced pyruvate dehydrogenase activity (*18*). In sports where success is determined by high-intensity aerobic exercise, either throughout the event (such as in a cycling time trial or 10,000-m run) or at critical stages [within team sports or the "breakaways" and finishes in marathons, Ironman triathlons (*19*), and longer cycle races (*20*)], the highest sustainable rates of muscle energy turnover require the better economy of ATP production from CHO oxidation. Short-term fat adaptation strategies, or even long-term adaptation to ketogenic LCHF diets (80% fat, <50 g of CHO/day), which can increase normal rates of fat oxidation by two or three times (*21*, *22*), are limited in application to a small range of sporting events in which utilization is low enough for muscle energy to be provided by fat oxidation (*21*, *23*). To date, it appears that protocols that substantially increase fat oxidation also decrease metabolic flexibility by reducing CHO substrate pools and/or the ability to rapidly oxidize them. The bottom line is that when elite athletes train for and compete in most sporting events, CHO fuels are the predominant and critical substrate for the working muscles, and the availability of CHO (*22*, *24*), rather than fat, wins gold medals. We propose that the increased rates of fat oxidation observed after endurance training and "train-low" strategies (see When less is more) are a proxy for an increase in mitochondrial density; for competition success, this machinery is best utilized by harnessing it to enhance the oxidation of CHO-based fuels.

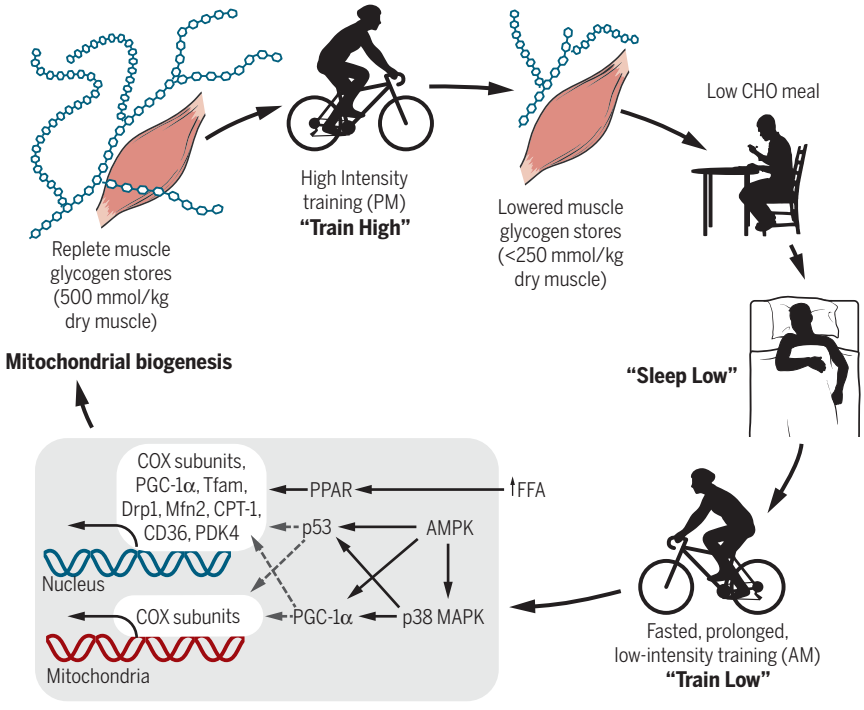

Fig. 1. Periodized nutrition: Evolution of a nutritional practice. Commencing endurance training with lowered muscle glycogen stores (training low) results in greater transcriptional activation of enzymes involved in CHO and fat oxidation, as well as greater mitochondrial biogenesis, than undertaking exercise with a normal or elevated glycogen content (*29*, *30*). Restricting CHO availability during the early (1 to 5 hours) postexercise recovery period also acutely up-regulates various markers of substrate metabolism and endurance training adaptation in skeletal muscle (*45*). Against this background, we formulated a novel approach in which we can undertake high-quality, high-intensity training and then prolong the duration of low CHO availability during recovery and subsequent aerobic exercise, thereby potentially extending the time course of transcriptional activation of metabolic genes and their target proteins. We have termed this practice "train high, sleep low" (*45*, *46*). PPAR, peroxisome proliferator–activated receptor; AMPK, 5′-AMP–activated protein kinase; MAPK, mitogen-activated protein kinase; COX, cyclooxygenase.

ILLUSTRATION: V. FALCONIERI BASED ON L. M. BURKE AND J. A. HAWLEY

Training nutrition: A balancing act

A reductionist view of training identifies a range of interdependent adaptations that permit athletes to sustain the highest rate and yield of energy production, optimize economy of motion, defend cellular homeostasis, and delay the onset of fatigue while simultaneously attaining the optimal physique and technical skills specific to their events (*3*, *25*). To achieve these ends, elite athletes and their coaches integrate a series of workouts that individually target important competition performance traits into a periodized training program composed of (weekly) microcycles and (3- to 6-week) mesocycles, culminating in targeted competition peaks within the (annual) macrocycle. The long-term adaptations to exercise training, such as those observed in elite athletes, result from the cumulative effect of the many transient increases in mRNA transcripts encoding various proteins after each acute exercise session (*26*, *27*). These repeated bursts in mRNA expression appear to be essential to drive the chronic intracellular adaptive response to exercise training (*27*).

With regard to the training diet, early nutrition guidelines promoted a singular and somewhat static approach, focusing predominantly on CHO-based fuels as the major energy source for muscle. However, contemporary guidelines acknowledge differences in the requirements and goals of different sessions or phases of training, leading to a periodization of the athlete's diet (*2*, *28*). In principle, nutrient support is organized around each training session to maximize physiological outcomes within a framework that addresses larger nutrition goals. Recommendations target total energy and fuel availability, with a focus on protein and CHO intakes and their distribution throughout the day (*2*). For high-intensity or high-quality training sessions, high endogenous and exogenous CHO availability is recommended, with the timing and intake of CHO matching or exceeding the muscle fuel requirements to support training quality (*2*, *28*, *29*). Some training sessions should develop competition fluid and CHO intake plans, incorporating practice of event-specific behaviors as well as training the gut function needed to tolerate and deliver these nutrients into the bloodstream. CHO intake can be reduced for lighter training loads (*2*, *29*); furthermore, adaptations to endurance training may be enhanced by deliberately commencing some sessions under conditions of low exogenous and endogenous CHO availability (*28*–*30*) (see When less is more and Fig. 1). As a result, daily CHO intakes typically vary from 2 to 12 g per kilogram of BM among athletes and across training cycles (*31*).

New perspectives on protein intake target the daily consumption of useful amounts (~0.3 g per kilogram of BM) of high-quality sources at four to six meals or snacks, particularly during the 1- to 3-hour window after key training sessions (*32*, *33*) and, perhaps, a double dose before sleep (*34*). This approach extends previous recognition that athletes have total daily protein requirements in excess of the standard Recommended Dietary Allowances to optimize the sustained (~24-hour) increase in contraction-stimulated synthesis of muscle protein that occurs after strength or endurance exercise by supplying leucine to further up-regulate the mammalian target of rapamycin complex 1 (mTORC1) pathway (*32*, *33*). Attention to nutrients for which athletes have increased requirements [such as water, electrolytes, and iron (*35*)] or risks of deficiency [such as vitamin D (*36*)] is also important in maximizing training adaptation, especially during training blocks undertaken in the heat or at high altitude (*3*).

Elite athletes straddle a thin line between maximizing overall training stimulus to promote sport-specific adaptation and remaining free of illness or injury. Within the framework of any periodized training program, each acute exercise session is an integral part of a long-term goal, with the training impulse (the sum of the intensity, duration, and frequency of sessions) being finely balanced to underpin optimal adaptation for a specific competition peak. The integration of nutrition goals for a specific training session or phase within the larger nutrition plan often creates tension between opposing themes. Athletes, both males and females, can develop relative energy deficiency in sport (RED-S), with a mismatch between energy intake and the energy expended in exercise leading to impairments in metabolic rate, bone health, protein synthesis, production of reproductive hormones, and performance gains (*37*). Yet, RED-S can occur secondarily to the body fat manipulation and very high training volumes that typically underpin success (*38*); this necessitates careful implementation and scheduling of such phases into the annual plan (*39*). Other strategies that need to be balanced or strategically managed include training with low CHO availability, which increases the inflammatory (interleukin-6) response to exercise, with acute disturbances to the immune system (*40*) and bone metabolism (*41*) that appear to persist with long-term exposure (*42*). Similarly, the use of antioxidant supplements acutely reduces free oxygen radical damage to muscle fibers but potentially dampens the training response by interfering with redox-sensitive signaling pathways; this has also been seen to translate into a reduction in performance (*43*).

When less is more

The application of molecular biology techniques to exercise science has identified the complexity and breadth of intracellular signaling networks by which different exercise modes drive adaptive changes that underpin the athletic phenotype (*3*, *25*). Altering nutrient availability, particularly endogenous CHO stores, selectively modulates gene expression and intracellular signaling within the muscle; mechanisms include alterations in cell osmolality and increased activity of molecules within the regulatory CHO-binding domain of the AMP-activated protein kinase, as well as perturbations to circulating FFAs and hormones in concert with plasma glucose and

Box 2. Performance in a bottle.

Sports products represent a lucrative portion of the worldwide explosion in the manufacture and marketing of supplements; according to one report, sports supplements generated global revenue of $9 billion in 2017, with a doubling of this value forecasted by 2025 (*81*). Surveys confirm the high prevalence of sports food and supplement use among athletes, including greater use at higher levels of competition (*82*). Despite earlier reluctance, many expert groups, including the International Olympic Committee (*83*), now pragmatically accept the use of supplements passing a risk-benefit analysis as being safe, effective, legal, and appropriate to an athlete's age and maturation in their sport. Supplements used by athletes fall into different categories (*83*): nutrient supplements for the treatment or prevention of deficiencies (e.g., iron and vitamin D); sports foods providing energy or nutrients when it is impractical to consume everyday foods (e.g., sports drinks and protein supplements); performance supplements that directly enhance exercise capacity; and supplements that provide indirect benefits through recovery, body composition management, and other goals. Despite enthusiastic marketing, from the latter two groups, only a few products enjoy robust evidence of efficacy [e.g., caffeine, creatine monohydrate, bicarbonate, β-alanine, and nitrate (*84*)] (Fig. 2).

Any benefits associated with supplement use must be balanced against the expense, the potential for adverse outcomes due to poor protocols for use (e.g., excessive doses or interactions with other supplements), and the dangers inherent with products whose manufacture and marketing are less regulated than those of foods or pharmaceutical goods. There are safety issues around dietary supplements in general, which accounted for ~23,000 notifiable emergency department visits in the United States in 2015 (*85*). Elite athletes also need to consider that supplements have been found to contain contaminants or undeclared ingredients that are prohibited by the antidoping codes (*86*) under which they compete; these include stimulants, anabolic agents, selective androgen receptor modulators, diuretics, anorectics, and β_2 agonists (*87*). Strict liability codes mean that a positive urine test can trigger an Adverse Doping Rule Violation with potentially serious effects on the athlete's career, livelihood, and reputation, despite unintentional intake or minute (ineffective) doses. Third-party auditing of products can help elite athletes make informed choices about supplement use but cannot provide an absolute guarantee of product safety (*83*).

insulin concentrations (*3*, *29*). Within their repertoire of training nutrition strategies, athletes can now include practices that augment adaptive processes in skeletal muscle; these include commencing training with low exogenous CHO availability (fasting overnight and/or withholding CHO during a session) or the more potent train-low strategy of deliberately commencing selected training sessions with lowered muscle glycogen stores (e.g., using a first session to deplete glycogen and then training for a second time after withholding CHO to prevent glycogen restoration) (*29*, *30*).

Although studies consistently report augmented cellular responses as a result of train-low strategies, the translation to performance enhancement has been less clear (*29*, *30*). Early investigations failed to detect superior performance outcomes; this was attributed to the overemphasis of such sessions within the training program and their resultant impairment of training intensity (*44*). These sessions need to be appropriately placed into a periodized program to complement high-quality training (*7*). A recent, clever sequencing of practices (Fig. 1) integrates a performance-promoting session and an adaptation-focused session while adding the benefits of a prolonged increase in exercise-stimulated cellular signaling and posttranscriptional regulation during glycogen-depleted recovery and exercise (*45*). In subelite populations at least, better integration of train-low and train-high sessions into the training sequence (Fig. 1) has been associated with superior performance compared with the same training undertaken with normal CHO availability (*46*). So far, however, this does not seem to be the case in studies involving elite populations (*22*, *47*), although it is often incorporated into real-world training sessions (*48*). Although further studies are needed, part of the challenge in advancing this area of research is the lack of agreement with regard to the terminology and implementation of the practices involved; we have tried to address this in a separate commentary (*7*).

Fighting fatigue: Eating to win

Each sport has distinct features, but characteristics shared by all competitors are a desire to pace their performance to achieve the highest sustainable outputs or speeds and maintain technical proficiency, with the likelihood of a reduction in some performance metrics intermittently, toward the end of the event, or both. "Fatigue" is defined operationally as a periodic or sustained decline in the athlete's ability to optimally perform the tasks required of their sport. Although fatigue is often characterized as muscular (decreased force or power production) or mental (increased ratings of perceived exertion or loss of skill and cognitive abilities), there is interplay between these phenomena. Muscular fatigue has both peripheral (related to the exercising muscle) and central [related to the ability of the central nervous system (CNS) to enervate the muscle fibers] input. Although some events require maximum performance to break world records or personal bests, others reward a superior performance relative to those of other competitors. The factors underpinning fatigue or performance power or speed are specific to the event, the environment in which it is undertaken, and the individual athlete.

Figure 2 provides a simplified summary of the most common fatigue factors in competitive sport to which evidence-based nutrition strategies can be applied to reduce or delay the onset. Such strategies can involve chronic protocols that work synergistically with training to make the body more resilient to these factors. For example, in team sports involving repetition of short (e.g., 6-s) high-intensity sprints, a progressive decay in speed related to the failure to fully recover PCr stores in the intervening recovery periods (>30 to 120 s) can be addressed by supplementation with creatine monohydrate to increase the size of the muscle PCr pool (*49*). This may not only directly enhance match performance by altering the sprint decay profile (*50*) but also allow the athlete to train harder (i.e., complete more sprints during training sessions) to increase adaptations in other physiological systems. Acute pre-event strategies such as CHO loading (24 to 48 hours of preparation) to increase the muscle glycogen stores or glycerol-assisted hyperhydration (2 hours of preparation) to increase body water storage can enhance performance in specific events if they can increase the time of optimal output before the body reaches a critical level of glycogen depletion (*51*) or fluid deficit (*52*), respectively. Intake of CHO (*10*) or fluid (*53*) during the event can also address these peripherally limiting factors but, intriguingly, may provide a benefit though a CNS effect associated with the oral sensing of these nutrients (Boxes 1 and 2).

Lastly, for real-world events, the development of a competition nutrition plan is challenged by the complexity of addressing a multitude and overlay of these fatigue factors, the practical constraints imposed by the event or the nature of the exercise, and the beliefs and tolerance of the athlete. This is covered in Box 3 and illustrated by recent activities around the marathon (42.2 km). In 2017, in a carefully orchestrated attempt to break the 2-hour barrier (*54*) and after much scientific banter (*55*), Kenyan Eliud Kipchoge came within 25 s of a sub-2-hour performance. Kipchoge already had two of the three "success factors" for prolonged endurance events: high aerobic power and the ability to run at a very high proportion of his aerobic capacity for prolonged periods without losing metabolic control (*56*). His attempt, albeit outside the International Association of Athletics Federations rules, targeted mainly the third factor: running economy (achieving the highest speed for the lowest oxygen cost). Strategies to improve economy included running on a flat motor racing track without sharp corners to preserve speed, running in aerodynamic formation behind other runners, using a car-mounted time clock to provide a windshield as well as pacing assistance, and wearing shoes developed to return 4% extra energy via carbon-fiber inserts (*57*).

Nutritional strategies were also used to enhance economy, and future improvements are likely. The beneficial effects of beetroot juice, a popular performance aid providing a supplemental source of inorganic nitrate, are mediated through the enhancement of exercise economy: A secondary nitric oxide (NO)–generating pathway (nitrate-nitrite-NO) is believed to enhance NO-mediated increases in capillary O_2 delivery to the muscle and reduce mitochondrial proton leakage (*58*). Furthermore, despite current claims that ketogenic LCHF diets provide unlimited substrate for prolonged exercise (*21*), both century-old empirical data (*59*) and recent interventions involving world-class race walkers (*22*) remind us that the oxidation of CHO yields ~5% more ATP per unit of O_2 than fat. Future nutrition strategies for the marathon may focus on increasing CHO availability and oxidation by shifting away from the use of fat from the mitochondrial furnace. Tactics include achieving maximally supercompensated glycogen stores, increasing the opportunities for aggressive in-race feedings, and training the gut to use multiple CHO sources to increase overall intestinal absorption of CHO (*12*).

"...the decisive day of this race,...over a challenging mountainous terrain, was achieved with a nutrition plan providing 6663 kcal and 18.9 g of CHO per kilogram (a total of 1.3 kg, equivalent to ~85 slices of bread)..."

Elite athletes are different

Scrutiny of the evidence base for current sports nutrition guidelines reveals that the individuals who contribute blood, sweat, and tears to scientific investigations are at best well trained, often male, and almost always subelite. Interventions with world-class athletes are rare: By definition, such athletes are few in number, and they are generally disinclined to interrupt successful training or nutrition programs or submit to invasive experimental techniques for the sake of science. It is reasonable to ask, therefore, whether the results of studies on nonelite populations apply to their elite counterparts. Issues include application of the intervention to the specific scenarios in which elite athletes train or compete, the inability of underpowered studies to detect small but worthwhile differences or changes in performance that could alter the outcomes of elite sport, and the translation of putative mechanisms to athletes who undertake substantially larger volumes of specialized training and potentially possess favorable genetic

traits (*60*). In relation to some nutrition interventions, evidence suggests a diminished response in elite competitors. For example, beetroot juice supplementation appears to be less effective in achieving economy or performance improvements in elite athletes (*61*); explanations for nonresponsiveness to this supplement in higher-caliber athletes include their different muscle fiber composition and the legacy of physiological adaptations attained through extensive training, such as greater activity of the primary arginine-NO pathway (*62, 63*). Nevertheless, because this pathway is oxygen dependent, scenarios can be identified in which elite athletes could benefit from activity from the alternative (oxygen- and pH-independent) nitrate-derived NO production, justifying beetroot juice supplementation; these include training or competing at high altitude and competing in sports involving small muscle groups, such as the arms, in which lower blood flow increases the likelihood of local hypoxia and acidosis (*62*, *63*).

The challenge remains to determine whether elite athletes are successful because, or in spite, of their nutrition practices. There are few studies of such groups or individuals, although elite East African athletes who have dominated middle-distance and distance running for the past decades have received scientific inquiry (*64*, *65*). Their dietary patterns include consistencies with current athlete guidelines [high CHO intakes (~60 to 80% of energy) but regular use of training in a fasted state to achieve train-low sessions],

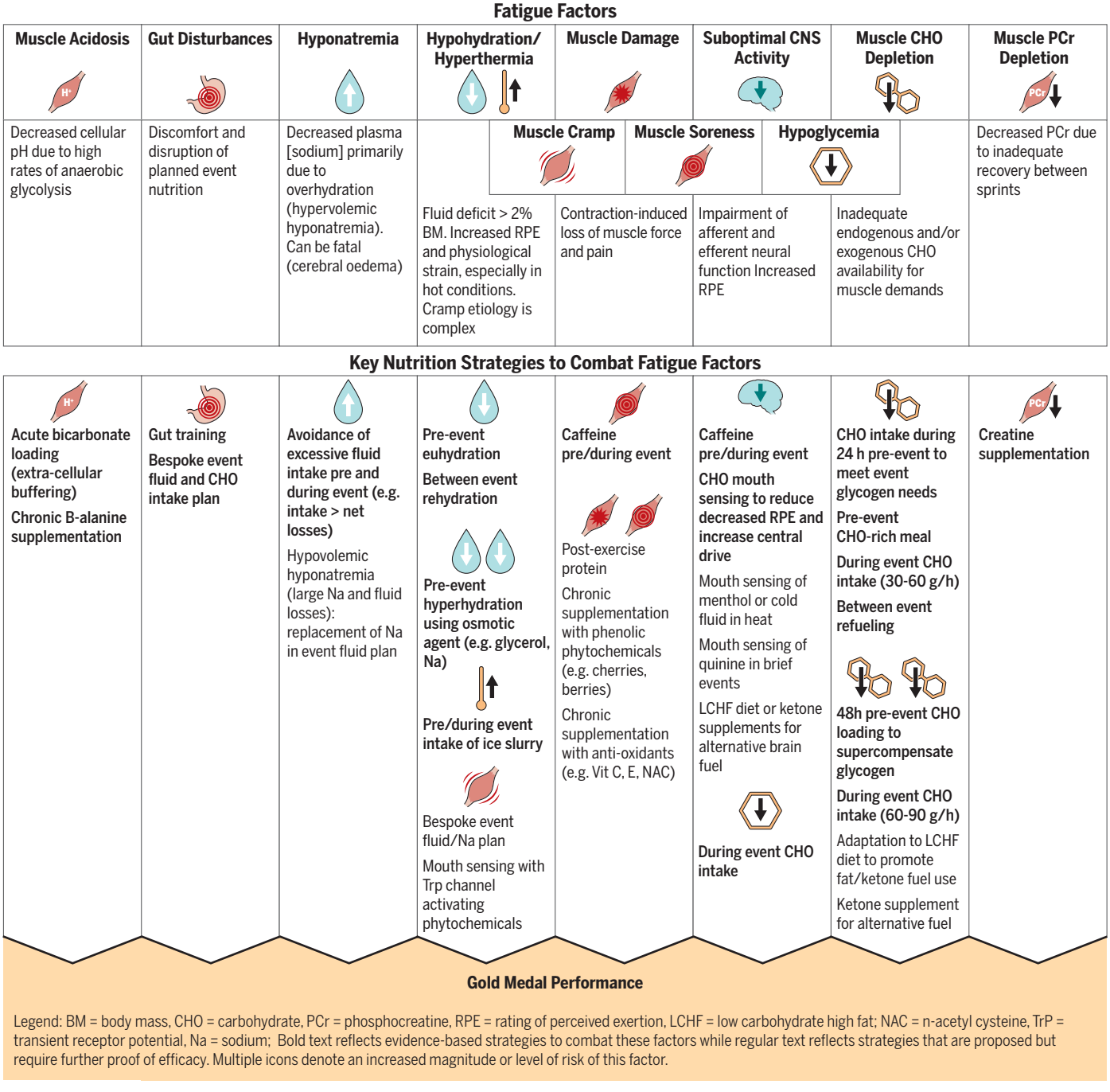

ILLUSTRATION: V. FALCONIERI BASED ON L. M. BURKE AND J. A. HAWLEY

Fig. 2. Nutrition can beat competition fatigue. Many factors that commonly cause fatigue (a periodic or sustained decline in the athlete's ability to optimally perform) in sporting events can be addressed by nutritional strategies that reduce the effects of these factors or delay their onset.

as well as inconsistencies with either the guidelines or typical practices of other elite athletes [reliance on vegetable (80 to 90% of diet) rather than animal food sources, very limited food variety, distribution of energy to a small number of meals in the day, and chronic periods of low energy availability]. Case histories of scientist-devised approaches to performance for elite competitors, such as "weight making" for a professional boxer (*66*) or a complex nutrition plan followed by the winner of the 3-week Giro d'Italia cycling race, do not necessarily allow firm and reproducible conclusions about the benefits of these strategies but show how practices can be achieved within the complexities of the sporting environment (see Box 3 and Fig. 3). In the latter case, the competition plan manipulated BM (by slight energy restriction and the use of a low-residue diet to reduce gastrointestinal contents) according to the benefits of being lighter on hilly sections and fluctuated daily energy and CHO intakes according to the estimated metabolic cost of each stage (*67*). Notably, the decisive day of this race, involving a solo ride over a challenging mountainous terrain, was achieved with a nutrition plan providing 6663 kcal and 18.9 g of CHO per kilogram

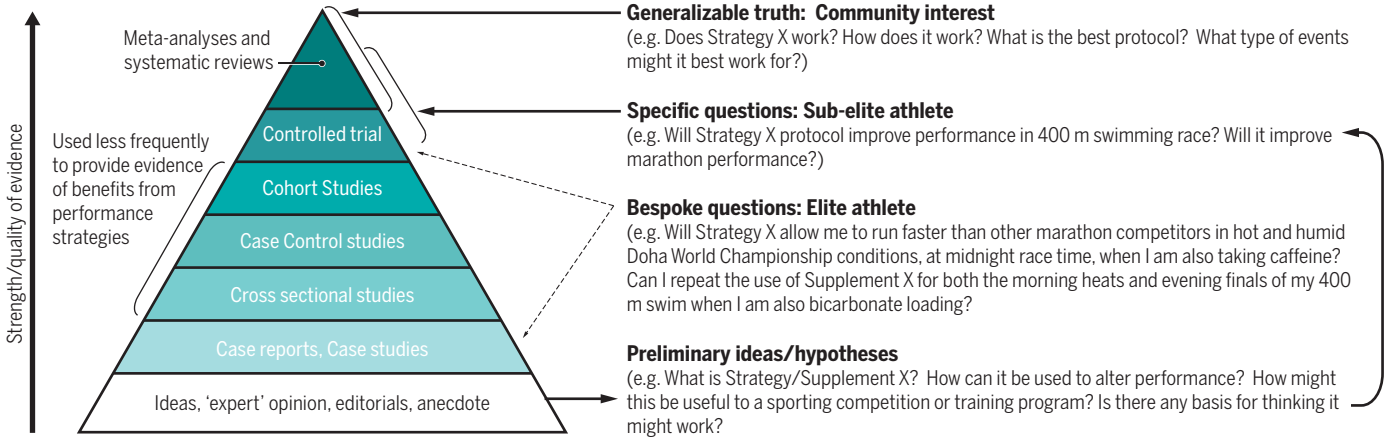

Fig. 3. Perspectives on the evidence base for elite athlete practices. Developing an evidence base for the nutritional practices of elite athletes requires acknowledgment that specific answers to research questions and interpretations of guidelines are needed. [Adapted from (*60*)]

Box 3. Specificity and practicality require bespoke solutions.

The practical implementation of nutrition strategies by athletes in real-world settings confounds the establishment of an evidence base by traditional research methods and the development of generalizable (and uncontroversial) guidelines. In most sports, performance is limited by a number of interdependent factors, typically addressed by a coordinated plan. We often consider several independently valuable nutrition strategies in combination, despite the potential for redundancy, amplification, attenuation, and competition between effects. The individual benefits of fluid and CHO replacement for performance in the heat are additive (*88*), caffeine is less effective when CHO intake is also used to attenuate the performance decline during prolonged exercise (*89*), and combining caffeine and bicarbonate supplementation impairs the benefits of the former because of gastrointestinal disturbances (*90*). However, because it is impractical to investigate the many permutations and combinations of evidence-based nutrition strategies (*90*), the overall effects on performance are unknown.

Environmental conditions and competition schedules add further practical challenges. Premiere championships can be hosted under "hostile" conditions (such as high altitude in the 1968 Mexico City Olympic Games or heat in the 2019 Doha Athletics World Championships) or with unusual timetables (such as late-night swimming at the 2016 Rio Olympic Games to coincide with primetime television in the United States). Thus, athletes often need bespoke strategies for different iterations of the same event. Lastly, sport involves rules, logistical considerations, and cultures that dictate opportunities for nutrient intake before, during, and between events (*91*). Some provide adequate opportunities for beneficial intake (e.g., basketball players drink during substitutions and time-outs). However, conditions in other events, such as weight-division sports, encourage substantial pre-event dehydration and energy restriction to "make weight" (*92*). Soccer prohibits breaks or access to fluids during each half, and the practical challenge of drinking while running at ~21 km/hour in a marathon limits the volumes ingested (*68*).

It is important to consider whether the traditional conduct and evaluation of scientific research adequately inform elite athletes. In many areas of our lives, we are content with generalizable truths (strategy X is good) and guidelines (we should all implement strategy X by doing Y). Figure 3 illustrates a hierarchy of types of scientific evidence. The types of studies that provide the strongest or highest-quality evidence (such as randomized controlled trials) are extremely hard to achieve with high-caliber competitors or may provide generic information inappropriate for a specific task. Lack of appreciation of these concepts has caused angst within the sports science community and an unfair dismissal of the integrity of its outputs.

Sports science was criticized in an assessment by epidemiologically trained scientists (*93*, *94*). Although valid methodological issues were raised, the analysis failed to appreciate that sports scientists working in elite sport typically seek highly context-specific information (Fig. 3). Evidence-based but bespoke solutions for small numbers of individuals require special designs and research tools; the validity, reliability, and sensitivity of measurements are critical. We must consider repeatability in study design or case history approaches to account for small sample sizes. Even individual responsiveness to interventions may vary. New or refined statistical approaches may be required (*60*, *90*).

Controversy regarding guidelines for fluid intake during sport exemplifies a lack of appreciation for context. Critics of current guidelines for an individualized approach (*95*) who argue that athletes should be told to drink only when thirsty during events (*96*) fail to recognize that opportunities for fluid intake are often beyond the athlete's control and unrelated to need. Therefore, it is reasonable to develop a bespoke plan for specific events that optimizes opportunities to consume fluid and CHO before and throughout the event to integrate gut comfort, fuel needs, a tolerable fluid deficit, and thirst management.

ILLUSTRATION: V. FALCONIERI BASED ON L. M. BURKE AND J. A. HAWLEY

(a total of 1.3 kg, equivalent to ~85 slices of bread), with race supplies being provided by *domestique* teammates and a support crew at planned intervals to avoid the need for the cyclist to carry the weight burden (*67*). We can never know how much this plan contributed to the rider's eventual success. Equally, we need to intellectualize that athletic success can be achieved in the face of apparently suboptimal practice. For example, that the winner of an elite marathon incurred a loss of 10% of BM over the race (*68*) fails to disprove that hypohydration impairs performance; rather, it demonstrates that this athlete was faster than other competitors on that day and potentially was best able to tolerate the conditions.

Although elite athletes can learn from sports science, many lessons have also flowed in the opposite direction. Sports nutrition recommendations have often been updated when practices observed among elite athletes were found to be beneficial. For example, caffeine guidelines for sport changed when the flat cola beverages consumed by elite cyclists toward the end of prolonged races (~1 to 2 mg of caffeine per kilogram at the onset of fatigue) were found to be as effective as the "scientifically proven" protocols (6 to 9 mg/kg taken 1 hour pre-event) (*69*). Ammunition to update guidelines for CHO intake during prolonged (>2.5 hours) events came from observations that the intakes of many elite cyclists and triathletes (~90 g/hour) were higher than the earlier recommendations (30 to 60 g/hour) and correlated with success (*70*). Clearly, future outcomes will be best achieved with a two-way interaction between sports scientists and elite athletes and their coaches.

In the final analyses, modern sports nutrition offers a feast of opportunities to assist elite athletes to train hard, optimize adaptation, stay healthy and injury free, achieve their desired physique, and fight against fatigue factors that limit success. Although there will be challenges and changes to sports nutrition guidelines as they evolve beyond the frontiers of current knowledge and practice, we can be excited to know that sports science in many guises contributes to the outcomes that delight and amaze us from our sofas and the grandstand.

REFERENCES AND NOTES

1. L. E. Grivetti, E. A. Applegate, *J. Nutr.* **127** (Suppl), 860S–868S (1997).
2. D. T. Thomas, K. A. Erdman, L. M. Burke, *Med. Sci. Sports Exerc.* **48**, 543–568 (2016).
3. J. A. Hawley, C. Lundby, J. D. Cotter, L. M. Burke, *Cell Metab.* **27**, 962–976 (2018).
4. B. Egan, J. A. Hawley, J. R. Zierath, *Cell Metab.* **24**, 342–342.e1 (2016).
5. J. Bergström, E. Hultman, *Nature* **210**, 309–310 (1966).
6. L. M. Burke, L. J. C. van Loon, J. A. Hawley, *J. Appl. Physiol.* **122**, 1055–1067 (2017).
7. L. M. Burke *et al.*, *Int. J. Sport Nutr. Exerc. Metab.* **28**, 451–463 (2018).
8. A. N. Bosch, S. C. Dennis, T. D. Noakes, *J. Appl. Physiol.* **76**, 2364–2372 (1994).
9. E. F. Coyle, A. R. Coggan, M. K. Hemmert, J. L. Ivy, *J. Appl. Physiol.* **61**, 165–172 (1986).
10. T. Stellingwerff, G. R. Cox, *Appl. Physiol. Nutr. Metab.* **39**, 998–1011 (2014).
11. J. A. Hawley, A. N. Bosch, S. M. Weltan, S. C. Dennis, T. D. Noakes, *Pfluegers Arch.* **426**, 378–386 (1994).
12. A. E. Jeukendrup, *Sports Med.* **47** (suppl. 1), 101–110 (2017).
13. R. J. S. Costa *et al.*, *Appl. Physiol. Nutr. Metab.* **42**, 547–557 (2017).
14. A. E. Jeukendrup, *Curr. Opin. Clin. Nutr. Metab. Care* **13**, 452–457 (2010).
15. L. M. Burke, J. A. Hawley, *Med. Sci. Sports Exerc.* **34**, 1492–1498 (2002).
16. L. M. Burke *et al.*, *Med. Sci. Sports Exerc.* **34**, 83–91 (2002).
17. L. M. Burke, *Sports Med.* **45** (suppl. 1), 33–49 (2015).
18. T. Stellingwerff *et al.*, *Am. J. Physiol. Endocrinol. Metab.* **290**, E380–E388 (2006).
19. E. Maunder, A. E. Kilding, D. J. Plews, *Sports Med.* **48**, 2219–2226 (2018).
20. L. Havemann *et al.*, *J. Appl. Physiol.* **100**, 194–202 (2006).
21. J. S. Volek *et al.*, *Metabolism* **65**, 100–110 (2016).
22. L. M. Burke *et al.*, *J. Physiol. (London)* **595**, 2785–2807 (2017).
23. S. D. Phinney, B. R. Bistrian, W. J. Evans, E. Gervino, G. L. Blackburn, *Metabolism* **32**, 769–776 (1983).
24. J. A. Hawley, J. J. Leckey, *Sports Med.* **45**, S5–S12 (2015).
25. J. A. Hawley, M. Hargreaves, M. J. Joyner, J. R. Zierath, *Cell* **159**, 738–749 (2014).
26. V. G. Coffey, J. A. Hawley, *Sports Med.* **37**, 737–763 (2007).
27. C. G. Perry *et al.*, *J. Physiol. (London)* **588**, 4795–4810 (2010).
28. A. E. Jeukendrup, *Sports Med.* **47** (suppl. 1), 51–63 (2017).
29. S. G. Impey *et al.*, *Sports Med.* **48**, 1031–1048 (2018).
30. J. D. Bartlett, J. A. Hawley, J. P. Morton, *Eur. J. Sport Sci.* **15**, 3–12 (2015).
31. L. M. Burke, G. R. Cox, N. K. Culmmings, B. Desbrow, *Sports Med.* **31**, 267–299 (2001).
32. T. Stokes, A. J. Hector, R. W. Morton, C. McGlory, S. M. Phillips, *Nutrients* **10**, 180 (2018).
33. D. R. Moore, D. M. Camera, J. L. Areta, J. A. Hawley, *Appl. Physiol. Nutr. Metab.* **39**, 987–997 (2014).
34. P. T. Res *et al.*, *Med. Sci. Sports Exerc.* **44**, 1560–1569 (2012).
35. G. Clénin *et al.*, *Swiss Med. Wkly.* **145**, w14196 (2015).
36. D. J. Owens, R. Allison, G. L. Close, *Sports Med.* **48** (suppl. 1), 3–16 (2018).
37. M. Mountjoy *et al.*, *Int. J. Sport Nutr. Exerc. Metab.* **28**, 316–331 (2018).
38. L. M. Burke, B. Lundy, I. L. Fahrenholtz, A. K. Melin, *Int. J. Sport Nutr. Exerc. Metab.* **28**, 350–363 (2018).
39. T. Stellingwerff, *Int. J. Sport Nutr. Exerc. Metab.* **28**, 428–433 (2018).
40. S. Bermon *et al.*, *Exerc. Immunol. Rev.* **23**, 8–50 (2017).
41. C. Sale *et al.*, *J. Appl. Physiol.* **119**, 824–830 (2015).
42. A. K. A. McKay *et al.*, *Med. Sci. Sports Exerc.* 10.1249/MSS.0000000000001816 (2018).
43. T. L. Merry, M. Ristow, *J. Physiol. (London)* **594**, 5135–5147 (2016).
44. W. K. Yeo *et al.*, *J. Appl. Physiol.* **105**, 1462–1470 (2008).
45. S. C. Lane *et al.*, *J. Appl. Physiol.* **119**, 643–655 (2015).
46. L. A. Marquet *et al.*, *Med. Sci. Sports Exerc.* **48**, 663–672 (2016).
47. K. D. Gejl *et al.*, *Med. Sci. Sports Exerc.* **49**, 2486–2497 (2017).
48. T. Stellingwerf, *Int. J. Sport Nutr. Exerc. Metab.* **22**, 392–400 (2012).
49. D. Bishop, *Sports Med.* **40**, 995–1017 (2010).
50. G. Cox, I. Mujika, D. Tumilty, L. Burke, *Int. J. Sport Nutr. Exerc. Metab.* **12**, 33–46 (2002).
51. J. A. Hawley, E. J. Schabort, T. D. Noakes, S. C. Dennis, *Sports Med.* **24**, 73–81 (1997).
52. E. D. B. Goulet, M. Aubertin-Leheudre, G. E. Plante, I. J. Dionne, *Int. J. Sport Nutr. Exerc. Metab.* **17**, 391–410 (2007).
53. R. W. Kenefick, *Sports Med.* **48** (suppl. 1), 31–37 (2018).
54. M. Z. Donahue, "Runner comes excruciatingly close to breaking two-hour marathon banner," 6 May 2017; https://news.nationalgeographic.com/2017/05/extreme-running-marathon-nike-science/.
55. M. J. Joyner, J. R. Ruiz, A. Lucia, *J. Appl. Physiol.* **110**, 275–277 (2011).
56. M. J. Joyner, E. F. Coyle, *J. Physiol. (London)* **586**, 35–44 (2008).
57. W. Hoogkamer *et al.*, *Sports Med.* **48**, 1009–1019 (2018).
58. A. M. Jones, *Appl. Physiol. Nutr. Metab.* **39**, 1019–1028 (2014).
59. A. Krogh, J. Lindhard, *Biochem. J.* **14**, 290–363 (1920).
60. L. M. Burke, P. Peeling, *Int. J. Sport Nutr. Exerc. Metab.* **28**, 159–169 (2018).
61. R. K. Boorsma, J. Whitfield, L. L. Spriet, *Med. Sci. Sports Exerc.* **46**, 2326–2334 (2014).
62. K. L. Jonvik, J. Nyakayiru, L. J. van Loon, L. B. Verdijk, *J. Appl. Physiol.* **119**, 759–761 (2015).
63. M. Hultström *et al.*, *J. Appl. Physiol.* **119**, 762–769 (2015).
64. L. Y. Beis *et al.*, *J. Int. Soc. Sports Nutr.* **8**, 7 (2011).
65. V. O. Onywera, F. K. Kiplamai, P. J. Tuitoek, M. K. Boit, Y. P. Pitsiladis, *Int. J. Sport Nutr. Exerc. Metab.* **14**, 709–719 (2004).
66. J. P. Morton, C. Robertson, L. Sutton, D. P. MacLaren, *Int. J. Sport Nutr. Exerc. Metab.* **20**, 80–85 (2010).
67. T. Fordyce, "Chris Froome: Team Sky's unprecedented release of data reveals how British rider won Giro d'Italia," 4 July 2018; https://www.bbc.com/sport/cycling/44694122.
68. L. Y. Beis, M. Wright-Whyte, B. Fudge, T. Noakes, Y. P. Pitsiladis, *Clin. J. Sport Med.* **22**, 254–261 (2012).
69. G. R. Cox *et al.*, *J. Appl. Physiol.* **93**, 990–999 (2002).
70. A. Jeukendrup, *Sports Med.* **44** (suppl. 1), S25–S33 (2014).
71. F. A. Bainbridge, *The Physiology of Muscular Exercise* (Longmans, Green & Co., 1919).
72. J. A. Hawley, R. J. Maughan, M. Hargreaves, *Cell Metab.* **22**, 12–17 (2015).
73. S. A. Levine, B. Gordon, C. L. Derick, *JAMA* **82**, 1778–1779 (1924).
74. T. Matsui *et al.*, *J. Physiol. (London)* **590**, 607–616 (2012).
75. L. L. Spriet, *Sports Med.* **44** (suppl. 2), S175–S184 (2014).
76. L. M. Burke, R. J. Maughan, *Eur. J. Sport Sci.* **15**, 29–40 (2015).
77. J. M. Carter, A. E. Jeukendrup, D. A. Jones, *Med. Sci. Sports Exerc.* **36**, 2107–2111 (2004).
78. E. S. Chambers, M. W. Bridge, D. A. Jones, *J. Physiol. (London)* **587**, 1779–1794 (2009).
79. S. Gam, K. J. Guelfi, P. A. Fournier, *Sports Med.* **46**, 1385–1390 (2016).
80. D. H. Craighead *et al.*, *Muscle Nerve* **56**, 379–385 (2017).
81. Persistence Market Research, "Global market study on sports supplements: Non-protein products to witness substantial growth during 2017 – 2025" (Rep. PMRREP3034, Persistence Market Research, January 2018); https://www.persistencemarketresearch.com/market-research/sports-supplements-market.asp.
82. I. Garthe, R. J. Maughan, *Int. J. Sport Nutr. Exerc. Metab.* **28**, 126–138 (2018).
83. R. J. Maughan *et al.*, *Int. J. Sport Nutr. Exerc. Metab.* **28**, 104–125 (2018).
84. P. Peeling, M. J. Binnie, P. S. R. Goods, M. Sim, L. M. Burke, *Int. J. Sport Nutr. Exerc. Metab.* **28**, 178–187 (2018).
85. A. I. Geller *et al.*, *N. Engl. J. Med.* **373**, 1531–1540 (2015).
86. World Anti-Doping Agency, The Code; https://www.wada-ama.org/en/what-we-do/the-code.
87. J. M. Martínez-Sanz *et al.*, *Nutrients* **9**, 1093 (2017).
88. P. R. Below, R. Mora-Rodríguez, J. González-Alonso, E. F. Coyle, *Med. Sci. Sports Exerc.* **27**, 200–210 (1995).
89. S. A. Conger, G. L. Warren, M. A. Hardy, M. L. Millard-Stafford, *Int. J. Sport Nutr. Exerc. Metab.* **21**, 71–84 (2011).
90. L. M. Burke, *Sports Med.* **47** (suppl. 1), 79–100 (2017).
91. A. K. Garth, L. M. Burke, *Sports Med.* **43**, 539–564 (2013).
92. R. Reale, G. Slater, L. M. Burke, *Int. J. Sports Physiol. Perform.* **13**, 459–466 (2018).
93. C. Heneghan, R. Perera, D. Nunan, K. Mahtani, P. Gill, *BMJ* **345**, e4797 (2012).
94. C. Heneghan *et al.*, *BMJ* **345**, e4848 (2012).
95. M. N. Sawka *et al.*, *Med. Sci. Sports Exerc.* **39**, 377–390 (2007).
96. D. Cohen, *BMJ* **345**, e4737 (2012).

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Swifter, higher, stronger: What's on the menu?

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