

From podium to daily practice: A narrative review of energy-based nutrition strategies for athletes and everyday exercisers

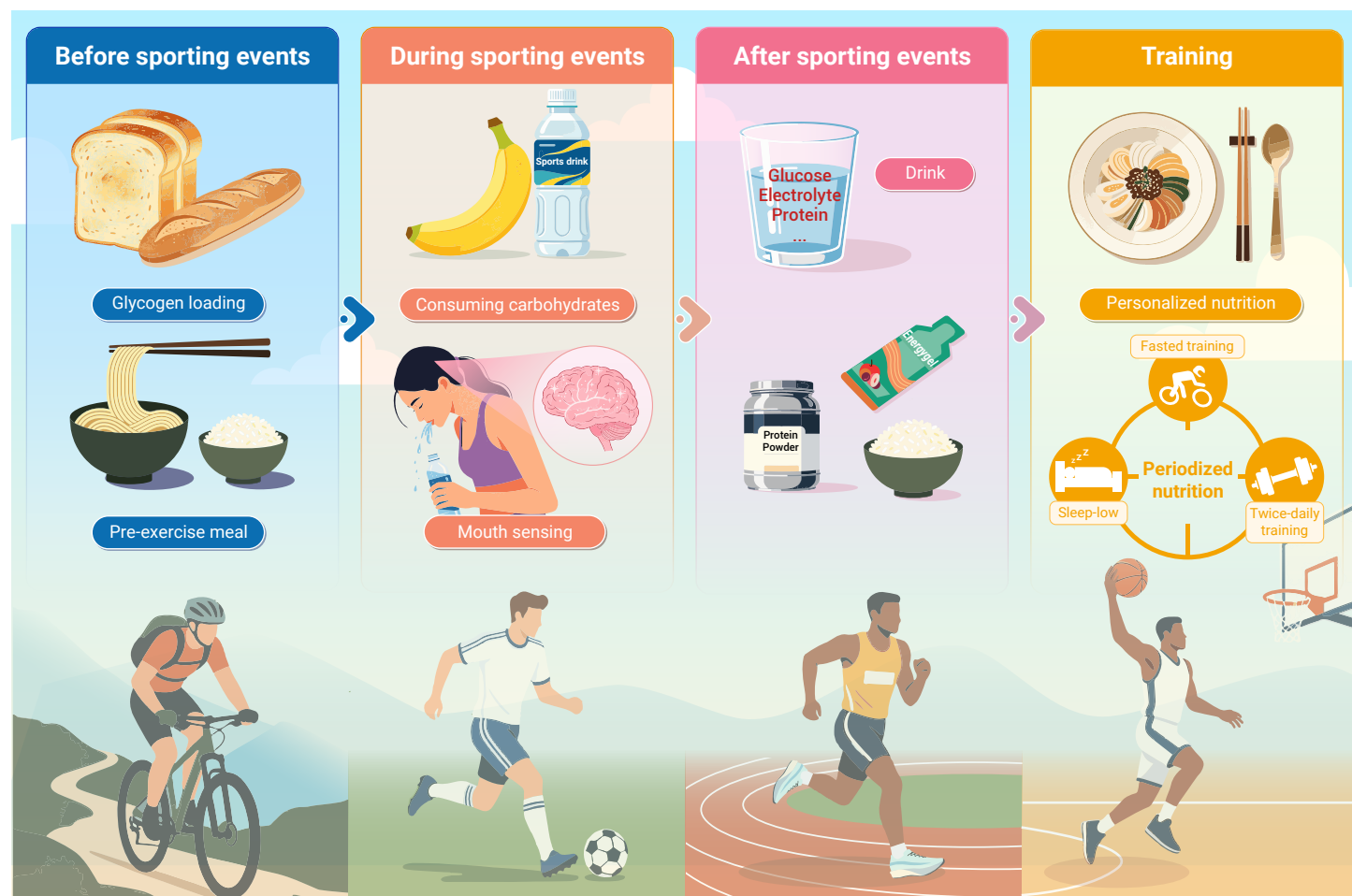
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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Before competitions, an appropriate high-carbohydrate diet to increase glycogen stores can enhance performance.
- Avoiding low energy availability is very important for maintaining optimal health and performance.
- During competitions, carbohydrate supplementation and carbohydrate mouth rinsing are beneficial.
- Post-competition supplementation is essential for recovery, and current evidence suggests that multi-channel carbohydrate intake is particularly effective.
- Current evidence does not support the efficacy of high-fat, low-carbohydrate diets or medium-chain triglycerides in significantly enhancing athletic performance.

From podium to daily practice: A narrative review of energy-based nutrition strategies for athletes and everyday exercisers

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Energy support plays a crucial role for athletes and everyday exercisers, with various nutritional strategies being developed to optimize energy metabolism. This review summarizes nutritional approaches related to energy metabolism, including the prevention of low energy availability, carbohydrate supplementation across different competition phases, and approaches to enhance fat oxidation. Avoiding low energy availability is very important for maintaining optimal health and performance; thus, the key is to identify and address the specific underlying causes of the energy deficit. Nutritional supplementation strategies vary across different phases of exercise. Before competitions, an appropriate high-carbohydrate diet to increase glycogen stores can enhance performance. During competitions, carbohydrate supplementation and carbohydrate mouth rinsing are beneficial. Post-competition supplementation is essential for recovery, and current evidence suggests that multiple-transportable carbohydrate intake is particularly effective. Additionally, periodized training with limited carbohydrate availability to boost metabolic adaptation is receiving significant attention; however, more research is still needed to validate its effects. Similarly, although both high-fat low-carbohydrate diets and medium-chain triglycerides may increase fat oxidation rates, current evidence does not support their efficacy in significantly enhancing athletic performance. Overall, individualized and periodized nutrition strategies are essential for optimizing athletic performance and maintaining athlete health.

INTRODUCTION

With the increasing prevalence of chronic diseases,^{1,2} physical activity has become an important strategy for disease prevention and health promotion. However, metabolic processes during exercise are highly dynamic and depend on the type and intensity of exercise. For athletes, the metabolic requirements are highly specific and precisely regulated. Competitions often differ significantly in terms of strength, speed, flexibility, endurance, balance, and reaction time.³ Athletes must balance maximizing training benefits with minimizing the risk of illness and injury. In addition to innate talent and scientific training, nutrition plays a key role in achieving this balance.⁴

Beyond competitive athletics, sports nutrition is also essential for recreational sports enthusiasts, particularly during high-intensity activities such as middle- and long-distance running, marathons, triathlons, road cycling, and skiing. Inadequate knowledge or misconceptions may lead to adverse effects, such as fatigue, weakness, impaired performance, and injuries.⁵ Scientific nutritional strategies can provide essential nutrients and energy, helping to maintain strength, reduce fatigue, promote recovery, and improve endurance. Consequently, nutritional support is also indispensable for both health maintenance and performance optimization in everyday exercisers.

Appropriate energy intake is fundamental for athletes and everyday exercisers, as it supports optimal physiological function, influences macronutrient and micronutrient absorption, and contributes to body composition management. It is now widely recognized that carbohydrates are the most crucial energy source for elite athletes.^{4,6} However, this consensus evolved over several decades. The early scientific misconception that protein served as the primary fuel for exercise was reflected in the Olympic Games menus from 1932 to 1968.⁷ Although studies began to show the crucial role of

carbohydrates as sources of energy for muscles as early as the 1920s,⁸ it was the pivotal research in the 1960s that illustrated the significance of carbohydrates in exercise.⁹ Alongside advancements in physiology and training methodologies, the role of carbohydrates as an energy source in enhancing athletic performance has gained significant recognition. Concurrently, strategies aimed at enhancing fat oxidation have led to growing interest in their potential to improve performance.

This review aims to explore the role of nutrition strategies – centered on energy availability (EA) – in the optimization of athletic performance. Specifically, it will focus on main sources of energy (carbohydrates and fat oxidation) to discuss controversial nutritional strategies. Additionally, the review will highlight the importance of specificity, periodization, and personalization in developing sports nutrition strategies. To frame this narrative review, we performed a non-systematic literature search in PubMed up to December 2025 using terms including “sports nutrition”, “athlete”, “exercise”, “energy”, and other related keywords. We also screened reference lists of recent reviews and guidelines.

ENERGY SOURCES AND EA

Understanding the process of energy metabolism during exercise is essential for developing targeted nutritional strategies. During exercise, chemical energy (intramuscular glycogen and triglycerides) is converted into adenosine triphosphate (ATP), which is then converted into mechanical energy (contraction) to achieve movement.¹⁰ Intramuscular ATP stores are limited, and during the initial phase of intense exercise, ATP is rapidly regenerated through two primary pathways: substrate-level phosphorylation via creatine phosphate breakdown, and anaerobic glycolysis utilizing muscle glycogen.¹⁰ The immediate mobilization of these energy sources is critical for acute exercise performance. Moreover, overall energy balance can influence long-term physiological health and sustained athletic performance. This broader impact from acute fueling to overall energy balance is related to EA.

EA

EA, defined by Loucks in 2004,^{11,12} is the amount of ingested energy that remains available for bodily functions and physiological processes after deducting the energy expended during exercise or training.

$$EA = \{ EI [Energy\ intake\ (kcal)] - EEE [Exercise\ energy\ expenditure\ (kcal)] \} / FFM [Fat-Free\ Mass\ (kg)/day]$$

Crucially, the optimal energy balance is not static; rather, individual energy requirements fluctuate significantly based on a variety of biological and environmental constraints. Energy needs may be decreased by aging, reductions in FFM, and certain physiological conditions like the follicular phase of the menstrual cycle.¹³ Conversely, some factors can increase energy requirements, such as extreme temperatures, fear, stress, high altitude, physical injuries, specific drugs or medications (e.g., caffeine, nicotine), increases in FFM and the luteal phase of the menstrual cycle.

Low EA (LEA) and relative energy deficiency in sport (REDs)

LEA, the mismatch between EI and EEE, results in insufficient energy to maintain optimal health and performance. As summarized in Figure 1, there are various causes of LEA – reduced energy intake (e.g., anorexia, losing

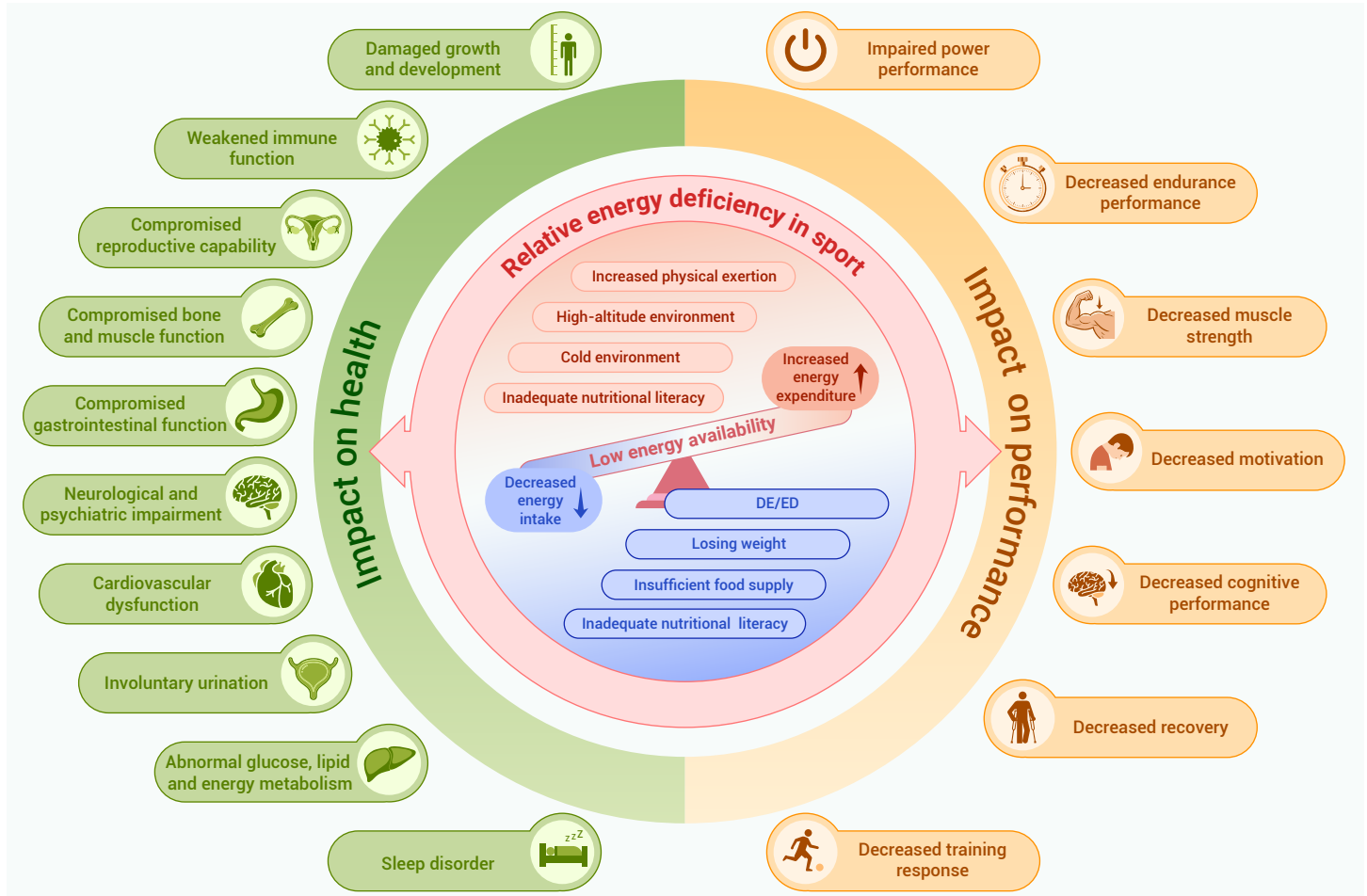


Figure 1. The impacts of low energy availability and Relative Energy Deficiency in Sport on health and performance The innermost circle represents factors affecting energy availability, and the outermost layer represents the health impacts and performance impacts caused by Relative Energy Deficiency in Sport. DE: disordered eating; ED: eating disorder.

weight, insufficient food supply) and increased exercise energy expenditure (e.g., exercise consumption, cold temperatures and high altitudes). Some studies showed that when LEA is below the threshold (30 kcal/kg FFM/day), health problems may occur.^{14,15} However, this threshold remains controversial and should be interpreted with caution. Some researchers reported thresholds ranging from approximately 9 to 25 kcal/kg FFM/day in males.¹⁶⁻¹⁸ Overall, evidence supporting a single universal threshold is limited, with variability across sex, age and training status.

When athletes experience prolonged or severe LEA, they may develop a syndrome called REDs. REDs was first introduced by the International Olympic Committee in 2014.¹⁹ As summarized in Figure 1, the systemic impact of REDs encompasses impaired health functions and exercise performance. REDs can compromise multiple physiological functions, such as bone health, reproductive capability, gastrointestinal function, etc. REDs also diminishes athletic performance by reducing muscle strength, decreasing cognitive performance, and impairing endurance capacity.

The key points for reversing REDs primarily involve addressing the LEA causes. Such improvements often require collaboration among multiple parties, including physicians, psychologists, sports nutritionists, and coaches.²⁰ This collaborative approach is particularly crucial for individuals exhibiting disordered eating behaviors or diagnosed with eating disorders, as well as for those with limited food access or increased metabolic demands. The primary principle is to personalize the strategy to the individual. After assessing energy requirements, an appropriate EI goal and dietary management plan should be established based on factors such as weight control goals, body composition, exercise levels, training and competition schedules, and environmental conditions. The plan should be modified based on observed physiological changes or performance outcomes.²¹

In addition to addressing the LEA causes, optimizing the supplementation and utilization of energy substrates, particularly carbohydrates and fats, is essential for maximizing athletic performance. The optimization not only provides adequate energy but also improves the efficiency of energy utilization, thereby serving as a proactive measure to prevent LEA.

CARBOHYDRATE APPLICATION FOR ATHLETES

Although both fats and carbohydrates can provide energy for ATP production, carbohydrates are a predominant fuel source, particularly during high-intensity exercise.^{22,23} Research also shows that in elite athletes, rather than fat utilization, carbohydrates are essential for maintaining the exercise intensity, especially in endurance exercise.^{24,25} Carbohydrates can be utilized in both aerobic and anaerobic pathways to produce ATP, but fat can not directly provide energy under anaerobic conditions. This metabolic flexibility of carbohydrates enables the fulfillment of diverse energy requirements and facilitates the transitions between different energy pathways.²⁶ Meanwhile, carbohydrate oxidation generates ATP more economically than lipid oxidation, which means consuming one liter of oxygen can boost ATP production by 5%-7%.⁸

The muscles use carbohydrates for fuel, drawing from the glycogen stores and blood glucose. Storage and utilization of glycogen within the muscle cell are related to the performance during exercise, especially the endurance exercise. Research demonstrates that glycogen loading enhances exercise capacity through glycogen conservation, with the intramyofibrillar pool in type I muscle fibers serving as the critical indicator of extended exercise capability.²⁷ This enhancement is attributed to the increased quantity of glycogen particles, rather than their size, allowing for fast utilization rates.²⁸ However, internal carbohydrate stores are insufficient to meet the energy

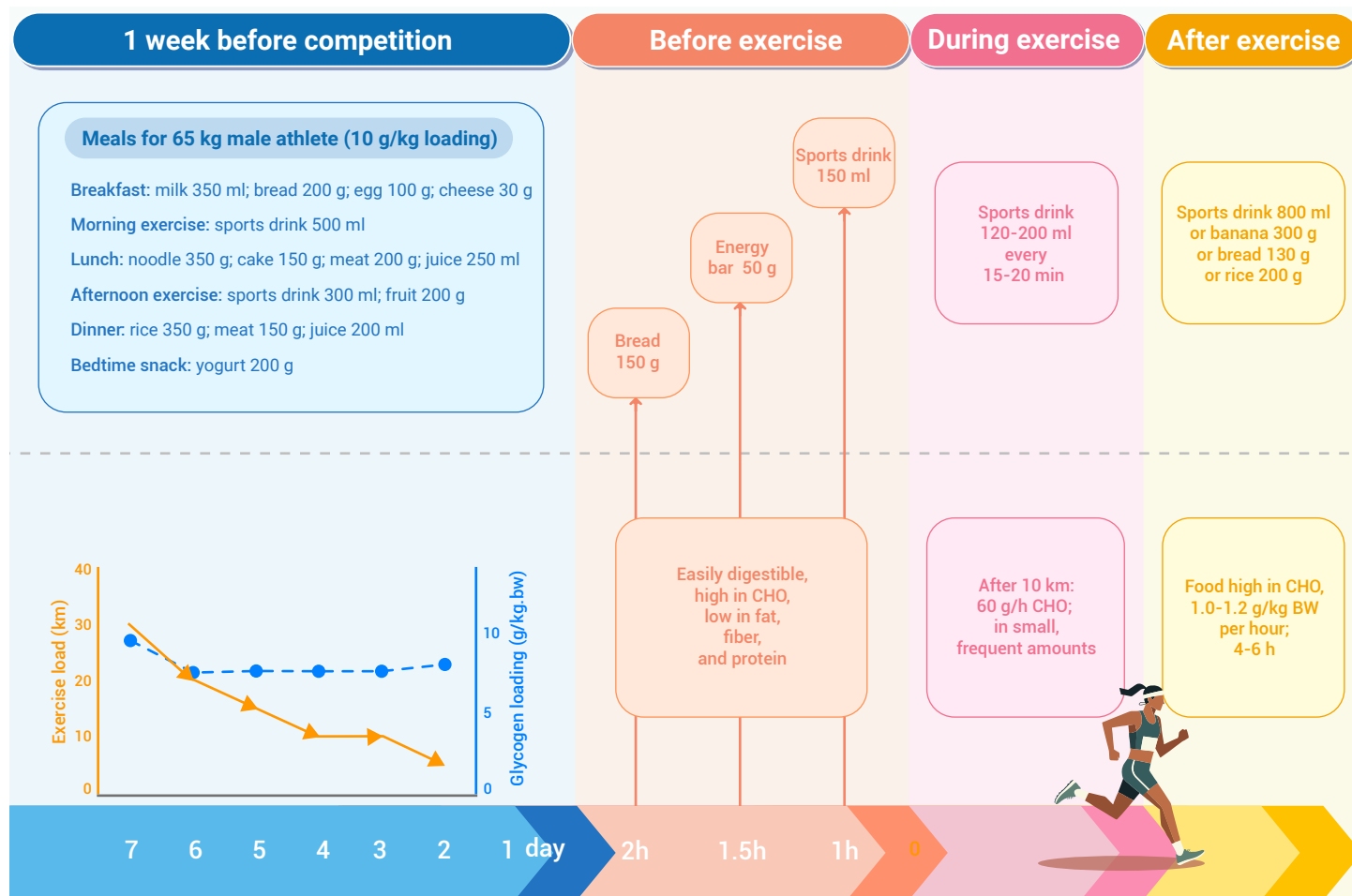


Figure 2. An example of a diet plan for a 60 kg male marathon runner In the week before the competition, glycogen loading and exercise volume are constantly changing. The daily meals shown in the figure is based on an example of 10 g/kg glycogen loading. CHO: carbohydrate; BW: body weight.

demands of competitive sports. Consequently, the rapid replenishment is vital for performance and recovery. Glycogen synthesis is influenced by a number of factors, such as training status, dietary carbohydrate intake, degree of glycogen depletion, and post-exercise nutritional intake.^{29,30} Therefore, strategies to promote the carbohydrate availability and to increase the storage of glycogen are important for improving athletic performance. The quantity, type, and methods of carbohydrate supplementation vary significantly across different phases of athletic training and competition.

Carbohydrate intake before sporting events

Over several decades, extensive studies have shown that carbohydrate stores prior to exercise significantly affect athletic performance, especially for endurance athletes and ball players.³¹ Carbohydrate or glycogen loading, a strategy to effectively enhance muscle glycogen synthesis in the days prior to a competition, was developed based on the critical role of muscle glycogen availability.^{6,32} Glycogen loading goals can be determined based on the duration and intensity of different sports, starting from a few days before the competition (Figure 2). For endurance or intermittent events lasting more than 90 minutes, it is recommended that athletes perform carbohydrate loading. These recommendations are primarily derived from studies in endurance exercise contexts. The classic 7-day carbohydrate loading model includes an initial 3-4 day "glycogen depletion phase" combining intense training with low carbohydrate intake, followed by a subsequent 3-4 day "glycogen supercompensation phase" characterized by high carbohydrate intake and exercise taper. Generally, modern carbohydrate loading is achieved through a commonly recommended carbohydrates intake of 8-12 g/kg for 36-48 h before a competition to maximize muscle glycogen storage (Table 1).^{4,6} Additionally, a rapid loading strategy involves consuming 7-12 g/kg of carbohydrates within the 24 h before exercise to restore glycogen levels.^{33,34} Currently,

it is generally not advised to engage in glycogen loading for events lasting less than 90 minutes.³² These carbohydrate loading strategies are primarily applicable to endurance athletes and ball game players competing in events lasting more than 90 minutes.

In addition to glycogen loading, carbohydrate intake 1-4 hours before exercise can spare glycogen and help maintain blood glucose homeostasis, preferably through easily digestible, high-carbohydrate, and low-fat/fiber foods (Figure 2).^{35,36} These pre-exercise carbohydrate strategies are primarily applicable to endurance athletes and other competitive athletes performing prolonged exercise. However, avoiding carbohydrate intake within 1 hour before endurance exercise has become a widely accepted principle in sports nutrition. This is because elevated blood glucose levels can trigger increased insulin release, which may impair fat oxidation capacity and lead to hypoglycemia or similar symptoms.³⁷ Beyond timing, the glycemic index (GI) of pre-exercise meals remains controversial. While low-GI foods were previously favored for sustaining energy, especially during the latter phases of prolonged exercise,³⁸ the meta-analysis by Burdon et al.³⁹ revealed no significant performance-enhancing effect of a low GI pre-exercise meal compared with a high GI meal. However, a limited number of studies and varied experimental protocols affected the robustness of the findings. Therefore, the choice of pre-exercise meal GI should be individually tailored based on the athlete's gastrointestinal tolerance, personal habits, and carbohydrate intake strategy during exercise.

While carbohydrate loading is recommended for prolonged events, it is generally discouraged for short-term, high-intensity exercise. Although short intense exercise sessions can significantly deplete muscle glycogen levels,⁴⁰⁻⁴² suggesting that glycogen loading might be beneficial, evidence fails to consistently support this assumption.⁴⁰ Moreover, it is worth noting that glycogen loading can also bring some adverse effects, such as water reten-

Table 1. Practical recommendations for carbohydrate intake by athletes.

Timing of exercise	Event duration and intensity	Recommended intake	Evidence level
Training	Low intensity or skill-based activities	3-5 g/kg per day	Consensus
	Moderate exercise program (e.g., ~1 h per day)	5-7 g/kg per day	Consensus
	Endurance program (e.g., 1-3 h moderate-to-high-intensity exercise)	6-10 g/kg per day	Consensus
	Extreme commitment (e.g., > 4-5 h moderate-to-high-intensity exercise)	8-12 g/kg per day	Consensus
Before sports events	Events > 90 min of sustained / intermittent exercise	10-12 g/kg per 24 h (36-48 h before events)	Consensus
During sports events	Endurance exercise 1-2.5 h	30-60 g/h	Consensus
	Ultra-endurance exercise >2.5-3 h	Up to 90 g/h	Consensus
After sports events	Endurance program (e.g., 2-3 h moderate-to-high-intensity exercise)	1.0-1.2 g/kg per hour	Consensus

tion and body mass elevation.^{43,44} These changes might significantly impact performance by lowering the sustainable exercise intensity or decreasing exercise efficiency.

While it is broadly accepted that carbohydrate loading strategies target the optimization of muscle glycogen, prioritizing liver glycogen loading appears to be less effective. Muscle glycogen is not affected by overnight fasting, whereas liver glycogen is.⁴⁵ After a night of fasting, liver glycogen can be substantially depleted. Consequently, multi-day carbohydrate loading strategies are ineffective for maintaining elevated liver glycogen level. Furthermore, muscle glycogen supplies energy faster because it is located in the muscle cells. In contrast, liver glycogen must be broken down into glucose first, then released into the blood, and subsequently transported to muscles, which takes more time. Although some studies have attempted to explore the supercompensation effect of liver glycogen, the results remain less than promising.⁴⁶ Previous observational research^{47,48} reported that after carbohydrate supplementation, liver glycogen concentrations increased to 1.5-3 times their original level. However, the supplementation occurred post-exercise rather than pre-exercise in their study. Podlogar et al.⁴⁹ found that endurance exercise capacity was higher in the fructose and rice group as compared with the glucose and rice group. The authors attributed this improvement to higher pre-exercise liver glycogen stores because of the rapid rate of fructose metabolism to liver glycogen. However, since they did not measure the liver and muscle glycogen concentrations, the credibility of this conjecture was undermined.

Carbohydrate intake during sporting events

Consuming carbohydrates during exercise provides an exogenous energy source that helps to maintain stable blood glucose over extended periods, and to sustain carbohydrate oxidation rates even as muscle glycogen stores decline. This allows the ingested carbohydrates to be used as a replacement for internal carbohydrate reserves.⁵⁰⁻⁵²

Athletes are traditionally advised to consume enough carbohydrates for exercise sessions lasting longer than 90 minutes. Usually, rapidly oxidized carbohydrates, such as glucose, glucose polymers, and glucose-fructose combinations, are primarily selected.⁵³ Galactose has typically not been recommended during exercise because it was thought to be less readily oxidized.^{54,55} However, emerging evidence shows that when lactose (a disaccharide of glucose and galactose) was consumed at moderate levels, it can be oxidized as effectively as sucrose.⁵⁶ These findings suggest that galactose oxidation during exercise is not as restricted as previously assumed. It also indicates that lactose might serve as an alternative carbohydrate source for lactose-tolerant individuals during exercise, but further direct evidence is needed.

The recommended amount of carbohydrates during exercise is 60 g/h, which was supported by substantial evidence. Some studies have shown that even with increased ingestion rates, the rate of oxidation does not continue to accelerate after reaching 1 to 1.1 g/min.^{57,58} A widely recognized reason is

that glucose absorption relies on Sodium Glucose Linked Transporter 1 (SGLT1). Once these transport proteins are saturated, it is not possible to further increase the rate of glucose oxidation.⁵⁹ This phenomenon also presents another possibility: combining glucose with other carbohydrates that do not require the SGLT1 for absorption could potentially enhance carbohydrate uptake. The concept of multiple transportable carbohydrates is grounded in this mechanism. Among these, the combination of glucose and fructose has been the most extensively studied. Generally, a 2:1 ratio of glucose to fructose is most commonly used in research and has become a standard recommendation.⁵⁹ However, Rowlands et al.⁶⁰ discovered that, compared with both lower and higher ratios, a fructose to glucose ratio of 0.8:1 provided the most effective boost in exogenous carbohydrate energy and endurance performance. Therefore, more high-quality research is needed to determine the optimal ratio. Beyond the ratio itself, another point of contention regarding multiple transportable carbohydrates is the minimum exercise duration required to see a benefit. For instance, Podlogar et al.⁶¹ believe that improvements can be seen even in exercise lasting 1-2.5 hours, while Barker et al.²¹ argue that improvements are only observable in exercises lasting more than 2.5 hours.

Regarding the upper limit of carbohydrate intake, it is currently not recommended to exceed 90 g/h (Table 1).^{4,6} For instance, Podlogar et al.⁶² discovered that consuming 120 g/h of carbohydrates, as opposed to 90 g/h, did not further spare endogenous carbohydrates nor did it offer any additional benefits. It is worth noting that these studies primarily involve athletes in moderate to high-intensity exercise; however, elite athletes with very high absolute energy demands may benefit from exceeding the 90 g/h threshold. Viribay et al.⁶³ also suggested that higher carbohydrate intake may be advantageous for elite athletes. They recruited elite male athletes, including two world champions to take carbohydrate during a mountain marathon, and found that a carbohydrate intake of 120 g/h effectively reduced exercise-induced muscle damage, as indicated by lower levels of creatine kinase, lactate dehydrogenase, glutamic oxaloacetic transaminase compared with intake rates of 60 and 90 g/h. Nevertheless, at present, it is not advisable to revise the current recommendation of a 90 g/h maximum carbohydrate intake for general endurance exercise.^{4,6}

Carbohydrate mouth sensing during sporting events

Interestingly, in addition to nutrients that can enter the digestive tract, certain nutrients can improve athletic performance even if they only remain in the oral cavity for a period of time without being absorbed.⁶⁴ The improvement in exercise performance could be a result of the brain's reaction to oral receptors, triggering the activation of brain regions involved in reward and motor control rather than metabolic mechanisms, and these receptors might be independent of sweetness receptors.⁶⁵ Consequently, carbohydrate mouth sensing has emerged as a pivotal area of investigation for optimizing athletic performance.

Over the past decade, a variety of studies have explored the effects of

carbohydrate mouth rinse on performance. It is widely accepted that carbohydrate mouth rinse enhances performance during moderate-high intensity endurance exercise.^{64,66} For example, Lane et al.⁶⁷ found that, compared with the placebo (artificially sweetened solution), the carbohydrate (10% maltodextrin solution + artificial sweetener) mouth rinse significantly improved mean power during the 60 min time trial, regardless of whether participants were in an overnight fasted or a fed state. A meta-analysis of 16 trials⁶⁶ found that a carbohydrate mouth rinse has the potential to increase mean power output in cycling trials, which is also consistent with the findings in another meta-analysis.⁶⁸ These carbohydrate mouth rinse strategies are primarily applicable to athletes and everyday exercisers performing endurance events.

In addition to the effects of carbohydrate mouth sensing on endurance performance, a meta-analysis of 13 trials reported a notable finding: there was a significant positive effect of carbohydrate mouth rinse on muscular endurance.⁶⁹ However, because this study did not have a rigorous Grading of Recommendations Assessment, Development and Evaluation system to evaluate the certainty of the evidence, it is essential to interpret the results with caution.⁷⁰ Although controversy persists regarding whether mouth sensing can improve muscular endurance, its ability to enhance athletic performance is largely recognized. Even for athletes who have already undergone pre-race carbohydrate loading, the mouth rinse strategy still can be recommended. A study confirmed that the optimal performance in a 1-hour time trial was achieved by combining pre-event carbohydrate intake with a carbohydrate mouth rinse during the event.⁶⁷

Carbohydrate intake after sporting competitions

Post-exercise carbohydrate replenishment is mainly aimed at restoring the body's glycogen stores, which is especially important for performance when the next training session or competition is approaching soon. It is generally accepted that restoring muscle glycogen fully requires 24 to 36 hours, whereas liver glycogen replenishment takes about 11 to 25 hours.^{71,72} Current nutritional recommendations suggest that after competition athletes should consume carbohydrates at a rate of 1.0-1.2 g/kg of body weight per hour during the first 4-6 hours (Figure 2 and Table 1). However, this dosage may be more adequate for average-level athletes. It may still be insufficient for elite athletes. Unfortunately, despite research finding a favorable dose-response relationship between the rate of muscle glycogen synthesis and the exogenous carbohydrate intake rate within the range below 1.8 g/kg per hour,⁷³ there is no direct evidence indicating that exceeding this dose could bring additional benefits. These strategies are primarily intended for athletes and everyday exercisers with limited recovery time (e.g., less than 24 hours) before subsequent exercise.

The evaluation of different types of monosaccharides in supplemental carbohydrates for post-exercise recovery is currently a hot topic. Supplementing with different types of monosaccharides is beneficial for the faster restoration of liver glycogen, but it does not seem to have better effect on muscle glycogen storage than glucose.^{47,48} For instance, Maunder et al.⁷⁴ found that endurance capacity (a second bout of treadmill running to exhaustion) was significantly enhanced with fructose-maltodextrin versus glucose-maltodextrin ingestion during recovery. However, this team further explored the topic and found that supplementing with combined fructose and glucose after intense exercise did not enhance subsequent cycle time trial performance compared with glucose only.⁷⁵ The underlying reasons for this situation remain unclear. However, preliminary findings indicate that different advantages of carbohydrate supplementation may vary depending on specific exercise modalities and conditions.

Studies have investigated whether combining carbohydrates with protein or amino acids provides additional recovery benefits compared with carbohydrates alone. Several studies have reported that post-exercise ingestion of carbohydrates and protein enhances muscle glycogen replenishment, decreases muscle soreness, and mitigates increases in muscle damage markers, such as creatine kinase, myoglobin,^{76,77} and lactate dehydrogenase.⁷⁸ However, the impact of carbohydrates and protein on recovery markers remains debated, since many studies have failed to observe any significant improvement.⁷⁹⁻⁸² Similarly, conflicting results have been observed regarding the effects on exercise performance, with some

studies reporting improvements,^{78,80} while others have found no significant benefits.^{77,81} Importantly, the evidence supporting a lack of significant effect is relatively weak. Therefore, it is generally recommended to supplement protein, peptides or amino acids alongside carbohydrates after exercise, particularly when rapid post-exercise recovery is required.⁸³

CARBOHYDRATE PERIODIZATION FOR TRAINING

Periodized nutrition involves the intentional and strategic application of specific dietary strategies to enhance adaptations to exercise. It is used for specific training plans in certain periods to improve performance over the long term.⁸⁴ A method called "train low" is gaining attention in sports nutrition. It involves intentionally training with limited carbohydrate availability to increase metabolic adaptations in skeletal muscle for endurance exercise. Training with low glycogen stores or fasting status can enhance cellular signaling pathways, increase mitochondrial adaptation, regulate hormone levels, influence protein synthesis and other metabolic pathways.⁸⁴⁻⁸⁶ Train-low models include twice daily training, fasted training, and sleep-low protocols.

Twice-daily training has been widely studied, but whether it actually improves athletic performance is still unclear. The study by Hansen et al.⁸⁷ compared the effects of skeletal muscle adaptation using a single-legged kicking model between two training regimens: once daily versus twice every second day. In the latter regimen, participants perform a morning exercise to deplete muscle glycogen. This is followed by several hours of limited carbohydrate intake, ensuring that the second training session begins with reduced muscle glycogen levels. Resting muscle glycogen and the activity of the mitochondrial enzyme 3-hydroxyacyl-CoA dehydrogenase increased in the train low group. Parallel studies explored the effects of training frequency in well-trained cyclists. Hulston et al.⁸⁸ found that muscle-derived triacylglycerol oxidation and β -hydroxyacyl-CoA-dehydrogenase protein both increased following training under low glycogen conditions. Similarly, Yeo et al.⁸⁹ found that phosphorylation of AMPK increased more in the train low group after high intensity training. Notably, while these studies showed significant changes in biological indicators, they failed to translate into improved athletic performance. In contrast, Cochran et al.⁹⁰ reported more pronounced improvements in 250-kJ time trial within the train low group, suggesting that a short-term "train low, compete high" may enhance overall exercise capacity. However, the participants in the study were not highly trained athletes. Therefore, although training twice a day might promote adaptations of fat metabolism, the evidence supporting performance enhancement is of low-to-moderate quality, and it remains premature to definitively conclude that this method will yield long-term performance benefits, particularly for elite athletes.

Similar findings are reported with fasted training, which has been shown to improve physiological markers, but the effects on athletic performance remain unclear. Fasted training is a model to exercise in the morning before having breakfast. Overnight fasting does not significantly impact muscle glycogen levels; however, it can result in substantially reduced liver glycogen level.⁹¹ Some studies have shown that fasted training could enhance oxidative enzymes, boost intramuscular fat utilization,⁹² improve glycogen resynthesis,⁹³ increase AMPK activity⁹⁶ and boost post-exercise gene expression.⁹⁴ However, no research has demonstrated significant improvements in performance with fasted training.⁹⁵

In the sleep-low model, individuals perform an evening training session, limit carbohydrate intake during the overnight recovery, and complete a fasted morning training session. According to Marquet et al.,⁹⁶ short-term sleep-low training leads to improvements in 20-km cycling time-trial and 10-km running performance in elite triathletes and cyclists compared with traditional training with high carbohydrate availability. This study suggested that "sleep low" may have potential beneficial effects on training performance. However, due to the limited number of available studies and the small sample sizes of the included participants, the evidence is of low quality. More research is still required for validation.

FAT OXIDATION BASED STRATEGIES

While carbohydrate-based energy supply strategies have been extensively studied for enhancing athletic performance, alternative approaches focusing

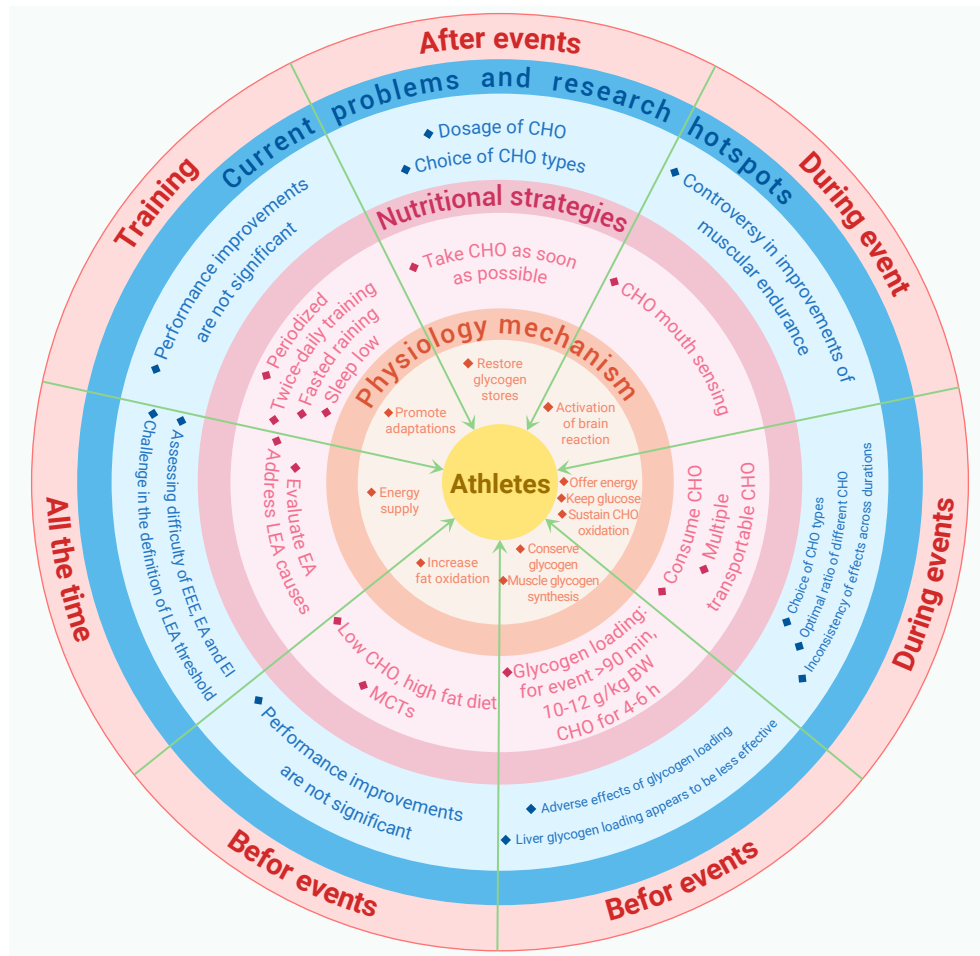


Figure 3. The foundational mechanisms, strategies, and current research issues related to nutritional strategies involving energy metabolism for athletes CHO: carbohydrate; EEE: exercise energy expenditure; EA: energy availability; LEA: low energy availability; MCTs: medium-chain triglycerides; EI: energy intake.

on fat oxidation may also provide performance benefits.

Low carbohydrate high fat diet

A low carbohydrate, high fat (LCHF) diet may increase fat utilization during exercise.⁹⁷ This hypothesis is supported by the fact that even the leanest athletes have substantially larger fat stores than carbohydrate reserves. High-fat diets can enhance the mobilization, transport, absorption, and utilization of fat in muscles.⁹⁸ In the past 40 years, two main models have been primarily studied: a ketogenic LCHF diet (< 20 g/d carbohydrate and 80% of energy supplied by fat)⁹⁹ or a nonketogenic LCHF diet (15%-20% of energy supplied by restricted carbohydrate and 60%-65% of energy supplied by fat).¹⁰⁰ Research on LCHF diets involves short-term application, long-term application, short-term adaptation of LCHF combined with high-carbohydrate utilization. While LCHF diets lead to increased fat oxidation rates during exercise, this metabolic adaptation does not necessarily translate into improvements in athletic performance, and there is insufficient evidence to prove that changes in substrate utilization could significantly enhance sports performance.¹⁰¹

Short-term LCHF diet strategies have been proven unsuccessful for prolonged endurance exercise performance. Although the diet alters fuel utilization patterns to favor fat oxidation, the modest increase in free fatty acid oxidation is insufficient to replace the contribution of carbohydrate.¹⁰² Long-term application also showed similar results. For example, a 3-week intervention trial in elite race walkers found that, compared with high carbohydrate diets, adhering to an LCHF diet impaired performance in elite endurance athletes (-1.6% (-8.5%, 5.3%) for 10 km race walk), even though there was a notable improvement in their $V_{O_{2peak}}$ levels.⁹⁸ Does a short-term LCHF diet followed by a high carbohydrate diet enhance the availability and utilization of fats and carbohydrates simultaneously, thereby optimizing

performance? Indeed, there were some studies testing the effects of these two diets on athletic performance, but the results were not satisfactory. Havemann et al.¹⁰³ investigated the effects of a LCHF followed by 1 day of high carbohydrate diet, and they found that, compared with high-carbohydrate diet, the LCHF-carbohydrate dietary strategy increased fat oxidation, but this did not translate into improved performance and even reduced high intensity sprint performance, with lower 1-km sprint power output. Current evidence suggests that LCHF may provide limited benefits for enhancing athletic performance.

Medium-chain triglycerides

Medium-chain triglycerides (MCTs), composed of 6-12 carbon fatty acids, are rapidly hydrolyzed primarily by pancreatic lipase into medium-chain fatty acids, which are then absorbed by intestinal cells without the need for bile emulsification. MCTs are known to be metabolized more easily by beta-oxidation than long-chain triacylglycerols. Although some studies suggest that sustained MCTs intake may enhance fat oxidation and exercise performance, the evidence remains limited due to methodological weaknesses. For example, Nosaka et al.^{104,105} reported that MCTs increased fat oxidation during moderate exercise and extended high-intensity exercise duration in recreational athletes, but the small sample size ($n=8$) limited the study's statistical power and generalizability. Similarly, a very small sample size was also found in Van's study.¹⁰⁶ Although Tsuchiya et al.¹⁰⁷ found that MCTs supplementation improved muscular endurance and reduced fatigue, these effects were observed when combined with eicosapentaenoic acid, making it unclear whether they can be attributed solely to MCTs. Given the very limited number of studies and consistent methodological weaknesses, the evidence is of low quality. In conclusion, using MCTs as a significant energy source during exercise seems impractical and is not sufficiently supported by evidence.

PERSONALIZING NUTRITION STRATEGIES

A one-size-fits-all nutrition strategy cannot meet personalized needs of elite athletes, especially since significant differences in energy consumption and metabolic levels are observed among different athletes. To optimize athletic performance and maintain optimal health, personalized nutrition for athletes must take into account their unique physical conditions, the type of sport they engage in, and the demands of their competition and training. Given the variability in competition duration, intensity, and dynamic environmental conditions, it is crucial for nutritional strategies to be dynamically adapted to meet the requirements of each situation. Moreover, scientific nutritional supplementation focuses not only on "what to supplement" but also on "how much to supplement," "when to supplement," and "how to supplement." The timing of nutrient intake and methods of supplementation are critical for athletes' performance and recovery.

For scientifically rigorous personalization, it is important to employ technological methods, including various devices and instruments. Energy expenditure equipment can effectively track changes in energy during physical activity, providing valuable assistance in personalized energy strategies. But for glycogen monitoring, it is not as accurate as energy monitoring. At present, glycogen breakdown is typically estimated based on glycogen degradation results from muscle biopsies of athletes. Although technologies such as ultrasound have been attempted to monitor glycogen consumption, there is currently no low-cost, non-invasive, and mature method available for monitoring glycogen during actual exercise.¹⁰⁸ Near-infrared spectroscopy has emerged as a promising tool for monitoring muscle metabolism during exercise, which can measure oxygenated and deoxygenated hemoglobin to assess muscle oxygenation and blood flow. However, it can not directly monitor glycogen levels, as it reflects oxygen use rather than direct glycogen measurement.¹⁰⁹

The blood glucose level of athletes may serve as a potential indicator for the intake of energy. However, a current challenge is to determine the appropriate threshold values for blood glucose in athletes, as the standard ranges for the general population are clearly not suitable for athletes. This may require extensive research for validation. Additionally, monitoring blood glucose levels in athletes is of significant importance. In recent years, continuous glucose monitoring has been utilized to monitor glucose variations in endurance athletes. However, due to significant differences between athletes and the general population, the distinctive longer duration of hyperglycemic and hypoglycemic states in athletes, and the complexity of glucose regulation and utilization, the use of continuous glucose monitoring to guide carbohydrate intake in athletes is currently not recommended.^{110,111} Furthermore, stable carbon isotopes help track exogenous carbohydrate oxidation rates to provide insights into carbohydrate requirements, potentially serving as a reference for personalized intake recommendations of energy.⁵⁹

CURRENT PREDICAMENT AND FUTURE DIRECTIONS

As summarized in Figure 3, the strength of evidence varies considerably across strategies, and several challenges remain in their practical application. Although the importance of EA is well recognized, how to define its threshold and identify risk factors for LEA remain major challenges; pre-exercise muscle glycogen loading is effective, whereas liver glycogen loading appears to be less effective; LCHF and train-low show favorable mechanistic adaptations but limited performance benefits; and although consuming carbohydrate is important during and after sports, the optimal selection of carbohydrate dosage and type remains a critical scientific question requiring further exploration. Beyond these strategy-specific challenges, there are several broader, more systemic issues that demand our attention. These predicaments include balancing health and performance, resolving implementation barriers, addressing the limited research on elite athletes, and overcoming additional methodological constraints.

Developing more scientific nutritional strategies to optimize the health-performance balance will be a primary research focus in sports nutrition. Equal consideration should be given to athletes' health and performance outcomes. Some studies have found that long-term implementation of conventional nutritional strategies may be associated with adverse health outcomes. For example, long-term high-carbohydrate diet may increase the risk of insulin resistance,¹¹² and poor dental health has been observed in

many Olympic athletes.¹¹³ Moreover, some studies reported that habitual marathon runners may have coronary artery disease.¹¹⁴ Although these adverse health effects might be related to the physiological processes of excessive exercise, they also could be associated with the insulin resistance and inflammatory state induced by a high-carbohydrate diet.⁹⁷ Thus, exploring more reasonable nutrition strategies is not only beneficial for achieving victory in competitions but also advantageous for prolonging athletes' careers. Breakthroughs in the following directions may facilitate an optimal health-performance balance: systematic adjustment of carbohydrate intake according to training phases; scientific selection of carbohydrate quality; strategic co-administration with proteins, fatty acids, and other nutrients; personalized dietary protocols based on the circadian rhythms.

Ensuring the effective implementation of nutritional strategies for athletes encounters several challenges. Firstly, the training and competition schedules often influence the adherence to scientifically based nutrition plans, for example, not all fluid replenishment during a competition is allowed. Secondly, variations in dietary habits and cultural backgrounds can influence the acceptance and compliance of athletes. Furthermore, extreme weather conditions, such as heat, cold, and high altitude, can adversely affect athletes' physical conditions, consequently impacting the nutritional strategies. Additionally, limited access to high-quality guidance further obstructs the effective implementation of these strategies. Lastly, strategies are different for athletes living communally compared with those living individually, which also brings challenges for the formulation of nutrition strategies. Potential improvements may be achieved through the following measures: precision nutrition strategies assisted by intelligent monitoring systems and artificial intelligence technology,¹¹⁵ although these approaches require further validation before routine implementation; development of athlete nutrition literacy; implementation of a six-party collaborative framework integrating athletes, coaches, nutritionists, team physicians, psychologists, and chefs.

Conducting studies focusing on elite athletes is transformative, but it faces some significant challenges. Research on elite athletes is actually quite scarce. Top world-class athletes are inherently rare, and it must be acknowledged that the legendary achievements of many top athletes can not be completely replicated. Elite athletes may differ from ordinary athletes in energy supply, strength, and skill. Many current studies focus on amateur athletes or sub-elite athletes because of the scarcity of top athletes and the difficulty in obtaining their cooperation. However, what concerns us is that these conclusions derived from non-elite athletes may not apply to elite athletes. Intervention studies on elite athletes may not always be practical. Cohort analysis might provide valuable insights. Additionally, exploring methods to extrapolate findings from sub-elite athletes to elite athletes could help address this limitation. Moreover, scientific and objective biological markers can help to evaluate the effects and mechanisms. Multi-omics technologies have undergone major breakthroughs over time, which brings hope for exploring related mechanisms.^{116,117} However, translating these findings into personalized nutrition strategies remains challenging.

TRANSLATING ELITE EVIDENCE TO EVERYDAY EXERCISERS

In addition to professional athletes, this article also holds significant implications for general sports enthusiasts. In recent years, the scope of sports medicine research has expanded from competitive athletics to population health management, providing evidence-based guidance for public health promotion. Exercise is a key intervention for managing chronic diseases.¹¹⁸⁻¹²⁰ However, engaging in intense physical activity without paying attention to dietary strategies may not only influence exercise efficacy but could also lead to potential health risks. Exercise enthusiasts demonstrate elevated susceptibility to sports-related pathologies, including exertional anemia, gastrointestinal disturbances, and musculoskeletal injuries. Nutritional strategies can effectively prevent and relieve these conditions. Many principles discussed herein, such as EA and nutrient timing, are also applicable to the active public, helping to exercise more effectively and to minimize health risks.

Although the nutritional strategies discussed above might be effective for enhancing athletic performance, their application to everyday exercisers requires careful individualization. For amateur athletes, their training time and intensity often resemble those of professional athletes. Therefore, these strategies are largely applicable to amateur athletes, although the recom-

mended doses may need to be moderately reduced based on their training load. For enthusiasts with a high training load (e.g., >90 min/session or >6-8 hours per week), even if they do not have competitions, some strategies aimed at maintaining performance and promoting recovery (e.g., carbohydrate intake during long sessions, supplementation after exercise) may be beneficial. For recreational exercisers, there is a minimal need for aggressive carbohydrate strategies beyond mouth rinsing. High-dose carbohydrate strategies provide few performance benefits but bring excess caloric intake and metabolic burden.

SUMMARY

This review identifies multiple nutritional strategies for optimizing energy metabolism, with different certainty of evidence. First, regarding LEA, the evidence is clear: avoiding energy deficits is very important for maintaining optimal health and performance. The challenge now is to identify and address the specific underlying causes. Second, for carbohydrate periodization, the evidence is well-established for several specific strategies: glycogen loading before sporting events, carbohydrate supplementation (including mouth rinsing) during sporting events, and multiple-transportable carbohydrate intake after sporting events. These strategies enhance performance and facilitate recovery. Third, for nutritional interventions to increase fat oxidation, the quality of evidence is low, and current evidence does not support the efficacy of LCHF diets or MCTs in significantly enhancing athletic performance. Similarly, periodized training with low carbohydrate availability also lacks sufficient evidence. These findings caution against prioritizing metabolic changes over performance.

ABBREVIATION

ATP: adenosine triphosphate; EA: energy availability; EEE: exercise energy expenditure; EI: energy intake; FFM: fat-free mass; GI: glycemic index; LCHF: low carbohydrate, high fat; LEA: low energy availability; MCTs: medium-chain triglycerides; REDs: Relative Energy Deficiency in Sport; SGLT1: Sodium Glucose Linked Transporter 1.

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AUTHOR CONTRIBUTIONS

C.C. and D.J. supervised and revised the manuscript. W.L. wrote and revised the manuscript. H.A. revised the manuscript. X.L. and J.Y. drew the figures. All authors contributed to and approved the manuscript.

DECLARATION OF INTERESTS

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DATA AND CODE AVAILABILITY

Not applicable.