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COMMENTARY

Toward a Common Understanding of Diet–Exercise Strategies to Manipulate Fuel Availability for Training and Competition Preparation in Endurance Sport

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From the breakthrough studies of dietary carbohydrate and exercise capacity in the 1960s through to the more recent studies of cellular signaling and the adaptive response to exercise in muscle, it has become apparent that manipulations of dietary fat and carbohydrate within training phases, or in the immediate preparation for competition, can profoundly alter the availability and utilization of these major fuels and, subsequently, the performance of endurance sport (events >30 min up to ~24 hr). A variety of terms have emerged to describe new or nuanced versions of such exercise–diet strategies (e.g., train low, train high, low-carbohydrate high-fat diet, periodized carbohydrate diet). However, the nonuniform meanings of these terms have caused confusion and miscommunication, both in the popular press and among the scientific community. Sports scientists will continue to hold different views on optimal protocols of fuel support for training and competition in different endurance events. However, to promote collaboration and shared discussions, a commonly accepted and consistent terminology will help to strengthen hypotheses and experimental/experiential data around various strategies. We propose a series of definitions and explanations as a starting point for a more unified dialogue around acute and chronic manipulations of fat and carbohydrate in the athlete's diet, noting philosophies of approaches rather than a single/definitive macronutrient prescription. We also summarize some of the key questions that need to be tackled to help produce greater insight into this exciting area of sports nutrition research and practice.

Keywords*:* carbohydrate periodization, LCHF diet, train high, train low

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Fifty years ago, Scandinavian scientists used the needle biopsy technique to sample skeletal muscle, including their own, allowing them to identify mechanisms by which manipulation of the carbohydrate (CHO) content of the preceding diet could alter exercise endurance (Hultman, 1967). This work built on earlier studies (Krogh & Lindhard, 1920; Christensen & Hansen, 1939) of the effects of the macronutrient composition of the diet on fuel utilization and exercise capacity; however, these earlier investigators were limited by the techniques available at the time and by the contemporary understanding of the regulation of muscle metabolism. Research undertaken during the 1960s and 1970s on glycogen "supercompensation" spanned mechanistic descriptions of the cellular events underpinning the improvements in exercise capacity (Ahlborg et al., 1967; Bergstrom et al., 1967; Hermansen et al., 1967) to real-world proof that dietary CHO interventions in laboratory settings could translate into enhanced sports performance (Karlsson & Saltin, 1971).

The outcomes of these activities included a publication in *Nature* (Bergstrom & Hultman, 1966) and the rapid adoption of new dietary practices by the athletic community. For example, as early as May 1968, Dr. Griffith Pugh and the International Athletes' Club organized two 40-km races for 10 top-class race walkers; half of the group prepared with a high-CHO diet for the first race, whereas the other half did so for the second. Their findings—that the walkers achieved significantly faster times over the final 10 km of their high-CHO trial—were passed on to the British competitors at the Mexico Olympic Games (Hyman, 1970). Furthermore, British runner Ron Hill attributed at least part of his success at the 1969 European Marathon Championships to a version of the CHO supercompensation diet described by Hermansen et al. (1967). The final outcome of this work was the introduction of the term "carbohydrate loading" into the general lexicon, with such popularity that it would become almost synonymous with sports nutrition. It is unlikely that any modern sports nutrition intervention will ever achieve the trifecta of a publication in the highest impact scientific journal, rapid adoption by its target audience to achieve success in elite sport, and household fame. Since then, many scientists have continued to refine aspects of this work to evolve modern sports nutrition into a vibrant environment of applied research leading to practice. There is no doubt that the interaction of diet and exercise provides a powerful tool for the study of the regulation of muscle metabolism and to enhance metabolic health and sports performance.

One of the downsides of the proliferation of activities across many stakeholders, including researchers, clinicians, coaches, and athletes, is that a variety of terms have emerged to describe new or nuanced versions of exercise–nutrition strategies that target similar areas of interest. The nonuniform use of terms has subsequently caused confusion and miscommunication in both the popular press and the scientific community. Even within the toolbox of such strategies, there is confusion over the names of the tools, how they should be used, and what they might achieve in reengineering the muscle. This arises because of the different nomenclature used in the original studies and the tweaking of both names and protocols in further research or real-world applications. In some cases, the same term may mean different things in the same literature but also have another meaning in an adjoining field for coaches/athletes. For example, the term "train low" has been used to describe a single acute training session in which the availability of muscle CHO and/or exogenous CHO has been manipulated to "lower" levels before and/or during the session by a variety of techniques that have different metabolic and cellular consequences (for reviews, see Bartlett et al., 2015; Hawley et al., 2018; Impey et al., 2018). However, the term has also been used to describe a chronic training period in which such strategies were undertaken in differing combinations over many days to weeks (Hansen et al., 2005; Yeo et al., 2008); furthermore, to many sports scientists and coaches, "train low" is more likely to be aligned with altitude/hypoxia exposure protocols (Girard et al., 2013).

Historically, the scientific literature has provided confusing information and nonmeaningful terminology, such as using the ratio of energy contributed by CHO in the athlete's diet as the single metric of the adequacy of CHO intake (Burke et al., 2004). However, even this literature presents erroneous information. For example, proponents of low-CHO high-fat dietary philosophies commonly state that contemporary sports nutrition guidelines promote high CHO intakes at all times for all athletes (Brukner, 2013; Noakes et al., 2014; Volek et al., 2015). Yet, as far back as 2003, official recommendations from an International Olympic Committee expert panel noted that fuel demands differed between different types of events or training intensities and volumes, leading to a sliding scale of daily CHO intake targets and the promotion of specific scenarios, rather than a universal recommendation for aggressive CHO fueling strategies (Burke et al., 2004). Indeed, between and among even elite endurance athletes, training loads can vary from 10 to 12 hr/week, with the duration of a key session being 60–120 min (e.g., track runner), up to 25–30 hr/week, with single sessions lasting for 4–6 hr (e.g., triathletes, cyclists). Accordingly, a further update in 2010 recommended that CHO availability, rather than absolute intake, be used to evaluate the athlete's dietary CHO consumption (Burke et al., 2011). Here, the amount and timing of daily CHO intake are defined in relation to the fuel cost of the day's exercise load—recently termed "fuel for the work required" (Impey et al., 2018). Accordingly, "high CHO availability" denotes that this intake is able to provide sufficient endogenous and/or exogenous CHO supplies to meet the demands of the muscle (and central nervous system), whereas "low CHO availability" signifies a shortfall between supplies and exercise/energy demand (Burke et al., 2011). Indeed, according to the example of variability in workloads between and within even elite athletes previously provided, any given amount of CHO and its timing of intake might achieve "high CHO availability" for one athlete or one day's training, whereas in another context it would be considered "low."

The 2010 update refined the concept of the different and changing CHO requirements between and within athletes by explicitly stating that: (a) high CHO availability is required only for sessions in which training or competition involves higher intensity workloads and the need to perform optimally or train with high-quality outputs and/or maximize recovery; (b) training loads, which are light and/or based on low–moderate intensity exercise, may not need to be supported by high CHO availability; and (c) there is an emerging interest in the concept of deliberately exercising with low CHO availability in some training sessions to take advantage of upregulated cellular signaling and adaptive responses to the increased metabolic training stress (Burke et al., 2011). The most recent sports nutrition guidelines (Thomas et al., 2016) have strengthened their recognition of this last point, noting increased confidence in the molecular underpinning of training with low CHO availability (Hawley et al., 2018; Hearris et al., 2018; Impey et al., 2018), published case studies of its use by elite athletes (Stellingwerff, 2012), and research evidence, at least in subelite athletes, that its careful integration into a training program can lead to superior performance (Marquet et al., 2016a, 2016b). Indeed, the latest guidelines include acknowledgment of potential benefits from a personalized approach to manipulating CHO availability within the training diet (Thomas et al., 2016; Jeukendrup 2017a).

The press and social media amplify the confusion by mispresenting/misreporting sports nutrition research or practice and by generally oversimplifying the sophistication of contemporary sports nutrition knowledge (Burke, 2017). In July 2016, a Twitter war erupted after Tour De France winner Chris Froome uploaded a photo of his breakfast on a rest day during the middle of this grueling stage race. This single picture of eggs, smoked salmon, and avocado caused an avalanche of claims and counterclaims

Table 1 Chronic Dietary Strategies Used for Training Adaptation and Event Preparation by Endurance Athletes to Potentially Enhance Fuel Availability, Utilization, and Performance

Name	Current description/definition	Original underpinning principles	Contextual comments and/or disparities
High-CHO diet	• Lacks a single or clear definition. • Is typically considered a static target. • Various metrics for CHO intake have included a ratio of energy intake (e.g., >50% or 60–70%), absolute amounts (e.g., 500–600 g/day), or amounts relative to BM as a proxy for the size of the exercising musculature (e.g., 7–10 g/kg).	• (All) endurance athletes have a consistently high fuel demand, which must be met by dietary CHO intakes to support hard training and competition preparation and to optimize event performance (Coyle, 1991).	• Represents original sports nutrition guidelines (Coyle, 1991). • Largely anachronistic since the concept is not clearly defined and does not recognize an athlete's specific and changing fuel needs related to active muscle mass and total training loads. • Absolute CHO targets (e.g., 500 g/day) or relative energy targets (e.g., 60% of energy) should not be used in isolation since they are poorly correlated with the muscle fuel needs for training (Burke et al., 2004).
High CHO availability diet	• Dietary plan in which total daily CHO intake, and its spread over the day, is targeted at optimizing muscle glycogen stores and additional exogenous CHO supplies to meet the fuel demands of the day's training or event commitments. • Total daily targets vary according to goals and are typically represented as gram per kilogram BM as a proxy for the size of the exercising musculature; the daily range may vary from 3 to 12 $g^{-1} \cdot kg^{-1} \cdot day^{-1}$ according to the training load. • Includes CHO intake before, during, and/or between key sessions if needed for fuel support.	• Consistent high-quality training is underpinned by optimal CHO fuel. • Adequate CHO intake is also important for the optimal function of the central nervous system, immune system, and other body systems (e.g., bone metabolism for injury resilience). • Daily CHO intake should be tailored to the individual's exercise commitments, integrated with other nutrition goals (e.g., energy needs), and fine-tuned with experience.	• This plan most closely achieves the principles of the original sports nutrition guidelines, but includes the following updates: ○ Providing different and changing amounts of CHO between and within athletes according to variable training/event fuel demands. ○ Specifically targeting intakes around and during training sessions. • Actual fuel needs of many training loads are unknown and require guesswork and experimentation. • In the case of high-volume training (>2 sessions/day; >25 hr/week), even aggressive CHO intake may not allow full replacement of fuel needs; some sessions will inevitably be undertaken with low CHO availability.
Periodized CHO availability diet	• Dietary plan in which CHO availability for each workout is varied according to the type of session and its goals within a periodized training cycle. May include single sessions of variants of "train high" and "train low" as well as sequences of these strategies (see below).	• Training-nutrient interaction is achieved for each session to maximize the outcome of enhanced stimulus/adaptation from scenarios of low CHO availability and enhanced training quality/intensity with high CHO availability (see definitions in Table 2 of each acute strategy) and for a general review of the concept (Impey et al., 2018; Jeukendrup, 2017a). • Requires good collaboration between the athlete, coach, and sports scientist to develop optimal periodization strategies, balancing priorities of adaptation vs. performance, and managing fatigue. • Periodization plans are expected to change across the different phases of training.	• Integration of periodized CHO availability into a training program over 3 weeks (Marquet et al., 2016a) and 1 week (Marquet et al., 2016b) has been shown to enhance performance in subelite athletes compared with similar CHO intake consumed to promote high CHO availability for all sessions. However, these benefits have not yet been demonstrated in elite competitors (Burke et al., 2017a; Gejl et al., 2017), although they are used in real-world practice (Stellingwerff, 2012).

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Table 1 (continued)

Name	Current description/definition	Original underpinning principles	Contextual comments and/or disparities
Nonketogenic low-CHO high-fat (NK-LCHF) diet	• Dietary plan in which CHO availability is chronically (days/weeks/months) maintained below muscle CHO needs to promote adaptations favoring fat oxidation, but with sufficient CHO to avoid sustained ketosis. • Typical intake = 15–20% energy from CHO ($<2.5\ g^{-1} \cdot kg^{-1} \cdot day^{-1}$), 15–20% protein, 60–65% fat in combination with a moderate-endurance training volume (>5 hr/week).	• Deprivation of CHO for muscle fuel needs while consuming high amounts of dietary fat causes adaptations to increase availability of muscle fats and capacity to oxidize them as muscle fuel (e.g., increased IMTG stores, increased fatty acid mobilization and transport, increased enzyme activity associated with fat metabolism; for review, see Spriet, 2014; Burke, 2015). • Robust adaptations occur in as little as 5 days and withstand short-term (e.g., 2 days) restoration of CHO availability (Burke et al., 2002). Time course of deadaptation is not known. • Although most of the metabolic effects of this diet have been attributed to CHO restriction, new evidence has identified separate effects of high fat intake, including reductions in mitochondrial respiration and increases in whole-body rates of fat oxidation (Leckey et al., 2018), which leads to decreased exercise economy (Burke et al., 2017a).	• Although the NK-LCHF diet may double rates of fat oxidation, this is not associated with enhanced endurance performance, except in isolated scenarios or individuals (for review, see Burke 2015). • Adaptation to NK-LCHF diet in just 5 days has been shown to downregulate CHO oxidation by reduced rates of glycogenolysis and reduced activity of PDH enzyme complex (Stellingwerff et al., 2006).
Ketogenic LCHF (K-LCHF) diet	• Dietary plan in which chronic ketosis is achieved by severely restricted CHO intake and moderate protein intake. Fats, principally saturated and monounsaturated, contribute the major energy source. • Typical intake = <5% energy from CHO (<50 g/day), 15–20% protein, and 75–80% fat. • Popular K-LCHF book (Volek & Phinney, 2012) recommends electrolyte supplementation to combat sodium diuresis associated with this diet.	• Adaptations achieve extremely high rates of fat oxidation during exercise (up to 1.8–2 g/min; Burke et al., 2017a; Volek et al., 2015). • While adaptation to increase fat oxidation occurs within ~5 days, it takes 2–3 weeks for fatigue and lethargy associated with initial exposure to K-LCHF diet to attenuate (Burke et al., 2017a; Phinney et al., 1983). • See comments for NK-LCHF, regarding the separate effects of high fat intake on metabolism. • Cross-sectional study has shown that chronic K-LCHF adaptation does not alter gluconeogenesis or glycogen synthesis rates, but reduces glycogenolysis and glucose oxidation at rest and during exercise (Webster et al., 2016). • Anecdotal reports and case history (Webster et al., 2017) suggest that some K-LCHF athletes may consume CHO on the day of an endurance/ultraendurance event and may practice this strategy during some training sessions (see below; Webster et al., 2017).	• Although K-LCHF adaptation and enhanced fat oxidation may support exercise of moderate intensity (<75% VO_2max; Phinney et al., 1983; Volek et al., 2016; Webster et al., 2016), it is less economical (less ATP production per milliliter oxygen consumption) and less able to support higher exercise rates (>75% VO_2max; Burke et al., 2017a). • Restricted food variety with K-LCHF diet (e.g., avoidance of grains and most fruit, limited intake of dairy, seeds, vegetables, and nuts) reduces dietary nutrient density compared with higher CHO diets (Mirtschin et al., 2018). • There are few investigations on skeletal muscle, which can demonstrate metabolic mechanisms.

Note. These strategies should support adequate energy availability unless a separate strategy is undertaken to manipulate this. BM = body mass; CHO = carbohydrate; IMTG = intramuscular triglycerides; PDH = pyruvate dehydrogenase; LCHF = low-carbohydrate high-fat diet; K-LCHF = ketogenic low-carbohydrate high-fat diet; NK-LCHF = nonketogenic low-carbohydrate high-fat diet.

Table 2 Common Acute Interventions in Which CHO Availability is Manipulated to Achieve a Specific Outcome Related to Training Adaptation and Performance Support

Name	Description/definition	Original underpinning principles	Contextual comments and/or disparities
Train high (glycogen) session	• Completion of a training session with muscle glycogen stores that are able to meet the demands of the workout. • Achieved by combination of sufficient time and CHO intake after prior training session to store targeted glycogen stores; total CHO intake target typically ranges from 5 to 12 $g^{-1}\cdot kg^{-1}\cdot day^{-1}$ according to training load. • Depending on glycogen depletion in last session, may require proactive refueling after previous session ("recover high" strategies; see below) and presession fueling (see below).	• Sessions requiring high quality/intensity are best performed with sufficient glycogen to meet fuel demands and optimize the training and/or racing situation.	• Key sessions of this type should be programmed into the training plan, allowing sufficient recovery and dietary support following the prior training session(s) to achieve adequate glycogen stores for the targeted "train high" session. • Generally, the higher the requirement for quality, intensity, and technical proficiency a sport requires, the greater emphasis required for training high the majority of training sessions.
Train high (exogenous CHO) session	• Deliberate intake of CHOs during a session at or toward targets for optimal performance to provide exogenous CHO supply for muscle (e.g., 30–60 g/hr for sessions <~2–2.5 hr, up to 90 g/hr for sessions >2.5 hr). • In some scenarios, may be superimposed on low/suboptimal muscle glycogen stores that occur as a natural by-product of a heavy training load or as a deliberate strategy within a periodization sequence or chronic K-LCHF diet.	• Proactive CHO intake during session may provide alternative fuel source when muscle glycogen stores are depleted and support high-quality/intensity training. • Training with CHO intake during the session upregulates the intestinal glucose transporters (SGLT1), increasing the capacity for gut absorption of CHOs to provide greater contribution to muscle fuel needs (Cox et al., 2010), decreased risk of gut discomfort (Costa et al., 2017; Miall et al., 2018), and enhanced performance (Costa et al., 2017). • Targeted use of this strategy for high-intensity sessions while on the K-LCHF diet may support better quality training and reduce the downregulation of gut CHO absorption or pathways of muscle CHO oxidation typically associated with chronic CHO restriction.	• May help to rescue training quality when program naturally or deliberately achieves suboptimal glycogen stores. • A case study reports that a K-LCHF-adapted ultraendurance triathlete who included CHO intake (60 g/hr) during twice weekly high-intensity training sessions and subsequent performance trials showed enhancement of brief higher intensity exercise (4–30 min) duration, while maintaining characteristics of fat adaptation (Webster et al., 2017). • Unknown as to how many train high sessions can occur during K-LCHF before ketogenic adaptation erodes.
Train high (glycogen + exogenous CHO) session	• Completion of a training session with muscle glycogen stores and active intake of CHO to fully meet the fuel demands of the session (see above for general targets for presession CHO for session CHO intake).	• Optimal training and support of other body systems (e.g., immune and inflammatory response to exercise and brain) is achieved with high CHO availability. • Sessions of this type may also serve as a practice or rehearsal of event nutrition strategies, including gut training (see above).	• These strategies are consistent with the guidelines for optimal performance of endurance events (Jeukendrup, 2011) but may be difficult to achieve for all sessions within the typical training load of elite athletes: periodization of training and diet should achieve these conditions for targeted sessions.
Recover high strategy	• Rapid refueling undertaken after a training session, usually to promote glycogen restoration for an upcoming session with <8-hr recovery. • CHO targets: ~1 g/kg BM soon after completion of the session, with intake repeated hourly until daily CHO targets are resumed.	• Maximal glycogen storage typically occurs at an hourly rate of ~5–7 mmol/kg wet weight muscle (~about 5%/hr) when CHO intake is optimal (Burke et al., 2017b). • CHO intake guidelines for optimal postexercise glycogen storage include immediate intake to take advantage of the short window of increased synthesis, plus ongoing intake for the next 4 hr equivalent to hourly intake ~1 g/kg BM (for review, see Burke et al., 2017a); followed by resumption of daily CHO targets.	• Glycogen resynthesis rates are reduced in the presence of low energy availability (Tarnopolsky et al., 2001); some athletes may have to periodize higher energy intakes around scenarios where optimal refueling is desired, although coingestion of protein intake may increase glycogen storage when CHO intake is suboptimal (Betts & Williams, 2010).

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Table 2 (continued)

Name	Description/definition	Original underpinning principles	Contextual comments and/or disparities
Presession fueling strategy	• Deliberate intake of CHO in 1–4 hr presession to top up liver glycogen (especially after overnight fast) and suboptimal muscle glycogen stores. • Targets = 1–4 g/kg CHO, with a focus on food/fluid choices that will not cause gut discomfort during the session.	• CHO consumed in the 4-hr period preexercise may increase body glycogen stores if these are suboptimal due to overnight fast (liver glycogen) or failure to restore from the prior exercise session (muscle). It may also provide an ongoing release of glucose from the gut during exercise. When such outcomes increase CHO availability for the next training session, they may be associated with increased training capacity (for review, see Hargreaves et al., 2004).	• The hyperinsulinemia associated with preexercise CHO intake alters metabolism during exercise to increase rates of CHO oxidation due to the suppression of lipolysis; this may be problematic for a minor number of individuals if it leads to premature CHO depletion or symptomatic hypoglycemia (Hargreaves et al., 2004). Strategies to combat this include further intake of CHO during the session.
Train low (glycogen) session	• Completion of a training session that commenced with, or achieves, suboptimal/low muscle glycogen stores in comparison with fuel demands. • A common protocol to set up this scenario involves "two a day" training, in which the first session is undertaken to deplete muscle glycogen, and the second session is undertaken after a brief recovery period in which minimal CHOs are consumed (Hansen et al., 2005).	• Muscle glycogen is more than a fuel; its presence or absence in the cell affects osmolality, the release of chemicals that are bound to it and the hormonal environment. This has downstream effects on metabolism and the cellular response to exercise (Philp et al., 2012). • Commencing exercise with low muscle glycogen stores and/or sustaining exercise intensity and/or duration to a specific level of absolute glycogen depletion is associated with the activation of key cell signaling proteins (e.g., AMPK, p38, PPAR, PGC-1α), which achieve a coordinated upregulation of the nuclear and mitochondrial genomes (for review, see Bartlett et al., 2015; Hawley et al., 2018; Hearris et al., 2018; Impey et al., 2018). Over a chronic training period, this may increase oxidative enzyme protein content/activity, upregulate whole body and intramuscular lipid metabolism, and potentially improve exercise performance and capacity. • The "costs" of training with low glycogen include an increased perception of effort and reduced training capacity/intensity (Hulston et al., 2010; Yeo et al., 2008); however, greater metabolic stress and adaptive responses are achieved (Hargreaves et al., 2004; Impey et al., 2018).	• Train low (glycogen) strategies should be integrated into the program with care, due to the reduction in training quality, increased risk of overreaching (Halson et al., 2004), and potential effects on other body systems around illness and injury. • CHO mouth rinse (Lane et al., 2013; Kasper et al., 2016) or caffeine supplementation (Kasper et al., 2016) may be used during the session to reduce fatigue or perception of effort and partially restore training quality/intensity compared with sessions undertaken with high CHO availability.
Train low (fasted) session	• Completion of a training session with low liver glycogen stores and low exogenous CHO availability due to fasted conditions (overnight fast or >6 hr since last CHO intake) and lack of CHO intake during session. • Sessions probably need to be at least 45–60 min in duration to exert a significant altered metabolic stress (significant changes in glucose and/or FFA, altering muscle fuel oxidation). • When undertaken according to typical patterns (e.g., morning session undertaken before breakfast and with intake only of water [or, in the case of prolonged sessions; water for the first hour(s) followed by small amounts of CHO to allow session to be completed]). Muscle glycogen may be adequate for the session.	• After a period of >6 hr since the last CHO intake, the suppression of FFA concentrations by insulin are overturned, allowing exercise to be undertaken under the influence of greater FFA availability and rates of fat oxidation. • Exercise undertaken under these conditions of increased metabolic stress for the muscle, central nervous system, and/or liver gluconeogenesis leads to upregulation of AMPK and signaling pathways that increase expression of molecules involved with muscle glucose and fat transport (e.g., GLUT 4 and CD36, FABPm, respectively) and substrate utilization (e.g., PDK4, HK, CS, β-HAD; De Bock et al., 2008). • If fasted training results in greater muscle glycogen utilization during prolonged training, it may also cause a Train low (glycogen) session stimulus (see above).	• See contextual comments above for Train low (glycogen) session. • Train low (fasted) protocols have been less well studied, but appear to cause less overall stress to the athlete and possibly fewer overall adaptations or functional changes that can improve performance. Currently, there is no convincing evidence that such training, by itself, leads to greater performance benefits. • Athletes report that fasted training is easier than low-glycogen training (Stellingwerff, 2012).

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Table 2 (continued)

Name	Description/definition	Original underpinning principles	Contextual comments and/or disparities
Train low (glycogen + fasted)	• Completion of a session with glycogen below the critical threshold for much of the workout (see, Train low [glycogen] above) and low levels of liver glycogen/exogenous CHO. • May be undertaken as part of a chronic LCHF diet or an acute sequence of Train high/sleep low/train low (see Table 3).	• See comments for Train low (glycogen) and Train low (fasted) sections. This protocol probably represents the most metabolically stressful environment for undertaking exercise.	• Represents the maximum training/nutritional stress for the body and requires the most care with its integration into the training plan so that any metabolic advantages are balanced against the potential negative effects on training quality and the risk of injuries and illness.
Ketone-supplemented training session	• Completion of a training session with acute intake of ketone supplements, especially ester forms, which rapidly achieves high blood concentrations of ketone bodies during and after exercise.	• Acute supplementation with ketone supplements provides the (claimed) advantages of exposure to high circulating concentrates of ketone bodies with greater simplicity than chronic K-LCHF diets, while also allowing athletes to acutely periodize this strategy into their larger dietary plans. • Potentially provides an additional fuel source, while altering muscle substrate use during exercise, as well as achieving other claimed benefits during and after exercise, such as enhancement of protein synthesis, glycogen restoration, and cellular signaling (for review, see Evans et al., 2017).	• Despite many claims and anecdotes that some athletes are using ketone supplements, only one paper has shown an acute performance advantage, presumably due to the provision of an additional muscle fuel source (Cox et al., 2016); claims of enhancement of mental clarity and cellular signaling remain largely unexplored in relation to sport performance (Evans et al., 2017; Pinckaers et al., 2017). • There is preliminary but inconclusive evidence for enhancement of postexercise recovery (e.g., glycogen and protein synthesis) following ketone supplementation (Holdsworth et al., 2017; Vandoorne et al., 2017). • There may be an optimal range for blood concentrations of ketone bodies, below which there are minimal effects and above which there is inhibition of metabolic pathways (Evans et al., 2017). • Many studies of ketone supplementation report gastrointestinal side-effects ranging from mild to severe; these can be performance impairing (Leckey et al., 2018).
Recover low/ sleep low strategy	• Deliberate restriction of CHO in meals after an exercise session to delay restoration of muscle glycogen. May be undertaken as CHO restriction after the morning training session, or as an overnight CHO restriction following an evening workout. • Postexercise intake of protein supports adaptive processes without dampening the effects of the low CHO availability.	• Restricting CHO intake in the postexercise period maintains postexercise muscle and liver glycogen at reduced levels as well as prolongs the duration of postexercise elevations in circulating FFA availability (for review, see Impey et al., 2018). • The interactive effects of changes in substrate availability may sustain the postexercise upregulation of cell signaling pathways thus leading to increases in the adaptive response to the session (Impey et al., 2016; Pilegaard et al., 2005).	• The duration of the postexercise period in which CHO intake is restricted is dependent on both the extent of glycogen depletion and work completed as well as the scheduling of the next training session. • Failing to carefully consider such factors could impact upon immune function and subsequent training intensity (Impey et al., 2018) as well as negatively influencing markers of bone turnover (Townsend et al., 2017).

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Table 2 (continued)

Name	Description/definition	Original underpinning principles	Contextual comments and/or disparities
Classical CHO loading strategy	• First glycogen loading protocol, developed serendipitously from studies of training/diet manipulation in the 1960s to achieve an increase in muscle fuel stores in preparation for a lengthy sporting event in which these stores would otherwise be limiting for performance. • Original models involved 3 days low-CHO diet (CHO = ~10–100 g/day; 5–15% energy) and training to deplete glycogen followed by 3 days CHO-rich diet (CHO = 500 g+/days; 70%+ of energy) and taper.	• Reported to double glycogen stores in moderately trained individuals, but only in muscle that had been previously depleted (Bergstrom & Hultman, 1966). • Shown in field studies to improve running performance over a 30-km race (Karlsson et al., 1971) and race walking performance over a 40-km race (Hyman, 1970), by reducing the decline in race speed over the last ~5–10 km of the race as athletes became glycogen depleted in the control trial. • Depletion phase is associated with fatigue and psychological discomfort (Howley, 1996) as well as the requirement for sufficient knowledge to achieve its unusual nutritional profile.	• This protocol was immediately adopted by high-caliber athletes, with further publicity introducing into widespread use during the general population running boom of the 1970s and 1980s. • Although well publicized, there is evidence that many runners during this period did not fully understand the principles or have sufficient nutrition knowledge to achieve the nutrient prescriptions (Burke & Read, 1987). • The gain of 1–3% BM associated with the storage of additional muscle glycogen and water, as well as a prerace taper might be detrimental to the performance of weight-sensitive sports.
Contemporary CHO loading strategy	• Current guidelines for glycogen supercompensation protocol have evolved from further studies of CHO loading in well-trained individuals, which show that previous (impractical or fatiguing) elements of the protocol are unnecessary. • Protocol now recommends CHO intakes of 10–12 $g^{-1}\cdot kg^{-1}\cdot day^{-1}$ CHO for 36–48 hr prior to endurance event with training taper, according to the individual dictates and practical considerations of the event preparation. • Many athletes also superimpose a 72 hr low-residue diet on CHO loading protocols to significantly reduce bowel contents for race day.	• Due to regular glycogen depletion/restoration cycles that occur during normal high-volume training, well-trained athletes already exhibit upregulation of glycogen synthase enzyme activity, with allows rapid glycogen storage and supercompensation without the need for a specific prior depletion phase (Sherman et al., 1981). • Further investigation of the time course of supercompensation of glycogen shows that it occurs within ~36 hr of taper and high-CHO diet (Bussau et al., 2002). • Contemporary CHO loading protocols have been shown to achieve a significant increase in muscle glycogen content compared with a control condition during regular athlete preevent tapers (Burke et al., 2000a, 2000b; McInerney et al., 2005). • CHO loading enhances performance in a range of protocols in which glycogen would otherwise become limiting for performance (for review, see Hawley et al., 1997), but not in events that are too short in duration (Sherman et al., 1981) and/or supported with additional CHO fuel just prior to/during the event to create a fuel crisis (Burke et al., 2002). • The coimplementation of low residue (low fiber) with CHO loading may help to offset the 1–3% BM gain associated with the storage of additional glycogen/water by reducing the mass of gut contents. It also offers the practical advantage of a reduced need to defecate before and during the event.	• Adequate energy availability is required for optimal glycogen storage (Tarnopolsky et al., 2001); weight-conscious athletes might need to periodize greater energy intake to support CHO loading protocols. • There is some indication that the muscle may not be able to repetitively supercompensate over successive 48-hr periods of depletion and high intakes of CHO (McInerney et al., 2005).

Note. These strategies should support adequate energy availability unless a separate strategy is undertaken to manipulate this. Further information can be found in several excellent reviews (Bartlett et al., 2015; Hawley et al., 2018; Hearris et al., 2018; Impey et al., 2018; Jeukendrup 2017a, 2017b). BM = body mass; CHO = carbohydrate; K-LCHF = ketogenic low-carbohydrate high-fat diet; SGLT1 = sodium-dependent glucose cotransporter 1; AMPK = AMP-activated protein kinase; β-HAD = β-hydroxyacyl CoA dehydrogenase; CD36 = cluster of differentiation 36 also known as fatty acid translocase; CS = citrate synthase; FABPm = membrane associated fatty acid binding protein; GLUT 4 = glucose transporter Type 4; HK = hexokinase; p38 = p38 mitogen-activated protein kinase, also known as MAPK; PPAR = peroxisome proliferator-activated receptor; PGC-1α, peroxisome proliferator-activated receptor gamma coactivator 1-alpha; PDK4 = pyruvate dehydrogenase kinase 4; FFA = free-fatty acids.

Table 3 Common Sequences in Which CHO Availability has been Periodized to Integrate Different Concepts of Training Adaptation and Performance Support (for review, see Impey et al., 2018)

Name	Description/definition	Original underpinning principles	Contextual comments and/or disparities
Train high + recover/sleep low + Train low sequence	• Training sequence involving p.m. Train high (glycogen and exogenous CHO) for high-intensity/quality session followed by overnight CHO restriction and a.m. moderate-intensity session (Train low glycogen + fasted). • Alternatively: training sequence involving a.m. Train high (glycogen and exogenous CHO) for high-intensity/quality session followed by CHO restriction for rest of day and p.m. moderate-intensity session (Train low glycogen + fasted).	• This sequence integrates a key session, undertaken with full fuel support to promote a high-quality training outcome, while depleting muscle glycogen to create an opportunity for a subsequent session of moderate-intensity training undertaken with a "Train low (glycogen + exogenous CHO) preparation." A prolonged recovery phase with restricted glycogen storage increases the period of amplified response to the first quality session. • This sequence is efficient in matching the optimal stimulus during/after two training sessions and can be undertaken within 24 hr, thus allowing it to be repeated several times within a microcycle of training.	• When repeated 3 per week for a week or 3 weeks by trained but nonelite cyclists/triathletes, this sequence was associated with superior performance outcomes compared with training undertaken on similar macronutrient intake without periodized sequence (Marquet 2016a, 2016b). However, similar results were not seen in elite athletes who undertook two to three sequences per week for 3 weeks (Burke et al., 2017a; Gejl et al., 2017).
Fat adaptation/CHO restoration sequence	• Event preparation involving >5 days exposure to LCHF diet to retool muscle for increased fat oxidation followed by 1 day CHO restoration/loading + CHO intake before and during event with the goal of simultaneously enhancing both CHO and fat oxidation pathways. • Typical protocol = 5–6 days 15–20% energy from CHO (<2.5 $g^{-1}\cdot kg\ BM^{-1}\cdot day^{-1}$), 15–20% protein, 60–65% fat <2.5 g/kg, while undertaking endurance training, followed by 1 day taper and CHO intake = 10–12 $g^{-1}\cdot kg^{-1}\cdot day^{-1}$ plus preevent CHO (2 g/kg BM) and CHO intake during event (60–90 g/hr).	• Fat adaptation period upregulates rates of fat oxidation during exercise (see Table 1) with muscle tooling remaining intake despite 36 hr CHO restoration. Subsequent moderate-intensity exercise can be undertaken with reduction in glycogen cost and increased rates of fat use. • However, this protocol is also associated with reduction in glycogenolysis and CHO oxidation rates by downregulation of key enzymes (e.g., PDH activity; see comments for NK-LCHF in Table 2). • No overall improvement in performance has been seen except for isolated individuals/scenarios. Furthermore, impairment of CHO oxidation is associated with reduction in performance of higher intensity exercise or pieces within an endurance task (Havemann et al., 2006).	• This protocol may have utility for prolonged submaximal exercise in which there is no requirement for high rates of CHO oxidation and/or it is difficult to consume CHO during exercise. In elite athletes, fat oxidation may play a role in well-fueled endurance performance in events 8+ hr in duration, while in recreational athletes, fat oxidation may be already key over just several hours of exercise. • Despite substantial increases in muscle utilization of fats, there is a potential for performance impairment of higher intensity exercise (see Burke, 2015).
K-LCHF + event CHO	• Event preparation in which chronic exposure to K-LCHF diet is integrated with increased CHO availability just prior to and during the event to provide additional CHO fuel source. • This scenario is described in anecdotes around K-LCHF use but has not been investigated using scientific methods.	• Theoretical protocol to acutely expand event fuel sources by adding acute ingestion of CHO to chronically enhanced oxidation of fats and ketone bodies. • Potential issues include impairment of gut CHO absorption due to downregulation of SGLT1; this would interfere with delivery of fuel to the muscle as well as increase risk of gut discomfort. • Reductions in rates of CHO oxidation also likely.	• This protocol is popularly described on lay and social media sites around the K-LCHF diet as a useful strategy for endurance and ultraendurance events; in the absence of scientific trials, it is unwise to speculate on its benefits and disadvantages.

Note. BM = body mass; CHO = carbohydrate; LCHF = low-carbohydrate high-fat diet; K-LCHF = ketogenic low-carbohydrate high-fat diet; NK-LCHF = nonketogenic low-carbohydrate high-fat diet; PDH = pyruvate dehydrogenase; SGLT1 = sodium-dependent glucose cotransporter 1.

about Froome's advocacy of the low-CHO high-fat diet, despite wider evidence presented by the athlete himself that he follows a plan in which CHO availability is periodized according to his specific goals (Palfreeman, 2016). Further support and background are available from an author of this commentary who works with this athlete and has written extensively on the general philosophy of "fueling for the work required" (Hearris et al., 2018; Impey et al., 2018), as well as nutrition support for the Tour de France in particular (Morton & Fell, 2016). Nevertheless, a Google search can quickly locate a range of lay pieces that claim that Froome's success is due to low-CHO high-fat. Ironically, Team Sky recently released data to illustrate the sophisticated periodization of body mass and energy/CHO intakes according to the demands of each stage in a cycling tour, including estimates of Froome's intake on the critical 19th day of his 2018 Giro D'Italia title: an astonishing 6,663 kcal (27.98 MJ) and 18.9 g/kg CHO (Fordyce, 2018).

It is likely, and indeed healthy, that scientists will continue to hold different views on a variety of sports nutrition themes, including different ways in which fuel support for training and competition preparation can be organized to promote performance according to the specific demands of the event. However, we propose that both research scientists and practitioners require collaboration and shared discussions, underpinned by a commonly accepted and consistent terminology, which serve to strengthen hypotheses and experimental/experiential data around various strategies. We also propose that athletes and coaches would be better served by less confusion and misinformation in all levels of literature. Therefore, we propose the following table of definitions and explanations as a starting point for a more unified dialogue (Tables 1–3), and we encourage our colleagues in this area of research and practice to provide as much objective detail as possible about the dietary strategies with which they experiment and apply in the field with athletes. Indeed, this issue contains a methods paper with a lengthy explanation of the principles, practices, and outcomes of organizing a tightly controlled diet-training intervention of this type (Mirtschin et al., 2018). We note that our efforts typically describe the philosophy of different approaches rather than a single/definitive macronutrient prescription. This is necessitated by the need for great clarity around optimal protocols for various strategies, but more so because the variability of the training loads/modes undertaken by athletes is too great to allow a single "one size fits all" approach to nutrition support. Accordingly, we hope our efforts will be appreciated, adopted, and further evolved toward greater definition consistency and precision and detail around optimal fueling strategies. Table 4 summarizes some of the key questions that still need to be tackled to help produce this insight.

Table 4 Targeted Questions for Future Research

High-priority questions to be answered around periodization of CHO availability in the training diet and for event preparation

- What are the fuel costs, glycogen utilization rates, and associated CHO intake requirements of various training sessions commonly undertaken by athletes? (for review, see Areta & Hopkins, 2018)
- Are there dietary factors that can enhance muscle glycogen storage either in situations where CHO/energy intake meets guidelines for optimal intake or in situations where these are inadequate?
- What is the threshold of "low muscle glycogen" availability needed preexercise or during exercise to amplify the signaling response to exercise or to be maintained postexercise to maintain the increase in postexercise signaling? (Impey et al., 2018)
- Are there differences between elite athletes and their subelite counterparts in terms of metabolic and performance responses to deliberate strategies to periodize CHO availability in the training diet?
- What is the optimal type, ratio, and integration of "train low" CHO strategies versus "train high" strategies within a periodized training diet to optimize the overall outcomes of a training block?
- What is the optimal type, ratio, and integration of "train high" CHO fueling practice to optimize CHO oxidation and gastrointestinal function prior to racing in endurance athletes?
- What are the immediate and functional consequences of acute or chronic exposure to low CHO availability during exercise on cytokines (e.g., interleukin-6) and downstream responses of other body systems such as hepcidin/iron status (Badenhorst et al., 2015), osteocalcin/CTX-1/bone status (Sale et al., 2015), and immune status (Hennigar et al., 2017)?
- What is the optimal protocol for periodic acute exposure to high exogenous CHO availability during a training session to overcome some of the negative systemic effects of low glycogen availability (e.g., to promote better quality training, reverse effects on the brain, immune system, gut absorption and other organs/body systems), while retaining the (claimed) benefits of chronic K-LCHF diet?
- What is the time course of the reversal of impairment of muscle CHO oxidation associated with adaptation to NK-LCHF or K-LCHF interventions and can this be achieved, while retaining some of the adaptations to increase capacity for fat oxidation?
- What is the relative exercise intensity beyond which there is an impairment of performance if CHO oxidation rates are impaired?
- What are the long-term effects of the differences of lower micronutrient density and fiber content of a K-LCHF diet on health?
- Do long-term adaptations to a K-LCHF diet enhance metabolism and performance, and what is the time course of these adaptations?
- Are there any long-term metabolic, health, or performance effects of exposure to high circulating levels of ketone bodies and can these be replicated by the use of ketone supplements?
- Is there an optimal range of blood ketone body concentrations that should be targeted by acute or chronic strategies to achieve ketosis?

Note. CTX-1 = COOH-terminal telopeptide region of collagen Type 1; CHO = carbohydrate; K-LCHF = ketogenic low-carbohydrate high-fat diet; NK-LCHF = nonketogenic low-carbohydrate high-fat diet.

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