Abstract

The aim of training is to achieve optimum performance on the day of competition via three processes or paradigms; training hard to create the required training stimulus, training smart to maximize adaptations to the training stimulus, and training specifically to fine-turn the behaviors or physiology needed for competition strategies. Dietary strategies for competition must target the factors that would otherwise cause fatigue during the event, promoting an enhancement of performance by reducing or delaying the onset of these factors. In some cases, the nutritional strategies needed to achieve these various paradigms are different, and even opposite to each other, so athletes need to periodize their nutrition, just as they periodize their training program. The evolution of new knowledge from sports nutrition research, such as presented in this book, usually starts with a stark concept that must be further refined; to move from individual nutrients to food, from ‘one size fits all’ to the individual needs and practices of different athletes, and from single issues to an integrated picture of sports nutrition. The translation from science to practice usually requires a large body of follow-up studies as well as experimentation in the field.

Introduction

The origins of sports nutrition date back as far back as the earliest records of sporting competition: the original Olympians in Greece believed that certain foods would confer strength or other special attributes to assist performance. However, the science of sports nutrition really gained momentum only in the 1960s when Scandinavian sports scientists used the percutaneous biopsy technique to examine muscle substrates, muscle enzymes and the capacity for exercise. They found that, by altering dietary intake in extreme ways, recent
nutrition influenced fuel use and cycling endurance. A half-century later we are still refining the practical details of the technique known as carbohydrate loading that emanated from their work. This episode demonstrates the general way in which sports nutrition has evolved. Typically, some scientific technique is undertaken to measure the effects of a dietary manipulation and a gross result is reported. While this may receive much attention in scientific journals, it needs further refinement and filtering before it is fully translated into optimum practice in the real-life world of sport.

This book has provided a series of reviews of topics that are cutting edge in sports science; the aim of this final chapter is to summarize the ways in which the current knowledge in these areas can be implemented into athletic practice and to highlight some of the limitations and potential pitfalls. Before undertaking this, however, it is worth considering the principles of training to understand how the interaction of exercise and nutrition can adapt the body to enhance its function. It is also important to consider the challenges of translating science into practice.

**An Overview of the Principles of Training**

The aim of athletic training is to enhance performance by altering the various physiological, mechanical, metabolic, psychological and other factors that limit exercise performance. The basic principles of athletic training are well established. A well-designed program based on the principle of progressive overload should result in an improvement in performance that is proportional to the training stimulus. The training load can be quantified in terms of the intensity, duration and frequency of the individual training sessions. Training may last no more than a few minutes on one or two days per week for the child or novice athlete or for the athlete returning from injury, but elite athletes in most sports will undertake one or more training sessions per day, each lasting an hour or longer. Within limits, increasing the training load will result in greater improvements in performance. There are limits, however, and overtraining will have negative effects on both health and performance.

Training is more than simply undertaking the athlete’s specific event or sport. Most athletes undertake a variety of training modes or practices that target the muscle or whole body characteristics that will achieve enhancements of performance. Such training is highly specific: muscles that are not trained will not adapt and the changes taking place in the structural and functional properties of the muscles are specific to the nature of the training stimulus [1]. Strength training should increase muscle strength, but will have little effect on endurance capacity. Endurance training, on the other hand, has little or no effect on muscle strength – marathon runners generally have a small muscle mass and low muscle strength in spite of very high volumes of training. To achieve these...
adaptations, the muscle must respond with a selective stimulation of muscle protein synthesis and degradation: the aim is to make more of the proteins that promote performance while breaking down some of those proteins that do not contribute to performance. These adaptations must occur not only in skeletal muscle but in all other tissues that influence performance.

At one time, it was thought that the primary role of sports nutrition was to support consistent intensive training by allowing the athlete to train harder without succumbing to illness, injury and chronic fatigue. It is increasingly recognized, however, that nutrition interventions can allow athletes to train ‘smarter’ rather than just training harder. This can allow athletes to maximize the adaptations taking place in muscle and other tissues without risking over-training. In sports where skill and tactics are major elements in successful performance, good nutrition strategies might allow the same level of fitness to be achieved with less training, allowing more time to be devoted to technical work while also reducing the risk of chronic fatigue and injury.

A final role of training is to prepare the athlete to undertake the nutritional strategies that will be important in their competition eating plan. Although training prepares the athlete to get to the starting line or opening phase of their event, performance can be further fine-tuned by nutritional practices undertaken before, during or after (between) competition bouts. These practices must specifically target nutritionally influenced factors that limit performance, such as depletion of fuel stores or disturbances to homeostasis. Competition nutrition strategies may include the targeted intake of fluid and carbohydrate in the days and hours prior to the event, as well as fluid, carbohydrate, electrolytes and perhaps other nutrients during exercise. Where a series of bouts is required to determine the outcome of competition, the intake of carbohydrate, protein, fluid and electrolytes may be part of promoting recovery between events. Practicing competition strategies during the training phase, particularly the consumption of fluids and foods during exercise, is an important part of the preparation. Part of the process may be adapting the plan to the athlete, so that competition fluid and food intake is adjusted to suit individual tolerance and opportunities for nutrient intake during the event. However, there is also opportunity to adapt the athlete to the plan, to learn the behavioral skills associated with obtaining and consuming fluids and foods during exercise and to train the gut to tolerate or process the ingested nutrients.

Translating Sports Science Research to Practice in the Field

The scientific process typically starts with the testing of a hypothesis. To provide the best opportunity to see a measurable effect of the intervention under scrutiny, the initial studies are usually undertaken with a large dose or a lengthy duration of application. Typically, the intervention is presented as a single entity,
under baseline metabolic conditions (e.g. fasted), which bears little resemblance to everyday nutrition or the conditions of sport. Sometimes, sophisticated methodologies are available: the use of percutaneous biopsies to measure characteristics of the muscle, the use of radioactive or stable isotope tracers to follow the utilization or storage of nutrients, or the use of magnetic resonance spectroscopy or other nuclear medicine techniques to measure changes in metabolites. However, the expense and logistics associated with these techniques have implications for the number and caliber of subjects in experiments.

There are many reasons to study the interaction of nutrition and exercise, with worthy outcomes aimed at prevention and treatment of community health issues such as diabetes, obesity or sarcopenia. Many studies do not therefore have a primary interest in sporting outcomes, or even the performance of exercise. Indeed, the measurement of sports performance is a highly challenging area, with most scientific investigations being unable to detect the changes or differences in performance that would be worthwhile in the world of competitive sport, where millimeters and milliseconds can separate the winners from the rest of the field [2]. In some of the newest research techniques, scientists can measure factors that underpin the function of an exercising muscle or the process of its adaptation to exercise (e.g. enzymes, signaling proteins, transcription factors). While these factors are critical in explaining the mechanisms of function or adaptation, they are often used as a proxy for exercise capacity, which becomes a proxy for sports performance per se. Enhanced access to scientific reports, via media such as PubMed or sports science websites and blogs, means that there is rapid communication of ‘breakthrough’ studies of nutrition and exercise interaction to sports scientists, coaches and athletes themselves. All these factors interact to create enthusiasm in the sports world for the results of diet-exercise studies, but they can also make it difficult to find a direct application of the results to the athlete.

In an ideal world, once a tested hypothesis provides information about a nutritional intervention that could be promising to the athlete or sports performance, further studies would take place to determine how the information can be applied to conditions of sport. This would include dose-response studies to delineate the ideal amount, timing and duration of an intervention, and the best opportunity to use it within an athlete's periodized program of training and competition. Suitable or ideal forms of the intervention might be tested, ranging from individual nutrients, special sports foods or supplements to everyday foods. It should be tested on athletes of different gender, age, training history and sporting caliber to identify the suitable recipient(s) of the intervention. The application to different sports, different events, and different individuals should also be investigated to account for the various factors that ultimately limit performance as well as the individuality of responses between athletes. Interactions with other interventions or practices in sport need to be considered, and ultimately, an appropriate measurement of performance should be tested to confirm
the benefit. Even when all this is undertaken, the final analysis will require consideration of the practicality or logistics of the intervention: for example, can the athlete afford it (in expense or energy considerations)?; is it accessible and available (can it be found or undertaken within the athlete's environment or restraints)?; does it integrate with the athlete's other nutritional goals?; is it safe and ethical (are there side effects from its use; is it allowable within any anti-doping codes that exist)?

Understandably, this 'ideal world' is too intricate to be realistic. Therefore, the translation of most sports science research into practice relies mostly on interpolation and extrapolation of the available studies as well as individual experimentation in the field. In providing an analysis of the practical applications of the nutritional interventions reviewed in this book, we have had to undertake a theoretical cost-benefit analysis of the available information.

Role of Protein before, during and after Training

It is clear from studies that have measured rates of whole body or muscle-specific protein synthesis and breakdown that there is a transient increase in the rate of protein breakdown after an exercise bout [for review, see 3]. The intensity and duration of exercise necessary to trigger this effect either minimally or optimally are unknown, as the present dose-response studies are neither consistent in their findings nor exhaustive in their investigation. The coach and athlete know, however, that there is a threshold for the training stimulus below which adaptation will not occur. A single bout of intense resistance training will increase net protein synthesis for a period lasting from about 24 to 48 h [3]. For muscle hypertrophy to occur, net protein synthesis must exceed net protein breakdown, and muscle growth occurs through the cumulative effect of repeated periods of positive protein balance. However, it is often the case in sport that mature, already well-trained athletes do not seek to achieve muscle hypertrophy, as an increase in mass would bring a weight penalty that could impair performance. Similarly, the goal of endurance training is not to achieve a gain in muscle mass. Instead, a change in the muscle protein composition is sought by selective stimulation of synthesis and breakdown of specific proteins.

The available evidence suggests that it is the essential amino acids, and perhaps specifically leucine, that are effective in stimulating protein synthesis when ingested around the time of an exercise session [4, 5]. However, this should not be taken as an indication that ingestion of leucine itself, or a mixture of branched chain amino acids, or a mixture that includes all of the essential amino acids is necessarily the best strategy for athletes to adopt. Mixed protein sources that include both essential and non-essential amino acids may be just as effective as essential amino acids alone, and have advantages in terms of cost, convenience and palatability. These include animal protein sources such as meat, fish and
seafood, poultry, eggs and many dairy foods (milk, cheese, yoghurt, etc.), as well as the complementing of plant-rich proteins (e.g. soy and grains; see table 1). Ultimately, the athlete wants to know the amount, the type and the timing of intake of protein sources over the day, and in relation to an exercise bout, that they should consume to achieve their desired adaptation to training. The interaction of the composition of the amino acids in these foods and their rate of digestion and release of amino acids into the blood may alter their final effect on muscle protein synthesis.

Moore et al. [6] examined the relationship between increasing amounts of protein (in the form of egg protein) ingestion and postexercise muscle protein synthesis. The fractional synthetic rate of mixed muscle protein increased with increasing amounts of protein intake until an amount of 20 g was consumed: this corresponds to an intake of about 9 g of essential amino acids. Doubling the dose to 40 g had little further effect on protein synthesis, so it seems reasonable to recommend an intake of about 20–25 g of high-quality protein after training. Subjects in this study had a mean body mass of 86 kg with a large individual variation in body size. All were given the same fixed amounts of protein without any adjustment for body mass, and there was apparently no suggestion that the dose should be adjusted for body size, but it might seem prudent when dealing with subjects at the extremes of body mass to adjust the protein dose

<table>
<thead>
<tr>
<th>Food</th>
<th>Typical portion size, g</th>
<th>Amount for 20 g protein, g</th>
<th>Energy content</th>
<th>Total EAA g</th>
<th>Leucine g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bread (white)</td>
<td>75</td>
<td>238</td>
<td>559 kcal</td>
<td>2,385</td>
<td>6.48</td>
</tr>
<tr>
<td>Spaghetti (boiled)</td>
<td>50</td>
<td>667</td>
<td>574 kcal</td>
<td>2,435</td>
<td>10.11</td>
</tr>
<tr>
<td>Milk (semi-skimmed)</td>
<td>195</td>
<td>606</td>
<td>279 kcal</td>
<td>1,182</td>
<td>10.27</td>
</tr>
<tr>
<td>Egg (raw)</td>
<td>60</td>
<td>160</td>
<td>235 kcal</td>
<td>979</td>
<td>9.58</td>
</tr>
<tr>
<td>Steak, stewing (raw)</td>
<td>175</td>
<td>99</td>
<td>174 kcal</td>
<td>729</td>
<td>9.16</td>
</tr>
<tr>
<td>Chicken (roast, light meat)</td>
<td>85</td>
<td>75</td>
<td>106 kcal</td>
<td>449</td>
<td>8.52</td>
</tr>
<tr>
<td>Lentils (boiled)</td>
<td>155</td>
<td>263</td>
<td>263 kcal</td>
<td>1,115</td>
<td>7.91</td>
</tr>
<tr>
<td>Potato (new, boiled)</td>
<td>150</td>
<td>1,333</td>
<td>1,000 kcal</td>
<td>3,972</td>
<td>7.58</td>
</tr>
</tbody>
</table>

Note the very different amounts of food and the different energy contents for the same amount of total protein and for similar amounts of EAA.
accordingly. Table 1 shows the amounts of various protein foods that are necessary to provide 20 g of protein, and shows the essential amino acid content and leucine content of these foods: it also includes the total energy content of this food portion. Although various foods can provide the necessary amounts of protein and of essential amino acids, some foods would have to be eaten in improbably large amounts to achieve this, and would provide inappropriately large amounts of energy.

The present research suggests that the overall muscle protein synthetic response is influenced by the effect of dietary protein sources on plasma amino acid profiles. Whey protein seems most effective in stimulating muscle protein synthesis when ingested after exercise. This may be partly the result of its rapid digestion and absorption [7]. However, soy protein drinks cause a faster and more pronounced rise in plasma total amino acid concentration than occurs after ingestion of the same amount of protein in the form of milk proteins, but the milk results in a greater stimulation of protein synthesis and a greater net protein balance in the exercised muscle [8], perhaps as a result of its higher leucine content.

It is not feasible to undertake tracer studies to determine which dietary proteins achieve the highest rates of muscle protein synthesis. Indeed it is likely that the ingestion of a number and combination of different protein sources will be able, when combined with appropriate exercise, to achieve good results towards the athlete’s goals. In addition to knowing the amount of protein and leucine in a protein-rich food source, a rating of the speed of digestion of this food and its effect of plasma amino acid concentrations (i.e. which protein sources are ‘fast’ and which are ‘slow’, when eaten alone or in combination with other foods) might help the athlete to choose foods to consume to provide the desired amino acid profile. There is not complete agreement on the preferred time to consume a protein source in relation to a bout of exercise per se, with some studies showing that intake before and during a session is of benefit, while others show that soon after exercise is optimal [for review, see 9]. Of course, whatever the desired time point for achieving a desired elevation of amino acid profiles, there may be an interaction of the timing, type and amount of proteins ingested to achieve this. For example, it may be possible to achieve the same amino acid concentration with a small amount of a ‘fast’ protein food which achieves a peak amino acid concentration after 30 min (such as whey or a liquid protein like milk) as by eating a larger amount of protein in the form of a ‘slow’ protein (casein or a solid meat meal) at a time point an hour earlier than this.

It should be noted that there is a time lag between the peak plasma amino acid response and the muscle protein synthetic response. Plasma amino acid concentrations peak about 30 min after ingestion of a fast protein source at the completion of a resistance exercise bout, with concentrations returning to the fasting baseline within about 3 h of ingestion; however, the muscle protein synthetic response appears to reach peak levels at 3–5 h [7]. Since the muscle protein synthetic response is increased above baseline for 24–48 h after a single
resistance bout, the timing and amounts of protein consumed over the rest of the day also need to be considered. Repeated ingestion of small amounts of protein at frequent intervals may maximize net protein accretion. This accords with the reported practice of some bodybuilders who consume protein at intervals of no more than 2–3 h over the whole day, and bodybuilders are often recommended to eat protein at least 5–7 times per day during periods of training [10]. However, the muscle is also saturable after a single feeding of protein [6] and refractory to further intake of protein [11], so it is also possible that a more spread out pattern of protein intake might allow protein synthesis to be ‘turned off’ before it is then turned on maximally again. Studies of such hypotheses are required.

Athletes have been accustomed to ingestion of carbohydrate soon after training to begin the process of muscle glycogen resynthesis [12]. There have been some suggestions that addition of carbohydrate to protein ingested after exercise might further stimulate protein synthesis on account of the anabolic action of an elevated circulating insulin concentration. Borsheim et al. [13] showed an increased leg uptake of amino acids when carbohydrate was coingested with protein, suggesting an increased net protein synthesis. However, in a more recent study, even the ingestion of a very large amount of carbohydrate together with a large bolus of protein hydrolysate (0.3 g•kg⁻¹•h⁻¹ protein hydrolysate with 0, 0.15, or 0.6 g•kg⁻¹•h⁻¹ carbohydrate during a 6-hour recovery period) was not effective in promoting further increases in muscle protein synthesis [14].

Most of these studies have focused on the effects of various feeding strategies on acute measures of whole body or muscle protein synthesis, but the athlete’s concern is with functional outcomes. Training studies to investigate the efficacy of feeding varying types and amounts of different proteins at varying times after different types of training are extremely complex and time-consuming, so it is not surprising that there are few experimental studies. It is perhaps more surprising that there are any at all. Hartman et al. [15] investigated the effects of feeding skimmed milk, soy or carbohydrate after training in young novice weightlifters. Subjects trained 5 times per week for 12 weeks and ingested their allotted test drink before and after training. Although no differences in strength were observed between groups at the end of the training period, there was evidence of a greater increase in muscle mass in the milk group than in either of the other two groups. Therefore, there is some proof that the repetition of a practice shown to achieve better acute synthesis of protein will result in long-term benefits. This is encouraging, but more studies are needed before firm recommendations for protein intake can be provided to athletes.

New Ideas on Fat Loss for Athletes

Many people consider obesity to be a community health problem that can be prevented or treated with exercise. In fact, even those who undertake many hours of
exercise each day may still have a real or perceived need to reduce their body fat levels; it is often the primary reason for athletes to seek the services of a sports dietitian. Of course, only a small number of athletes need to lose body fat for health reasons. Some athletes have aesthetic motives for wanting to reduce body fat levels; these range from a personal desire to improve appearance in tight-fitting or skimpy Lycra uniforms (e.g. female athletes in team sports, swimmers, beach volleyball players) to actual performance enhancement in sports in which a subjective judgment of physique contributes to the final outcome (e.g. body building, gymnastics, diving, figure skating). In many sports, however, physical improvements in performance are associated with increasing the athlete’s power to weight ratio (enhancing the ability to move body mass, particularly against gravity) or reducing the athlete’s size (enabling complex movements to be completed in a small space). The first of these benefits is seen in sports such as distance running, cycling, high jumping and gymnastics, while the second is seen in sports such as diving and gymnastics. Finally, in other sports there are weight categories designed to create a ‘level playing’ field in which athletes of similar size, reach and strength compete against each other (e.g. combat sports, lightweight rowing, lifting sports). Most athletes do not arrive naturally at their optimum physique but must work to achieve it. This can become a particular issue following periods of weight gain, such as the off-season or while injured, when it is easy to develop an energy surplus.

Given the interest in fat loss as an issue in sports nutrition, it is surprising that few studies have investigated different strategies in athletes. Instead the major focus has been on practices for rapid reduction in body weight in weight division sports (‘weight making’) involving dehydration and fasting [16]. A reduction in body fat levels requires the achievement of an energy deficit, either by reducing energy intake, increasing energy expenditure or by combining both methods. The suitability of these various options will vary according to the athlete but may pose some problems: additional exercise may increase the risk of injury or otherwise interfere with the athlete’s primary training, while restricting energy intake may reduce the athlete’s ability to meet the nutritional goals for optimum training. Furthermore, the loss of body fat is usually accompanied by a loss of lean mass: this is not desirable to most athletes. In addition to choosing the right time within their periodized calendar to undertake loss of body fat, the athlete will want to choose a method that minimizes the negative impact on their training capacity or performance. The review by Phillips and Zemel [17] provides some potential strategies to achieve these goals.

In the general population, there is some evidence that hypoenergetic diets lower in carbohydrate and higher in protein may promote the loss of body fat and retention of lean mass more than weight loss diets of the opposite macronutrient ratio [18, 19]. Other potentially beneficial strategies include the emphasis on carbohydrate-rich foods of low glycemic index [18] and an increased intake of dairy foods [20]. The evidence for these strategies comes from observational
studies, animal trials, and some clinical trials in overweight populations. Investigation in athletic populations seems warranted, although some modifications or periodization may be needed when these strategies are in opposition to the athlete's sports nutrition goals (e.g. carbohydrate needs for refueling or performance). The potential benefits of increased intake of dairy foods on fat loss via both calcium-dependent and calcium-independent mechanisms are of interest, however, since dairy protein may also assist with the athlete's goals for protein synthesis related to training adaptations. In fact, there is currently a high level of interest in dairy products in sports nutrition circles; products like flavored milk can provide useful quantities of fluid, electrolytes, protein and carbohydrate in a practical form for consumption in the athlete's diet [21].

**Increasing Substrate Availability by Increasing Fat Utilization**

Fat and carbohydrate have a reciprocal relationship as substrates for exercise. However, the total body stores of carbohydrate are limited, whereas even the leanest athlete has sufficient fat stores in the muscle and adipose tissue to support very lengthy exercise. A well-known adaptation to training is to increase the capacity for fat utilization at the same absolute and relative work rates compared with pretraining values. Since training alone does not equip the body to achieve maximum rates of fat utilization, it makes sense for athletes to consider other strategies that might further enhance fat use during exercise. Unfortunately, unlike animals such as rodents and migrating birds, fat oxidation cannot sustain the very high rates of power generation required for high-intensity exercise in humans. Instead, fat oxidation is inhibited at exercise intensities above ~75% of maximum aerobic capacity. Nevertheless, an increased use of fat to sustain low-moderate intensity exercise may spare glycogen as a substrate for the high-intensity work undertaken during an event or for prolonged events which are limited by glycogen depletion. Potential opportunities include strategies that acutely increase free fatty acid (FFA) concentrations during exercise, or more chronic strategies that re-tool the muscle to increase its capacity for fat oxidation (i.e. increases in fatty acid transport into the muscle, uptake into the mitochondria or capacity for β-oxidation).

Spriet [22] provides an elegant overview of the regulation of fat metabolism during exercise and recovery, identifying the potential points which could be targeted to allow an increase in fatty acid utilization during exercise. The first option of increasing the plasma concentrations of FFAs and their delivery to the muscle can be achieved by relatively short periods of fasting or restricted carbohydrate intake, as well as by acute or chronic consumption of a high-fat diet. High-fat diets can certainly improve exercise capacity in the rat [23, 24], but the early studies of Christensen and Hansen [25] showed a reduction in endurance in men fed a high-fat, low-carbohydrate diet for several days. In such studies, it
is theoretically impossible to separate the effects of the high fat intake from the absence of carbohydrate consumption. Short-term fasting can isolate the effects of carbohydrate withdrawal; this strategy also increases endurance capacity in the rat [26], but generally results in a decreased exercise tolerance in man [27]. One explanation for the failure of these strategies to enhance exercise capacity in humans is that although fat oxidation is increased, at best this only compensates for the reduced contribution of carbohydrate rather than enhancing total substrate availability, and in most cases it is unable to meet the shortfall caused by reduced body carbohydrate stores. Fat oxidation also requires a higher rate of oxygen consumption for the same energy demand, so may not be appropriate when oxygen delivery is limited.

A high-fat meal just before exercise could theoretically increase blood FFA availability without sacrificing body carbohydrate stores, but the digestion and absorption of fat is slow. A more effective way to achieve this outcome involves infusion of a lipid source with heparin injections, but this is not practical for athletes to use in the field (and it contravenes the WADA regulations). The ingestion of medium-chain fatty acids during exercise offers another potential way to increase plasma FA since these fats are digested, absorbed and transported into the muscle cell and mitochondria more efficiently than their long-chain counterparts. However, the practicality of this strategy is also limited since the amounts that can apparently be tolerated during exercise without causing gastrointestinal distress are too small to cause any worthwhile sparing of muscle glycogen [28]. A final dietary strategy known to acutely increase plasma FFAs is the ingestion of caffeine. Although an increased fat utilization and concomitant glycogen sparing was one of the mechanisms first suggested to explain the beneficial effects of caffeine on exercise capacity, more recent studies have shown that this effect is short lived (disappearing by ~20 min into exercise) and not universally observed [29]. In summary, there does not appear to be a simple and practical way for athletes to achieve an acute manipulation of plasma FFA levels to benefit exercise performance.

Retooling the muscle to enhance FFA transport across the muscle or mitochondrial membranes or to upregulate β-oxidation pathways offers other options to usefully enhance fatty acid utilization during exercise. Carnitine supplementation has been promoted for many decades as a potential enhancer of fatty acid oxidation (and fat loss, by the weight loss industry) due to its role in transporting fatty acids into the mitochondria. This has occurred without any proof, until recently, that increased carnitine intake is taken up by the muscle. There is emerging evidence that intake of supplemental carnitine with insulin-stimulating carbohydrate-rich meals may slowly increase muscle carnitine concentrations [30]. The functional outcome of this finding requires further investigation, and the commercial possibilities will surely drive this forward.

Longer term exposure to a high-fat, low-carbohydrate diet has been shown to cause chronic adaptations in the muscle to increase its capacity for fat oxidation.
at rest and during exercise; these changes include increases in fatty acid transport proteins and enzymes involved in fat mobilization, uptake and oxidation [31]. A couple of studies have reported that 2–4 weeks of intake of such a diet by trained individuals was associated with enhanced capacity for endurance exercise, but the majority of studies have reported no benefits to exercise endurance or performance, and a longer term study (7 week) actually found a compromised adaptation to the training process [31]. Certainly, the ability to train at high intensities is impaired by a low-carbohydrate diet, and there may be some alteration of the adaptive response to the same training stimulus. For this and general health concerns, long-term exposure to a high-fat diet is not recommended to athletes. However, changes in the muscle in response to a high-fat diet and high-volume exercise appear to be achieved in about 5 days in well-trained subjects and are maintained in the face of restored carbohydrate availability, at least in the short-term [32]. Thus, the concept of dietary periodization has been proposed, involving rapid adaptation to a high-fat diet followed by carbohydrate loading and carbohydrate feeding during exercise; this offers the potential benefits of the combination of high carbohydrate availability with spared use. Again, despite clear evidence of altered substrate use during exercise, no benefits to exercise capacity or performance have been detected with this strategy [33]. One explanation for this apparently incongruous finding is that the exposure to a high-fat (low-carbohydrate) diet not only upregulates fat utilization during exercise, but downregulates glycogen use due to a reduction in activity of the pyruvate dehydrogenase complex [34]. The practical implication of this finding of impaired rather than spared glycogen use is a reduction in performance of high-intensity bouts within an exercise protocol [35]. This is likely to be of major practical importance in the world of sport in which the decisive moments in even ultra-endurance events lasting many hours involve high-intensity activities. In summary, there appears to be a sophisticated reciprocal relationship between fat and carbohydrate utilization during exercise that can be manipulated to show interesting outcomes in terms of exercise metabolism. However, the practical outcomes do not favor performance benefits and may even impair critical aspects of sports performance.

Adaptation of the Gut and Exogenous Fuel Supply

In exercise lasting longer than about 40–60 min, ingestion of carbohydrate can enhance performance [36]. Ingested carbohydrate must first be emptied from the stomach into the small intestine where it is absorbed and made available to the working muscles. The rate of intestinal absorption seems to be the main limitation to the provision of exogenous carbohydrate to the working muscle during exercise. High rates of oxidation of exogenous carbohydrate can be achieved whether this is ingested in liquid, semi-solid, or solid form [37, 38], though
there may be performance advantages to liquid formulations which can simultaneously provide fluid as well as carbohydrate [39]. Ingestion of mixtures of different carbohydrates, including glucose and fructose, which are absorbed by different pathways, may allow maximization of intestinal absorption rates, and can lead to higher rates of exogenous carbohydrate oxidation during exercise: this has been shown to result in better endurance performance [40]. In events that last up to 2 h, a carbohydrate intake of up to about 60 g per hour might be recommended. When exercise lasts more than 2 h, slightly greater amounts of carbohydrate (up to 90 g/h) may be preferred. When such high rates of carbohydrate ingestion are attempted, they should consist of a mix of multiple transportable carbohydrates, such as glucose:fructose or maltodextrin:fructose.

The gut is capable of rapid adaptation to periods of feeding and fasting, and is highly responsive to changes in the composition of the diet. The maximum rates of carbohydrate absorption that can be achieved may be enhanced by a period of adaptation to a high-carbohydrate diet. In a study of highly-trained athletes, a group who consumed glucose during each of their workouts over a 4-week training block increased their ability to oxidize this carbohydrate, while muscle oxidation of carbohydrate consumed during exercise remained constant in a matched group who did the same training with ingestion of water [41]. The design of this study could not distinguish whether the adaptation was achieved by a higher intake of carbohydrate or the specific intake of the carbohydrate during exercise. However, it seems sensible to advise athletes who plan to consume carbohydrate during competition to practice this in training to train their behaviors and race plan, as well as to take advantage of this gut adaptation.

**Recovery and Replenishment of Fuel Stores: Training Harder versus Training Smarter**

The adaptations to a training program are proportional to the training load, so nutrition strategies that allow greater intensity of training and allow faster recovery between training sessions are important to maximize the benefits. For many years, athletes have been encouraged to consume a high-carbohydrate diet during periods of intensive training and to begin the process of carbohydrate ingestion soon after the end of a training session [12]. These strategies are designed to allow the athlete to train hard and, indeed, some training studies have shown that such strategies achieve a better performance outcome at the end of a block of intensive training or help to reduce the effects of a block of overtraining [33].

Recent investigations of the muscle metabolic response to a training stimulus have found, in fact, that compared with a comparable situation featuring high muscle glycogen content, an acute bout of (endurance) exercise commenced with low muscle glycogen stores results in a greater transcriptional activation of
enzymes involved in carbohydrate metabolism (i.e. the AMP-activated protein kinase, GLUT-4, hexokinase and the pyruvate dehydrogenase complex), and an increase in adaptive responses favoring fat metabolism [42, 43]. In other words, training with low carbohydrate availability might enhance the response to the same exercise stimulus – or ‘train smart’. This has led to another concept of dietary periodization where an athlete would ‘train low’ to promote a greater training response, before switching to high carbohydrate availability for competition when optimum performance was required [42]. The watershed study undertaken by Hansen et al. [44] intrigued sports scientists and coaches/athletes alike by purportedly providing evidence to support this view. Previously sedentary men consumed a carbohydrate-rich diet while training one leg with a ‘two a day’ protocol (two sessions every second day, with a rest day between) and the other leg with a single daily training schedule. Although each leg completed the same training load and increased its maximum power output equally, the ‘two a day’ leg which commenced 50% of its training sessions with a low glycogen concentration, showed a greater enhancement of its capacity to work at ~90% of pre-training maximum power output. While these findings have significant scientific merit and possible application for exercise programs targeting metabolic improvements and health outcomes, there is potential for misunderstanding by athletes and coaches.

First, it should be noted that train low does not require a long-term adherence to a low-carbohydrate diet, and there are a number of options for reducing carbohydrate availability in the training environment that might enhance adaptation to the training stimulus. These include exercising after an overnight fast, consuming only water during prolonged training sessions, withholding carbohydrate in the hours after exercise or restricting carbohydrate below the fuel requirements of the training load [45]. Such protocols differ in the duration of the period in which the body is exposed to a low carbohydrate environment as well as the focus on reducing endogenous and/or exogenous muscle fuel sources. As described above, the two a day training protocol of current interest involves a carbohydrate-rich diet, and uses the rescheduling of training sessions to achieve a low glycogen environment for some of the sessions, but possible supercompensation of glycogen during the rest day [44].

Second, the transference of changes in enzyme or protein content of the muscle cell to athletic performance needs to be questioned. To date, the train low literature has found that undertaking some exercise sessions with low glycogen concentrations or low exogenous carbohydrate availability can enhance the metabolic adaptations associated with training, even in well-trained individuals, but fails to provide a performance enhancement over a conventional training diet with high carbohydrate availability [46]. The final issue of importance is the consideration that train low strategies may cause some negative outcomes. A common finding from several train low studies is that capacity for training or training intensity may be impaired in sessions undertaken with low carbohydrate availability [47, 48]. This is important; coaches typically prescribe training
sessions in which athletes are required to work at intensities/speeds/power outputs that are higher than their ‘race pace’. Intuitively, a sacrifice of the capacity to train at high intensities should be made with reluctance until there is evidence that this does not impair performance. Finally, the effect of repeated training with low carbohydrate status on the risk of illness injury and overtraining needs to be considered [45].

Of course, most elite athletes practice an intricate periodization of both diet and exercise loads within their training program, which may change within a macrocycle or microcycle. Either by intent or for practicality, some training sessions are undertaken with low carbohydrate status (overnight fasting, high-volume training involving several sessions in the day, little carbohydrate intake during the workout), while others are undertaken using strategies that promote carbohydrate status (more recovery time, post-meal, carbohydrate intake during the session) [45]. Therefore, in real life, elite athletes already undertake a proportion of their training with low glycogen content. It makes sense that sessions undertaken at lower intensity or at the beginning of a training cycle are most suited to, or perhaps, least disadvantaged by train low strategies. Conversely, ‘quality’ sessions done at higher intensities or in the transition to peaking for competition are likely to be best undertaken with better fuel support. Athletes may, by accident or design, develop a mix-and-match of nutrition strategies that achieves their overall nutrition goals, suits their lifestyle and resources, and maximizes their training and competition performances.

**Hydration and Salt Balance**

Major disturbances of cell volume have profound effects on cellular metabolism [49]. Cell swelling will favor anabolic reactions, including protein synthesis and glycogen synthesis, while cell shrinkage will encourage these reactions to proceed in the opposite direction [50]. It is also apparent that metabolic activity within the cell or in other tissues can alter the distribution of water between the intracellular and extracellular space. During intense exercise, the concentration of the products of glycolysis will rise sharply; changes in glycogen concentration will have little effect on the osmolality of the intracellular space, but the concentration of phosphorylated intermediates and of pyruvate and lactate can rise markedly. Muscle lactate concentration can exceed 25–30 mmol/kg after intense exercise [51], and the rise in intracellular osmolality will cause the rapid movement of water into the active muscles leading to cell swelling and the initiation of compensatory mechanisms.

There is clearly potential for the athlete to exploit these mechanisms to promote desirable metabolic outcomes and to minimize unwanted effects. At present, however, our understanding does not allow practical recommendations to be made.
Conclusions

Current areas of discovery in sports nutrition include the interaction of nutrition and exercise on muscle protein synthesis, the nutritional environment for optimum training adaptations, the gut limits on providing exercising muscle with a supply of exogenous carbohydrate, and the manipulation of cell metabolism by changes in cell volume. We presently know that the ingestion of small amounts of protein after an exercise bout will promote net muscle protein synthesis to enhance the adaptive response to the session. This response can be maximized by ingestion of about 20–25 g of high-quality protein that provides about 10 g of essential amino acids. Endurance training on a carbohydrate-restricted diet will enhance the capacity for fat oxidation and may enhance the adaptive processes taking place in muscle. However, the downside includes a reduced capacity for training at high intensities as well as impairment of pathways promoting carbohydrate utilization. In well-trained athletes, at least, there is no evidence of performance improvements from strategies to ‘fat adapt’ or train low exclusively. However, there may be opportunities to include individual training sessions or blocks of training within the athlete’s periodized training program to integrate the benefits of training with reduced carbohydrate availability. Intestinal absorptive capacity may limit the supply of exogenous carbohydrate during exercise, but this can be trained by following a high-carbohydrate diet and perhaps also by ingestion of carbohydrate during training. Such adaptations will allow the athlete to have better opportunity to supply additional sources of carbohydrate to enhance performance during events lasting more than 2–3 h. Manipulation of hydration status has profound effects on cellular metabolism, but the available evidence does not yet allow identification of effective strategies that can be applied by the athlete. Over the coming years, we expect to see refinements of this knowledge to allow athletes to fully exploit it to achieve their sporting goals.

References


