

70th Anniversary Conference on ‘From plough through practice to policy’

Plenary Lecture 2 Nutrition for sports performance: issues and opportunities

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Diet can significantly influence athletic performance, but recent research developments have substantially changed our understanding of sport and exercise nutrition. Athletes adopt various nutritional strategies in training and competition in the pursuit of success. The aim of training is to promote changes in the structure and function of muscle and other tissues by selective modulation of protein synthesis and breakdown in response to the training stimulus. This process is affected by the availability of essential amino acids in the post-exercise period. Athletes have been encouraged to eat diets high in carbohydrate, but low-carbohydrate diets up-regulate the capacity of muscle for fat oxidation, potentially sparing the limited carbohydrate stores. Such diets, however, do not enhance endurance performance. It is not yet known whether the increased capacity for fat oxidation that results from training in a carbohydrate-deficient state can promote loss of body fat. Preventing excessive fluid deficits will maintain exercise capacity, and ensuring adequate hydration status can also reduce subjective perception of effort. This latter effect may be important in encouraging exercise participation and promoting adherence to exercise programmes. Dietary supplement use is popular in sport, and a few supplements may improve performance in specific exercise tasks. Athletes must be cautious, however, not to contravene the doping regulations. There is an increasing recognition of the role of the brain in determining exercise performance: various nutritional strategies have been proposed, but with limited success. Nutrition strategies developed for use by athletes can also be used to achieve functional benefits in other populations.

Sport: Exercise: Training: Fatigue

Many different factors contribute to successful performance in sport. Among these, genetic endowment is undoubtedly the most important, but the innate sporting talent conferred by the genotype can be modified by various factors. Among these, a systematic programme of consistent and intensive training carried out over many years probably plays the greatest role. Successful athletes will possess the motivation to undertake this training, and tactics and other factors will also contribute. When all else is equal, however, as it usually is in elite sport which is structured in such a way that the outcome is always in doubt, an assortment of minor factors can determine who will be successful. Good food choices will not make a mediocre athlete into a champion, but poor food choices may prevent the potential champion from realising his/her potential.

Based on emerging evidence from nutrition science in the last two decades, there have been substantial changes in the approach to nutrition support of elite athletes. Until recently, the primary focus of sports nutrition was on recovery between training sessions to allow the athlete to undertake consistent intensive training without succumbing to injury, illness and chronic fatigue. This led to a particular focus on a high daily carbohydrate intake and high fluid intakes to ensure replacement of sweat losses. More recently, however, there has been a shift towards looking for ways in which sports nutrition can help promote the adaptations that take place in tissues in response to the training stimulus. Athletes still need energy, macronutrients and micronutrients, but sports nutrition is now more about using nutrition strategies to modulate training-induced muscle adaptations⁽¹⁾.

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Table 1. Issues and opportunities from specific nutrition strategies that may apply to the elite athlete or to other population groups

Issue	Athlete	Other applications
Build and repair muscle	Performance	Sarcopenia/rehabilitation after injury or surgery
High-fat diets	Performance	Weight loss
Hydration	Performance	Reduced sensation of effort
Supplements	Performance	Various
Nutrition and the brain	Performance	Promotion of exercise adherence

A number of other new developments have arisen in sports nutrition. While each of these has attractions to the athlete in terms of the prospect of enhanced performance in competition, there are also opportunities to apply these same practices and principles to other population groups who have no interest in sport, but who may be physically active in their occupations, who may engage in exercise for the health benefits that ensue, or who may seek the improved functional outcomes that result (Table 1).

There is also now a growing realisation that eating strategies for athletes must take account of the fact that each individual has different nutrition goals. At the elite level in sport, it is not acceptable any more to make generic prescriptions for all members of a team or for all competitors in any event. A strategy must be devised to take account of each athlete's physiological and biochemical characteristics as well as the training load and competition goals.

Building and repairing muscle

The aim of training is to improve exercise performance, and this is achieved by modulation of gene expression to induce changes in the structure and function of skeletal muscle and other tissues. The nature of the adaptation to training is specific to the nature of the stimulus applied: endurance training will enhance the capacity for endurance performance but elite athletes have low muscle strength⁽²⁾ and highly trained strength athletes generally have poor endurance. The degree of response is proportional to the training load, i.e. to the intensity, duration and frequency of training. These responses to training are induced by selective alterations in the rates of synthesis and degradation of specific proteins: the tissue content of functional proteins is increased and the content of proteins that serve no functional role is decreased. The response is modulated by the nutrient, metabolic and hormonal environment, and this can be modified by food intake before, during and after training⁽³⁾. In this context, it is interesting to note that the 2011 list of prohibited substances and methods issued by the World Anti-Doping Agency includes, under Category M3, Gene Doping, the following prohibition⁽⁴⁾:

'The following, with the potential to enhance sport performance, are prohibited:

3. The use of agents that directly or indirectly affect functions known to influence performance by altering gene expression.'

This clearly suggests that the use of nutrition manipulations that alter gene expression after training, and indeed

training itself, are considered to be doping methods. It seems unlikely, however, that any athlete would be penalised for applying these methods.

Many athletes, especially those engaged in strength and power sports, consume a high-protein diet in the belief that this is necessary for muscle growth and repair, and the habitual protein intakes of some groups of athletes can reach values in excess of 2.5 g/kg body mass per d⁽⁵⁾, with some individual values far higher than this. However, while a diet deficient in protein will prevent muscle hypertrophy, very high dietary protein intakes will not drive the system in favour of protein synthesis. Excess protein will simply be used as a substrate for oxidative metabolism, either directly or as a precursor of glucose, and the excess nitrogen will be lost in the urine. All forms of exercise will cause an increased rate of protein oxidation compared with the resting state⁽⁶⁾, leading to an increase in the minimum daily protein requirement. Exercise, however, will increase the energy demand and any increased protein requirement will be met if a normal mixed diet adequate to meet the increased energy expenditure is consumed.

The timing of protein intake relative to training may be more important than the amount of protein consumed⁽³⁾. Remodelling of the muscle tissues takes place in the hours and days after the training stimulus has been applied: consumption of small amounts of protein can ensure positive protein balance. As little as 6 g essential amino acids or about 20 g high-quality mixed protein, ingested either just before or soon after training may help promote that the adaptations taking place within the muscles and further increases in the amount of protein ingested have little further effect^(7,8). Resistance training in the fasted state and without ingesting some protein-containing foods soon after training will not optimise the training response. Milk protein, especially whey, which is high in leucine, may be more effective than some other proteins in promoting net muscle protein synthesis after a resistance training session⁽⁹⁾. Studies that have relied on net muscle protein balance as a marker for training adaptation have been criticised on the grounds that these short-term responses may not be predictive of longer term functional outcomes. The emerging evidence, however, does suggest that the acute responses observed in the few hours after a single resistance training session do translate into measurable effects on muscle mass and muscle strength that become measurable within a few weeks if the training and nutrition interventions are repeated a few times each week⁽³⁾. Some recent evidence suggests that it may be possible to simultaneously increase lean tissue mass while losing fat mass by combining a resistance exercise programme with intake

of a fat-free milk drink after training: a matched group who consumed an isoenergetic carbohydrate drink after training gained a smaller amount of lean tissue mass and did not lose body fat⁽¹⁰⁾. Subsequent to this observation in subjects undergoing resistance training, a similar effect has also been seen in overweight and obese individuals in the absence of exercise⁽¹¹⁾: daily supplementation of the normal diet with 56 g whey protein for 23 weeks resulted in a mean reduction in body mass of 1.8 kg and in fat mass of 2.3 kg (suggesting a small gain in lean tissue mass), but supplementation with isoenergetic amounts of soya protein or carbohydrate had no effect.

Advances in molecular biology are beginning to clarify the intracellular mechanisms that underpin these adaptive responses. The mechanical and metabolic stresses of exercise cause changes in energy status and Ca concentrations in the active muscles and these activate or inhibit various signalling cascades that in turn affect the transcriptional co-activators that regulate gene expression. Coffey *et al.* showed an increased rate of myofibrillar protein synthesis, but no effect on mitochondrial protein synthesis, following high intensity sprint exercise when subjects ingested a protein-carbohydrate supplement (24 g whey protein, 4.8 g additional leucine and 50 g maltodextrin) 30 min prior to exercise: there was no effect on these signalling molecules when an energy-free placebo was ingested before exercise⁽¹²⁾. A substantial increase in the phosphorylation of Akt-mTOR-S6K-rpS6 was observed in the fed trial, but there was no change in the placebo trial.

Moore *et al.* have recently used a unilateral exercise model to investigate the interactions between training and protein intake: resistance exercise followed by ingestion of 25 g whey protein was shown to stimulate myofibrillar protein synthesis over that induced by feeding alone⁽¹³⁾. This was attributed in part to greater phosphorylation of specific mammalian target of rapamycin signalling proteins (p70S6K and eEF2) and the activation of mitogen-activated protein kinases (extracellular-signal-regulated kinase 1/2 and p90RSK) signalling. Van Proeyen *et al.* looked at endurance rather than resistance training and showed that the acute response of the signalling proteins to a single bout of exercise is affected by nutrient status during training: 6 weeks of endurance training in the fed state (high carbohydrate pre-exercise meals and carbohydrate ingestion during exercise) resulted in slower re-activation of muscle protein translation than the same training regimen in the fasted state⁽¹⁴⁾. New training and nutrition strategies that maximise the adaptations taking place in the muscle will undoubtedly emerge as these mechanisms are further clarified.

These findings may have implications beyond the needs of athletes who wish to gain mass and strength. Disuse, whether due to a chronic condition or acute injury, leads to muscle wasting. The ageing process is also associated with loss of muscle mass and strength which may limit the ability to lead an independent life. Strategies to limit muscle loss and to maintain or restore function are therefore important. It is clear that the basic principles of exercise and nutrition that govern muscle responses to use and disuse are similar in athletes and in muscle-wasting conditions⁽¹⁵⁾. Recommendations aimed at maintaining

function in the elderly differ in extent, but not in principle, from those aimed at athletes⁽¹⁶⁾.

Low-carbohydrate, high-fat diets, performance and weight loss

The energy requirements of training are largely met by oxidation of fat and carbohydrate. The higher the intensity of exercise, the greater the reliance on carbohydrate as a fuel: at an exercise intensity corresponding to about 50% of an individual's maximum oxygen uptake ($\text{VO}_2 \text{ max}$), approximately two-thirds of the total energy requirement is met by fat oxidation, with carbohydrate oxidation supplying about one-third⁽¹⁷⁾. If the exercise intensity is increased to about 75% of $\text{VO}_2 \text{ max}$, the total energy expenditure is increased, and carbohydrate is now the major fuel. If carbohydrate is not available, or is available in only a limited amount, the intensity of the exercise must be reduced to a level where the energy requirement can be met by fat oxidation. The classic studies of Hultman, Bergstrom, Saltin and others in the 1960s clearly established the association between the availability of muscle glycogen and the capacity for endurance exercise⁽¹⁸⁾.

The practical message taken by coaches and athletes from these studies has been that carbohydrate intake should be sufficient to enable the training load to be sustained at the high level necessary to produce a response. During each strenuous training session, substantial depletion of the glycogen stores in the exercising muscles and in the liver takes place. If this carbohydrate reserve is not replenished by ingestion of high-carbohydrate foods before the next training session, training intensity must be reduced, leading to corresponding decrements in the training response. Any athlete training hard on a daily basis can readily observe this; if a low-carbohydrate diet, consisting mostly of fat and protein, is consumed after a day's training, it will be difficult to repeat the same training load on the following day. These observations led to the promotion of high-carbohydrate diets for all athletes in training. In a perceptive article written in 2000, however, Coyle wrote that 'Although it is generally assumed that optimal adaptation to the demands of repeated training sessions requires a diet that can sustain muscle energy reserves, this premise does not consider the unsolved longstanding question of whether it is a lack or surplus of a substrate that triggers the training adaptation'⁽¹⁹⁾. This comment was prompted by some recent studies suggested that training on a high-fat diet could increase the amount of fat oxidised during exercise but that it could also reduce the adaptations taking place within the muscle and potentially compromise the performance improvements that result from training⁽²⁰⁾.

Feeding a high-fat, low-carbohydrate diet for prolonged periods has been shown to increase the capacity of muscle to oxidise fat by stimulating mitochondrial biogenesis⁽²¹⁾. This can certainly improve endurance capacity in the rat, but may not be as effective in man; similarly short-term fasting increases endurance capacity in the rat, but generally results in a decreased exercise tolerance in man⁽²²⁾. The training diet, therefore should generally be high in carbohydrate, with a large proportion of total energy intake

in the form of complex carbohydrates and simple sugars, though there may be advantages in restricting carbohydrate availability before and during some training sessions⁽²¹⁾. Some long training sessions should perhaps be performed in a fasted or carbohydrate-depleted state to maximise the capacity for fat oxidation, but athletes should probably ensure that carbohydrate stores are replete for high intensity training sessions. Thus, a daily intake of 10 g/kg body mass or even more may be necessary for athletes during periods of intensive training⁽²³⁾. These high levels of intake are difficult to achieve without consuming large amounts of simple sugars and other compact forms of carbohydrate, as well as increasing the frequency of meals and snacks towards a 'grazing' eating pattern.

Failure to meet carbohydrate needs may also make the athlete more susceptible to minor infectious illnesses. Exercising with low carbohydrate reserves can result in increased levels of stress hormones, which in turn impairs the functional capacity of the immune system. While usually trivial in themselves, these illnesses can disrupt training and may prevent participation in important competitions⁽²⁴⁾.

The possibility of increased fat oxidation during exercise is attractive to those who seek to use a modest exercise programme to reduce body fat content. While it is clear that exercising in the fasted state or while consuming a carbohydrate-restricted diet can increase fat oxidation⁽²⁵⁾, this is usually accompanied by an increase in the subjective perception of effort, and the total amount of work done, and therefore the effect on energy balance, is likely to be less⁽²⁶⁾. It is also not at present clear whether carbohydrate-restricted diets are successful in promoting weight loss: most reviews have concluded that they are not more effective than isoenergetic low-fat diets^(27,28). The increase in perceived effort associated with exercise in a carbohydrate-depleted state is also likely to discourage adherence to an exercise programme.

Hydration

There is scope for nutritional intervention during exercise only when the duration of events is sufficient to allow absorption of drinks or foods ingested and this usually means only in exercise lasting more than about 40–60 min. The rules of some sports also limit opportunities for ingestion of food or fluid. The primary aims must be to ingest a source of energy, usually in the form of carbohydrate, and fluid for replacement of water (and, when losses are high) of electrolytes, especially Na, lost as sweat. High rates of sweat secretion are necessary during hard exercise in order to limit the rise in body temperature which would otherwise occur. If the exercise is prolonged, this leads to progressive dehydration and loss of electrolytes. Fatigue towards the end of a prolonged event may result as much from the effects of dehydration as from substrate depletion. Beginning exercise in a dehydrated state is certainly harmful to performance of high intensity exercise⁽²⁹⁾ and to endurance performance⁽³⁰⁾.

Laboratory tests of exercise performance may not truly reflect the conditions of sports competition. The choice of

exercise model is therefore important, and many studies now use tests that more closely simulate the demands of sport, including time trials and variable intensity exercise tests. It is also recognised that indoor exercise in still air on a treadmill or stationary ergometer may impose a much greater heat stress than exercise of comparable intensity in an outdoor environment at the same temperature and relative humidity⁽³¹⁾. In many exercise situations, it is not necessary to drink anything during exercise. Most athletes finish endurance events with some degree of dehydration, but some slower performers may consume fluid in excess of sweat losses. This is not helpful to performance and may in extreme cases lead to hyponatraemia, which is occasionally fatal⁽³²⁾.

Even in apparently homogeneous populations exercising at similar intensities in the same environment, there is a large individual variability in both sweat rate and sweat composition, and so some individual prescription is necessary, and the composition of drinks to be taken during exercise should be chosen to suit individual circumstances⁽³³⁾. Prescription of fixed rates of fluid intake is generally not helpful. During exercise in the cold, fluid replacement may not be necessary as sweat rates will be low, but there is still a need to supply additional glucose to the exercising muscles. Although consumption of a high-carbohydrate diet in the days prior to exercise should reduce the need for carbohydrate ingestion during exercise in events lasting less than about 2 h, it is not always possible to achieve this; competition on successive days, for example, may prevent adequate glycogen replacement between exercise periods. In this situation, more concentrated glucose drinks are to be preferred, and recent evidence supports the inclusion of glucose/fructose mixtures when high rates of carbohydrate delivery are needed⁽³⁴⁾. These will supply more glucose, thus sparing the limited glycogen stores in the muscles and liver without overloading the body with fluid. In many sports, there is little provision for fluid replacement: participants in games such as football or hockey can lose large amounts of fluid, but replacement is possible only at the half-time interval. Cold drinks can enhance endurance performance in warm weather more effectively than warm drinks by acting as a heat sink to slow the rate of rise of core temperature^(35,36).

Sports drinks containing glycerol, which acts to expand the plasma volume, have been popular with some endurance athletes, but as of 1 January 2010, these fall within the prohibited list of the World Anti-Doping Agency, and so their use in competition is not permitted⁽⁴⁾. Many other compounds have similar effects, though, and it remains to be seen whether these will also be prohibited on the basis that they act through similar mechanisms.

In the post-exercise period, replacement of fluid and electrolytes can usually be achieved through the normal dietary intake. If there is a need to ensure adequate replacement before exercise is repeated, extra fluids should be taken and additional salt (NaCl) might usefully be added to food or drinks⁽³⁷⁾. The other major electrolytes, particularly K, Mg and Ca, are present in abundance in fruit and fruit juices. Salt or mineral supplements are not normally necessary, though some cases of muscle cramp may be

associated with high salt losses and may be prevented by ingestion of drinks with moderate–high salt content⁽³⁸⁾.

Although the focus of most research on hydration and exercise has been on performance outcomes, this is of little relevance to the majority of active individuals who exercise for enjoyment or health reasons. Fatigue and discomfort are major obstacles to exercise participation for many who would benefit from a regular exercise programme. The subjective perception of effort is therefore an important consideration: if the exercise feels hard, the duration will often be cut short and adherence is likely to be poor. It is well recognised that the subjective rating of perceived exertion is higher when exercise is performed in warm environments than in cool environments⁽³⁹⁾ and is also increased by even moderate levels of hypohydration⁽⁴⁰⁾. Ensuring an adequate hydration status prior to exercise and ingestion of fluids during exercise to limit the development of hypohydration may therefore prove to be important elements of an exercise prescription.

Dietary supplements

With regular strenuous training, there must be an increased total energy intake to balance the increased energy expenditure. Provided that a reasonably varied diet is consumed, this will generally supply more than adequate amounts of protein, minerals, vitamins and other essential dietary components. Athletes who chronically restrict energy intake to limit body mass, and especially fat mass, may benefit from a broad spectrum of vitamin and mineral supplements. Athletes with limited finances, little interest in the foods they eat, or those lacking in food preparation skills may also fail to consume a varied diet. While supplements are no substitute for good dietary choices, they may have a use in some of these situations.

There are a few well-recognised exceptions to the generalisation about the value of dietary supplements in meeting micronutrient needs, including Fe, and, in the case of very active women, Ca. More recently, there has been considerable interest in the role of vitamin D beyond its well-recognised effects on bone metabolism. There is growing evidence that many athletes are vitamin D deficient or insufficient, especially those who train indoors, who wear protective clothing while outdoors or who live at high latitudes⁽⁴¹⁾, but the issue of whether athletes should supplement with vitamin D is at present controversial. Although there is no good evidence that routine vitamin D supplementation is beneficial to athletes, there is some evidence from cross-sectional studies of an association between circulating vitamin D levels and athletic performance⁽⁴²⁾. It therefore seems prudent to recommend that athletes seek professional help to monitor their serum vitamin D status.

A wide range of supplements is on sale to athletes, often with exaggerated claims of efficacy in enhancing performance in competition. Many of these are not supported by evidence of either their effects on performance or their safety when taken in high doses for prolonged periods⁽⁴³⁾. Sports supplements that may be useful in helping the athlete meet nutritional goals during training and competition

include sports drinks, high-carbohydrate supplements and liquid meal supplements. These are more expensive than everyday foods, but often provide a convenient and practical way of meeting dietary needs in a specific situation. There is good evidence for an ergogenic effect of a few supplements in some specific situations, including caffeine, creatine and bicarbonate or other buffering agents, possibly including β -alanine. Caffeine in relatively small doses, typically 2–4 mg/kg, can improve performance in a variety of exercise tasks, with greater effects generally seen in prolonged exercise, probably by actions on adenosine receptors in the central nervous system rather than on lipolysis as was previously thought⁽⁴⁴⁾. Creatine, in the form of creatine phosphate, acts as an energy source for ATP re-synthesis in high intensity exercise. Meat eaters normally obtain about 1 g creatine/d from their diet, which is about 50% of the daily requirement, with the remainder synthesised from amino acids. Ingestion of about 10–20 g creatine for a period of 4–6 d can increase the muscle creatine content by 10–20%, leading to improvements in strength and sprint performance⁽⁴⁵⁾. The biggest improvements in performance are generally seen in repeated sprints with limited recovery. Acute ingestion of large doses of NaHCO_3 (about 0.3 g/kg) can increase the extracellular buffering capacity and improve performance in exercise lasting from about 30 s to about 10 min. Similar benefits may be seen from a few days of β -alanine supplementation, which leads to an increase in muscle carnosine content and hence in buffer capacity⁽⁴⁶⁾. Recent data suggest a beneficial effect on exercise performance of large doses of dietary nitrate, which have been shown to reduce the oxygen cost of exercise^(47,48) and to improve performance⁽⁴⁹⁾. Both inorganic nitrate and vegetable sources, such as beetroot juice, have been shown to be effective.

A concern with many supplements on sale, apart from the lack of evidence of efficacy and safety, is the recent spate of reports of contamination of supplements with prohibited substances, including stimulants and anabolic steroids⁽⁵⁰⁾. The amounts present are generally, though not always, too small to be effective in improving performance or to pose a risk to health but can cause a positive drugs test⁽⁵¹⁾. In some cases, however, high doses, even higher than the normal therapeutic dose, of steroids, stimulants and anorectic agents have been found in supplements, not only with potential performance benefits but also with a real risk of adverse health effects. One of the best-selling supplements, hydroxycut, was withdrawn from sale in 2009 because of links with liver damage that reportedly led to at least one fatality⁽⁵²⁾.

Nutrition and the brain

Anyone who is physically active is familiar with the sensations that accompany a bout of hard exercise: these generally include breathlessness and muscle discomfort or even pain. It is easy to ascribe the cause of fatigue in these situations to a limitation occurring at the level of the lungs or in the active muscles. There is considerable interest, however, in the possibility that exercise performance is limited by events within the brain. There is, of course,

nothing new in this idea and in 1889, Lagrange wrote that 'Fatigue is ... a kind of regulator, warning us that we are exceeding the limits of useful exercise, and that work will soon become dangerous. Numerous physiological phenomena show us that the sensation of fatigue has its seat rather in the nerve-centres than in the muscles'⁽⁵³⁾. The concept of a 'central governor' that is commonly ascribed to A.V. Hill was generally accepted long before his work on the nature and causes of muscular fatigue.

As well as being of interest to the scientist, this has, of course, implications for nutrition strategies that might affect performance. A century after Lagrange wrote the words quoted earlier, Newsholme *et al.* sought to identify a mechanism by which the brain might influence fatigue⁽⁵⁴⁾. Their central fatigue hypothesis was based on the role of the neurotransmitter serotonin (5-hydroxytryptamine) in symptoms of lethargy, low arousal, loss of motivation and increased sensation of effort, and they proposed that fatigue developed due to a reduced uptake into cerebral neurones of tryptophan, the metabolic precursor on 5-hydroxytryptamine. This elegant hypothesis was underpinned by well-recognised metabolic responses that would reduce the availability of tryptophan for uptake into active muscle during prolonged exercise. Support for this hypothesis has come from some, but not all, interventions that used drugs to manipulate 5-hydroxytryptamine activity in the brain^(55,56) and there is a growing awareness that dopaminergic activity may be of major importance. Amphetamines, which act on dopamine receptors, have long been known to enhance exercise performance, and modern agents that have more specific actions are increasingly investigated for their actions on exercise performance⁽⁵⁶⁾. As mentioned earlier, it has also been shown that the action of caffeine in enhancing exercise performance may be mediated by actions on central adenosine receptors rather than by actions on muscle metabolism or contractility as was previously thought⁽⁴⁴⁾.

Although pharmacological agents have clear effects on exercise performance, nutritional interventions to induce changes in brain function by altering the availability of neurotransmitter precursors have generally not been successful, though there have been some exceptions. Mittleman *et al.* showed that ingestion of a moderate dose of branched-chain amino acids would prolong endurance capacity during cycling exercise in the heat⁽⁵⁷⁾. This is consistent with the Newsholme hypothesis: an elevated plasma branched-chain amino acids concentration would compete with tryptophan for uptake into the brain. A recent report has suggested that pre-exercise ingestion of the amino acid tyrosine, a metabolic precursor of dopamine, can enhance endurance cycling performance in a warm (30°C) environment⁽⁵⁸⁾. It is notable that both of these studies involve a combination of prolonged exercise and heat stress, and the evidence for a role of central fatigue is greater in the heat than in cooler environments.

Central dopaminergic neurones are also implicated in a number of neurological disorders and in addictive behaviours, and recent studies suggest a role for exercise in the management of a range of clinical disorders⁽⁵⁹⁾. There is also evidence from animal studies that habitually physically active animals may have an enhanced ability to

increase DA synthesis, which may have implications for the supply of the tyrosine precursor⁽⁶⁰⁾. There is clearly scope for interactive effects of nutrition and exercise and investigations in this area are currently in progress.

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