THE COMPLETE GUIDE TO

Anita Bean

SPORTS NUTRITION

9th edition

‘an absolute must-have for anyone working in the health and fitness industry’

YMCAfit

‘the most comprehensive guide to sports nutrition’

Athletics Weekly

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9TH EDITION

Anita Bean

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FOREWORD

Nutrition has always played an important role in my running career and without a doubt has been a key factor in helping me achieve my best performances. In the early days of my career, there was very little reliable information about sports nutrition. Like most runners, I had to work out for myself what to eat before races, the timings of my food intake, how much fluid to drink to prepare for races and also what to take onboard during longer races such as the marathon. This was done mostly by trying out different things rather than having a definite plan. Sometimes I was finding it difficult to get my blood sugar levels right to race well. On occasion I also felt like I'd taken on too much fluid too close to the start of shorter races. Earlier in my career I found it more difficult to recover between tough workouts too. Without some expert advice, it can definitely be very hard to optimise your nutrition strategies.

I've known Anita for many years and have always found her advice invaluable. Learning how to fuel my training has meant that I could train harder and recover quicker – and that was critical at times when I was training up to 100 miles a week or when I was doing intense interval sessions in preparation for championships. Without good nutrition, sports people are much more likely to get injured or pick up illnesses. It's a such a shame when athletes who are motivated to train hard don't achieve their goals due to their nutrition being inadequate.

Anita is absolutely brilliant at translating complex science into easily understandable advice for athletes. This book is such a fantastic resource to me. It contains a huge amount of information that is backed up by science. It is also very practical and displays the wealth of knowledge that Anita has. I've been able to gain fantastic advice from this book and I think it will be an absolute must for all aspiring athletes who want to enjoy their sport and achieve their optimal performances.

Jo Pavey
World, European and Commonwealth
medalist and five-time Olympian

PREFACE TO THE NINTH EDITION

It seems extraordinary that this book is now in its ninth edition. Since the first edition, it has undergone many revisions and updates as the science of sport and exercise nutrition has evolved over the years. When it was first published in 1993, sports nutrition was in its infancy and there was little reliable nutrition information available to athletes, coaches and nutrition practitioners. Since then, our knowledge of how nutrition influences sport and exercise performance has grown enormously, new guidelines have been developed and high-quality research continues to be published. There is now overwhelming evidence that diet significantly influences performance and recovery. Having advised hundreds of athletes over the past 30 years, I have seen first-hand how important diet is in supporting any training programme and helping athletes reach their goals.

The aim of this book has always been to translate the science of sport and exercise nutrition into practical information that athletes can understand and use. It provides evidence-based facts and recommendations in an easy-to-digest format, not opinions or anecdotes. All the information is backed with scientific studies, which are referenced in the text and listed at the back of the book. I am happy to report that, over the years, this book has remained a trusted reference and practical handbook for athletes, trainers, coaches, sports scientists, nutritionists and dietitians.

So, what's new? This ninth edition includes brand new chapters on relative energy deficiency in sport (RED-S), gut health, immunity and recovery from injury. I have added research updates and findings from hundreds of sports nutrition studies around the world. Since the last edition, there has been a huge rise in interest in plant-based diets, with many athletes now reducing meat or switching to a vegan diet for health, ethical, environmental or performance reasons. As a result, research on the benefits of plant proteins has increased dramatically. The thinking around hydration, race fuelling and the management of gut problems has also evolved.

In recent years, research in sports nutrition has focused on new topics such as nutrition periodisation, 'training low', protein timing, low energy availability and optimisation of body composition. There has been a trend towards higher fat intakes and a move away from very low-fat diets once believed beneficial for athletes. However, the controversy surrounding low-carbohydrate diets is ongoing and new research is beginning to provide some interesting insights into the effects of strategic periods of carbohydrate restriction on training adaptations, body composition and performance.

Sports nutrition advice has changed considerably over recent years. For example, guidelines for carbohydrate and protein are now expressed in grams per kg body weight, instead of as a percentage of total energy, and tailored according to the fuel requirements and training goals of specific training sessions. There have been new recommendations on the optimal amount of protein to be consumed after training sessions as well as the timing and type of protein. New concepts such as metabolic efficiency and flexibility have evolved.

It is clear that when it comes to optimal performance, one size doesn't fit all. Athletes should follow a personalised nutrition and hydration plan that takes account of the specific physiological demands of their event, their training and performance goals, practical considerations, food preferences and individual circumstances.

Scientists have also made progress in the quest for giving elite athletes the edge in long-duration competitions, with the development of sports drinks containing 'multiple transportable carbohydrates' that allow the body to absorb higher amounts of carbohydrate per hour. Other changes include the abolition of advice to drink ahead of thirst and a warning against overhydration during long events. There are no longer hard and fast guidelines on fluid intake and, in practice, athletes have to find a compromise between preventing hypohydration (*see* p. 147) and ensuring they don't overhydrate.

I have always taken a 'food first' approach when it comes to optimising nutrition for performance, despite the enormous array of expensive engineered supplements out there! Pills, powders and gels cannot replicate the complex matrix of nutrients and phytochemicals provided by natural food. What's more, food tastes so much nicer and provides a lot more pleasure than any supplement. If it can improve recovery and performance then this has to be great news for every athlete.

I've watched with equal fascination and scepticism as more and more sports supplements appear on the market. Science continues to disprove the claims of most, which I continue to report in this book. However, there is sound evidence for the benefits of a small handful of supplements, which I have outlined in Chapter 7.

In this book, I have attempted to condense decades of sports nutrition research into practical guidelines and, ultimately, a step-by-step guide to developing a personalised nutrition plan. I hope you will find the information useful and that it will help you reach your sporting potential.

Anita Bean

An Overview of Sports Nutrition

1

There is universal scientific consensus that diet affects health, performance and recovery. A well-planned eating strategy will help support any training programme, whether you are training for fitness or for competition; promote efficient recovery between workouts; reduce the risk of illness or overtraining; and help you to achieve your potential in sport.

Of course, everyone has different nutritional needs and there is no single diet that suits all. Some athletes require more calories, protein or vitamins than others; and each sport has its unique nutritional demands. But it is possible to find broad scientific agreement as to what constitutes a healthy diet for sport generally. The following guidelines are based on the Joint Position Statement on Nutrition and Athletic Performance from the American College of Sports Medicine, Academy of Nutrition and Dietetics and Dietitians of Canada (Thomas *et al.*, 2016), the International Olympic Committee Consensus Conference on Sports Nutrition (IOC, 2011) and the International Association of Athletics Federation (IAAF) Consensus Statement (Burke *et al.*, 2019).

These organisations highlight the importance of nutrition strategies in optimising elite performance. They recognise the advances in sports nutrition research in recent years, including the need for nutrition periodisation, individualisation of nutrition plans to take into account the specificity and uniqueness of the event and performance goals, the new concepts of metabolic efficiency and flexibility, and energy availability (energy intake minus the energy cost of exercise); the importance of nutrient timing and optimising the intakes of protein after training to aid long-term maintenance or gain of muscle; greater intakes of carbohydrate (90 g/hr) for exercise over 3 hours; the importance of vitamin D for performance; and the need for a personalised hydration plan to prevent hypohydration as well as hyponatraemia. They recommend that the requirement for energy, carbohydrate and protein should be expressed using guidelines per kg body weight to take account of a range of body sizes.

The process leading to publication was extremely thorough and drew on the combined expertise of many of the world's leading sports nutrition experts. Of course, these guidelines are only intended to give you an overview of the evidence linking nutrition and performance. Everyone is different and some people respond better or worse to various dietary strategies. So it is important to experiment and find out what works best for you. But, being based on high-quality research, these guidelines are a great place to start.

1. Energy

It is crucial that athletes meet their energy (calorie) needs during hard periods of training in order to achieve improvements in performance and maintain good health. Failure to consume sufficient energy can result in muscle loss, reduced performance, slow recovery, disruption of hormonal function (in females) and increased risk of fatigue, injury and illness. Researchers have recently identified the concept of energy availability (EA), defined as dietary intake minus exercise energy expenditure, or the amount of energy available to the body to perform all other functions after exercise training expenditure is subtracted. In healthy adults, a value of 45 kcal/kg fat-free mass (FFM)/day equates with energy balance and optimum health. It has been suggested that 30 kcal/kg FFM/day should be the lower threshold of energy availability in females. (Fat-free mass includes muscles, organs, fluid and bones.) A low EA may compromise athletic performance in the short and long term. It may occur when energy intake is too low, energy expenditure is too high or a combination of both. The term 'relative energy deficiency in sport (RED-S)' refers to the impaired physiological function, including metabolic rate, menstrual function, bone health, immunity, protein synthesis and cardiovascular health, caused by relative energy deficiency or low EA in male and female athletes. It more accurately describes the clinical syndrome previously known as the Female Athlete Triad.

Your daily calorie needs will depend on your genetic make-up, age, weight, body composition, your daily activity and your training programme. It is possible to estimate the number of calories you need daily from your body weight (BW) and your level of daily physical activity.

STEP 1: ESTIMATE YOUR RESTING METABOLIC RATE (RMR)

Your RMR is an estimate of how many calories you would burn if you were to do nothing but rest for 24 hours. It represents the minimum amount of energy needed to keep your body functioning, including breathing and keeping your heart beating. It can be estimated using the Mifflin-St Jeor equation, which utilises age, weight and height, and is considered more accurate than the more commonly used Harris-Benedict equation.

Men

(10 x weight (kg)) + (6.25 x height (cm))
– (5 x age (y)) + 5

Women

(10 x weight (kg)) + (6.25 x height (cm))
– (5 x age (y)) – 161

STEP 2: WORK OUT YOUR PHYSICAL ACTIVITY LEVEL (PAL)

This is the ratio of your overall daily energy expenditure to your RMR – a rough measure of your lifestyle activity.

- mostly inactive or sedentary (mainly sitting): 1.2
- fairly active (include walking and exercise 1–2 x week): 1.3

- moderately active (exercise 2–3 x weekly): 1.4
- active (exercise hard more than 3 x weekly): 1.5
- very active (exercise hard daily): 1.7

STEP 3: MULTIPLY YOUR RMR BY YOUR PAL TO WORK OUT YOUR TOTAL DAILY ENERGY EXPENDITURE

Daily calorie needs = RMR x PAL

This figure gives you a rough idea of your daily calorie requirement to maintain your weight. If you eat fewer calories, you will lose weight; if you eat more then you will gain weight.

Resting metabolic rate

The resting metabolic rate (RMR) is the amount of energy required to maintain the body's normal metabolic activity, such as respiration, maintenance of body temperature and digestion. Specifically, it is the amount of energy required at rest with no additional activity. The energy consumed is sufficient only for the functioning of the vital organs. It is closely related to the basal metabolic rate (BMR), which can only be measured in an awake but totally rested and post-absorptive state, and in a neutrally temperate environment. It is quite restrictive and only used in clinical or laboratory settings. RMR accounts for 60–75% of the calories you burn daily. Generally, men have a higher RMR than women.

Physical activity includes all activities from doing the housework to walking and working out in the gym. The number of calories you burn in any activity depends on your weight, the type of activity and the duration of that activity.

2. Body composition

There is no single or 'optimal' body composition for a particular event or sport. Each individual athlete has an optimal fat range at which their performance improves yet their health does not suffer. However, this should not be achieved at the expense of continual low energy availability, otherwise performance and health are likely to be impaired. Instead, weight and body composition should be periodised in line with the training programme, accepting fluctuations throughout the year. Excessive weight gain should be avoided in the off-season and rapid weight loss strategies avoided in the competition season. The best time to lose weight is in the base training phase or well out from competition to minimise loss of performance. A modest energy deficit of 250–500 kcal/day to achieve a slow rate of weight loss (<1% per week) is recommended along with increasing protein intake to 1.8–2.7 g/kg BW/day to preserve muscle mass.

3. Carbohydrate

Carbohydrate is an important fuel for the brain and central nervous system as well as for muscular work. It is stored as glycogen in your liver and muscles. The size of the body's carbohydrate stores is relatively limited. Approximately 100 g glycogen (equivalent to 400 kilocalories) may be stored in the liver, and up to 400 g glycogen (equivalent to 1600 kilocalories) in muscle cells. It is almost entirely depleted by the end of 90–120 minutes of moderate- to high-intensity exercise. The purpose of liver glycogen is to maintain blood sugar levels. When blood glucose dips, glycogen in the liver breaks down to release glucose into the bloodstream. The purpose of muscle glycogen is to fuel physical activity.

Carbohydrate offers advantages over fat as a fuel since it provides more adenosine triphosphate (ATP) (*see* p. 16 'What is ATP?') per volume of oxygen and is therefore considered a more efficient fuel. There is significant evidence that performance of prolonged, sustained or intermittent high-intensity exercise is enhanced by strategies that maintain high carbohydrate availability (i.e. matching glycogen stores and blood glucose to the fuel demands of exercise).

When it is important to train hard or with high intensity, daily carbohydrate intakes should match the fuel needs of training and glycogen replenishment. General guidelines for carbohydrate intake to provide high carbohydrate availability are based on body weight (a proxy for the volume of muscle) and exercise load. These are shown in Table 1.1. The more active you are and the greater your muscle mass, the higher your carbohydrate needs.

While guidelines for carbohydrate intake have been provided in terms of percentage contribution to total dietary energy intake in the past, experts now recommend expressing carbohydrate requirements in terms of grams per kg body weight. Guidelines for daily intakes are 3–5 g to 5–7 g per kg of body weight (BW) per day for low- and moderate-intensity daily training lasting up to 1 hour respectively. Depending on the fuel cost of the training schedule, an endurance athlete may need to consume 8–12 g of carbohydrate per kg body weight each day (560–840 g per day for a 70 kg athlete) to ensure adequate glycogen stores.

To promote rapid post-exercise recovery, experts recommend consuming 1.0–1.2 g carbohydrate per kg BW per hour for the first 4 hours after exercise. If you plan to train again within 8 hours, it is important to begin refuelling as soon as possible after exercise. Moderate and high glycaemic index (GI) carbohydrates (*see* p. 38) will promote faster recovery during this period. When carbohydrate intake is suboptimal for refuelling, adding protein to a meal/snack will enhance glycogen storage. However, for recovery periods of 24 hours or longer, the type and timing of carbohydrate intake is less critical, although you should choose nutrient-dense sources wherever possible.

It is recommended that the pre-exercise meal provides 1–4 g carbohydrate per kg body weight, depending on exercise intensity and duration, and

Table 1.1 GUIDELINES FOR DAILY CARBOHYDRATE INTAKE

Activity level	Recommended carbohydrate intake
Very light training (low-intensity or skill-based exercise)	3–5 g/kg BW daily
Moderate-intensity training (approx. 1 h daily)	5–7 g/kg BW daily
Moderate–high-intensity training (1–3 h daily)	6–10 g/kg BW daily
Very high-intensity training (>4 h daily)	8–12 g/kg BW daily

Source: Burke *et al.*, 2011.

that this should be consumed between 1 and 4 hours before exercise.

During exercise lasting less than 45 minutes, there is no performance advantage to be gained by consuming additional carbohydrates. For intense exercise lasting between 45 and 75 minutes, simply swilling (not swallowing) an energy drink in your mouth ('mouth rinsing') can improve performance. The carbohydrates stimulate oral sensors that act on the central nervous system (brain) to mask fatigue and reduce perceived exertion, thus allowing you to maintain exercise intensity for longer. But for exercise lasting longer than about 1 hour, consuming between 30 and 60 g carbohydrate helps maintain your blood glucose level, spare muscle glycogen stores, delay fatigue and increase your endurance. The amount depends on the intensity and duration of exercise, and is unrelated to body size.

The longer and the more intense your workout or event, the greater your carbohydrate needs. Previously, it was thought that the body could absorb only a maximum of 60 g carbohydrate per hour. However, recent research suggests that it may be higher – as much as 90 g, a level that would be appropriate during intense exercise lasting more than 3 hours. Studies have shown that consuming multiple transportable carbohydrates (e.g. glucose and fructose) increases the rate of carbohydrate uptake and oxidation during exercise compared with glucose alone. A 2:1 mixture of glucose + fructose is generally associated with minimal GI distress. Choose high-GI carbohydrates (e.g. sports drinks, energy gels and energy bars, bananas, fruit bars, cereal or breakfast bars), according to your personal preference and tolerance.

However, recent research has shown that training in a glycogen-depleted state can enhance the adaptive responses to exercise stimulus and increase exercise capacity. The concept of 'training low but competing high' as well as 'carbohydrate periodisation' (integrating short periods of 'training low' into the training programme) has become very popular among elite endurance athletes. Strategies include occasional fasted training, training following an overnight fast, and not replenishing carbohydrate stores after the first of two training sessions of the day. These have been shown to increase muscle adaptation to training by altering signalling and upregulating the metabolic response to

Table 1.2 RECOMMENDATIONS FOR PRE- AND POST-EXERCISE CARBOHYDRATE INTAKE

Dietary strategy	When	Recommended carbohydrate intake
Pre-exercise fuelling	Before exercise >60 min	1–4 g/kg BW consumed 1–4 h before exercise
Post-exercise rapid refuelling	<8 h recovery between two sessions	1.0–1.2 g $\cdot$ kg^{-1} $\cdot$ h^{-1} for first 4 h then resume daily fuel needs
Carbohydrate loading	For events >90 min of sustained/intermittent exercise	36–48 h of 10–12 g/kg BW/24 h

Source: Burke *et al.*, 2011.

exercise. However, it is important to undertake high-intensity training sessions with high carbohydrate stores. Whether implementing these strategies ultimately improves performance is unclear.

4. Protein

Amino acids from proteins form the building blocks for new tissues and the repair of body cells. They are also used for making enzymes, hormones and antibodies. Protein also provides a (small) fuel source for exercising muscles.

Athletes have higher protein requirements than non-active people. Extra protein is needed to compensate for the increased muscle breakdown that occurs during and after intense exercise, as well as to build new muscle cells. The Thomas *et al.* consensus statement recommends between 1.2 and 2.0 g protein/kg BW/day for athletes, which equates to 84–140 g daily for a 70 kg person, considerably more than for a sedentary person, who requires 0.75 g protein/kg BW daily. These recommendations encompass a range of training programmes and allow for adjustment according to individual needs, training goals and experience.

The timing as well as the amount of protein is crucial when it comes to promoting muscle repair and growth. It is best to distribute protein intake throughout the day rather than consuming it in just one or two meals. Experts recommend consuming 0.25 g protein/kg BW or 15–25 g protein with each main meal as well as immediately after exercise.

Several studies have found that eating carbohydrate and protein together immediately after exercise enhances recovery and promotes muscle building. The types of protein eaten after exercise is important – high-quality proteins, particularly fast-absorbed proteins that contain leucine (such as whey), are considered optimal for recovery. Leucine is both a substrate and a trigger for muscle protein synthesis (MPS). An intake of 2–3 g leucine has been shown to stimulate maximum MPS.

Some athletes eat high-protein diets in the belief that extra protein leads to increased strength and muscle mass, but this isn't true – it is stimulation of muscle tissue through exercise plus adequate – not *extra* – protein that leads to muscle growth. As protein is found in so many foods, most people – including athletes – eat a little more protein than they need. This isn't harmful – the excess is broken down into urea (which is excreted) and fuel, which is either used for energy or stored as fat if your calorie intake exceeds your output.

5. Fat

Some fat is essential – it makes up part of the structure of all cell membranes, your brain tissue, nerve sheaths and bone marrow and it cushions your organs. Fat in food also provides essential fatty acids and the fat-soluble vitamins A, D and E, and is an important source of energy for exercise. The ACSM position statement currently makes no specific recommendation for fat intake. The focus should be on meeting carbohydrate and protein goals with fat making up the calorie balance. It is recommended that athletes' fat intakes are consistent with public health guidelines for fat intake: less than 35% of daily energy intake. The exact amount depends on individual training and body composition goals. However, it is recommended that athletes should consume a minimum of 20% energy from fat, otherwise they risk deficient intakes of fat-soluble vitamins and essential fatty acids (Thomas *et al.*, 2016).

The UK government recommends that the proportion of energy from saturated fatty acids be less than 10%, with the majority coming from unsaturated fatty acids. Omega-3s may be particularly beneficial for athletes, as they help increase the delivery of oxygen to muscles, improve endurance and may speed recovery and reduce inflammation and joint stiffness.

6. Hydration

You should ensure you are hydrated before starting training or competition by consuming 5–10 ml/kg body weight in the 2–4 hours prior to exercise, and aim to minimise hypohydration (see p 147) during exercise. Severe hypohydration can result in reduced endurance and strength, and heat-related illness. The IOC and American College of Sports Medicine advise matching your fluid intake to your fluid losses as closely as possible and limiting hypohydration to no more than 2–3% loss of body weight (e.g. a body weight loss of no more than 1.5 kg for a 75 kg person). Routinely weigh yourself before and after exercise, accounting for fluid consumed and urine lost, to estimate your sweat loss during exercise. A loss of 1 kg body weight equates to 1 litre of sweat lost.

Additionally, experts caution against overhydrating yourself before and during exercise, particularly in events lasting longer than 4 hours. Drinking too much water may dilute your blood so that your sodium levels fall. Although this is quite rare, it is potentially fatal. The American College of Sports Medicine advises drinking when you're thirsty or drinking only to the point at which you're maintaining your weight, not gaining weight.

Sports drinks containing sodium are advantageous when sweat losses are high (more than 1.2 litres/h) – for example, during intense exercise lasting more than 2 hours – because their sodium content will promote water retention and prevent hyponatraemia.

After exercise, both water and sodium need to be replaced to re-establish normal hydration. This can be achieved by normal eating and drinking practices if there is no urgent need for recovery. But for rapid recovery, or if you are severely hypohydrated, it is recommended you drink 25–50% more fluid than lost in sweat. You can replace fluid and sodium losses with rehydration drinks or water plus salty foods.

7. Vitamins and minerals

While intense exercise increases the requirement for several vitamins and minerals, there is no need for supplementation provided you are eating a balanced diet and consuming adequate energy to maintain body weight. The IOC, IAAF and ACSM believe most athletes are well able to meet their needs from food rather than supplements. There's scant proof that vitamin and mineral supplements improve performance, although supplementation may be warranted in athletes eating a restricted diet or when food intake or choices are limited – for example, due to travel. However, athletes should be particularly aware of their needs for calcium, iron and vitamin D, as low intakes are relatively common among female athletes. The role of vitamin D in muscle structure and function, and the risk of deficiency, has been highlighted by the IOC and ASCM/AND/DC. Those who have low vitamin D intakes and get little exposure to the sun may need to take vitamin D supplements.

Similarly, there is insufficient evidence to recommend antioxidant supplementation for

athletes. Caution against antioxidant supplements is currently advised during training, as oxidative stress may be beneficial to the muscles' adaptation to exercise. The IOC also cautions against the indiscriminate use of supplements and warns of the risk of contamination with banned substances. Only a few have any performance benefit; these include creatine, caffeine, nitrate (as found in beetroot juice), beta-alanine and sodium bicarbonate, along with sports drinks, gels and bars and protein supplements. For the majority, there is little evidence to support their use as ergogenic aids (*see* p. 107, 'Definition of sports supplements and ergogenic aids').

8. Competition nutrition

PRE-EVENT

Performance in endurance events lasting longer than 90 minutes may benefit from carbohydrate loading in the 36–48 hours prior to the event (10–12 g carbohydrate/kg BW/24 hours). During the 1–4 hours prior to a race, consume 1–4 g of carbohydrate per kg of body weight. Food choices should be high in carbohydrate and moderate in protein, while low in fat and fibre to reduce risk of gastrointestinal problems.

DURING THE EVENT

In events lasting less than 75 minutes, additional carbohydrate will not benefit performance but rinsing the mouth with an energy drink may reduce perception of fatigue via the central nervous system. In events lasting 1–2½ hours, consuming 30–60 g carbohydrate/h will help maintain blood glucose and liver glycogen, and increase endurance. In events lasting more than 2½ hours, it may be beneficial to increase carbohydrate intake to up to 90 g carbohydrate/h. This may be in the form of dual energy source drinks or gels, containing a mixture of glucose/maltodextrin and fructose to achieve faster carbohydrate absorption.

AFTER THE EVENT

Replenish glycogen by consuming 1–1.2 g of carbohydrate/kg body weight in the first 4–6 hours after finishing. Consuming protein (in 15–25 g servings) in the recovery period also promotes glycogen recovery and enhances muscle protein resynthesis. Rehydrate with 25–50% more fluid than that lost in sweat.

The 'Athlete's Plate'

A balanced training diet is one that provides enough energy, carbohydrate, protein, fat, fibre, vitamins and minerals to support the physical demands of your training. These nutrients should come from a wide variety of foods. The key is consuming the right amounts and types of different foods that will fuel your workouts and events. To help you do this, I have created the Athlete's Plate, which can be tailored to the day-to-day fuel demands of your training programme. It is based on the Public Health England's EatWell Guide (Public Health England, 2016) and the Athlete's Plate developed by the US Olympic Committee (USOC) dietitians and University of Colorado (UCCS). It gives you a simple guide to the types and proportions of foods you need to achieve a balanced training diet. Each food group supplies a similar profile of nutrients, thus giving you plenty of options and flexibility for planning

your meals. It is a good idea to vary your meals as much as possible; the wider the variety of foods you eat, the more likely you are to meet your nutritional needs. The Athlete's Plate can be adapted to meet the different fuel demands of your training on different days. Some days may be recovery or easy training days while others may comprise moderate or hard training.

The Athlete's Plate divides foods into four main groups:

1. fruit and vegetables
2. protein-rich foods (including calcium-rich foods)
3. carbohydrate-rich foods
4. healthy fats

Fruit and vegetables – Aim to eat at least five portions a day. A portion is 80 g of any fresh or frozen fruit or vegetable, or 30 g of dried. For example, one small apple, banana or orange, about six strawberries, three broccoli florets or one carrot. Foods in this group are good sources of vitamin C, beta-carotene, folate and potassium, as well as fibre and phytonutrients. At each meal, aim to achieve a rainbow of colours – green, red, purple, yellow, white, and orange – varying them as much as possible. Each colour has its unique set of health-promoting phytonutrients, many of which act as antioxidants that help protect cells from damage and reduce inflammation after exercise.

Protein-rich foods – Include at least one serving of meat, poultry, fish, dairy (e.g. milk, cheese and yoghurt), eggs, beans, lentils, peas or soya products (e.g. soya milk alternative, tofu, tempeh and soya yoghurt alternative) in each meal. These foods should comprise roughly one-quarter of your plate. They also provide fibre, iron, zinc, and magnesium. Athletes need more protein than sedentary people so aim for at least 20 g protein per meal (*see* p. 72).

Calcium-rich foods sub-group – Ensure that you include at least two portions of calcium-rich foods each day: dairy and calcium-fortified plant milk and yoghurt alternatives and calcium-set tofu. These also count towards your protein-rich foods.

Carbohydrate-rich foods – These include pasta, rice, oats, noodles, potatoes, sweet potatoes, bread and cereals. There is no minimum requirement for carbohydrate so adjust your portion size according to your activity level. The more active you are, the bigger the portions you must consume. Whole grains are preferred to refined grains because they contain the entire grain, which means they are richer in fibre, B vitamins and iron.

Healthy fats – These include nuts, seeds, avocados, and olive and rapeseed oil. Aim to include one food from this group in most of your meals. Nuts and seeds also provide protein, magnesium, fibre, iron and zinc.

EASY TRAINING OR RECOVERY DAYS

On recovery and easy training days, your fuel and carbohydrate needs will be relatively low. To ensure you get all the nutrients you need, aim for roughly one-half of your plate to be made up of fruit and vegetables, roughly one-quarter carbohydrate-rich foods, and roughly one-quarter protein-rich and calcium-rich foods. Include some healthy fats such as olive or rapeseed oil, nuts, seeds, nut butter or avocado in each meal.

MODERATE TRAINING DAYS

On moderate training days that comprise 1–2 hours' moderate- or high-intensity endurance exercise your fuel and carbohydrate needs will be higher than on easy training days. Increase your intake of carbohydrate-rich foods. This will allow you to maintain muscle glycogen stores and support your training. Divide your plate into thirds and aim to have roughly one-third of your meal plate made up of carbohydrate-rich foods, roughly one-third protein-rich and calcium-rich foods and roughly one-third fruit and vegetables. Include some healthy fats such as olive or rapeseed oil, nuts, seeds, nut butter or avocado in each meal. You may add extra nutrient-rich snacks to meet your increased energy and nutritional needs.

HARD TRAINING DAYS

On hard training days that comprise more than 2 hours' high-intensity endurance exercise, or two moderate- or high-intensity training sessions or events, your fuel and carbohydrate needs will be very high. Increase your intake of carbohydrate-rich foods. This will allow you to maintain muscle glycogen stores and support your training. Aim to have roughly one-half of your meal plate made up of carbohydrate-rich foods, roughly one-quarter protein-rich and calcium-rich foods and roughly one-quarter fruit and vegetables. Include some healthy fats such as olive or rapeseed oil, nuts, seeds, nut butter or avocado in each meal. You may add extra nutrient-rich snacks to meet your increased energy and nutritional needs.

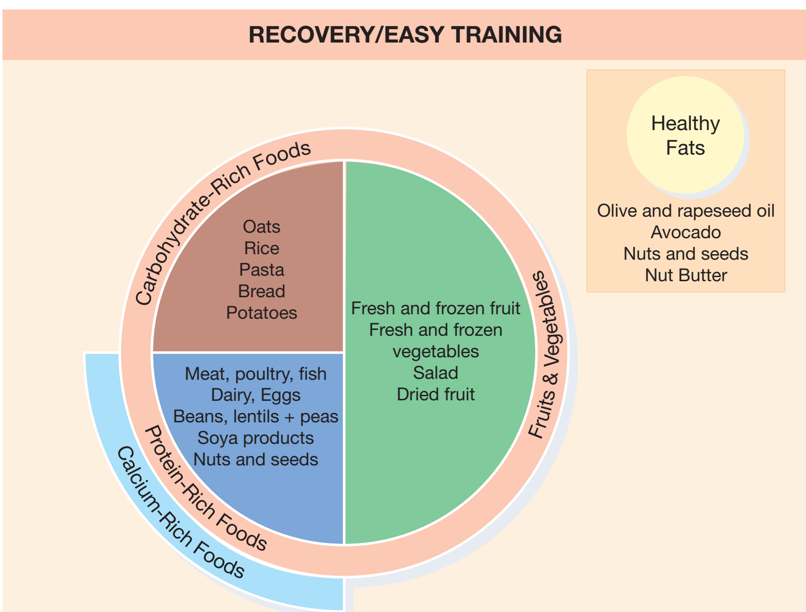

Figure 1.1 The Athlete's Plate for Easy Training or Recovery Days

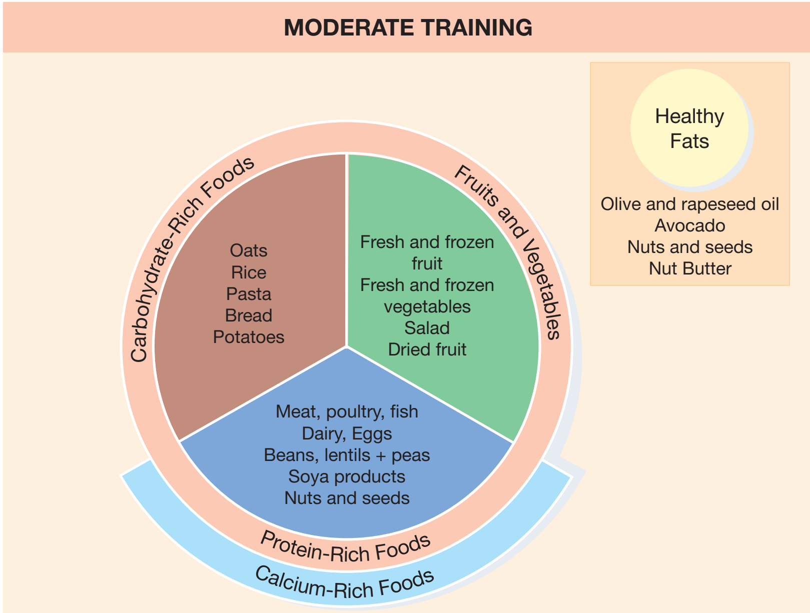

Figure 1.2 The Athlete's Plate for Moderate Training Days

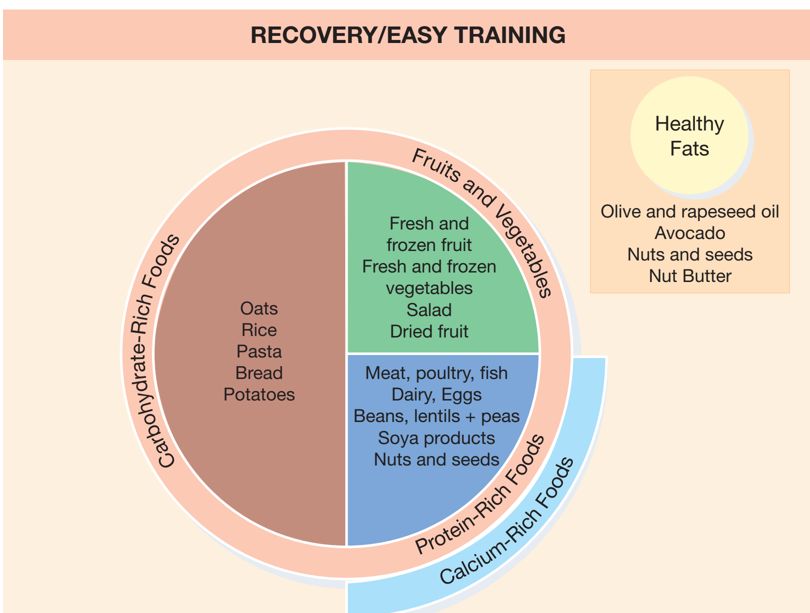

Figure 1.3 The Athlete's Plate for Hard Training Days

2 // Energy for Exercise

When you exercise, your body must start producing energy much faster than it does when it is at rest. The muscles start to contract more strenuously, the heart beats faster to pump blood around the body more rapidly, and the lungs work harder. All these processes require extra energy. Where does it come from, and how can you make sure you have enough to last through a training session?

Before we can fully answer such questions, it is important to understand how the body produces energy, and what happens to it. This chapter looks at what takes place in the body when you exercise, where extra energy comes from, and how the fuel mixture used differs according to the intensity of exercise. It explains why fatigue occurs, how it might be delayed, and how you can get more out of training by changing your diet.

WHAT IS ENERGY?

Although we cannot actually see energy, we can see and feel its effects in terms of heat and physical work. But what exactly is it?

Energy is produced by the splitting of a chemical bond in a substance called adenosine triphosphate (ATP). This is often referred to as the body's 'energy currency'. It is produced in every cell of the body from the breakdown of carbohydrate, fat, protein and alcohol – four fuels that are transported and transformed by various biochemical processes into the same end product.

WHAT IS ATP?

ATP is a small molecule consisting of an adenosine 'backbone' with three phosphate groups attached (*see* Fig 2.1).

Energy is released when one of the phosphate groups splits off. When ATP loses one of its phosphate groups it becomes adenosine diphosphate, or ADP. Some energy is used to carry out work (such as muscle contractions), but most (around three-quarters) is given off as heat. This is why you feel warmer when you exercise. Once this has

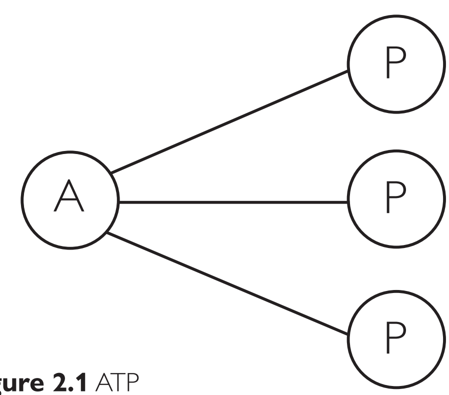

Figure 2.1 ATP

happened, ADP is converted back into ATP. A continual cycle takes place, in which ATP forms ADP and then becomes ATP again (*see* Fig 2.2).

THE INTER-CONVERSION OF ATP AND ADP

The body stores only very small amounts of ATP at any one time. There is just enough to keep up basic energy requirements while you are at rest – sufficient to keep the body ticking over. When you start exercising, energy demand suddenly increases, and ATP is used up within a few seconds. Therefore, more ATP must be produced in order to continue exercising. During intense exercise, muscle ATP production can increase 1000-fold.

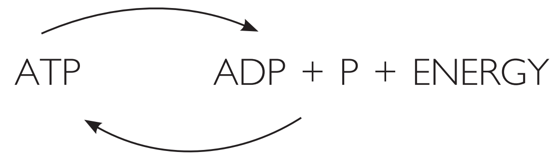

Figure 2.2 The relationship between ATP and ADP

HOW DOES THE BODY BURN ENERGY?

Total daily energy expenditure (TDEE) is comprised of four components: 1) resting metabolic rate (RMR, 2) the thermic effect of food (TEF), 3) exercise activity thermogenesis (EAT) and 4) non-exercise activity thermogenesis (NEAT) (*see* Fig 2.3). RMR is the energy burned at rest and makes up the largest component of TDEE, on average between 60 and 75%. TEF is the increase in energy expenditure above RMR that occurs after a meal and is the result of the digestion, absorption, metabolism and storage of food. It represents approximately 10% of TDEE, although the TEF for each macronutrient is different (*see* p. 183). NEAT is the energy burned during all unplanned activity, and may include day-to-day activities such as walking, or involuntary movements such as fidgeting. It typically makes up 15% of TDEE. EAT is the energy burned during planned exercise and is the most variable component of TDEE, ranging from 5% in sedentary people up to 50% in athletes involved in heavy training. EAT and NEAT can both be controlled voluntarily and are therefore extremely important for maintenance of daily energy balance.

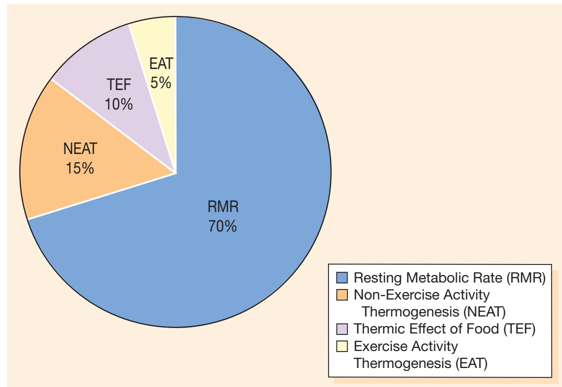

Figure 2.3 The components of total daily energy expenditure (TDEE)

WHERE DOES ENERGY COME FROM?

There are four components in food and drink that are capable of providing energy (ATP):

1. carbohydrate
2. protein
3. fat
4. alcohol

When you eat a meal or have a drink, these components are broken down in the digestive system into their various constituents or building blocks. Then they are absorbed into the bloodstream. Carbohydrates are broken down into small, single sugar units, the monosaccharides: glucose (the most common unit), fructose and galactose. Fats are broken down into fatty acids, and proteins into amino acids. Alcohol is mostly absorbed directly into the blood.

The ultimate fate of all of these components is energy production, although carbohydrates, proteins and fats also have other important functions.

Carbohydrates and alcohol are used mainly for energy in the short term, while fats are used as a long-term energy store. Proteins can be used to produce energy either in 'emergencies' (for instance, when carbohydrates are in short supply) or when they have reached the end of their useful life. Sooner or later, all food and drink components are broken down to release energy. But the body is not very efficient at converting this energy into power. For example, during cycling, only 20% of the energy produced is converted into power. The rest becomes heat.

HOW IS ENERGY MEASURED?

Energy is measured in calories or joules. In scientific terms, 1 calorie is defined as the amount of heat required to increase the temperature of 1 gram (or 1 ml) of water by 1 degree centigrade (°C) (from 14.5 to 15.5 °C). The SI (International Unit System) unit for energy is the joule (J). One joule is defined as the work required to exert a force of 1 Newton for a distance of 1 metre.

As the calorie and the joule represent very small amounts of energy, kilocalories (kcal or Cal) and kilojoules (kJ) are more often used. As their names suggest, a kilocalorie is 1000 calories and a kilojoule 1000 joules. You have probably seen these units on food labels. When we mention calories in the everyday sense, we are really talking about Calories with a capital C, or kilocalories. So, food containing 100 kcal has enough energy potential to raise the temperature of 100 litres of water by 1°C.

To convert kilocalories into kilojoules, simply multiply by 4.2. For example:

- 1 kcal = 4.2 kJ
- 10 kcal = 42 kJ

To convert kilojoules into kilocalories, divide

Metabolism

Metabolism is the sum of all the biochemical processes that occur in the body. There are two aspects: 1) anabolism is the formation of larger molecules; 2) catabolism is the breakdown of larger molecules into smaller molecules. Aerobic metabolism includes oxygen in the processes; anaerobic metabolism takes place without oxygen. A metabolite is a product of metabolism. That means that anything made in the body is a metabolite.

The body's rate of energy expenditure is called the metabolic rate. Your basal metabolic rate (BMR) is the number of calories expended to maintain essential processes such as breathing and organ function during sleep. However, most methods measure the resting metabolic rate (RMR), which is the number of calories burned over 24 hours while lying down but not sleeping.

by 4.2. For example, if 100 g of food provides 400 kJ, and you wish to know how many kilocalories that is, divide 400 by 4.2 to find the equivalent number of kilocalories:

- 400 kJ ÷ 4.2 = 95 kcal

WHY DO DIFFERENT FOODS PROVIDE DIFFERENT AMOUNTS OF ENERGY?

Foods are made of different amounts of carbohydrates, fats, proteins and alcohol. Each of these nutrients provides a certain quantity of energy when it is broken down in the body. For instance, 1 g of carbohydrate or protein releases about 4 kcal of energy, while 1 g of fat releases 9 kcal, and 1 g of alcohol releases 7 kcal.

THE ENERGY VALUE OF DIFFERENT FOOD COMPONENTS

1 g of each of the following provides:

- carbohydrate: 4 kcal (17 kj)
- fat: 9 kcal (38 kj)
- protein: 4 kcal (17 kj)
- alcohol: 7 kcal (29 kj)

Fat is the most concentrated form of energy, providing the body with more than twice as much energy as carbohydrate or protein, and also more than alcohol. However, it is not necessarily the 'best' form of energy for exercise.

All foods contain a mixture of nutrients, and the energy value of a particular food depends on the amount of carbohydrate, fat and protein it contains. For example, one slice of wholemeal bread provides roughly the same amount of energy as one pat (7 g) of butter. However, their composition is very different. In bread, most energy (75%) comes from carbohydrate, while in butter, virtually all (99.7%) comes from fat.

HOW DOES MY BODY STORE CARBOHYDRATE?

Carbohydrate is stored as *glycogen* in the muscles and liver, along with about three times its own weight of water. Altogether there is about three times more glycogen stored in the muscles than in the liver. Glycogen is a large molecule, similar to starch, made up of many glucose units joined together. However, the body can store only a relatively small amount of glycogen – there is no endless supply! Like the petrol tank in a car, the body can hold only a certain amount.

The total store of glycogen in the average body amounts to about 500 g, with approximately 400 g in the muscles and 100 g in the liver. This store is equivalent to about 2000 kcal – enough to last 1 day if you were to eat nothing and do no activity. This is why a low-carbohydrate diet tends to make people lose quite a lot of weight in the first few days. The weight loss is almost entirely due to loss of glycogen and water.

Glycogen stores can be almost entirely depleted by the end of 90–120 minutes of moderate- or high-intensity exercise and at this point you would experience extreme fatigue. Endurance athletes have higher muscle glycogen concentrations compared with sedentary people. Increasing your muscle mass will also increase your storage capacity for glycogen.

The purpose of liver glycogen is to maintain blood glucose levels both at rest and during prolonged exercise.

Small amounts of glucose are present in the blood (approximately 4 g, which is equivalent to 16 kcal) and the concentration is kept within a

very narrow range (between 4 and 5.5 mmol/litre, or 70–100 mg/100 ml), both at rest and during exercise. This allows normal body functions to continue. When blood glucose levels rise, the pancreas releases insulin, which causes glucose to move from the blood into the liver and muscle cells. If glucose is not needed for energy immediately it is stored in the form of glycogen, a process known as glycogenesis. Conversely, when blood glucose levels fall, the pancreas releases glucagon, which tells the liver and muscles to break down glycogen and release it back into the bloodstream as glucose, a process known as glycogenolysis.

Once glycogen stores are full, surplus glucose may be converted to fat in a process known as de novo lipogenesis (DNL). However, this process is inefficient and only stores a small amount of fat when you are in positive energy balance (Acheson *et al.*, 1988). Rather than being converted to fat, excessive carbohydrate intake usually leads to fat storage from fat. This is due to oxidative priority: carbohydrate is preferentially oxidised at the expense of fat oxidation (Cronise *et al.*, 2017). Thus, an excessive carbohydrate intake slows or displaces fat oxidation, resulting in fat storage mainly from dietary fat.

HOW DOES MY BODY STORE FAT?

Fat is stored as *adipose* (fat) tissue in almost every region of the body. A small amount of fat, about 300–400 g, is stored in muscles – this is called intramuscular fat – but the majority is stored around the organs and beneath the skin. The amount stored in different parts of the body depends on genetic make-up and individual hormone balance. The average 70 kg person stores 10–15 kg fat. Interestingly, people who store fat mostly around their abdomen (the classic potbelly shape) have a higher risk of heart disease than those who store fat mostly around their hips and thighs (the classic pear shape).

Unfortunately, there is little you can do to change the way that your body distributes fat. But you can definitely change the *amount* of fat that is stored, as you will see in Chapter 9.

You will probably find that your basic shape is similar to that of one or both of your parents. Males usually take after their father, and females after their mother. Female hormones tend to favour fat storage around the hips and thighs, while male hormones encourage fat storage around the middle. This is why, in general, women are 'pear shaped' and men are 'apple shaped'.

Table 2.1 ENERGY RESERVES IN A PERSON WEIGHING 70 KG

Fuel stores	Potential energy available (kcal)		
	Glycogen	Fat	Protein
Liver	400	450	400
Adipose tissue (fat)	0	135,000	0
Muscle	1600	350	24,000

Source: Cahill, 1976.

HOW DOES MY BODY STORE PROTEIN?

Protein is not stored in the same way as carbohydrate and fat. It forms muscle and organ tissue, so it is mainly used as a building material rather than an energy store. However, proteins *can* be broken down to release energy if need be, so muscles and organs represent a large source of potential energy.

WHICH FUELS ARE MOST IMPORTANT FOR EXERCISE?

Carbohydrates, fats and proteins are all capable of providing energy for exercise; they can all be transported to, and broken down in, muscle cells. Alcohol, however, cannot be used directly by muscles for energy during exercise, no matter how strenuously they may be working. Only the liver has the specific enzymes needed to break down alcohol. You cannot break down alcohol faster by exercising harder, either – the liver carries out its job at a fixed speed. Do not think you can work off a few drinks by going for a jog, or by drinking a cup of black coffee!

Proteins do not make a substantial contribution to the fuel mixture. It is only when carbohydrate availability is low, such as during very prolonged or very intense bouts of exercise, that proteins play a more important role in giving the body energy.

The production of ATP during most forms of exercise comes mainly from broken-down carbohydrates and fats.

Table 2.1 illustrates the potential energy available from the different types of fuel that are stored in the body.

WHEN IS PROTEIN USED FOR ENERGY?

Protein is not usually a major source of energy, but it may play a more important role during the latter stages of very strenuous or prolonged exercise as glycogen stores become depleted. For example, during the last stages of a marathon or a long-distance cycle race, when glycogen stores are exhausted, protein in muscles (and organs) may be broken down to make up to 15% of the body's fuel mixture.

During a period of semi-starvation, or if a person follows a low-carbohydrate diet, glycogen would be in short supply, so more proteins would be broken down to provide the body with fuel. Up to half of the weight lost by someone following a low-calorie or low-carbohydrate diet comes from protein (muscle) loss. Some people think that if they deplete their glycogen stores by following a low-carbohydrate diet, they will force their body to break down more fat and lose weight. This is not the case: you risk losing muscle as well as fat, and there are many other disadvantages, too. These are discussed in Chapter 3.

How is energy produced?

The body has three main energy systems it can use for different types of physical activity. These are called:

1. the ATP–PC (phosphagen) system
2. the anaerobic glycolytic, or lactic acid, system
3. the aerobic system – comprising the glycolytic (carbohydrate) and lipolytic (fat) systems

At rest, muscle cells contain only a very small amount of ATP, enough to maintain basic energy needs and allow you to exercise at maximal intensity for about 1 second. To continue exercising, ATP must be regenerated from one of the three energy systems, each of which has a very different biochemical pathway and rate at which it produces ATP.

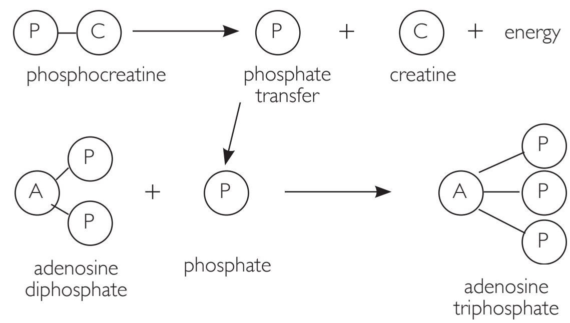

Figure 2.4 PC splits to release energy to regenerate ATP rapidly

HOW DOES THE ATP–PC SYSTEM WORK?

This system uses ATP and phosphocreatine (PC) that is stored within the muscle cells to generate energy for maximal bursts of strength and speed that last for up to 6 seconds. The ATP–PC system would be used, for example, during a 20 m sprint, a near-maximal lift in the gym, or a single jump. Phosphocreatine is a high-energy compound formed when the protein, creatine, is linked to a phosphate molecule (*see* p. 23). The PC system can be thought of as a back-up to ATP. The job of PC is to regenerate ATP rapidly (*see* Fig. 2.4). PC breaks down into creatine and phosphate, and the free phosphate bond transfers to a molecule of ADP forming a new ATP molecule. The ATP–PC system can release energy very quickly, but, unfortunately, it is in very

What is creatine?

Creatine is a compound that's made naturally in our bodies to supply energy. It is mainly produced in the liver from the amino acids glycine, arginine and methionine. From the liver, it is transported in the blood to the muscle cells where it is combined with phosphate to make phosphocreatine (PC).

The muscle cells turn over about 2–3 g of creatine a day. Once PC is broken down into ATP (energy), it can be recycled into PC or converted into another substance called creatinine, which is then removed via the kidneys in the urine.

Creatine can be obtained in the diet from fish (tuna, salmon, cod), beef and pork (approx. 3–5 g creatine/kg uncooked fish or meat). That means vegetarians have no dietary sources. However, to have a performance-boosting effect, creatine has to be taken in large doses. This is higher than you could reasonably expect to get from food. You would need to eat at least 2 kg of raw steak a day to load your muscles with creatine.

The average-sized person stores about 120 g creatine, almost all in skeletal muscles (higher levels in fast-twitch muscle fibres, *see* p. 25). Of this amount, 60–70% is stored as PC, 30–40% as free creatine.

limited supply and can provide only 3–4 kcal. After this, the amount of energy produced by the ATP–PC system falls dramatically, and ATP must be produced from other fuels, such as glycogen or fat. When this happens, other systems take over.

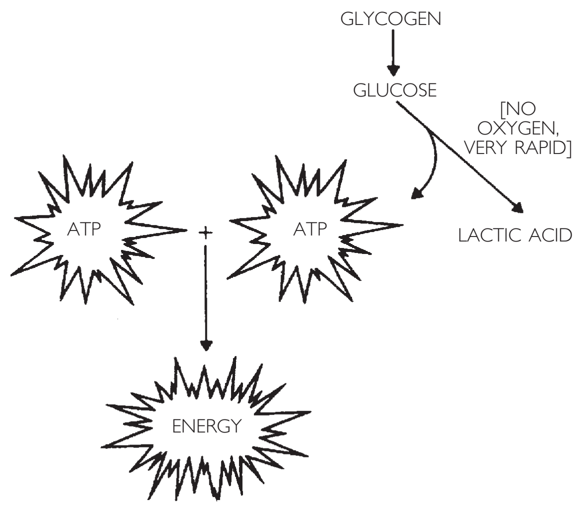

Figure 2.5 Anaerobic energy system

HOW DOES THE ANAEROBIC GLYCOLYTIC SYSTEM WORK?

This system is activated as soon as you begin high-intensity activity. It dominates in events lasting up to 90 seconds, such as a weight training set in the gym or a 400–800 m sprint. In order to meet sudden, large demands for energy, glucose bypasses the energy producing pathways that would normally use oxygen, and follows a different route that does not use oxygen. This saves a good deal of time. After 30 seconds of high-intensity exercise this system contributes up to 60% of your energy output; after 2 minutes its contribution falls to only 35%.

The anaerobic glycolytic system uses carbohydrate in the form of muscle glycogen or glucose as fuel. Glycogen is broken down to glucose, which rapidly breaks down in the absence of oxygen to form ATP and pyruvate, which is then converted into lactate (*see* Fig. 2.5). Each glucose molecule

What happens to the lactate?

Lactate produced by the muscles is not a wasted by-product. It constitutes a valuable fuel. When the exercise intensity is reduced or you stop exercising, lactate has two possible fates. Some may be converted into another substance called pyruvic acid, which can then be broken down in the presence of oxygen into ATP. In other words, lactate produces ATP and constitutes a valuable fuel for aerobic exercise. Alternatively, lactate may be carried away from the muscle in the bloodstream to the liver where it can be converted back into glucose, released back into the bloodstream or stored as glycogen in the liver (a process called gluconeogenesis). This mechanism for removing lactic acid from the muscles is called the lactate shuttle.

This explains why the muscle soreness and stiffness experienced after hard training is not due to lactate or lactic acid accumulation. In fact, the lactate is usually cleared within 15 minutes of exercise.

produces only two ATP molecules under anaerobic conditions, making it a very inefficient system. The body's glycogen stores dwindle quickly, proving that the benefits of a fast delivery service come at a price. The gradual build-up of lactate and the associated hydrogen ions causes the pH in the cell to fall (i.e. an increase in acidity), preventing further muscle contractions. At this point, exercise can no longer be maintained at the same intensity – you'll experience temporary fatigue and will either need to drop your intensity or take a short rest before resuming all-out effort. Once hydrogen ions are removed and the pH rises, you will be able to resume exercising at a high intensity. Contrary to popular belief, it is not lactic acid but the build-up of hydrogen ions (acidity) that causes the 'burning' feeling during or immediately after maximal exercise.

HOW DOES THE AEROBIC SYSTEM WORK?

The aerobic system can generate ATP from the breakdown of carbohydrates (by glycolysis) and fat (by lipolysis) in the presence of oxygen (*see* Fig. 2.6). Although the aerobic system cannot produce ATP as rapidly as can the other two anaerobic systems, it can produce larger amounts. When you start to exercise, you initially use the ATP–PC and anaerobic glycolytic systems, but after a few minutes your energy supply gradually switches to the aerobic system.

Most of the carbohydrate that fuels aerobic glycolysis comes from muscle glycogen. Additional glucose from the bloodstream becomes more important as exercise continues for longer than 1 hour and muscle glycogen concentration dwindles. Typically, after 2 hours of high-intensity exercise (greater than 70% VO_2max), almost all of your muscle glycogen will be depleted. Glucose delivered from the bloodstream is then used to fuel your muscles, along with increasing amounts of fat (lipolytic glycolysis). Glucose from the bloodstream may be derived from the breakdown of liver glycogen or from carbohydrate consumed during exercise.

In aerobic exercise, the demand for energy is slower and smaller than in an anaerobic activity, so there is more time to transport sufficient oxygen from the lungs to the muscles and for glucose to generate ATP with the help of the oxygen. Under these circumstances, one molecule of glucose can create up to 38 molecules of ATP. Thus, aerobic energy production is about 20 times more efficient than anaerobic energy production.

Anaerobic exercise uses only glycogen, whereas aerobic exercise uses both glycogen and fat, so it can be kept up for longer. The disadvantage, though, is that it produces energy more slowly.

Fats can also be used to produce energy in the aerobic system. One fatty acid can produce between 80 and 200 ATP molecules, depending on its type (*see* Fig. 2.6). Fats are therefore an even more efficient energy source than carbohydrates. However, they can only be broken down into ATP under aerobic conditions when energy demands are relatively low, and so energy production is slower.

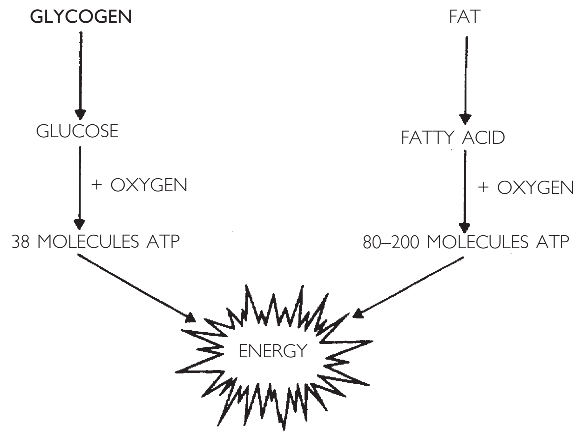

Figure 2.6 Aerobic energy system

MUSCLE FIBRE TYPES AND ENERGY PRODUCTION

The body has several different muscle fibre types, which can be broadly classified into fast-twitch (FT) or type II, and slow-twitch (ST) or type I (endurance) fibres. Both muscle fibre types use all three energy systems to produce ATP, but the FT fibres use mainly the ATP–PC and anaerobic glycolytic systems, while the ST fibres use mainly the aerobic system.

Everyone is born with a specific distribution of muscle fibre types; the proportion of FT fibres to ST fibres can vary quite considerably between individuals. The proportion of each muscle fibre type you have has implications for sport. For example, top sprinters have a greater proportion of FT fibres than average and thus can generate explosive power and speed. Distance runners, on the other hand, have proportionally more ST fibres and are better able to develop aerobic power and endurance.

HOW DO MY MUSCLES DECIDE WHETHER TO USE CARBOHYDRATE OR FAT DURING AEROBIC EXERCISE?

During aerobic exercise, the use of carbohydrate relative to fat varies according to a number of factors. The most important are:

1. the intensity of exercise
2. the duration of exercise
3. your fitness level
4. your pre-exercise diet

Intensity

The greater the exercise intensity, the greater the rate at which muscle glycogen is broken down (*see* Fig. 2.7). During anaerobic exercise, energy is produced by the ATP–PC and anaerobic glycolytic systems. So, for example, during sprints, heavy weight training and intermittent maximal bursts during sports such as football and rugby,

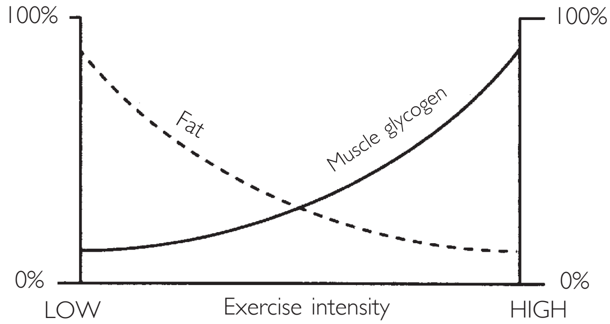

Figure 2.7 Fuel mixture/exercise intensity
Source: Costill, 1986.

muscle glycogen, rather than fat, is the major fuel. As a result, muscle glycogen stores can become quickly depleted even though the total duration of the activity may be relatively short.

During aerobic exercise you will use a mixture of muscle glycogen and fat for energy. Exercise at a low intensity (less than 50% of VO_2max) is fuelled mainly by fat. As you increase your exercise intensity – for example, as you increase your running speed – you will use a higher proportion of glycogen than fat. During moderate-intensity exercise (50–70% VO_2max), muscle glycogen supplies around half your energy needs; the rest comes from fat. When your exercise intensity exceeds 70% VO_2max, fat cannot be broken down and transported fast enough to meet energy demands, so muscle glycogen provides at least 75% of your energy needs.

Duration

Muscle glycogen is unable to provide energy indefinitely because it is stored in relatively small quantities. As you continue exercising, your muscle glycogen stores become progressively lower (*see* Fig. 2.8). Thus, as muscle glycogen concentration drops, the contribution that blood glucose makes to your energy needs increases. The proportion of fat used for energy also increases but it can never be burned without the presence of carbohydrate.

On average, you have enough muscle glycogen to fuel 90–180 minutes of endurance activity; the higher the intensity, the faster your muscle glycogen stores will be depleted. During interval training, i.e. a mixture of endurance and anaerobic activity, muscle glycogen stores will become depleted after 45–90 minutes. During mainly anaerobic activities, muscle glycogen will deplete within 30–45 minutes.

Once muscle glycogen stores are depleted, protein makes an increasing contribution to energy needs. Muscle proteins break down to provide amino acids for energy production and to maintain normal blood glucose levels.

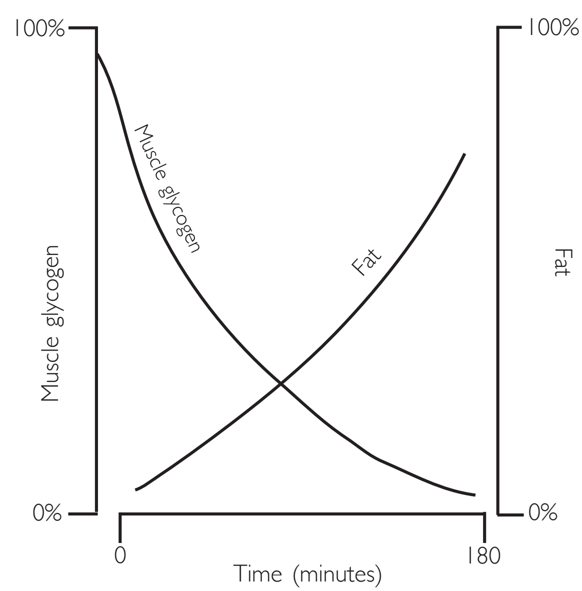

Figure 2.8 Fuel mixture/exercise duration

Fitness level

As a result of aerobic training, your muscles make a number of adaptations to improve your performance, and your body's ability to use fat as a fuel improves. Aerobic training increases the numbers of key fat-oxidising enzymes, such as hormone-sensitive lipase, which means your body becomes more efficient at breaking down fat into fatty acids. The number of blood capillaries serving the muscle increases so you can transport the fatty acids to the muscle cells. The number of mitochondria (the sites of fatty acid oxidation) also increases, which means you have a greater capacity to burn fatty acids in each muscle cell. Thus, improved aerobic fitness enables you to break down fat at a faster rate at any given intensity, thus allowing you to spare glycogen (*see* Fig. 2.9). This is important because glycogen is in much shorter supply than fat. By using proportionally more fat, you will be able to exercise for longer before muscle glycogen is depleted and fatigue sets in.

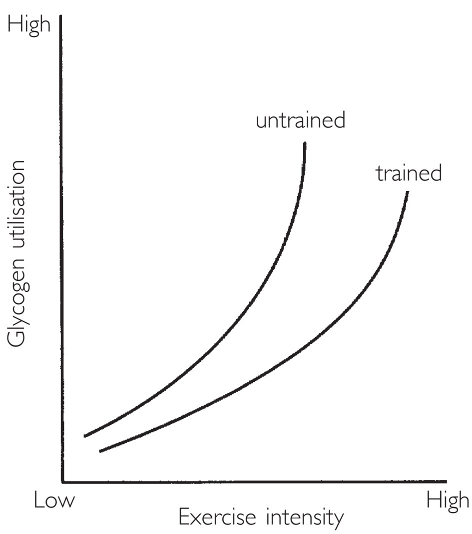

Figure 2.9 Trained people use less glycogen and more fat

Pre-exercise diet

A low-carbohydrate diet will result in low muscle and liver glycogen stores. Many studies have shown that initial muscle glycogen concentration is critical to your performance and that low muscle glycogen can reduce your ability to sustain exercise at 70% VO_2max for longer than 1 hour (Bergstrom *et al.*, 1967). It also affects your ability to perform during shorter periods of maximal power output.

When your muscle glycogen stores are low, your body will rely heavily on fat and protein. However, this is not a recommended strategy for fat loss, as you will lose lean tissue. (*See* Chapter 10 for appropriate ways of reducing body fat.)

Which energy systems do I use in my sport?

Virtually every activity uses all three energy systems to a greater or lesser extent. No single energy system is used exclusively and at any given time energy is being derived from each of the three systems (*see* Fig. 2.10). In every activity, ATP is always used and is replaced by PC. Anaerobic glycolysis and aerobic energy production depend on exercise intensity.

For example, during explosive strength and power activities lasting up to 5 seconds, such as a sprint start, the existing store of ATP is the primary energy source. For activities involving high power and speed lasting 5–30 seconds, such as 100–200 m sprints, the ATP–PC system is the primary energy source, together with some muscle glycogen broken down through anaerobic glycolysis. During power endurance activities such as 400–800 m events, muscle glycogen is the primary energy source and produces ATP via both anaerobic and aerobic glycolysis. In aerobic power activities, such as running 5–10 km, muscle glycogen is the primary energy source producing ATP via aerobic glycolysis. During aerobic events lasting 2 hours or more, such as half- and full marathons, muscle glycogen, liver glycogen, intramuscular fat and fat from adipose tissue are the main fuels used. The energy systems and fuels used for various types of activities are summarised in Table 2.2.

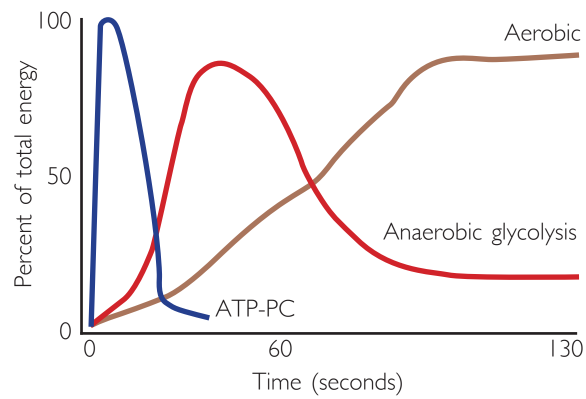

Figure 2.10 Percentage contribution of energy systems during exercise of different durations

Table 2.2 THE MAIN ENERGY SYSTEMS USED DURING DIFFERENT TYPES OF EXERCISE

Type of exercise	Main energy system	Major storage fuels used
Maximal short bursts lasting less than 6 sec	ATP–PC (phosphagen)	ATP and PC
High-intensity lasting up to 30 sec	ATP–PC Anaerobic glycolytic	ATP and PC Muscle glycogen
High-intensity lasting up to 15 min	Anaerobic glycolytic Aerobic	Muscle glycogen
Moderate–high-intensity lasting 15–60 min	Aerobic	Muscle glycogen Adipose tissue
Moderate–high-intensity lasting 60–90 min	Aerobic	Muscle glycogen Liver glycogen Blood glucose Intramuscular fat Adipose tissue
Moderate intensity lasting longer than 90 min	Aerobic	Muscle glycogen Liver glycogen Blood glucose Intramuscular fat Adipose tissue

WHAT HAPPENS IN MY BODY WHEN I START EXERCISING?

When you begin to exercise, energy is produced without oxygen for at least the first few seconds, before your breathing rate and heart can catch up with oxygen demands. In effect, the anaerobic system 'buys time' in the first few seconds to minutes of exercise, before the body's slower aerobic system can start to function.

If you continue to exercise aerobically, more oxygen is delivered around the body and fat can be broken down into fatty acids. Carbohydrate (glucose and glycogen) and fatty acids are then broken down with oxygen to produce energy.

For the first 5–15 minutes of exercise (depending on your aerobic fitness level) the main fuel is carbohydrate (glycogen). As time goes on, however, more oxygen is delivered to the muscles, and you will use proportionally less carbohydrate and more fat.

On the other hand, if you begin exercising very strenuously (e.g. by running fast), lactate quickly builds up in the muscles. The delivery of oxygen cannot keep pace with the huge energy demand, so lactate and hydrogen ions accumulate and very soon you will feel fatigue (temporarily). You must then either slow down and exercise more slowly, or stop. Nobody can maintain all-out exercise for very long.

If you start a distance race or training run too fast, you will suffer from fatigue early on and be forced to reduce your pace considerably. A head start will not necessarily give any benefit at all. Warm up *before* the start of a race (by walking, slow jogging, or performing gentle mobility exercises), so that the heart and lungs can start to work a little harder, and oxygen delivery to the muscles can increase. Start the race at a moderate pace, gradually building up to an optimal speed. This will prevent a large 'oxygen debt' and avoid an early depletion of glycogen. In this way, your optimal pace can be sustained for longer.

The anaerobic system can also 'cut in' to help energy production, for instance when the demand for energy temporarily exceeds the body's oxygen supply. If you run uphill at the same pace as on the flat, your energy demand increases. The body will generate extra energy by breaking down glycogen/glucose anaerobically. However, this can be kept up for only a short period of time, because there will be a gradual build-up of hydrogen ions. The lactate and hydrogen ions can be removed aerobically afterwards, by running back down the hill, for example.

The same principle applies during fast bursts of activity in interval training, when energy is produced anaerobically. Lactic acid accumulates and is then removed during the rest interval.

What is fatigue?

In scientific terms, fatigue is an inability to sustain a given power output or speed. It is a mismatch between the demand for energy by the exercising muscles and the supply of energy in the form of ATP. Runners experience fatigue when they are no longer able to maintain their speed; footballers are slower to sprint for the ball and their technical ability falters; in the gym, you can no longer lift the weight; in an aerobics class, you will be unable to maintain the pace and intensity. Subjectively, you will find that exercise feels much harder to perform, your legs may feel hollow and it becomes increasingly hard to push yourself.

WHY DOES FATIGUE DEVELOP DURING ANAEROBIC EXERCISE?

During explosive activities involving maximal power output, fatigue develops due to ATP and PC depletion. In other words, the demand for ATP exceeds the readily available supply.

During activities lasting between 30 seconds and 30 minutes, fatigue is caused by a different mechanism. The rate of lactate removal in the bloodstream cannot keep pace with the rate of lactic acid production. This means that during high-intensity exercise there is a gradual increase in muscle acidity, which reduces the ability of the muscles to maintain intense contractions. It is not possible to continue high-intensity exercise indefinitely because the acute acid environment in your muscles would inhibit further contractions and cause cell death. The burning feeling you experience when a high concentration of hydrogen ions develops is a kind of safety mechanism, preventing the muscle cells from destruction.

Reducing your exercise intensity will lower the rate of lactate production, reduce the hydrogen ion build-up, and enable the muscles to switch to the aerobic energy system, thus enabling you to continue exercising.

WHY DOES FATIGUE DEVELOP DURING AEROBIC EXERCISE?

Fatigue during moderate- and high-intensity aerobic exercise lasting longer than 1 hour occurs when muscle glycogen stores are depleted. It's like running out of petrol in your car. Muscle glycogen is in short supply compared with the body's fat stores. Liver glycogen can help maintain blood glucose levels and a supply of carbohydrate to the exercising muscles, but stores are also very limited and eventually fatigue will develop as a result of both muscle and liver glycogen depletion and hypoglycaemia (*see* Fig. 2.11).

During low- to moderate- intensity exercise lasting more than 3 hours, fatigue is caused by additional factors. Once glycogen stores have been exhausted, the body switches to the aerobic lipolytic system where fat is able to supply most (not all) of the fuel for low-intensity exercise.

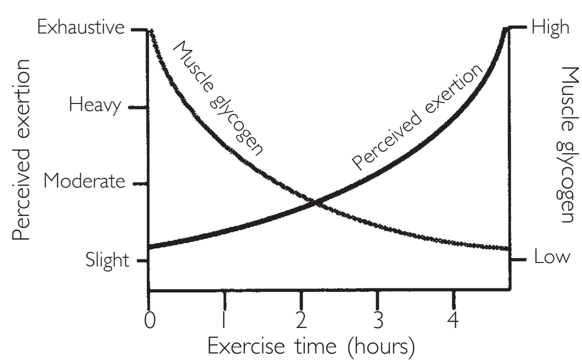

Figure 2.11 The increase in perceived exertion as glycogen stores become depleted
Source: Costill, 1986.

However, despite having relatively large fat reserves, you will not be able to continue exercise indefinitely because fat cannot be converted to energy fast enough to keep up with the demand by exercising muscles. Even if you slowed your pace to enable the energy supplied by fat to meet the energy demand, other factors will cause you to fatigue. These include a rise in the concentration of the brain chemical serotonin, which results in an overall feeling of tiredness, acute muscle damage, and fatigue due to lack of sleep.

HOW CAN I DELAY FATIGUE?

Glycogen is used during virtually every type of activity. Therefore the amount of glycogen stored in your muscles and, in certain events, your liver, before you begin exercise will have a direct effect on your endurance performance. The greater your pre-exercise muscle glycogen store, the longer you will be able to maintain your exercise intensity and delay the onset of fatigue. Conversely, suboptimal muscle glycogen stores can cause earlier fatigue, reduce your endurance, reduce your intensity level and result in smaller training gains.

You may also delay fatigue by reducing the rate at which you use up muscle glycogen. You can do this by pacing yourself, gradually building up to your optimal intensity, and/or by consuming carbohydrate during exercise.

Summary of key points

- The body uses three energy systems: 1) the ATP–PC, or phosphagen, system; 2) the anaerobic glycolytic, or lactic acid, system; 3) the aerobic system, which comprises both glycolytic (carbohydrate) and lipolytic (fat) systems.
- The ATP–PC system fuels maximal bursts of activity lasting up to 6 seconds.
- Anaerobic glycolysis provides energy for short-duration, high-intensity exercise lasting from 30 seconds to several minutes. Muscle glycogen is the main fuel.
- The lacate produced during anaerobic glycolysis is a valuable fuel for further energy production when exercise intensity is reduced.
- The aerobic system provides energy from the breakdown of carbohydrate and fat for submaximal intensity, prolonged exercise.
- Factors that influence the type of energy system and fuel usage are exercise intensity and duration, your fitness level and your pre-exercise diet.
- The proportion of muscle glycogen used for energy increases with exercise intensity and decreases with exercise duration.
- For most activities lasting longer than 30 seconds, all three energy systems are used to a greater or lesser extent; however, one system usually dominates.
- The main cause of fatigue during anaerobic activities lasting less than 6 seconds is ATP and PC depletion; during activities lasting between 30 seconds and 30 minutes, it is hydrogen ion accumulation and muscle cell acidity.
- Fatigue during moderate and high-intensity exercise lasting longer than 1 hour is usually due to muscle glycogen depletion. For events lasting longer than 2 hours, fatigue is associated with low liver glycogen and low blood sugar levels.
- For most activities, performance is limited by the amount of glycogen in the muscles. Low pre-exercise glycogen stores lead to early fatigue, reduced exercise intensity and reduced training gains.

//Carbohydrate

3

Since the beginning of the 20th century, it has been known that carbohydrate is related to performance. In 1924, researchers suggested that low blood glucose concentrations observed at the end of a marathon were associated with fatigue and an inability to concentrate (Levine *et al.*, 1924). In 1939, Christensen and Hansen, demonstrated that a high-carbohydrate diet significantly increased endurance (Christensen and Hansen, 1939). However, it wasn't until the 1960s that scientists discovered that the capacity for endurance exercise is related to pre-exercise glycogen stores and that a high-carbohydrate diet increases glycogen stores. In a pioneering study, Swedish researchers demonstrated that athletes who consumed a high-carbohydrate diet were able to increase their glycogen stores to a greater extent than those consuming a moderate- or low-carbohydrate diet, and were subsequently able to exercise significant longer before reaching fatigue (Bergstrom *et al.*, 1967). Another study in 1967 confirmed the link between glycogen storage in muscles and endurance (Ahlborg *et al.* 1967).

These observations led to the recommendations to carbohydrate load before competition. This was successfully used by runners such as the late Ron Hill who won the 1969 European Athletics championships by undergoing a 3-day glycogen depletion phase followed by a high carbohydrate intake for the final 3 days. In the 1980s, the effects of consuming carbohydrate during exercise on performance were further studied (Coyle and Coggan, 1984; Coyle *et al.* 1986).

This chapter explains the role of carbohydrate intake in exercise performance. More specifically, it looks at the optimal timing of carbohydrate intake in relation to exercise, and provides guidelines for pre-, during and post-exercise carbohydrate intake as well as total daily carbohydrate intake, and shows you how to calculate your daily requirements.

It also gives advice on which types of carbohydrate foods to eat. Finally, it considers the potential benefits and drawbacks of low-carbohydrate diets, training with low carbohydrate availability and carbohydrate periodisation.

Why is carbohydrate important for performance?

Carbohydrate, in the form of glucose, provides a fuel source for every cell in the body. It's the preferred fuel for the brain, nervous system and heart and is used by the muscles to support both aerobic and anaerobic activities. Any glucose that's not needed immediately for energy is converted to glycogen, which is stored in the cells of the liver and muscles (*see* p. 19 'How does my body store carbohydrate?'). The liver can store a maximum of 100 g of glycogen and the muscles a maximum of 400 g, equivalent to a total of 500 g or 2000 kcal worth of energy in an average person. This is sufficient to fuel approximately 90 to 120 minutes of moderate–high-intensity aerobic exercise. The size of your glycogen stores is relatively small compared to your fat stores, which can be several kilos, and can be acutely manipulated by your carbohydrate intake in the preceding hours or days, or even a single session of exercise.

The rate at which muscle glycogen is utilised depends mainly on exercise intensity. At low intensities, your muscles oxidise a mixture of fat and carbohydrate. As the exercise intensity increases, a higher proportion of carbohydrate from muscle glycogen is broken down (*see* pp. 25–26). At very high intensities, muscle glycogen is the dominant fuel as it can be broken down very rapidly to produce energy. During high-intensity

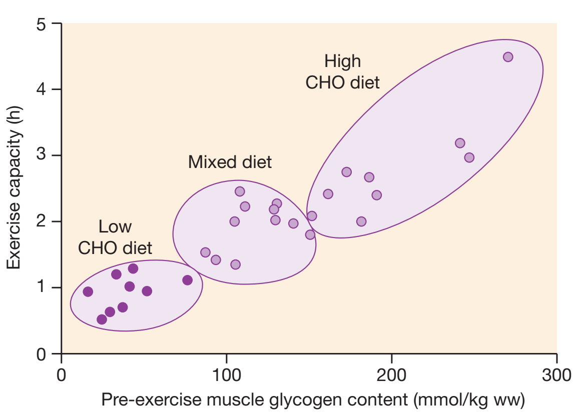

Figure 3.1 The effect of carbohydrate intake on performance

aerobic exercise, carbohydrate offers advantages over fat because it is a more efficient fuel, i.e. it provides more molecules of ATP per volume of oxygen consumed. For this reason, carbohydrate is sometimes referred to as a 'fast' fuel while fat is referred to as a 'slow' fuel because it produces energy relatively slowly. Carbohydrate can produce up to 25–30 kcal per minute; while fat produces only 6 kcal per minute.

How does carbohydrate affect performance?

Carbohydrate availability – the amount of glucose in your bloodstream and glycogen stored in your muscles and liver – has a direct effect on exercise performance. There is plentiful evidence that exercising with 'high carbohydrate availability' (i.e. when muscle glycogen stores and blood glucose are matched to the demands of exercise) enhances endurance and performance during exercise lasting longer than 90 minutes or intermittent high-intensity exercise (Hargreaves *et al.*, 2004; Coyle, 2004; Burke *et al.*, 2004; Thomas *et al.*, 2016; Burke *et al.*, 2011).

In a pioneering study, three groups of athletes were given a low-carbohydrate diet (about 10% of dietary energy), a high-carbohydrate diet (about 70%) or a moderate carbohydrate diet (about 50%) (Bergstrom *et al.*, 1967). Researchers measured the concentration of glycogen in their leg muscles and found that those eating the high-carbohydrate diet stored twice as much glycogen as those on the moderate carbohydrate diet and seven times as much as those eating the low-carbohydrate diet. Afterwards, the athletes were instructed to cycle to exhaustion on a stationary bicycle at 75% of VO_2max. Those on the high-carbohydrate diet managed to cycle for 170 minutes, considerably longer than those on the moderate carbohydrate diet (115 minutes) or the low-carbohydrate diet (60 minutes) (*see* Fig 3.1). There was a linear trend between between carbohydrate intake and exercise capacity, suggesting that a high-carbohydrate diet is beneficial for endurance performance (*see* Fig 3.2).

Therefore, for most endurance activities, scientists recommend consuming a high-carbohydrate diet to replenish muscle glycogen stores and promote optimal adaptation to regular training. Depletion of these stores ('low carbohydrate availability') results in fatigue and reduced work rates, impaired skill and concentration and increased perception of effort. In other words, when your glycogen stores become depleted, your capacity for high-intensity exercise will be limited and only low-intensity exercise is possible. This can easily happen if your pre-exercise glycogen stores are low.

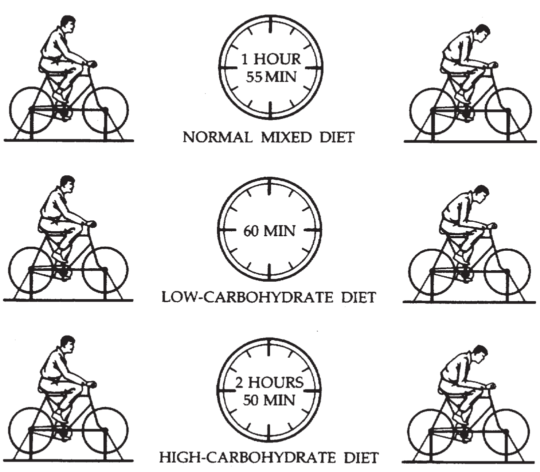

Figure 3.2 The effect of carbohydrate intake on exercise capacity (Bergstrom *et al.*, 1967)

In order to optimise your performance during high-intensity exercise longer than 90 minutes or doing high-intensity intermittent exercise, you should ensure your daily carbohydrate intake matches the fuel needs of your training and that pre-exercise glycogen stores are high. This will help to improve your endurance, delay exhaustion and help you exercise longer and harder (Coyle, 1988; Costill and Hargreaves, 1992).

In a study at Ball State University, Indiana, volunteers ran 16 km on three consecutive days at 80% VO_2max (Costill *et al.*, 1971) while consuming a moderate-carbohydrate diet (40% carbohydrate). A marked decrease in muscle glycogen occurred immediately after the run and although some glycogen was replenished before the next run session the starting glycogen concentrations were lower. Over successive days of training, their glycogen stores became progressively lower, suggesting that they were not consuming enough carbohydrate to fully restore muscle glycogen (*see* Fig 3.3 (b), p. 50).

In another study, volunteers were given a diet containing either 5 g or 10 g carbohydrate/kg of body weight for 7 successive days of training (Sherman *et al.*, 1993). Those consuming 5 g/kg BW experienced a significant decline in muscle glycogen, but those consuming 10 g/kg BW were able to maintain their muscle glycogen stores despite daily training. If you exercise every day then rapid replenishment of muscle glycogen is crucial.

How much carbohydrate should I eat per day?

Previously, researchers recommended a diet providing 60–70% energy from carbohydrate based on the consensus statement from the International Conference on Foods, Nutrition and Performance in 1991 (Williams and Devlin, 1992). However, this recommendation assumes an optimal energy (calorie) intake and does not take into account different training loads on different days. For these reasons, it is no longer considered valid.

Nowadays, scientists recommend calculating your daily carbohydrate requirement from your body weight and also your training volume (Burke *et al.*, 2011; IOC, 2011; Thomas *et al.*, 2016). The ACSM guidelines shown in Table 3.1 express carbohydrate intake in grams per kilogram of body weight. They are intended to provide high carbohydrate availability and enable you to replace your muscle glycogen stores within 24 hours. They assume that your glycogen storage capacity is roughly proportional to your muscle mass and body weight – i.e. the heavier you are, the greater your muscle mass and the greater your glycogen storage capacity. They also allow for daily adjustment according to your training load; the greater your training load, the more carbohydrate you will need to fuel your muscles.

These recommendations are general but most athletes training for up to 1 hour daily are likely to require 5–7 g carbohydrate/kg body weight; however, on heavier training days your requirements may be higher and on lighter training or recovery days your requirements may be lower.

For example, for a 70 kg athlete who trains for 1 hour a day:

- carbohydrate intake = 5–7 g/kg of body weight
- daily carbohydrate intake = (70 x 5) – (70 x 7) = 350–490 g

What types of carbohydrate are there?

Carbohydrates are traditionally classified according to their chemical structure. The most simplistic method divides them into two categories: *simple* (sugars) and *complex* (starches and fibres). These terms simply refer to the number of sugar units in the molecule.

Simple carbohydrates are very small molecules consisting of 1 or 2 sugar units. They comprise the *monosaccharides* (1-sugar units): glucose (dextrose), fructose (fruit sugar) and galactose; and the *disaccharides* (2-sugar units): sucrose

Table 3.1 GUIDELINES FOR DAILY CARBOHYDRATE INTAKE

Training load		Carbohydrate intake (g/kg body mass)
Light	Low-intensity or skill-based activities	3–5 g/kg/d
Moderate	Moderate exercise programme (e.g. 1 h/day)	5–7 g/kg/d
High	Endurance programme (e.g. 1–3 h/day of moderate–high intensity)	6–10 g/kg/d
Very high	Extreme commitment (e.g. >4–5 h/day of moderate–high intensity)	8–12 g/kg/d

Source: Thomas *et al.*, 2016.

(table sugar, which comprises a glucose and fructose molecule joined together) and lactose (milk sugar, which comprises a glucose and galactose molecule joined together).

Complex carbohydrates are much larger molecules, consisting of hundreds or thousands of sugar units (mostly glucose) joined together. They include the starches, amylose and amylopectin, and the non-starch polysaccharides (dietary fibre), such as cellulose, pectin and hemicellulose.

In between simple and complex carbohydrates are glucose polymers and maltodextrin, which comprise between 3- and 10-sugar units. They are made from the partial breakdown of corn starch in food processing, and are widely used as bulking and thickening agents in processed foods, such as sauces, dairy desserts, baby food, puddings and soft drinks. They are popular ingredients in sports drinks and meal-replacement products, owing to their low sweetness and high energy density relative to sucrose.

In practice, many foods contain a mixture of both simple and complex carbohydrates, making the traditional classification of foods into 'simple' and 'complex' very confusing. For example, biscuits and cakes contain flour (complex) and sugar (simple), and bananas contain a mixture of sugars and starches depending on their degree of ripeness.

The old notion about simple carbohydrates giving fast-release energy and complex carbohydrates giving slow-release energy is incorrect and misleading. For example, apples (containing mostly simple carbohydrates) produce a smaller and more prolonged rise in blood sugar than potatoes or bread (containing mainly complex carbohydrates), which are digested and absorbed relatively quickly and give a rapid rise in blood sugar.

Nowadays, carbohydrates are more often classified by their nutritional quality or nutrient density. This refers to the presence of other nutrients in the food, such as vitamins, minerals, fibre and phytochemicals (plant compounds). This classifi-

What are the practical difficulties with a high-carbohydrate diet?

For athletes with very high energy needs, eating a high-carbohydrate diet can be difficult. Many carbohydrate-rich foods, such as bread, potatoes and pasta, are quite bulky and filling, particularly if wholegrain and high-fibre foods make up most of your carbohydrate intake. Several surveys have found that endurance athletes often fail to consume the recommended carbohydrate levels (Frentsos and Baer, 1997). This may be partly due to the large number of calories needed and therefore the bulk of their diet, and partly due to lack of awareness of the benefits of a higher carbohydrate intake. It is interesting that most of the studies upon which the carbohydrate recommendations were made used liquid carbohydrates (i.e. drinks) to supplement meals. Tour de France cyclists and ultra-distance athletes, who require more than 5000 calories a day, often consume up to one-third of their carbohydrate in liquid form. If you are finding a high-carbohydrate diet impractical, try eating smaller, more frequent meals and supplementing your food with liquid forms of carbohydrate such as meal replacement products and energy drinks (see pp. 159–60).

cation method gives you a better idea of the food's overall nutritional value. Examples of nutrient-dense carbohydrate foods include whole grains, such as oats, wholemeal bread and brown rice; beans, chickpeas, lentils, fruit and vegetables. Aim to get most of your daily carbohydrate from these foods, while minimising refined carbohydrates. These include sweets, cakes, biscuits, sugar-sweetened drinks, sports drinks, gels, chocolate and refined grains (such as white bread, pasta and rice). While not devoid of nutritional value, these foods generally contain less fibre and fewer vitamins and minerals. You don't have to avoid them completely – simply balance them with nutrient-rich foods.

Is sugar harmful for health?

Sugar is a carbohydrate, which means it is an energy source for the body. Despite the negative press surrounding it, small amounts of sugar are unlikely to cause harm and, provided you time your sugar intake around exercise, it may even aid your performance. During high-intensity exercise lasting longer than an hour, consuming sugar either in the form of solid food (e.g. bananas, dried fruit, gels or energy bars) or drinks can help maintain blood glucose concentration, spare glycogen and increase endurance. Sugar may also be beneficial for promoting rapid glycogen refuelling during the 2-hour period after prolonged intense exercise.

However, one of the main problems with sugar is its ability to cause dental caries. Studies have shown that athletes who consume lots of sports drinks, bars and gels experience significant tooth decay and erosion (Needleman *et al.*, 2015). These products are high in sugar and as they are usually consumed at frequent intervals during exercise, they are particularly damaging to the teeth.

Another problem with sugar is that it has no real nutritional value (apart from providing energy). It makes food and drink more palatable and therefore easy to over-consume. Although sugar is not uniquely fattening, it can contribute towards an over-consumption of calories, especially when combined with lots of fat in the form of cakes, chocolates, biscuits and snacks. Rather than satisfy hunger, sugar can sometimes make us want to eat more! Although high intakes have been linked with obesity and type 2 diabetes, the main contributor to these diseases is excess calories rather than sugar itself.

It is also claimed that high sugar intakes can result in insulin resistance, where the body cells become less responsive to insulin (the hormone responsible for shunting glucose from the bloodstream to the muscles) and more prone to store fat. However, regular exercise blunts the negative effects of sugar, which means the body produces less insulin after consuming sugar. This is one of the many ways the body adapts to exercise: it becomes more sensitive to insulin (Hawley and Lessard, 2008). In other words, you need less insulin to do the same job and your body learns to handle sugar more efficiently.

Claims suggesting that sugar is toxic or addictive relate to studies carried out on mice that were given extremely large amounts of sugar. Such research cannot be extrapolated to humans. It has also been claimed that sugar, specifically the fructose part of the molecule, increases blood triglycerides and cardiovascular disease risk. However, doing regular exercise prevents this because the body increases its production of lipoprotein lipase, an enzyme that removes fats