

# The sprinter

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### Learning objectives

After studying this chapter, you should be able to . . .

1. give a general description of the characteristics and pathways of anaerobic metabolism
2. describe the roles of phosphocreatine and its contribution to energy supply in high-intensity dynamic exercise
3. appreciate the relative contributions of phosphocreatine and glycogen breakdown to anaerobic ATP resynthesis during sprinting
4. describe the concept of the cellular energy charge and explain why there is a loss of adenine nucleotides during very high-intensity exercise
5. discuss the causes of fatigue in sprinting
6. describe the time course of phosphocreatine resynthesis following very high-intensity exercise
7. appreciate the nutritional needs to sustain sprint training.

**Table 3.1** Approximate contribution of aerobic and anaerobic energy sources to total energy production in running events of different durations involving maximal work

Distance (m)	Exercise duration (s)* and [Running speed (km/h)] <sup>†</sup>		% Aerobic	% Anaerobic
	Men	Women		
100	9.78 [36.8]	10.49 [34.3]	10	90
200	19.32 [37.3]	21.34 [33.6]	20	80
400	43.18 [33.3]	47.60 [30.3]	30	70

\* Durations given are the current outdoor world records at 1 July 2003.

<sup>†</sup> Average running speed based on these current world record times. The peak running speed would be a little higher as the average running speed includes the initial acceleration phase and the slowing down due to fatigue during the final stages of the race.

## Introduction

A sprinter relies predominantly but not exclusively on anaerobic metabolism

The sprinter has to sustain a very high power output over a relatively short period of time (usually between 3 and 20 s). As the intramuscular supply of ATP is sufficient to last only about 2 s there is a pressing need to resynthesize ATP extremely quickly and this is achieved by the breakdown of intramuscular stores of phosphocreatine and the rapid activation of glycolysis. Both of these processes occur without the utilization of oxygen; that is they are anaerobic means of regenerating ATP. However, sprinting is not entirely anaerobic! There is a contribution of carbohydrate oxidation to ATP resynthesis during sprinting that increases as the duration and distance of the sprint increases. The approximate contributions of aerobic and anaerobic metabolism in sprint running events are shown in Table 3.1. Note that the average speed of running during these events is far higher than the speed that would elicit 100% maximal oxygen uptake ( $VO_{2max}$ ).

## Anaerobic metabolism

Anaerobic metabolism allows ATP resynthesis without the use of oxygen

Human skeletal muscle can perform work in the absence of an adequate supply of oxygen as a consequence of its ability to generate energy anaerobically. Two separate systems are available to the muscle to permit this, and these are the phosphagen system and the glycolytic system. Because the glycolytic system depends on the production of lactic acid whereas the

phosphagen system involves no lactate formation, these systems of anaerobic ATP regeneration are sometimes referred to as the lactic and the alactic systems, respectively. Note that the terms lactic acid and lactate are often used interchangeably, but although lactic acid is perhaps a more descriptive term, clearly indicating the acidic nature of the molecule, lactate is more accurate and is used here.

## Phosphagen system

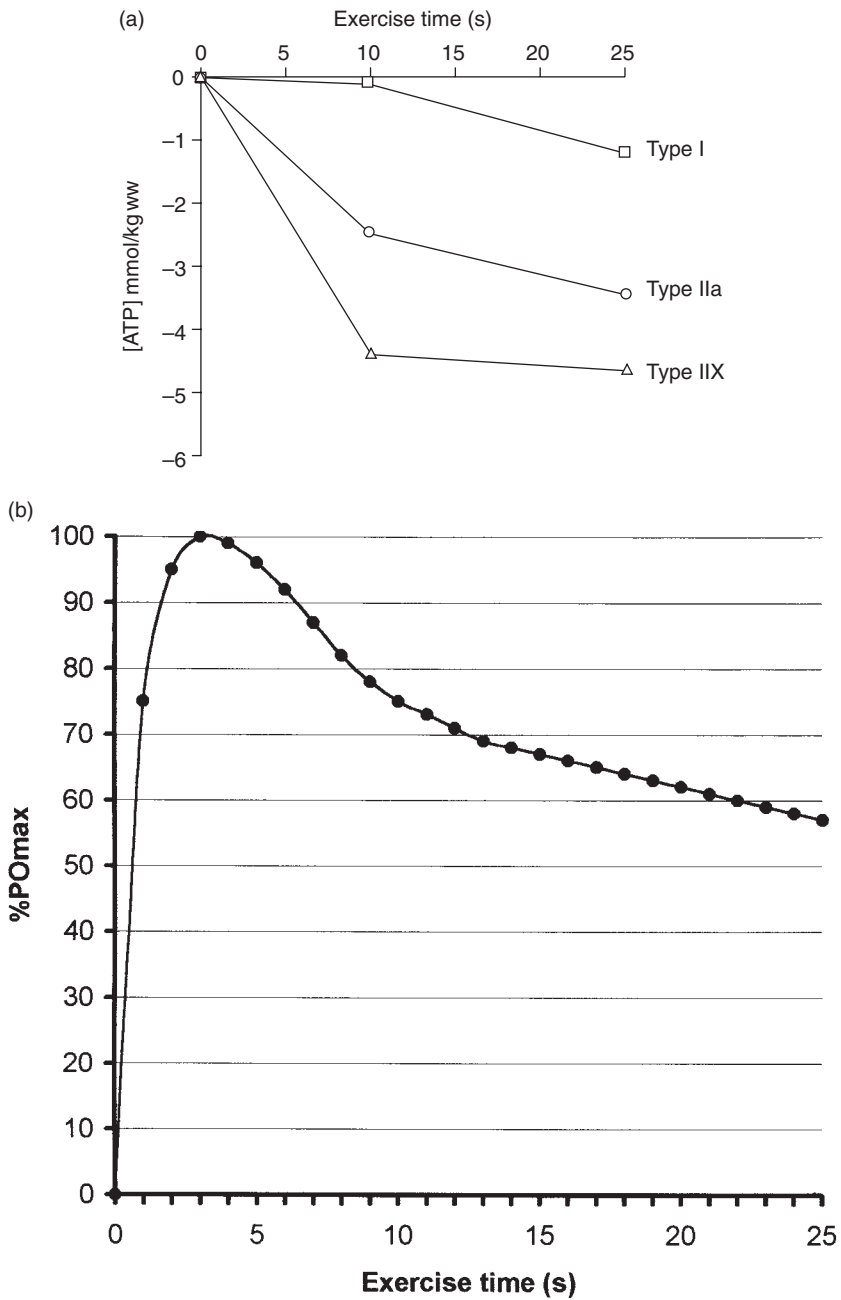
ATP and PCr are referred to as the phosphagens

Much of our knowledge about muscle energy metabolism has come from the study of isolated animal muscles made to contract by electrical stimulation of the motor nerve or of the muscle directly. In such isolated muscle preparations, if a muscle is poisoned with cyanide (preventing oxidative phosphorylation in the mitochondria) and iodoacetic acid (inhibiting glycolysis), so that it can derive no energy from oxidative metabolism, or from the production of lactate, it can still contract strongly for a short period of time before fatigue occurs. This tells us that the muscle has another source of energy, and also that the capacity of this energy source is limited. This source is the intramuscular store of ATP (see Chapter 2) and phosphocreatine (PCr, also known as creatine phosphate): together, ATP and PCr are referred to as the phosphagens. The most important property of the phosphagens is that the energy store they represent is available to the muscle almost immediately.

### *ATP use in very high-intensity exercise*

The muscle ATP concentration declines during very high-intensity exercise

Unlike the situation in prolonged submaximal exercise, the intramuscular ATP concentration does decline significantly during 10–60 s of all-out sprinting. During 10 s of maximal exercise the ATP concentration in Type I fibres is found to be unchanged, but in Type IIa fibres the ATP concentration falls by about 40%, and in Type IIX fibres by about 70% (see Figure 3.1). If maximal effort exercise is maintained for a further 15 s, then the ATP concentration in Type II fibres falls a little further and there is a significant drop (but only by about 20%) in the ATP concentration in Type I fibres. In maximal exercise peak power is attained within 2–3 s and after 10 s there is typically a 20–25% loss of power output. These findings suggest that Type II fibres contribute little to mechanical power output after the first 10 s of maximal exercise. Furthermore, it seems probable that the progressive muscle fatigue seen in a bout of all-out exercise is the consequence of a sequential failure of fibre-type populations in relation to their contractile and mechanical properties (i.e. the first fibres to fatigue are Type IIX, then Type IIa, followed by Type I).



**Figure 3.1** (a) Decline in the ATP concentration for Type I, IIa and IIX fibres of the human vastus lateralis muscle during 10 and 25 s of maximal isokinetic cycling. (b) Power output (PO) profile during 25 s of maximal isokinetic cycling. Note that peak power output is reached at about 3 s; thereafter power declines (i.e. fatigue ensues).

### Phosphocreatine

Phosphocreatine can be used to resynthesize ATP at a very high rate

The PCr in muscle can be used to resynthesize ATP at a very high rate (considerably higher than glycolysis or the oxidative metabolism of carbohydrate or fat). This high rate of energy transfer corresponds to the

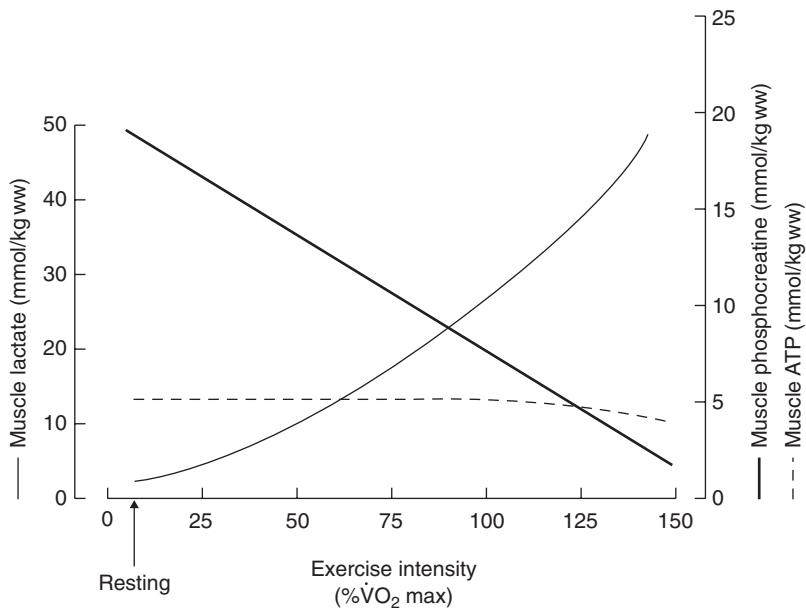
	Capacity (mmol ATP/kg dm)	Power (mmol ATP/kg dm/s)
Phosphagen system	80	9.0
Glycolytic system	300	4.5
Combined	380	11.0*

**Table 3.2** Capacity and power of anaerobic systems for the production of ATP

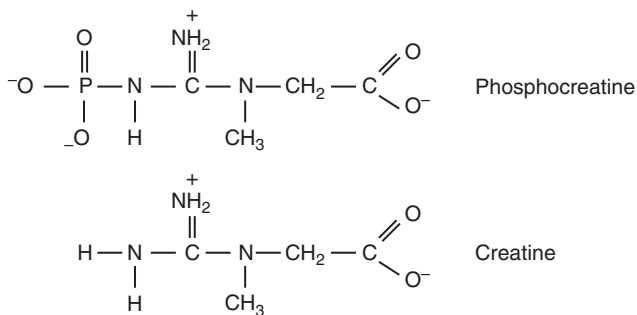
Values are expressed per kg dry mass (dm) of muscle [to convert to per kg wet weight (ww) simply divide by 4, as about 75% of muscle weight is water] and are based on estimates of ATP provision during high-intensity exercise of human vastus lateralis muscle. \* The combined maximum rate of ATP resynthesis is slightly lower than the sum of the maximum rates for the phosphagens (i.e. PCr breakdown) and glycolysis as these rates do not temporally coincide: the maximum rate of ATP resynthesis from PCr hydrolysis occurs in the first 1–2 s of exercise, whereas the maximum rate of ATP resynthesis from glycolysis is not reached until 5–10 s of exercise. Note that the maximum rates of ATP resynthesis from carbohydrate (glycogen) and fat oxidation are only about 2.8 and 1.0 mmol ATP/kg dm/s, respectively.

ability to produce a high power output (power being the rate at which work is performed). The major disadvantage of this system is its limited capacity—the total amount of energy available is small (Table 3.2). If no other energy source is available to the muscle, fatigue will occur rapidly. During short bursts of running over a distance of 30–50 m, no slowing down occurs over the last few metres—full power can be maintained all the way—and the energy requirements are largely met by breakdown of the phosphagen stores. Over longer distances, running speed begins to fall off, as these stores decline and power output starts to fall. However, the rate of recovery from a short sprint is quite rapid, and a second burst can be completed at the same speed after only 2–3 min recovery. For longer sprints (100 m or more) much longer recovery periods are needed before the ability to produce a maximum performance is restored. These are important considerations for sports that involve multiple sprints in the course of a game, such as football, rugby, hockey and basketball.

Figure 3.2 shows that at the onset of high-intensity exercise, the rates of PCr hydrolysis and lactate production are increased rapidly compared with rest. The greater the exercise intensity, the greater the rate of decline of PCr and accumulation of lactate. It is unclear whether these responses occur because of a lag in oxygen delivery and/or inertia in the activation of mitochondrial ATP resynthesis (TCA cycle and oxidative phosphorylation) at the onset of contraction. During brief all-out sprinting, the rate of ATP demand far exceeds the capacity of mitochondrial ATP resynthesis, and therefore anaerobic metabolism becomes the dominant contributor to ATP resynthesis. In physiological terms, this contribution from anaerobic metabolism to ATP resynthesis, whether at the onset of moderate intensity exercise or during high-intensity exercise, appears as the oxygen deficit.<sup>1</sup>



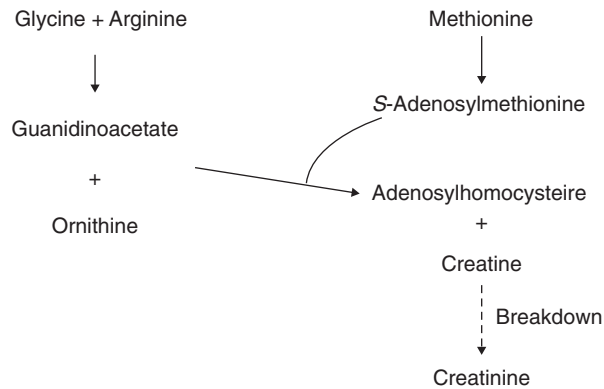
**Figure 3.2** Changes in the intramuscular concentration of phosphocreatine, lactate and ATP at different intensities of exercise.



**Figure 3.3** Structure of phosphocreatine and creatine.

Skeletal muscle contains about three to four times more phosphocreatine than ATP

Phosphocreatine is restricted to the cytoplasm of the muscle cell, where it is present at a concentration of about 20 mmol/kg ww [80 mmol/kg dry matter (dm)]. Note that this is about 3–4 times higher than the intramuscular ATP concentration. The structure of PCr is shown in Figure 3.3. Free creatine is present in resting skeletal muscle at a concentration of about 12–25 mmol/kg ww (50–100 mmol/kg dm), but it is not synthesized in muscle tissue. Creatine is obtained from the diet. Because over 95% of the body's creatine is contained in skeletal muscle, meat is a very good source of creatine, providing about 2g/day from a typical Western diet. The intramuscular creatine and PCr stores can be increased by dietary creatine supplementation; further consideration of this is given in Chapter 6.



**Figure 3.4** Biosynthesis of creatine from the amino acids arginine, glycine and methionine. The first step in creatine synthesis involves the reversible transfer of an amidine group from arginine to glycine to form guanidinoacetic acid. This is followed by an irreversible transfer of a methyl group from *S*-adenosylmethionine to guanidinoacetic acid, forming creatine. This pathway occurs in the liver and kidneys. In muscle creatine is broken down to creatinine, which is excreted in the urine.

Creatine transport into muscle is against the concentration gradient and is coupled to that of sodium

Creatine is also synthesized in the liver from several amino acids (Figure 3.4). Following its release into the circulation, creatine is taken up into muscle. Because the concentration of creatine is far greater in muscle than in the blood plasma, there is a tendency for creatine to leak out of the muscle by simple diffusion. Energy is required to transport the creatine across the sarcolemmal membrane from the plasma into the muscle against this concentration gradient. This type of membrane transport is called active transport and the requirement for energy is common to the transmembrane transport of all substances against their prevailing concentration gradients. For charged particles, the electrical gradient also has to be taken into account, because excitable cells such as muscle possess a resting membrane potential that makes them electrically negative on the inside compared to the outside. This electrical potential difference is usually about 70 mV. In the case of creatine its transport is coupled to that of sodium; the large concentration difference for sodium across the membrane (approximately 140 mmol/l in the extracellular fluid compared with only 12 mmol/l inside the cell) is set up by the activity of the ‘sodium pump’, otherwise known as the sodium-potassium ATPase, which exports three sodium ions out of the cell for every two potassium ions that enter the cell at the expense of ATP breakdown to ADP and  $P_i$ .

The free energy of PCr hydrolysis is greater than that of ATP

The rapid degradation of PCr at the onset of moderate intensity exercise and during high-intensity exercise occurs because it has a higher

phosphate group transfer potential than ATP. This means that the free energy of PCr hydrolysis ( $-43 \text{ kJ/mol}$ ) is greater than that of ATP hydrolysis ( $-31 \text{ kJ/mol}$ ), resulting in a greater likelihood for free energy transfer to occur from PCr to ADP to re-form ATP:



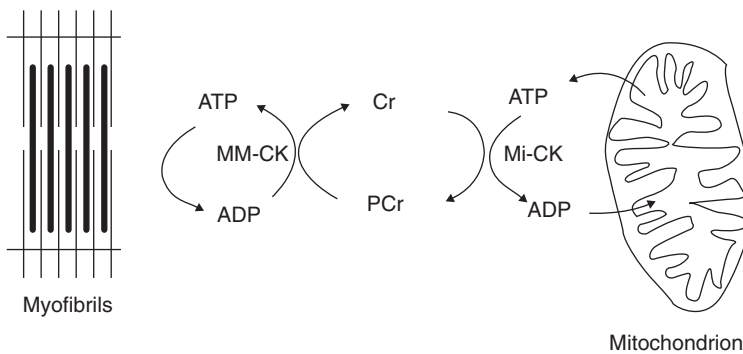
It can be seen, therefore, that this reaction functions to maintain ATP homeostasis during contraction at the expense of PCr. Note that the resynthesis of ATP via breakdown of PCr buffers some of the hydrogen ions formed as a result of ATP hydrolysis. The PCr in muscle is immediately available at the onset of exercise and can be used to resynthesize ATP at a very high rate.

Indeed, the rate at which this reaction can occur is far in excess of any of the ATP-utilizing reactions occurring in the cell, and it is not unusual for the muscle PCr store to be almost completely degraded during maximal exercise.<sup>2</sup> This reaction is termed the creatine kinase reaction because it is catalysed by the enzyme creatine kinase. Note that the reaction is reversible: depending on the energy state of the cell, it can go in either direction. During recovery from exercise, when ATP is regenerated from oxidative phosphorylation, creatine kinase can use ATP to replenish the PCr store.

Phosphocreatine appears to have multiple roles in muscle

It is now clear that creatine kinase has a number of isoenzymes (variations of the enzyme, having a slightly different structure but the same substrate specificity) that are located at different intracellular locations. At least three are known to be present in skeletal muscle. For example, MM-CK is located near the sites of muscle cross-bridge formation (i.e. near a site of ATP utilization) and Mi-CK is located at the mitochondrial membrane (i.e. near the site of ATP production). The discovery of the existence of isoenzymes of creatine kinase with discrete cellular locations has led to the hypothesis that PCr may have a number of different functions within skeletal muscle. The first, and possibly the most important, relates to its function described above, that is acting as a temporal buffer to maintain the cellular ATP concentration and the ATP to ADP ratio.

A second function, which is currently the subject of much debate, is that PCr may act as a spatial energy buffer, that is an energy transport system between the site of ATP production (the mitochondria) and the sites of ATP utilization (e.g. the myofibrils). This suggested function is illustrated in Figure 3.5 and has resulted in the use of the phrase 'the PCr shuttle'. Those researchers in favour of its existence have gone on to suggest that the primary role for PCr in Type I muscle fibres may be to operate as a spatial buffer, which contrasts with its suggested principal role in Type II fibres as a temporal energy buffer. The  $3\text{--}5 \text{ mmol/kg ww}$  ( $12\text{--}$



**Figure 3.5** The phosphocreatine shuttle. PCr, phosphocreatine; Cr, creatine; Mi-CK, mitochondrial creatine kinase; MM-CK, muscle (M isoform located at the M line of the sarcomere) creatine kinase. At the mitochondrial site, newly synthesized ATP enters the sarcoplasm where a portion is utilized by Mi-CK for the formation of PCr. The resulting ADP is transported into the mitochondrion. The PCr diffuses to the myofibrils where the CK located at the M line regenerates ATP from ADP formed during cross-bridge formation.

20 mmol/kg dm) higher concentration of PCr found in Type II fibres supports this suggestion.

A third suggested function for PCr is its functional coupling with several other cellular reactions, which facilitates the integration of energy metabolism during muscle contraction. For example, it is clear from the reactions described above that the adenylate kinase reaction will result in the generation of  $H^+$  ions and the creatine kinase reaction will result in the sequestering of  $H^+$  ions; it is the functional coupling of these two reactions that prevents the rapid acidification of the cell at the onset of contraction. Similarly, the rapid liberation of  $P_i$  by ATP hydrolysis during contraction plays an integral part in the activation of glycogen phosphorylase at the onset of exercise, thereby ensuring that energy production is maintained. Increased intracellular concentrations of ADP and AMP are also important in this regard.

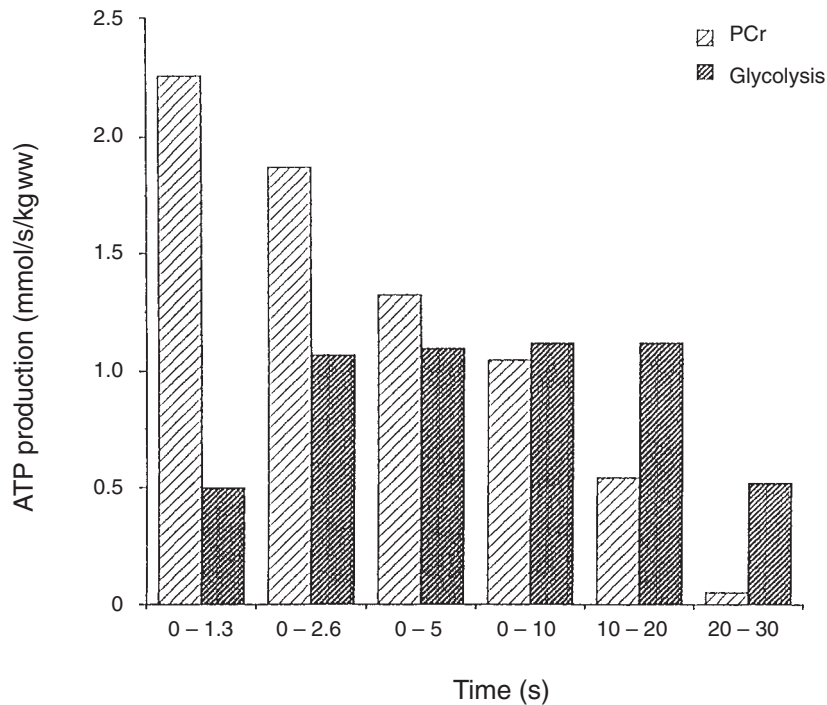
## Metabolic response to very high-intensity exercise

### ATP resynthesis from phosphocreatine breakdown

Phosphocreatine breakdown is initiated immediately at the onset of contraction

During high-intensity exercise, the relatively low rate of ATP resynthesis from oxidative phosphorylation results in the rapid activation of anaerobic energy production from both PCr and glycogen hydrolysis. PCr

**Figure 3.6** Rates of anaerobic ATP resynthesis from phosphocreatine (PCr) and glycolysis during 30 s of near maximal intensity isometric contraction in man. Values were calculated from metabolite changes measured in biopsy samples obtained during intermittent electrically evoked contraction (1.6 s stimulation at 50 Hz, 1.6 s rest).



breakdown is initiated immediately at the onset of contraction to prevent the rapid accumulation of ADP resulting from ATP hydrolysis. However, as you can see in Figure 3.6, the rate of PCr hydrolysis begins to decline after only a few seconds of very high force generation. The importance of PCr hydrolysis lies in the extremely rapid rates at which it can resynthesize ATP. This is especially true of maximal short-duration exercise. For example, Figure 3.6 shows the rate of muscle ATP resynthesis from PCr hydrolysis during 30 s of maximal fatiguing isometric contraction. First, note that PCr utilization is at its highest within 2 s of the initiation of contraction. Second, however, you can see that after only 2.6 s of contraction the ATP yield from PCr is reduced by about 15%, and following 10 s of contraction it is reduced by more than 50%. The contribution of PCr to ATP resynthesis in the last 10 s of a 30-s exercise bout is relatively small, amounting to only 2% of the initial yield. By this time, of course, the actual force (or power) will also have declined substantially. As the rate of PCr breakdown declines, so does the rate of ATP resynthesis because the other ATP regenerating mechanisms (glycolysis and oxidative phosphorylation) cannot resynthesize ATP at as fast a rate. The decreased turnover of ATP in the muscle means that the force or power must also fall.

Because PCr is so important to muscle performance during short bursts of activity, it is tempting to ask why the body does not store more PCr in its muscles. In the wild, many animals need to be able to move quickly to

catch prey or to escape from being eaten themselves. The requirement to develop athletic prowess in the animal kingdom has been a strong driver of evolution, but no animals seem to have adapted by greatly increasing the creatine or PCr contents of their muscles. The most likely reason for this is the weight penalty that would be incurred. PCr is a relatively small molecule and to increase its concentration in the muscle would have an osmotic effect, retaining more water in the muscle and therefore increasing body mass. Any improvement in muscle performance would be offset by the increased inertia and energy requirement to move a heavier body.

The mechanisms responsible for the almost instantaneous decline in the rate of PCr utilization during maximal exercise are at present unknown, but may be related to a local decline in the availability of PCr close to the cross-bridges where it is needed. Considering the high energy demand of maximal exercise, it is possible that the very rapid rate of PCr utilization at the onset of contraction could be responsible for a rapid depletion of stores at the sites of rapid energy translocation (actomyosin cross-bridges). Certainly, this seems plausible, because when intense exercise is continued for more than 20 s, the cellular store of PCr is almost completely depleted, probably as a consequence of mitochondrial ATP production being unable to match the rate of PCr hydrolysis. However, it should be borne in mind that even when the PCr store is almost zero, muscle can continue to function, albeit at a much reduced power.

### **ATP resynthesis from glycogen metabolism**

Glycogen breakdown and glycolysis are rapidly activated within the first few seconds of intense exercise

If high-intensity exercise is to continue beyond only a few seconds there must be a marked increase in the contribution from glycolysis to ATP resynthesis. Glycogenolysis is the hydrolysis of muscle glycogen to glucose 1-phosphate and glycolysis is the series of reactions involved in the degradation of glucose 1-phosphate to lactate (details of this pathway are given in Chapter 4). The integrative nature of energy metabolism ensures that the activation of muscle contraction by  $\text{Ca}^{2+}$  and the accumulation of the products of ATP and PCr hydrolysis (ADP, AMP, IMP,  $\text{NH}_3$  and  $P_i$ ) act as stimulators of glycogenolysis and glycolysis, and in this way guarantee that anaerobic ATP production is maintained, at least in the short term.

Anaerobic glycolysis involves several more steps than PCr hydrolysis, and can provide ATP at a slower rate, but compared with oxidative phosphorylation is still very rapid. As described in some detail in Chapter 4, the generation of ATP in glycolysis occurs via the phosphorylation of ADP in the second half of the pathway. It was thought for many years that PCr was the sole fuel used at the initiation of contraction, with glycogen utilization occurring only when the PCr concentration had become depleted.

This is now known not to be the case. As you can see in Figure 3.6, ATP resynthesis from glycolysis during 30 s of maximal fatiguing contraction begins almost immediately at the onset of exercise. Furthermore, unlike PCr hydrolysis, ATP production from glycolysis does not reach its maximal rate until after 5 s of exercise and is maintained at this high rate for several seconds. Over 30 s of exercise, the contribution from anaerobic glycolysis to ATP resynthesis is nearly double that from PCr.

Glycogen catabolism will supply the major part of the energy requirement for maximum intensity efforts lasting from 20 s to about 2 min

In sprinting, the muscle glycogen stores are broken down rapidly with a correspondingly high rate of lactate formation: some of the lactate diffuses out of the muscle fibres where it is produced and appears in the blood. A substantial proportion, amounting to about 25 mmol glucosyl units/kg ww (100 mmol/kg dm), of the muscle glycogen store can be used for anaerobic energy production during high-intensity exercise, and will supply the major part of the energy requirement for maximum intensity efforts lasting from 20 s to about 2 min (see Chapter 4). Because 3 mmol of ATP can be resynthesized by anaerobic glycolysis from each mmole of glucosyl units derived from the breakdown of glycogen, the capacity for ATP regeneration from anaerobic glycogen breakdown is about 75 mmol ATP/kg ww (300 mmol/kg dm), which is three to four times greater than that available from complete hydrolysis of the muscle PCr store. For sprints lasting less than 20 s, the phosphagens are the major energy source. Although the total capacity of the glycolytic system is greater than that of the phosphagen system, the rate at which it can produce energy (i.e. resynthesize ATP) is lower (Table 3.2). The power output that can be sustained by this system is therefore correspondingly lower, and it is for this reason that maximum speeds cannot be sustained for more than a few seconds; once the phosphagens are depleted, the rate of work output must necessarily fall. As mentioned in Chapter 2, Type II fibres have a higher content of PCr and glycogen than Type I fibres. Type II fibres also possess a greater amount of phosphorylase, the enzyme that breaks down glycogen. It is not surprising, therefore, that biopsy studies have shown a higher proportion of Type II fibres in elite sprinters than in endurance athletes and the sedentary population.

### **Phosphocreatine and glycogen breakdown in Type I and Type II fibres**

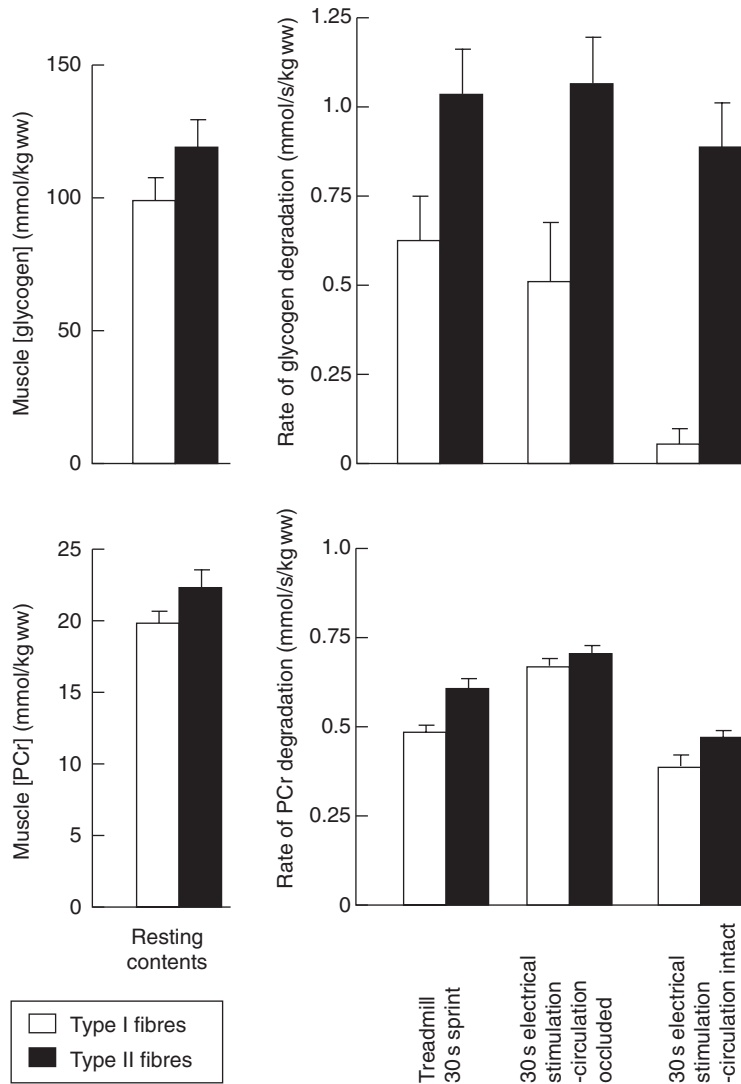
Rates of phosphocreatine and glycogen breakdown during very high-intensity exercise are faster in Type II muscle fibres

Most of the conclusions presented so far have been based on metabolite changes measured in studies of isolated animal muscle and from human

studies in which biopsy samples were obtained from the quadriceps femoris muscle group at the front of the thigh. However, human skeletal muscle is composed of at least two functionally and metabolically different fibre types (as described in Chapter 2). Type I fibres are characterized as being slow contracting, fatigue resistant, capable of a relatively low power output and favouring aerobic metabolism for ATP resynthesis during contraction. Conversely, Type II fibres are relatively fast contracting, fatigue rapidly, are capable of a high power output and favour mainly anaerobic metabolism for ATP resynthesis. Evidence from animal studies that have utilized muscles composed of predominantly Type I or Type II fibres suggests that the rapid and marked rise and subsequent decline in maximal power output observed during intense muscle contraction may be closely related to activation and rapid fatigue of Type II fibres. Similar evidence for humans is not readily available because human limb muscles tend to have a more mixed fibre type composition, although somewhat similar results have been reported from one study using bundles of similar human muscle fibre types.

Look at Figure 3.7, which shows the rates of PCr and glycogen degradation in Type I and Type II muscle fibres during maximal exercise under three different experimental conditions. Note, first, that at rest PCr and glycogen concentrations are higher in Type II muscle fibres than in Type I fibres, and second, that during intense contraction the rates of glycogenolysis and PCr degradation are higher in Type II than in Type I fibres. This is true for both dynamic exercise (treadmill sprinting) and electrically induced isometric contractions, which indicates that this response is not a function of the way in which the muscle is activated, but rather is a characteristic of the fibres themselves. The rates of glycogenolysis observed in both fibre types during treadmill sprinting and intermittent isometric contraction with circulation occluded are in good agreement with the maximal activity ( $V_{\max}$ ) of phosphorylase measured in both fibre types, suggesting that glycogenolysis is occurring at a near maximal rate during intense exercise.

Surprisingly, during repeated isometric contractions (each lasting 1.6 s) with circulation intact, when the rest interval between contractions is also 1.6 s, the rate of glycogenolysis in Type I fibres is almost negligible. The corresponding rate in Type II fibres is almost maximal and similar to that seen during contraction with circulatory occlusion. This suggests that during maximal exercise glycogenolysis in Type II fibres is invariably occurring at close to the maximum rate, irrespective of the experimental conditions, while the rate in Type I fibres is probably very much related to cellular oxygen availability and phosphorylation potential or energy charge of the cell (see following sections).



**Figure 3.7** Resting phosphocreatine (PCr) and glycogen contents and rates of degradation in Type I and II muscle fibres during 30 s of maximal treadmill sprinting and 30 s of intermittent electrical stimulation (1.6 s stimulation at 50 Hz, 1.6 s rest) with circulation occluded and intact.

### Myokinase reaction

The myokinase reaction uses two molecules of ADP to generate one molecule of ATP

An additional pathway to regenerate ATP when ATP and PCr stores are depleted is through a kinase reaction<sup>3</sup> that utilizes two molecules of ADP to generate one molecule of ATP (and one molecule of adenosine monophosphate, AMP). This reaction is catalysed by the enzyme called myokinase:



This reaction only becomes important during exercise of high intensity. Even then, the amount of energy it makes available in the form of ATP is extremely limited and the real importance of the reaction may be in the formation of AMP, which is a potent allosteric activator of a number of enzymes involved in energy metabolism, particularly those involved in glycogen breakdown and glycolysis.

Oxidative metabolism also makes a contribution to ATP resynthesis in a 10-s sprint. Although small (probably contributing less than 10% of total ATP resynthesis), it is still important, and, of course, the contribution from carbohydrate oxidation becomes increasingly greater as the duration of the bout of high-intensity exercise gets longer.

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### Loss of adenine nucleotides

Adenine nucleotide loss may be of importance to muscle function during conditions of metabolic crisis

It is known that the total adenylate pool can decline rapidly if the AMP concentration of the cell begins to rise during muscle force generation. This decline occurs principally via deamination of AMP to inosine monophosphate (IMP) but also by the dephosphorylation of AMP to adenosine. The loss of AMP may initially appear to be counterproductive because of the reduction in the total adenylate pool. However, it should be noted that the deamination of AMP to IMP only occurs under low ATP/ADP ratio conditions and, by preventing excessive accumulation of ADP and AMP, enables the adenylate kinase reactions to continue, resulting in an increase in the ATP/ADP ratio and continuing muscle force generation. Furthermore, it has been proposed that the free energy of ATP hydrolysis will decrease when ADP and  $P_i$  accumulate, which could further impair muscle force generation. For these reasons, adenine nucleotide loss has been suggested to be of importance to muscle function during conditions of metabolic crisis; for example during very high-intensity exercise such as sprinting and in the later stages of prolonged submaximal exercise when glycogen stores become depleted.

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### The cellular energy charge and the adenylate pool

The energy charge is a good indicator of the energy status of the cell

The concentrations of ATP, ADP and AMP can be used to calculate the energy charge of the cell. This concept was proposed by Atkinson in 1977

(see recommended reading) and it is a measure of the extent to which the total adenine nucleotide pool of the cell (ATP, ADP and AMP) is phosphorylated. It is described by the following equation:

$$\text{Energy charge} = \frac{[\text{ATP}] + 0.5 [\text{ADP}]}{[\text{ATP}] + [\text{ADP}] + [\text{AMP}]}$$

The energy charge is a good indicator of the energy status of the cell (i.e. its capacity to do work). For example, the energy charge of the cell would be 1.0 if the whole of the adenine nucleotide pool was in the form of ATP and under these conditions the cell would have a maximum energy charge. Conversely, the energy charge will be zero when ATP has been completely hydrolysed to AMP. Both these scenarios should only be viewed as theoretical examples, as the concentration of ATP in living human skeletal muscle will not decline by more than 60%, even during maximal exercise with blood flow completely occluded, and the adenylate nucleotide pool is never all in the form of ATP. Under normal resting conditions, the energy charge of skeletal muscle is in the region of 0.90 to 0.95. However, this has been shown to decline to around 0.85 in some disease states, and can fall to less than 0.7 during fatiguing high-intensity exercise. It should be noted that further falls are likely to be associated with irreversible cellular damage.

ATP, ADP and AMP act as allosteric activators or inhibitors of the key enzymatic reactions involved in energy metabolism

The rate of ATP resynthesis during exercise is regulated by the energy charge of the muscle cell. For example, the decrease in the energy charge at the onset of contraction, that is the momentary decline in ATP and increases in ADP and AMP, accelerates both anaerobic and oxidative ATP resynthesis, with the net effect of increasing the rate of energy supply to match the increased demand. If the energy charge continues to decline, ATP degradation will be inhibited, that is the muscle will fatigue and work output will fall. The relatively low concentration of ATP (and ADP) inside the cell means that any increase in the rate of hydrolysis of ATP (e.g. at the onset of exercise) produces a rapid change in the ratio of ATP to ADP and also increases the intracellular concentrations of AMP and  $P_i$ . These changes, in turn, activate enzymes that immediately stimulate the breakdown of intramuscular fuel stores to provide energy for ATP resynthesis. In this way energy metabolism increases rapidly following the start of exercise.

ATP, ADP and AMP act as allosteric activators or inhibitors of the key enzymatic reactions involved in PCr, carbohydrate (CHO) and fat degradation and utilization. For example, as already mentioned, creatine kinase, the enzyme responsible for the rapid rephosphorylation of ATP at the initiation of muscle force generation, is activated rapidly by an increase in cytoplasmic ADP concentration and is inhibited when the

cellular ATP concentration is high. Similarly, glycogen phosphorylase, the enzyme that catalyses the conversion of glycogen to glucose 1-phosphate and thus primes the glycolytic pathway, is activated by increases in AMP and  $P_i$  (and calcium ion) concentration and is inhibited by an increase in ATP concentration.

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## Causes of fatigue in sprinting

Even in a 100-m sprint, the runners are slowing down slightly in the final third of the race

Fatigue has been defined as the inability to maintain a given or expected force or power output and is an inevitable feature of maximal exercise. Typically, the loss of power output or force production is likely to be in the region of 40–60% of the maximum observed during 30 s of all-out exercise. Measurements on elite sprinters performing all-out effort on a cycle ergometer show that maximum power is reached after only 3–4 s; thereafter power declines. During sprint running, the acceleration phase takes place over the first 4–5 s by which time the athlete will have covered about 30–40 m of the track. Thereafter, running speed declines, but not to the same extent as is seen on the cycle ergometer; this is due to the forward momentum that is generated when running fast, helping to keep the speed up. This explains why the time for the 200-m race is invariably less than double the time for the 100-m race. However, even in a 100-m sprint, the runners are slowing down slightly in the final third of the race. In other words fatigue has already begun. Success in sprint events like the 100 and 200 m is therefore associated with the maximum running speed that can be achieved by the athlete and the ability to minimize the inevitable loss of power following the initial acceleration phase and attainment of maximum running speed.

The causes of fatigue in sprinting are multifactorial but the decline in phosphocreatine availability is probably the most important factor

Fatigue is not a simple process with a single cause; many factors can contribute to fatigue. However, during maximal effort exercise lasting less than 30 s, fatigue is caused primarily by a gradual decline in anaerobic ATP production or an increase in ADP accumulation caused by a depletion of PCr and a fall in the rate of glycolysis. In high-intensity exercise lasting 1–5 min,  $H^+$  ion accumulation may contribute to the fatigue process (see Chapter 4). The general consensus at the moment seems to be that the maintenance of force production during very high-intensity exercise is pH dependent, but the initial force generation during the first few seconds of activity is more related to PCr availability.

Accumulation of metabolites and altered calcium transport are also implicated in fatigue

One of the consequences of rapid ATP hydrolysis during high-intensity exercise is the accumulation of  $P_i$ , which has been shown to inhibit muscle excitation-contraction coupling directly. However, the depletion of PCr and the accumulation of  $P_i$  occur over a similar time course, which makes it difficult to separate the effect of PCr depletion from  $P_i$  accumulation *in vivo*. This problem is further confounded by the parallel increases in hydrogen and lactate ions that occur during high-intensity exercise. All of these metabolites have been independently implicated with muscle fatigue.

As described in Chapter 2, calcium release by the sarcoplasmic reticulum results from muscle depolarization and is essential for the activation of muscle contraction coupling. It has been demonstrated that during fatiguing contractions there is a slowing of calcium transport and progressively smaller calcium transients that has been attributed to a reduction in calcium re-uptake by the sarcoplasmic reticulum. Strong evidence that a disruption of calcium handling is responsible for fatigue comes from studies showing that the stimulation of sarcoplasmic reticulum calcium release caused by the administration of caffeine to isolated muscle whose fibres have had their surface membrane removed can improve muscle force production, even in the presence of a low muscle pH. Alternatively, fatigue during high-intensity exercise may be associated with an excitation-coupling failure and possibly a reduced nervous drive due to reflex inhibition at the spinal level. In the latter hypothesis, accumulation of interstitial potassium in muscle may play a major role (for details see Sjogaard 1991; Bangsbo 1997).

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### **Post-exercise recovery: the resynthesis of phosphocreatine**

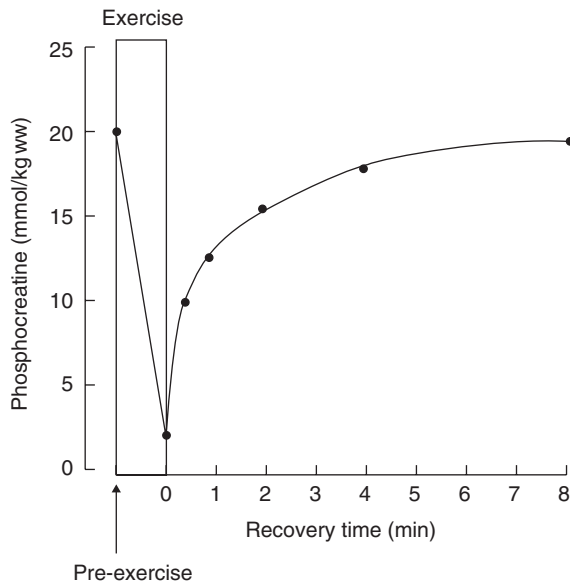
PCr resynthesis after exercise follows an exponential curve and about half of it is restored in the first 30 s post-exercise

The creatine kinase reaction is an equilibrium reaction (as is the adenylate kinase reaction) and is therefore reversible:



Following exercise, when the energy charge of the cell is increased and sufficient free energy is available to rephosphorylate Cr, the reaction will proceed from left to right to restore muscle PCr levels.

In general, the resynthesis of PCr following complete degradation follows an exponential curve and the half-time for resynthesis (the time to



**Figure 3.8** Time course of phosphocreatine resynthesis after maximal exercise.

resynthesize 50% of the resting store) is often quoted as 30 s (as illustrated in Figure 3.8). In reality, however, there appears to be a large variation in the time course of resynthesis depending on the type of exercise performed and the duration and number of exercise bouts completed. Factors known to influence the rate of PCr resynthesis during recovery from exercise are the cellular concentrations of ATP, ADP and Cr, which is not surprising given the equilibrium nature of the creatine kinase reaction. In addition, the  $H^+$  ion is known to be a potent inhibitor of creatine kinase. In practice, therefore, a low muscle pH, a low oxygen tension and/or a reduction in muscle blood flow will severely impair PCr resynthesis following exercise. Indeed, muscle ischaemia is often used as a tool in metabolic research to 'arrest' PCr resynthesis following muscle contraction, thereby providing sufficient time to enable relevant biochemical and physiological measurements to be made (see Figure 3.8).

The rate of phosphocreatine resynthesis is lower in Type II fibres

It is now clear that there are differences in the rates of PCr resynthesis between muscle fibre types following exercise-induced PCr depletion. It seems that the rate of PCr resynthesis is significantly lower in Type II muscle fibres during the first few minutes of recovery (possibly due to a greater fall in intracellular pH in this fibre type). After these initial few minutes, however, PCr resynthesis is accelerated in Type II muscle fibres, such that after 15 min of recovery the concentration of PCr is in fact greater than that observed at rest. The mechanism responsible for this PCr overshoot in Type II fibres or for how long this remains higher is currently unknown.

Following a bout of high-intensity exercise it takes considerably longer to remove the accumulated lactate and restore the muscle glycogen store than it does to fully resynthesize the PCr store. These other aspects of recovery are covered in subsequent chapters.

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## Nutritional effects on sprint performance

Creatine supplements may help sprinters to sustain higher training intensities

Sprinters are concerned with generating high power outputs and building large and powerful muscles is a key goal. It is not surprising, therefore, that they share many training and nutrition practices with strength athletes. High protein diets are common, but as with the strength athlete, these are probably often higher than is necessary for optimum performance. Creatine supplementation is also especially popular with sprinters: the first athletes to use this in major competition included some of the athletes who won gold medals in sprint events at the Barcelona Olympic Games in 1992. When creatine was first used, athletes would take it only in the last few days before competition to achieve a rapid boost of the phosphocreatine levels in their muscles. More often now, athletes use creatine supplementation over the whole season as a way of increasing the intensity of training that can be sustained. The reasoning is that training harder induces greater physiological and biochemical adaptations that in turn mean better performance in competition.

The obvious benefit of an increased creatine content in muscle (about two-thirds of the total is in the form of phosphocreatine) is an increased amount of immediately available high energy phosphate groups that can be transferred to ADP. An increased creatine content, however, also means that there is a faster rate of phosphocreatine resynthesis after an intense sprint. This may be why the greatest performance-enhancing effects of creatine supplementation are generally seen when several short sprints are performed with insufficient time for complete recovery of phosphocreatine between sprints. This is typical of the interval training sessions carried out by many athletes in the longer sprint events and may explain why more intensive training can be achieved. It is also typical of the patterns of play in many team sports, and the use of creatine supplementation will be considered in this respect in more detail in Chapter 6.

The use of creatine has generated much controversy as it can be effective in improving performance. Although not all studies show a positive effect, the balance of the available evidence does support this, but its use is not prohibited in sport at the present time. There are no reports of adverse effects on health or performance from long-term use, but only limited evidence is currently available.

Performing repeated sprints places high demands on the muscle glycogen stores

Performance in sprints is less affected by the pre-exercise diet than is performance in prolonged exercise. Muscle glycogen availability per se is not usually considered to be responsible for fatigue during high-intensity exercise, providing the pre-exercise glycogen store is not depleted to below 25 mmol/kg ww (100 mmol/kg dm). However, sprinters should be aware that performing repeated sprints in training will place high demands on the muscle glycogen stores. In a single 6-s all-out sprint on a laboratory treadmill, it was found that 16% of the glycogen present was broken down. Most of this was converted to lactate and some to the accumulated glycolytic intermediates, with only a small amount being oxidized (Gaitanos *et al.* 1993). After performing ten 6-s sprints (each separated by 30 s resting recovery) the muscle glycogen content had fallen by 40%. A typical training session for sprinters consists of several brief intense sprints, so it is clear that there will be a substantial decrease in the available muscle glycogen stores. Some of the lactate formed during the sprints are transported to the liver and used to resynthesize glucose, which can then be returned to the muscle for storage, but most is oxidized by the muscles during periods of low-intensity exercise between sprints. The body's substantial fat reserves cannot be converted to carbohydrate, so the diet must supply sufficient carbohydrate to allow replenishment of the glycogen stores between training sessions. The trend for sprinters and power athletes to eat a high protein diet (which in practice often means that the intake of fat is also high) may mean that the dietary intake of carbohydrate is inadequate to allow an intensive training programme to be sustained.

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## Key points

1. Human skeletal muscle can exert force without the use of oxygen as a consequence of its ability to generate energy anaerobically. Two separate systems are available in the muscle to permit this: the phosphagens and the glycolytic pathway.
2. The phosphagens are the intracellular stores of ATP and phosphocreatine (PCr). The energy store they represent is available to the muscle almost immediately. The muscle only uses ATP as the direct source of energy for contraction, but the PCr in muscle can be used to resynthesize ATP at a very high rate. The major disadvantage of this system is its limited capacity—the total amount of energy available is small.
3. Phosphocreatine is present in the cytosol of muscle at about three times the concentration of ATP. It is generally accepted that the rapid degradation of PCr in the creatine kinase reaction at the onset of muscle force generation occurs because the free energy released can be used to resynthesize ATP, thereby maintaining a high cellular ATP to ADP ratio. However, the discovery of several isoenzymes of creatine kinase with defined cellular locations has led to the hypothesis that PCr may have a number of different functions within skeletal muscle.
4. The creatine kinase reaction is reversible and occurs following exercise when sufficient energy is available to

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rephosphorylate Cr. The resynthesis of PCr follows an exponential curve but the time course of resynthesis is dependent on a number of factors.

**5.** The sum of cellular ATP, ADP and AMP concentrations is termed the total adenine nucleotide pool. The extent to which the total adenine nucleotide pool is phosphorylated is known as the energy charge of the cell, and it is a good indicator of the energy status of the cell. The rate at which ATP is resynthesized during exercise is known to be regulated by the energy charge of the muscle cell. For example, the decline in cellular concentration of ATP at the onset of muscle force generation and parallel increases in ADP and AMP concentrations (i.e. a decline in the energy charge) directly stimulate anaerobic and oxidative ATP resynthesis.

**6.** The total adenine nucleotide pool of the cell declines if the AMP concentration of the cell begins to rise during exercise. The loss of adenine nucleotides is potentially detrimental because it will reduce the availability of adenine nucleotides for phosphorylation. However, this adverse effect is outweighed in the short term by the stimulatory effect that the reduction in the cellular ADP and AMP concentrations has on the adenylate kinase reactions, resulting in an increase in the energy charge and continued force generation.

**7.** Skeletal muscle adenine nucleotide loss occurs first by the deamination of AMP to IMP and ammonia, and second by the dephosphorylation of AMP to adenosine. Both IMP and adenosine can be further degraded to inosine and then hypoxanthine, which then leaves muscle and is degraded and excreted by the kidneys. The predominant pathway for adenine nucleotide loss in man is via deamination of AMP to IMP and ammonia; however, substantial variation is known to exist between muscle fibre types and animal species.

**8.** An alternative fate for IMP is that it can be used to resynthesize AMP. The deamination of AMP to IMP and subsequent reamination of IMP forms the purine nucleotide cycle. Several important roles have been proposed for the purine nucleotide cycle in muscle energy metabolism.

**9.** The close association between muscle adenine nucleotide loss and the development of fatigue during short-lasting intense exercise and prolonged submaxi-

mal exercise might suggest that AMP deamination is implicated in fatigue development. However, it is more likely that this association is a reflection of energy delivery failing to meet the energy demands of the exercise and that fatigue is due to a number of factors, including a local cellular depletion of phosphocreatine and ATP and an accumulation of ADP,  $P_i$  and  $H^+$  ions.

**10.** For exercise lasting more than a few seconds, ATP derived from the anaerobic metabolism of glucose (or glycogen) becomes available. Glycolysis is the name given to this pathway and the end-product of this series of reactions is pyruvate or lactate.

**11.** Glycolysis makes two molecules of ATP available for each molecule of glucose that passes through the pathway. If muscle glycogen is the starting substrate, three ATP molecules are generated for each glucose unit passing down the pathway.

**12.** Anaerobic glycolysis involves several more steps than PCr hydrolysis; however, compared with oxidative phosphorylation it is still very rapid. It is initiated at the onset of contraction, but unlike PCr hydrolysis does not reach a maximal rate until after 5 s of exercise and can be maintained at this level for several seconds during maximal muscle force generation. The mechanism(s) responsible for the eventual decline in glycolysis during maximal exercise have not been resolved.

**13.** The resynthesis of PCr following its complete degradation during a bout of very high-intensity exercise follows an exponential curve and the half-time for resynthesis (the time to resynthesize 50% of the resting store) is about 30 s.

**14.** Sprinters share many training and nutrition practices with strength athletes. High protein diets are common, but as with the strength athlete, these are probably often higher than is necessary for optimum performance.

**15.** Creatine supplementation over the whole season may enable sprinters to increase the intensity of training that they can sustain.

**16.** Performance in sprints is less affected by the pre-exercise diet than is performance in prolonged exercise. Muscle glycogen availability per se is not usually consid-

ered to be responsible for fatigue during high-intensity exercise, providing the pre-exercise glycogen store is not depleted to below 25 mmol/kg ww (100 mmol/kg dm).

However, sprinters should be aware that performing repeated sprints in training will place high demands on the muscle glycogen stores.

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## Notes

1. The oxygen deficit represents the additional oxygen uptake that would be required to provide energy for muscular work at a work rate above 100%  $\text{VO}_{2\text{max}}$ .
  2. The reader may find the following definitions useful:  
*Maximal* exercise is used by different authors to mean:
    - (1) exercise at an intensity that elicits maximal oxygen uptake ( $\text{VO}_{2\text{max}}$ )
    - (2) completing a given amount of work or distance in the fastest possible time, or
    - (3) all-out effort as in sprinting or a maximal voluntary isometric contraction. This is the definition used in this chapter.
  3. A kinase reaction is an enzyme-catalysed reaction involving the transfer of an inorganic phosphate group ( $\text{H}_2\text{PO}_4^{2-}$  usually abbreviated as  $P_i$ ).
- Submaximal* exercise usually refers to exercise at an intensity less than that eliciting 100%  $\text{VO}_{2\text{max}}$ .  
Submaximal *steady-state* exercise usually refers to an exercise intensity that would elicit less than 80%  $\text{VO}_{2\text{max}}$ .  
*Supramaximal* exercise refers to exercise at an intensity above that eliciting 100%  $\text{VO}_{2\text{max}}$ .