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Aerobic Glycolytic and Aerobic Lipolytic Power Systems

A New Paradigm with Implications for Endurance and Ultraendurance Events

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In the traditional view of exercise metabolism, the energy for muscular contraction is produced by 3 independent systems: the phosphagen, anaerobic (or oxygen-independent) glycolytic, and aerobic (or oxygen-dependent) systems.[1-4] The phosphagen system uses intracellular stores of adenosine triphosphate (ATP) and creatine phosphate (CP) to provide the power needed for maximal bouts of strength or speed that last for a few seconds.[5-9] For high-intensity exercise of up to 1 minute in duration, energy is provided mostly by the anaerobic glycolytic system, which breaks down muscle glycogen without consuming oxygen.[5,10-13] Exercise lasting longer than 1 minute is powered mostly by the aerobic system, which uses oxygen in the breakdown of carbohydrate (glycogen, glucose), lipids (triglycerides, fatty acids and ketones) and, to a very small extent, amino acids.[2,3,14-16]

We believe that this traditional view of only 3 energy systems is too simplistic. Instead, we propose that the oxidation of carbohydrates and lipids should be regarded as the basis of 2 *functionally* distinct aerobic power systems: the aerobic glycolytic system (which oxidises carbohydrate for high-intensity endurance events) and the aerobic lipolytic system (which oxidises lipid to provide most of the energy for longer, less intense endurance and ultraendurance activities). A practical implication of this new paradigm is that dietary and training regimens for high-intensity endurance pursuits should continue to be aimed at enhancing the aerobic glycolytic system, but for ultraendurance events such regimens should be aimed at enhancement of the aerobic lipolytic system.

1. Power Systems

In most texts the term *energy system* is used to refer to a physiological entity that produces ATP to sustain cellular processes, including muscular contraction. What criteria must be satisfied for the 3 existing energy systems to be considered distinct from each other? We are unaware of any previous formal attempt to address this question, so we have devised our own criteria by examining the differences between the 3 systems. We suggest that these systems are considered distinct because: (1) they have substantially different metabolic pathways; (2) their relative contributions to the energy required for exercise depend on the intensity and duration of the exercise; and (3) their contributions can be modified selectively by training or other interventions. Debate amongst exercise scientists on whether these criteria are necessary and sufficient to define distinct energy systems would be appropriate. In the meantime, we suggest that the systems defined by these particular criteria be referred to as something other than *energy systems*, to avoid confusion with the existing nomenclature.

From the point of view of athletes and sports scientists, the main function of an energy system is to produce mechanical power rather than the energy required to sustain metabolic processes. Therefore, we will use the term *power system* to describe a system that satisfies our criteria. We will show that our putative aerobic glycolytic and aerobic lipolytic systems, along with the existing phosphagen and anaerobic glycolytic systems, satisfy these criteria.

1.1 Distinct Power Systems Have Different Metabolic Pathways

Different metabolic pathways are an essential feature of the 3 existing energy systems. Indeed, the names of the systems represent descriptive summaries of the pathways each uses to produce ATP. Thus, the phosphagen system is named for the 2 high-energy phosphate compounds (ATP and CP) that are used to store energy for this system; the anaerobic glycolytic system derives its name from the pathway that can produce ATP from the breakdown of carbohydrate without the use of oxygen; and the aerobic system is named for the fact that it generates ATP from the oxidative breakdown of fuels.

The pathways in the phosphagen and anaerobic glycolytic systems, along with the pathways for the metabolism of carbohydrate and lipid in the aerobic system, are summarised in figure 1. For the purposes of this article, the small contribution that the aerobic breakdown of amino acids makes to the metabolic demands of exercise has been ignored.

The pathways depicted in figure 1 are widely accepted. However, a new feature is the terminology for the 2 aerobic pathways, which we have devised to highlight the differences between the substrates metabolised in these and in the other pathways. The differences between the pathways for the breakdown and oxidation of lipids and carbohydrates are not insubstantial: a set of cytoplasmic and membrane-bound enzymes is responsible for the β-oxidation of lipids to fatty-acyl co-enzyme A (CoA), the transport of fatty-acyl CoA into mitochondria, and its conversion to acetyl CoA. A separate set of enzymes controls the conversion of intramuscular and extramuscular carbohydrate to pyruvate and then to acetyl CoA. Thereafter, the pathways for oxidation of the acetyl moieties from either lipid or carbohydrate are the same.

Each of the pathways has unique elements, but some also have common components. Thus, the anaerobic and aerobic glycolytic systems share the pathway for the breakdown of glycogen to pyruvate and, as discussed above, the aerobic glycolytic and lipolytic systems share the pathways for oxidative phosphorylation in the mitochondria. We note that under the existing paradigm of only 3 systems, the anaerobic glycolytic and aerobic systems share the pathway for the breakdown of glycogen to pyruvate. Overlap of pathways is, therefore, not a sufficient reason to reject the new scheme.

Although the pathways shown in figure 1 appear to be independent, the figure conceals a myriad of complex interactions between the pathways mediated by enzymes, metabolites, cofactors and intracellular messengers. Thus, at the biochemical level, all of the pathways are interdependent. The crucial issue is whether the macroscopic function of these pathways under different conditions provides sufficient grounds for the power systems to be considered distinct. We address this issue in sections 1.2 and 1.3.

1.2 Relative Contributions of Distinct Power Systems Differ with Exercise Intensity and Duration

The contributions of the power systems to the total energy requirements of exercise have been studied most frequently during exercise in which individuals perform either the maximal amount of work in a predetermined time or a given amount of work in the shortest possible time.[10-12,17-22] We will use the term *maximal* to define both kinds of exercise, even though for exercise lasting more than 1 minute, maximal effort may not be attained until the end of the exercise period. Most competitive athletic events require such maximal exercise.

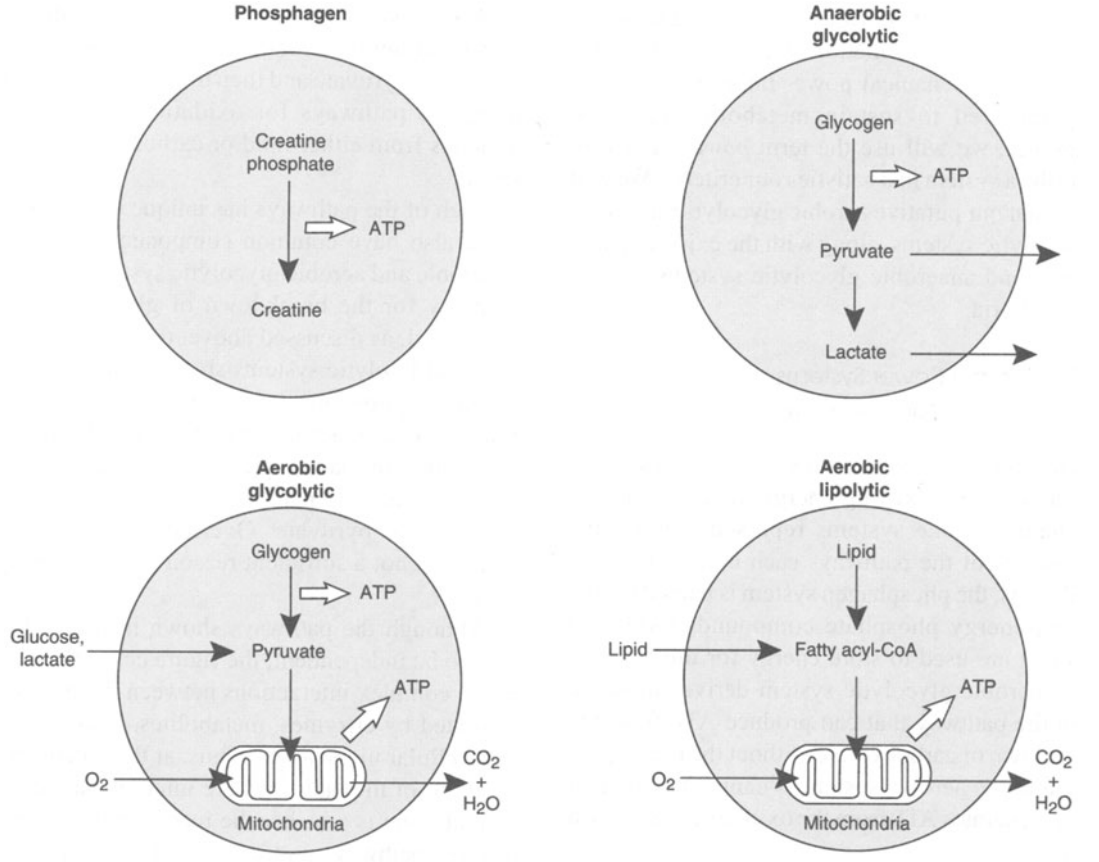

Fig. 1. The 4 metabolic pathways for the production of adenosine triphosphate in muscle cells. *Abbreviations:* ATP = adenosine triphosphate; CoA = co-enzyme A.

Figure 2 shows the contributions of the power systems to the total work performed during maximal exercise lasting ≈1 second to ≈1 day. The figure is similar to those depicted in many textbooks on exercise physiology,[1,23-26] but we have modified and updated the time courses to take into account recent data showing that the crossover points for the phosphagen, anaerobic glycolytic and aerobic glycolytic contributions occur at ≈6 seconds and ≈1 minute in athletes.[5,6,11,27,28] More importantly, we have separated the contributions derived from the aerobic breakdown of carbohydrates and lipids to illustrate how these too are affected by the duration of exercise. Carbohydrate provides most of the energy for short-term maximal endurance exercise,[19-21,29] whereas lipid makes substantial contributions to the energy requirements of more prolonged activities.[2,3,15,29-38] On the basis of the few relevant published studies,[29,35,37,38] we estimate that the total contributions made by aerobic glycolysis and aerobic lipolysis are equal after 3 to 5 hours of maximal exercise, although this duration is modified by training, diet and caloric supplementation during the exercise (see section 1.3).

When the exercise is lower in intensity than that necessary to achieve maximal work or work in minimal time, the relative contributions of the power systems change somewhat from those shown in figure 2. The phosphagen system is still the major source of ATP for activities lasting 1 or

2 seconds, so its contribution for such short activities is unaffected by intensity. For slightly longer activities, the contribution of the anaerobic glycolytic system will not only be delayed by the slower rate of change of concentrations of regulatory metabolites, but will also be truncated by the more rapid rate of activation of the aerobic system at lower exercise intensities.[39]

For submaximal endurance activities, utilisation of lipid relative to carbohydrate in the aerobic pathways increases as the intensity of endurance exercise decreases, a well known effect that has recently been termed the *crossover concept*.[40] The exercise intensity at which lipid and carbohydrate oxidation are equal defines the crossover: above it, the main fuel is carbohydrates[15,41-43]; below it, the main fuel is lipids.[15,44,45] The shift from lipid to carbohydrate at high power outputs is regulated mainly by changes in concentrations of metabolites within the active muscle fibres,[46-48] and by changes in muscle fibre activity from predominantly type I oxidative fibres at low intensity to increasing recruitment of type II glycolytic motor units at higher intensities.[49-51]

During relatively short-term exercise, the crossover occurs at 60 to 70% of maximum oxygen uptake ($\dot{V}O_{2max}$) in trained athletes.[38,40] If exercise is maintained at this intensity, the energy derived from lipid oxidation gradually increases, with a corresponding decline in carbohydrate oxidation.[29,31,33-35,37] The greater contribution from lipid oxidation to total energy metabolism with increasing exercise duration is most likely due to a combination of factors, including a gradual depletion of endogenous carbohydrate reserves[2,3,31] and changes in the hormonal milieu.[52] During prolonged exercise, plasma glucose and insulin levels fall[53,54] and the levels of circulating glucagon,[52-54] catecholamines[53,55-57] and growth hormone[55-57] rise; these responses promote the mobilisation of fatty acids and hepatic glucose production.[52]

What must have seemed an undifferentiated pattern of utilisation of carbohydrate and lipid in exercise of moderate intensities and durations may have led earlier authors to place aerobic glycolysis and aerobic lipolysis under the one rubric of the aerobic system. In reality, there are clear-cut effects of exercise intensity and duration: the lower the intensity or the longer the duration, the greater the dependence on lipid relative to carbohydrate. Our putative aerobic glycolytic and lipolytic power systems therefore satisfy the requirement

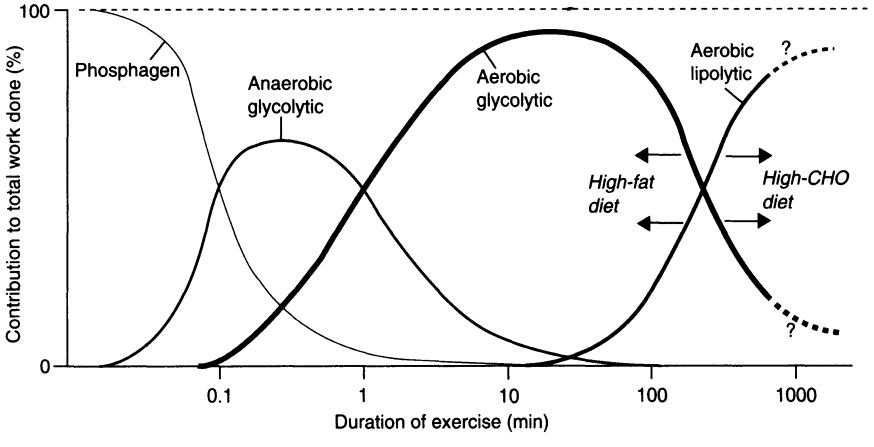

Fig. 2. The contribution of the 4 power systems to the maximal total work performed during exercise of a given duration. Adaptation to a high-fat diet shifts the aerobic lipolytic curve and the corresponding right-hand segment of the aerobic glycolytic curve to the left; adaptation to a high-carbohydrate (high-CHO) diet shifts these curves to the right. The dashed sections marked with a ? indicate present uncertainty about the relative contributions.

that their contributions to exercise change with exercise duration and intensity.

1.3 Contributions of Distinct Power Systems can be Modified Selectively

If 2 power systems were tightly coupled by underlying biochemical or physiological mechanisms, any intervention that modified the power provided by 1 system would produce a similar change in the power of the other. We would hesitate to regard such coupled systems as *functionally* distinct, regardless of differences in their pathways and in their contributions to energy metabolism during different kinds of exercise. Experimental evidence of the lack of coupling between power systems therefore seems to be essential if the systems are to be regarded as distinct or independent. There would appear to be 2 kinds of evidence: either it must be possible to change the maximal power of 1 system without affecting the maximal power of the other systems; or for exercise powered by 2 systems, it must be possible to change the relative proportions of energy provided by each system. We will cite first some well known examples of such selective modifications of the 3 traditional energy systems, then provide evidence of similar effects for the putative aerobic glycolytic and lipolytic systems.

Studies of the specificity of training provide 1 approach for testing whether power systems are distinct. In such studies, the main focus is usually the practical question of whether training bouts of a specific duration and intensity affect performance in exercise tests or competitive events of a different duration and intensity. Strength or power training of an intensity sufficient to engage predominantly the phosphagen system enhances maximal performance of this system but not of the aerobic system.[8,17,58-60] Similarly, prolonged endurance workouts enhance aerobic performance, but not strength.[61-65] Thus, these 2 systems are distinct, at least with respect to training. Training studies have yet to provide unequivocal evidence of the independence of the anaerobic glycolytic system, in part because activities that engage this pathway also engage either the phosphagen or aerobic glycolytic power systems (see figure 2). Nevertheless, it appears that very short, intense workouts that train only the phosphagen and anaerobic glycolytic systems do not result in enhanced maximal aerobic performance.[8,60,66]

Certain acute physiological interventions also provide evidence of the independence of the 3 traditional systems. A treatment aimed at improving oxygen transport that appears to enhance only the aerobic system is blood doping.[67-69] Breathing pure oxygen also enhances aerobic endurance[70] but not short-term exercise that makes use of the phosphagen and anaerobic glycolytic systems.[71] Conversely, the aerobic system can be inhibited selectively by conditions that compromise oxygen supply, such as hypobaric hypoxaemia.[72,73] Finally, bicarbonate ingestion enhances performance of sprint and short-term endurance activities that depend on anaerobic and aerobic glycolysis,[74-76] but feats of strength that rely only on power from the phosphagen system are unaffected. Bicarbonate appears to work by providing a buffer against the fatigue-inducing hydrogen ions released during anaerobic glycolysis.[77]

Evidence of the independence of the aerobic lipolytic and glycolytic systems comes from investigations of the effects of both acute and chronic dietary manipulations, which result in changes in the proportions of carbohydrate and lipid utilised during exercise that uses both substrates. When plasma free-fatty-acid (FFA) levels are elevated before exercise, either by a fatty meal and heparin injection or by caffeine ingestion, there is an increased utilisation of lipid and concomitant sparing of muscle glycogen during exercise, especially at the high intensities typical of endurance events.[78-81] On the other hand, when FFA availability is reduced by administration of nicotinic acid, muscle glycogen degradation during exercise is increased and exercise capacity is markedly reduced.[82-85]

Chronic adaptation to high-fat diets (>55% of total energy), which results in a decline in pre-exercise muscle glycogen content,[86-87] also results in an increased utilisation of lipid during ex-

ercise.[86-90] Conversely, adaptation to a diet high in carbohydrate (>65% of total energy) elevates muscle glycogen content[91,92] and increases the utilisation of carbohydrate during exercise.[90,93-95] The resulting effects on endurance performance are largely a function of training status and preceding period of dietary adaptation: untrained and moderately trained individuals show enhanced endurance after high-carbohydrate diets,[91-93] whereas highly endurance-trained individuals may, under certain conditions, benefit from a high-fat diet.[86-88,96] Regardless of the effects on performance, the fact that substrate utilisation during endurance exercise can be modified substantially by diet is confirmatory evidence of functional independence of aerobic glycolysis and lipolysis.

2. Training and Dietary Recommendations for Athletes

Research over the past 25 years has emphasised the role of carbohydrates in endurance exercise, and athletes generally appear to have accepted the advice that optimal performance will be obtained from a high-carbohydrate diet combined with carbohydrate supplementation during an event. Only recently have sports scientists begun to appreciate that lipids can make an important contribution to performance, even in the shorter endurance events where they are not the main fuel.[86-88,96-99] For the longer endurance events, lipids must play an even more important role.[37,38] Our new paradigm reflects and should augment the developing interest in the role of lipid utilisation during prolonged exercise. However, by asserting that there are 2 *functionally separate* aerobic power systems, we infer that there are 2 qualitatively different kinds of prolonged, maximal event: those lasting less than about 4 hours, performed at greater than 70% of $\dot{V}O_{2max}$ and powered by aerobic glycolysis; and the longer, lower-intensity events powered by aerobic lipolysis. We will define these respectively as endurance and ultraendurance events. This concept has important implications for athletes and sports scientists.

For athletes, the most important implication is that endurance and ultraendurance events require different dietary and training regimens. Research is urgently needed to better define such regimens. In the meantime, athletes can apply the new paradigm by invoking the specificity principle, which states that training must stress the physiological systems critical for optimal performance in a given event.[100] Thus, training for endurance events should consist mainly of maximal steady-state workouts or high intensity repetition training with short (<1 minute) rest intervals. Athletes should also be adapted to a high-carbohydrate diet, and any supplementation during and after an event should be high in carbohydrate. Conversely, training for ultraendurance events should consist of prolonged, continuous, moderate-intensity workouts; adaptation to a high-fat diet may be beneficial for performance, and supplements consumed during the event should contain some easily digested fats.[96,98] High-fat diets are associated with increased risk of various diseases, and although chronic endurance training attenuates the risk,[101,102] athletes should nevertheless limit their exposure to dietary fat. Optimal performance in ultraendurance events may still be obtained if an athlete trains for most of the year on a high-carbohydrate diet, then adapts to a high-fat diet for 1 to 2 weeks prior to a major event.[96]

It is difficult to recommend training and dietary regimes for events that make substantial demands on both the aerobic glycolytic and the aerobic lipolytic power systems. Clearly, both systems need to be trained, possibly by workouts that alternate between moderate and high intensities in combination with a mixed diet. However, a better strategy might emphasise maximal steady-state workouts combined with a period of adaptation to a moderate- to high-fat diet during training,[86-88] followed by a high-carbohydrate diet to increase glycogen levels during the final day or two before the event. Results of a recent study support the latter recommendation.[96] The optimal energy supplementation strategy for such endurance events is also unclear. For example, how does an athlete's diet

immediately preceding the event affect fuel utilisation during the event? Should supplementation begin at the start of the race, or part way through? What is the optimal mix of carbohydrate and fat? What is the optimal type of fat? Sports scientists will need to answer these practical questions by undertaking appropriately controlled experimental trials.

3. Implications for Sports Scientists

3.1 Specificity of Training

The new paradigm raises several issues. The most important of these is the extent to which the specificity principle operates in the training of the aerobic power systems. To investigate this issue, it will be necessary to assay changes in the maximal power of the aerobic glycolytic and aerobic lipolytic systems following training aimed specifically at one or other of the systems. The maximal power of the aerobic glycolytic system is relatively straightforward to assay. It can be measured indirectly as $\dot{V}O_{2max}$, because at this intensity of exercise very little fat will be oxidised.[40] It is also well represented by the maximal steady-state power or speed at the lactate threshold; such exercise is still of sufficient intensity to be powered predominantly by carbohydrates. Assaying the maximal power of the aerobic lipolytic system will be a little more challenging: researchers will need to find the maximum rate of lipid oxidation that occurs as exercise is gradually increased in intensity. The maximum rate could be derived simply from measurements of the respiratory exchange ratio, although tracer techniques would also be helpful in estimating the contributions of intramuscular and extramuscular lipids.

Our paradigm predicts that long workouts (>1 hour) at low to moderate intensities (≈50% of $\dot{V}O_{2max}$) should increase the maximal power of the aerobic lipolytic system but not of the aerobic glycolytic system. Studies showing little or no effect of such training on $\dot{V}O_{2max}$[103,104] are consistent with this prediction, but the effect on lipid utilisation in these studies is unclear. A clear demonstration that prolonged, low- to moderate-intensity training enhances lipid utilisation and improves ultraendurance performance is now required.

Our paradigm also predicts that endurance training of an intensity sufficiently high to engage only aerobic glycolysis should increase the power of the aerobic glycolytic system while leaving the aerobic lipolytic system unaffected. At first sight, this prediction may seem counterintuitive, because high-intensity endurance training will, *inter alia,* increase the density of muscle mitochondria, which should then be available for increased oxidation of lipid at moderate exercise intensities. However, the rate of lipid oxidation at these intensities may be limited not by the density of mitochondria, but by the availability of FFA to the mitochondria,[105] by the β-oxidation process in the cytoplasm, or by the enzymatic capacity of mitochondria to use FFA,[106,107] none of which may be increased substantially by high-intensity endurance training.

The effects of endurance training on lipid utilisation during exercise have already been addressed in several published studies.[108-110] A problem with some of these studies[108,109] is that the training consisted of a combination of high- and low-intensity workouts, which would have provided training stimuli to both the aerobic glycolytic and the lipolytic systems. A further problem is that lipid utilisation was investigated only at the same absolute intensity of submaximal exercise after training. The observed increase in lipid utilisation could, therefore, represent a change in the maximal power of the lipolytic system, or it could be a consequence simply of the fact that the same absolute exercise intensity represents a lower relative intensity following training, which favours utilisation of lipid.[40]

3.2 The Limits of Aerobic Lipolysis

Defining more precisely the factors that limit the power of the aerobic lipolytic system is itself an area for further research. Endurance training enhances fat oxidation and spares intramuscular glycogen stores by producing changes in the mix of fuel utilised for submaximal exercise that uses

both carbohydrate and fat.[2,111,112] A theoretical basis for this shift in substrate utilisation has been discussed elsewhere:[46,113] the shift is associated with an increased capillary density in muscle,[114] enhancement of skeletal muscle oxidative enzyme concentration,[115] and an increased oxidation of both intramuscular triglycerides[109,110,116] and plasma FFA.[117,118] It remains to be determined to what extent the maximal power of the aerobic lipolytic system can be modified independently of that of the aerobic glycolytic system.

The power of the aerobic lipolytic system could, theoretically, be increased by the ingestion of easily absorbed lipids, such as medium-chain (C_{8-10}) triglycerides (MCTs). Because MCTs are more water soluble than long-chain (C_{16-22}) triglycerides, they are absorbed more rapidly from the gut.[119] They also diffuse into muscle rapidly because they do not require the transport mechanisms that limit the rate of uptake of long-chain fatty acids. They can be oxidised rapidly during long term exercise,[120-122] and may enhance endurance by either sparing the intramuscular lipid and carbohydrate stores,[90,96,99] or by augmenting the rate of utilisation of extramuscular lipid when the intramuscular pool becomes depleted.

Further research also needs to be undertaken on the energy sources for maximal exercise lasting longer than 5 hours. The available evidence indicates that lipids will make the main contribution to energy requirements,[49,123,124] but there may be obligatory utilisation of a certain amount of carbohydrate to maintain citric acid cycle intermediates at a level needed to support the oxidative capacity of muscle.[125] For example, when the concentration of oxaloacetate in mitochondria is low, entry of acetyl groups to form citrate is reduced, which in turn markedly impairs fatty acid utilisation.[2,97,125] Some carbohydrates will therefore need to be consumed during the event, because stores of muscle and hepatic glycogen will become depleted after such long periods of exercise. Carbohydrate supplementation will also be necessary to prevent the hypoglycaemic fatigue associated with depletion of liver glycogen.[126] Appropriate carbohydrate supplementation will also limit the breakdown of muscle protein during maximal ultraendurance exercise.[127] The optimal composition and ingestion regimen for the supplement are further topics for research.

4. Conclusions

We have defined criteria for determining whether systems that provide power for exercise are distinct, and have presented evidence that the glycolytic and lipolytic components of the aerobic system satisfy such criteria. The evidence is persuasive but not yet conclusive: studies of the specificity of training and of the effects of different dietary manipulations on exercise metabolism are now required to confirm the existence of 4 functionally distinct systems rather than 3.

It is clear, nevertheless, that the body meets the metabolic demands of endurance and ultraendurance exercise in fundamentally different ways: carbohydrates are the optimal fuel for brief work bouts, but lipids can be the main fuel to sustain prolonged, submaximal exercise. The implications for athletes are considerable, because the existence of 2 aerobic power systems implies that different training and dietary regimens are necessary to optimise performance in endurance and ultraendurance events. By moving to 4 distinct power systems, we will accord lipid the autonomy and attention it deserves as the main fuel for sustaining the longest bouts of exercise that humans can endure.

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