The Three Energy Systems

All cells of the body need to convert chemical energy to some form of alternate energy form. Nerves generate electrical energy through the development and propagation of action potentials, tissues within the eye convert light energy to electrical energy, skin converts light energy to chemical energy in the form of vitamin D synthesis, and of course muscle converts chemical energy to mechanical energy. For us as exercise physiologists, our main interest is in skeletal muscle, which represents a great example of a tissue that has an enormous range of energy expenditure. Think about this for a moment. Muscle must function in extremes of complete relaxation with minimal energy demand, to sustained intense contractions that typify resistance training. Endurance athletes contract muscles repeatedly for hours, and all these examples require a coordinated process of regulation to sustain ATP provision for muscle contraction. In short, exercise is a phenomenal example of a tissue (muscle) and the need for rapid changes in metabolism that invoke responses in muscle and almost all body systems to ensure the right nutrients reach contracting muscle to support this energy need, and the right waste products are removed to prevent muscle poisoning. In this context, the cellular demand for ATP during exercise drives exercise physiology. If the body cannot meet the rate of ATP demand, then exercise eventually must stop or decrease in intensity. For the coach and athlete, knowing the limits to energy provision during a competitive event is crucial to ensure that peak performance occurs. This is the logic behind the final burst at the end of a race in many athletic events – the athletes knows the limits of his or he capacities, and if they are coached correctly, they time their final burst so that they collapse when the race is over, and not with 50 m remaining!

ATP Regeneration

Skeletal muscle uses the free energy of ATP hydrolysis to fuel muscle contraction in the development of muscular power and the completion of mechanical work (movement and/or the isometric force opposing gravitational force). To do this, the energy systems of skeletal muscle must continually sustain sufficient ATP to stabilize the muscle ATP concentration despite a continual ATP demand.

As you now know, cells break down ATP to ADP + Pi, releasing free energy. To reform ATP, the same reaction needs to be coupled to reactions that release more free energy than is needed to add a phosphate group back on to ADP (Figure 1). As such, ATP is not really produced or synthesized in muscle during contractions. Rather, ATP is regenerated from its constituent sub-components (ADP + Pi), in a repeated process of hydrolysis and phosphate addition, repeated again and again, etc. Once again, it is important to note that to adhere to the requirements of the second law of bioenergetics, phosphate addition to ADP occurs from transferring a phosphate group from a substrate from a highly energy releasing (exergonic) reaction, and not from solution. Due to this, I like to refer to **ATP regeneration** from energy catabolism, rather than ATP synthesis or production.

For skeletal muscle, the three main **energy systems** for ATP regeneration are as follows;

1. **The Phosphagen System**
2. **The Glycolytic System**
3. **Mitochondrial Respiration**

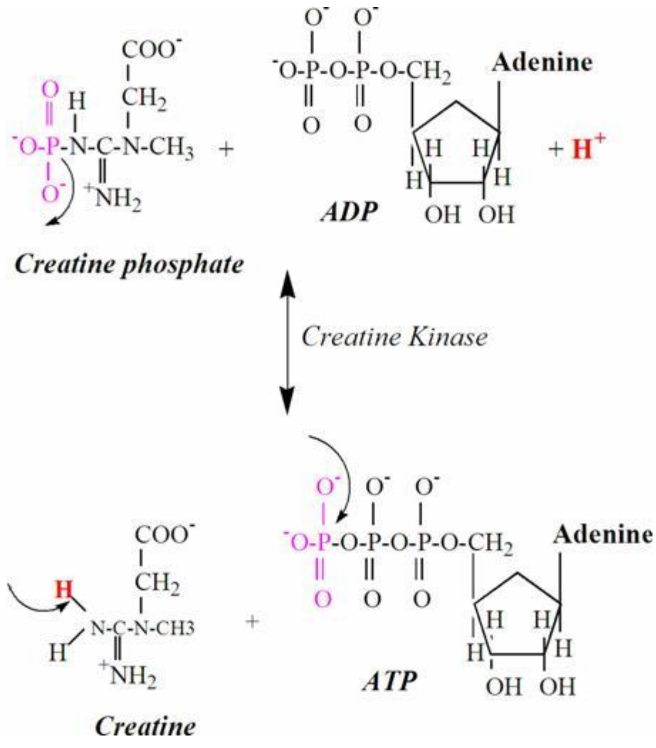

Figure 1. The coupling of ATP regeneration to a highly exergonic creatine kinase reaction.

No one system ever accounts for 100% of ATP regeneration, as there is always an underlying rate of oxygen consumption fueling mitochondrial respiration at rest. As long as blood circulation is in tact, this basal rate of mitochondrial respiration continues and is increased during muscle contraction. Similarly, at rest, even though there is minimal ATP demand from muscle, the incorporation of carbohydrate into energy catabolism involves glycolysis, which is always contributing to ATP regeneration without oxygen (anaerobically). As you will learn, the ATP yield of glycolysis is always anaerobic. However, at rest, muscle derives most of its energy need from lipid catabolism, with the involvement of carbohydrate increasing with increases in exercise intensity. Finally, there is growing evidence that the Phosphagen System is always involved in free energy transfer between the mitochondria and the cytosol. For example, creatine is involved in phosphate transfer from mitochondrial ATP to cytosolic creatine phopshate, which in turn transfers a phosphate to cytosolic ADP to form ATP. This shuttling of terminal phosphate groups is believed to occur throughout the cytosol, and explains how the free energy from the terminal phosphate of mitochondrial ATP can be translocated throughout what is relatively speaking an extremely large muscle cell with large spaces between mitochondria and many of the contractile proteins.

The point I am trying to develop here is that you should never think of the three energy systems as being independent from each other, or where one system works for one type of exercise, and another to different exercise demands. All systems work together, with different exercise conditions requiring a unique contribution of all three. For example, throwing a discuss may rely more than 85% on the Phosphagen System, 10% on the glycolytic system, and 5% on mitochondrial respiration. For the 10,000 m Olympic track race, the same three systems could contribute 10%, 15% and 75%, respectively.

These differences in energy system dependence for different intensities of muscle contraction reveal something very important between each system. When starting with generalities, it is obvious that the more intense the exercise, the greater the reliance on the phosphagen system for ATP regeneration. The lower the exercise intensity, the greater the reliance on mitochondrial respiration. Yes, the three systems differ in the power of their ATP regeneration. This is clearly shown in Figure 2, where the rate of ATP regeneration from the phosphagen system is the greatest, followed by the glycolytic System, and then mitochondrial respiration for carbohydrate and then lipid catabolism.

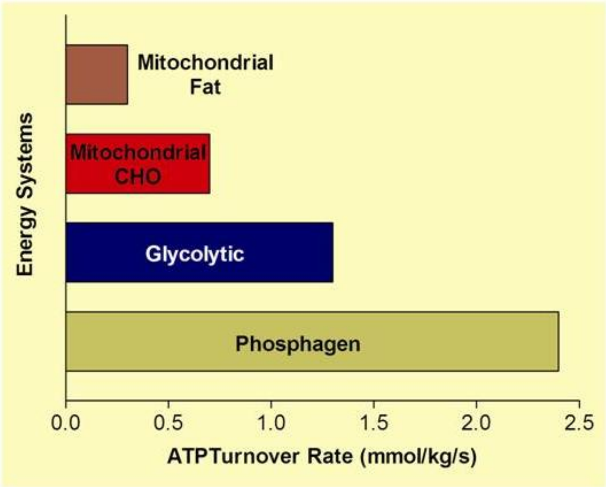

Figure 2. Comparisons of the rate of ATP regeneration between the three energy systems.

The numbers for each system presented in Figure 2 are not constants. A trained and genetically gifted sprint athlete will have a higher peak rate of ATP regeneration from the phosphagen and glycolytic systems, and a far lower peak rate of ATP regeneration from mitochondrial respiration compared to a trained and genetically gifted endurance athlete. Thus, the training status of any system combined with the genetic expression of muscle fiber types (motor units) will in fact determine the maximal ATP regeneration rate of each system. Nevertheless, the same order of “ATP power” remains true and unchangeable. For all individuals, once the exercise intensity and accompanied rate of ATP demand exceeds their maximal mitochondrial ATP power, then there will be an increased reliance on the Glycolytic and Phosphagen Systems. However, to repeat, in the body the cost of increasing exercise intensities beyond the maximal mitochondrial ATP power of the contracting muscle is muscular and systemic fatigue.

As you will learn in the next sections, intense exercise has a high reliance on the phosphagen and glycolytic systems, which leads to muscular fatigue and compromised performance. Why there is a difference in the rate of ATP regeneration between systems, and why fatigue develops using the phosphagen and glycolytic systems, and not mitochondrial respiration, will be revealed when you study each system in the Topics that follow.

Glossary Words

ATP regeneration occurs via the addition of a phosphate group to ADP to reform ATP.

energy systems involve metabolic pathways or individual reactions that comprise the

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phosphagen, glycolytic and mitochondrial respiration systems.

phosphagen energy system is the most immediate energy system consisting of the creatine kinase, adenylate kinase and AMP deaminase reactions.

glycolytic energy system is a intermediate energy system consisting of nine reactions that convert glucose to 2 pyruvate molecules.

mitochondrial respiration is the sum of all reactions of the mitochondria that contribute, directly or indirectly, to ATP regeneration.