The "Big Picture" of Physical Activity

How Fuel Supply, Conversion to Energy, and Conversion to Muscle Contraction Interrelate in the Human Body

By Thomas Griner

There exists among physical trainers and even textbooks an enormous amount of misinformation about skeletal muscle activity. This is so because they use a piecemeal "how" approach, without considering the holistic "why" approach. To simplify this incredibly complicated subject, a superficial discussion will be made on the aspects of some of the parts involved in the whole picture.

The heart and arteries are the pumping station and supply lines that push the "submarines" (subplasmines) that carry fuel and oxygen to the working muscles. Little consideration seems to be given to the veins and lymphatics which remove the waste products from the muscles. When an athlete "cramps-out", it is due to insufficient venous drainage, not inadequate arterial supply.

The liver is the 'filling station" which re-supplies the arterial blood with fuels, which are then deposited in the 'fuel tanks" located in the muscles. The liver holds as much carbohydrate fuel as do all the "fuel tanks" combined when activity starts. The liver also removes what the muscles treat as a "waste product", but which the liver converts back into fuel. The rate at which the liver can clear this waste product from the blood ultimately determines the maximum rate of activity that can be sustained.

The two standard fuels are carbohydrates, in the form of glucose, and free fatty acids, in the form of palmitic acid. To better understand the relation of their conversion to energy, it is helpful to know that fatty acids are treated as long-chain carbohydrates. It also explains why eating too many carbohydrates makes you fat.

A simple discussion of chemical reaction is needed in order to talk about converting fuel to energy. The two main types of chemical reactions are oxidation and reduction. You dont need to know the involvement of oxygen, hydrogen, and electrons in each type, you only need know that an oxidation reaction produces energy, while a reduction reaction consumes energy, and that an "oxidation reaction" doesn't always involve oxygen. Those oxidation reactions which do involve oxygen are called "aerobic", while those that do not are called "anaerobic".

The reactions which convert fuel to energy occur in cellular organelles called mitochondria. They provide the enzymes (catalysts) and substrate needed to cause reactions to occur at body temperature, and they control free radicals that result from some reactions. The muscles contain hundreds more anaerobic mitochondria than aerobic mitochondria. The aerobic mitochondria contain five activities: (1) the Krebs (or citric acid) cycle, strips off the hydrogens and, using H20, dumps the carbon as Co2while providing more hydrogen. The next three functions within the aerobic mitochondria are performed by cytochromic oxidase; (2) Strips electrons from the hydrogen. (3) accepts oxygen that is actively transported to the mitochondria by myoglobin (a first cousin to red cell hemoglobin), uses the 02 to dump spent hydrogyen as H20. (4) captures energy from the electrons along an "electron chain" where it is used for phosphorylation of ADP and creatine. This is similar to the manner in which a fuel cell produces electrical energy; the muscles are a form of electrical stepping motors. (5) The fifth and final activity is the fatty acid spiral,
which chops the 16 carbon fat chain into 2 carbon chains because that is what "fits" into the Krebs cycle. Before we discuss how the 6 carbon glucose is prepared for entry into the Krebs cycle, we need to describe the three different types of striated muscle fibers.

Gray's Anatomy has created confusion by discussing four different types of mammalian striated muscle fibers. We are of the Kingdom of animals but we are very different from most other animals; we are of the Class of mammals but we are also very different from most other mammals. We are of the Order of primates, and not so different from other primates. The point is, some mammals may indeed have four muscle types, but primates - including humans - only have three types of striated muscle fiber.
These three types are cardiac (heart), aerobic slow-twitch, and anaerobic fast-twitch (the last two being skeletal muscle fiber). They are all very different from one another, in structure as well as function. The fast and slow-twitch fibers are in a 50/50 mix in the muscles (which is not true of non-primates, whose skeletal muscles may be comprised of almost all fast or slow-twitch fibers). But the primate fast-twitch are twice the diameter of the slow-twitch, so the fibers which make up fibers are in fact an 80/20 mix volume-wise (remember ^R2).The difference in modes of energy production make it possible for the fast-twitch fiber to be larger.

When a nerve triggers a muscle to contract, it does so by causing calcium ions to rush into the fibrils. The waiting calcium is produced and stored in "cisterns" throughout the fibrils. The cisterns in the fast-twitch muscles are three times the capacity of the slow-twitch muscles (viola!). The cardiac muscles are very slow-twitching fibers, so they don't need cisterns; the concentration of calcium in body fluid is all they require. If your leg muscles were ail slow-twitch fibers, your top speed would be 8V2 MPH (sprinters reach
25 MPH). If your legs were powered by cardiac muscle, your top speed would be less than 4 MPH.

Since the fast-twitch fiber can contract three times faster than the slow-twitch fiber, it needs energy three times faster. Obviously the energy delivery system that is right for one will not do for the other. Aerobic mitochondria must be placed on the perimeter of a muscle fiber to be near an oxygen-providing capillary. The energy must then be transported to the interior fibers. This works OK for the slow-twitch fiber (and is also why they can't grow so large in diameter). This is why a fatty acid spiral was included in the description of the aerobic mitochondria; fatty acid is the fuel of choice for the slow-twitch fiber, so its fuel tank contains lipids, which are also stored on the perimeter near the mitochondria.

The fatty acid spiral consumes as much energy as it produces in chopping the chain into 2 carbon segments, so there is no anaerobic energy produced. Glucose can be split into two 3 carbon chains, and produce five times as much energy as it consumes. The Krebs cycle can accept a 3 carbon chain so long as the middle carbon has a double-bond oxygen (the fatty acid spiral can't do this).

This end product of glycolysis (the splitting of glucose) is called *pyruvic acid.* In addition not requiring a time-consuming trip from the periphery, the anaerobic glycolytic energy is provided two and one-half times faster than aerobic energy. The glucose fuel tanks are located all throughout the fiber, just as the anaerobic mitochondria are. The pyruvic acid near the center of the fiber now has a long trip to reach the aerobic mitochondria in adjacent slow-twitch fibers. (It would be wasteful as well as space-consuming for the fast-twitch fibers to also have aerobic mitochondria, because the slow-twitch aerobics aren't needed by the slow-twitch fiber after passing 8 ½ miles per hour, and can time-share below 8 ½ miles per hour.)

This rush to the border causes pyruvic acid to become so concentrated inside the fast-twitch fiber that it threatens to stop the glycolytic energy production. The PH triggers the pyruvic acid to be converted to lactic acid (the lactic acid has to be greater than 10 times more concentrated than pyruvic acid to prevent this conversion). Lactic acid is not caused by too little oxygen, but by too much pyruvic acid. So lactic acid acts as a pyruvic acid sinkhole. Lactic acid no longer has a double-bond oxygen on the middle carbon, so it cannot enter the Krebs cycle and there is no mitochondria in the muscle that can re-establish the double oxygen bond. (The mitochondria capable of doing this are only found in the heart and liver, and are three times the size of the aerobic mitochondria in the slow-twitch fiber. That aerobic mitochondria is three times the size of the anaerobic mitochondria which pervade the fast-twitch fiber. The cardiac muscle fibers, unlike the skeletal muscles, are loosely packed, thus leaving space for such a large mitochondria. That very large mitochondria is purple in color, and is so numerous as to cause both the heart and liver to have a purple cast.) The lactic acid must therefore diffuse to a capillary and exit the muscle, eventually to be removed by the liver as was mentioned earlier. This is why it takes about one hour for the excess

blood
lactic acid to be cleared after heavy exercise.

When the pyruvic acid does reach the aerobic mitochondria in the slow-twitch fiber, the number of hydrogens thrown off by the Krebs Cycle produces almost twice the energy as did the glycolysis that formed the pyruvic acid. That is more energy, but at a slower rate. The oxidizing of pyruvic acid is as important for reducing the amount that is converted to lactic acid as it is for the energy produced.

As we already mentioned, the slow-twitch fibers are surrounded by blood-red myoglobin
for rapid oxygen transport. Since the fast-twitch fibers have no aerobic mitochondria, they contain no red myoglobin. Hence, slow-twitch fibers are called ‘red muscle fibers', while fast-twitch fibers are called *pale muscle fibers' (dark meat and white meat).

You may have noticed that the anaerobic energy was not produced at a fast enough rate to allow the fast-twitch fiber to reach its 3X faster maximum twitch rate. That is because there is one last energy source to be discussed.

The energy source which provides the quantum energy needed to make the muscle contract comes from the oxidative breakdown of ATP (adenosine triphosphate) into ADP (adenosine di-phosphate) + phosphate. In the slow-twitch fiber, the ADP travels out to the aerobic mitochondria to be reduced back to ATP using the energy derived from electron energy. In the fast-twitch fiber, the adenosine does not move, but remains next to the site of contraction action. Energy is delivered to these fixed ADP by phospho-creatine (PC), which oxidatively breaks down to creatine and phosphate in order to reduce the ADP back to ATP. Most of the creatine moves to a nearby anaerobic mitochondria to be reduced back to PC by the energy provided by
glycolysis. A lesser amount makes the trip to the aerobic mitochondria to be reduced to PC by the energy produced there. (There is 3X as much creatine as adenosine.)

The PC and ATP are known as the 'phosphagen system'. This system can provide energy 4X faster than the aerobic. Even so, the increased friction of high-speed movement causes this rate of energy supply to fall just shy of allowing the fast-twitch fibers to achieve their full contraction rate.

The phosphagen system stores enough energy to provide 15 seconds of maximal muscle
output. During that 15 seconds, the anaerobic system re-charges 62% of the phosphagen system and so on, for a total of about 35 seconds of maximum output; and then you crash. The 100 and 200 meter dashes are true all-out events, while 400 meters requires some pacing. A 300 meter dash would be an interesting borderline all-out event- Power lifters also use the phosphagen system to obtain maximum output.
Marathon runners must run at a pace that allows the anaerobic system to always keep the phosphagen system fully charged. Moreover, they must not force the rate of lactic acid conversion to cause a concentration level that would prevent further conversion, thus forcing the pyruvic acid concentration to the point of stopping glycolysis (game over). The level at which this occurs has been measured as .45%. The blood lactic acid concentration of exhausted athletes never measures higher than .22%, thus showing
the concentration gradient needed to drive the lactic acid out of the muscle. Marathon training increases the number of aerobic mitochondria in the slow-twitch fiber three-fold to further reduce the need for lactic acid conversion.

Training also increases the number of capillaries, thus causing the blood lactic acid level to rise, because the muscle can dump more lactic acid for a given concentration gradient. Finally, it is the liver's responsibility to keep the blood concentration down.

Olympic marathon runners average around 12 MPH, leaving the slow-twitch muscle fibers far behind. That is why the banquet held the night before some marathons is dominant in carbohydrates, the fuel of choice for fast-twitch fibers.

The marathon is run in a state of equilibrium in which lactic acid is eliminated at the same rate it is produced, so the factor that limits the time and distance is fuel supply. The increased muscle friction which is so dominant in the dashes, starts to show up at 12 MPH. Above that speed, the increased workload needs oxygen at a higher rate than can be supplied in an equilibrium state.

The 20K race, which is a little less than half the marathon's 42K, is run at a little over 13 MPH. The runner is exhausted in 57 minutes, compared to about 130 minutes for the marathon. The marathon runner covers 20K in about 62 minutes. What a difference one mile per hour makes! Obviously, fuel is not the limiting factor in faster races; rather, it is lactic acid.

As a point of interest, the slower you run, the slower the rate of fuel consumption so the longer you can run. If you run less than 8½ MPH, you even increase the usable fuel supply. A trained athlete can sustain about 7½ MPH for 8 hours, giving a distance of 59 miles. That 7½ MPH is run with a mix of fast and slow-twitch muscle fibers. The muscles never operate totally aerobically.

At basal metabolic rate, 85% of the oxygen you breath is used by the aerobic slow-twitch fibers, and 15% by the anaerobic fast-twitch fibers. Pyruvic acid oxidation measurements show that at this lowest metabolic rate (basal), pyruvic acid to lactic acid conversion is 50%; so one pyruvic acid molecule is aerobically oxidized from the two produced by glycolysis. The others produce a measurable blood lactic acid level even
while you are asleep. A fatty acid molecule consumes 12X as much oxygen as a pyruvic acid molecule, so the 85/15 oxygen ratio becomes a fuel ratio of ~2 glucose/1 palmitate.

Natural athletes are not average bodies with above-average drive to excel; instead, their nervous systems have a quirk which allows them to be more efficient and rapid in movement than is the average person. Patterned movements are controlled by the cerebellum (rather than the cerebrum), and the interconnection between the cerebellum and nerves to the muscles is in a midbrain area called the pons (bridge). The pons is unusually well-developed in natural athletes, resulting in greater coordination, which allows them to perform a given physical output with less energy.

In addition, they are able to utilize oxygen more rapidly than the average person. Furthermore, in addition to greater coordination, this combination of reduced energy required and increased oxygen availability also results in another advantage: less lactic acid produced for a given output.

Finally, so-called "aerobic" exercises are done at such a rate that anaerobic metabolism is the dominant energy supplier. What's in a name?

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