Endurance Training: The Science Behind the Grueling Workouts

MISEP Capstone Project

Lauren Beal
MISEP Cohort 1
University of Pennsylvania
August 16, 2007

Endurance Training: The Science Behind the Grueling Workouts

Project Overview

I can still remember those Saturday morning practices. We were all still half-asleep as we piled out of our coach's van and into the pool at 5:30 am. The long practices on Saturday mornings were perfect for getting in a lot of yards; one of our coach's favorite sets to start the morning was 3 x 2000, a set of eighty laps repeated three times. My memories of the long sets and exhausting sprint repeats, while still vivid, are not unique. All serious athletes follow a tough training regimen comprised of large volume sets, interval training and fast repeats. But what is the scientific rationale behind this training? What is really happening within our bodies when we challenge them so severely?

Throughout this program, we have been challenged to examine phenomena through a variety of lenses and on many levels. I know from experience what it feels like to swim or run to the point of exhaustion, but I wanted to understand what was happening on a cellular level. How do individual cells respond and adapt to demands of exercise? How can we use this knowledge and translate it into better performances?

The science content portion of this capstone project focuses on the cellular adaptations – within skeletal muscle – to exercise and stress. I first address the major metabolic pathways supplying energy to the working muscle, and then move on to examine the structure and function of a skeletal muscle cell. Slow-twitch and fast-twitch fibers can be linked to specific types of activity, and I describe one recent study that suggests how a conversion between these fiber types might occur. Muscle fibers subjected to a certain amount of stress (i.e., exercise) undergo both acute and chronic adaptations. There are numerous factors considered as triggers for these adaptations; current research in this field focuses on the mechanisms involved in causing these adaptations. One specific area of research is the group of signaling cascades that lead to increased transcription activity within cells. It is still unclear how this knowledge might influence sports training and athletic performances.

The pedagogy portion of this paper applies some of this information to a seventh grade life science curriculum, in the hopes of extending the curriculum and connecting it to students' lives outside of school. So many of our students are athletes, and this unit will provide them with a deeper understanding of what is happening within their muscles. The unit is also designed to help students make connections between the cellular, tissue and organism levels of the life sciences and tie previous learning to new experiences; these connections are crucial to development of a coherent conceptual framework for the study of biology. Students will experience a variety of hands-on activities, labs and simulations as they learn about muscles from the cellular to the system level. Students will end their unit of study with a choice of a final project, which will be shared with the local school community.

My swimming days are long in the past, but the memories are still clear. This paper has helped me to understand the science behind the long sets we had to endure, while the pedagogy piece aims to illustrate this connection for today's student athletes.

Endurance Training: The Science Behind the Grueling Workouts

Science Content

On any given day, Olympic swimmer Michael Phelps logs between 5,000 and 10,000 yards in the pool. He practices 365 days a year – nearly half of which include double practices. His workouts are a mix of distance training, interval sets, technique drills and dry-land training (Bowman, 2003). Yet although Michael Phelps is one of the world's elite athletes - a status supported by the sheer volume of his workouts - the fundamental principles guiding his training program are the same as any other aspiring athlete. Whether one is a beginner hoping to get in shape or a competitive athlete striving to win a race, there is a general set of underlying training rules that apply. These training guidelines often vary between differing sports and levels of intensity.

Despite differences in training programs and sports, however, there is a common goal for all competitive athletes: increase the ability to sustain the highest possible power output or speed for a given distance or time. This ability is dependent on the rate at which chemical energy is converted into mechanical energy, allowing for skeletal muscle contractions (Hawley, 2002). It seems logical, then, to train in a way that induces responses or adaptations within the muscles that in turn increase this rate. Recent work by exercise biochemists has identified key mechanisms that trigger these responses and adaptations within muscle cells. These mechanisms help to explain some of the cellular adaptations found in elite athletes and trained individuals. By studying the effects of endurance training on the cellular level, it is possible to gain a greater understanding of cellular adaptations and in turn, influence new training programs to optimize athletic performance.

Metabolic Pathways Used to Produce ATP

Skeletal muscle, the predominant muscle type used in intense exercise, depends on adenosine triphosphate (ATP) for energy to power muscle contractions (Figure 1). Muscle cells produce ATP through three metabolic

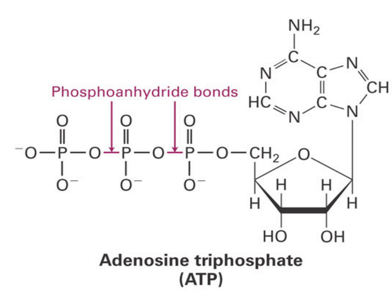

Figure 1. Adenosine triphosphate (ATP). Adapted from fig.cox.miami.edu.

pathways. The simplest and fastest way of producing ATP is through the breakdown of phosphocreatine (PCr). This is a simple, one enzyme reaction. The PCr molecule, which is synthesized in the liver and stored within the muscle cells, donates its phosphate group and bond energy to form ATP. This process does not require oxygen. However, there is only a small amount of PCr in the muscle cells and it cannot be replaced until recovery from exercise; therefore, this process is limited. The ATP-PCr system provides immediate energy for muscular contraction at the start of exercise, and lasts only for a few seconds (Krogh, 2005).

The much-needed ATP can also be produced anaerobically through the process of glycolysis. This process involves the breakdown of glucose or glycogen into either pyruvic acid or lactic acid along with net gain of two ATP molecules, as shown in Figure 2. Glycolysis takes place within the sarcoplasm of the muscle cell (Figure 3). Again, oxygen is not needed for glycolysis alone. Throughout the coupled reactions occurring during glycolysis, hydrogens are removed from glucose and transported by carrier molecules ($NAD^+$and FAD^+). These carrier molecules transport hydrogens to the mitochondria for further generation of ATP through aerobic processes. It is necessary to note the importance of these hydrogen ions; if there is no oxygen present to accept these hydrogens in the mitochondria, pyruvic acid can accept them to form lactic acid. The formation of lactic acid allows the carrier molecule NADH to be converted back into NAD^+, which in turn allows glycolysis to

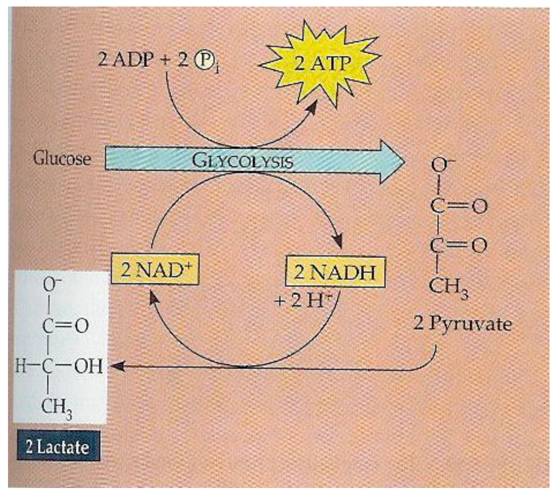

Figure 2. The anaerobic process of glycolysis converts glucose into pyruvate along with two ATP molecules. In the absence of oxygen, pyruvate is transformed into lactic acid. Adapted from Campbell, 1999.

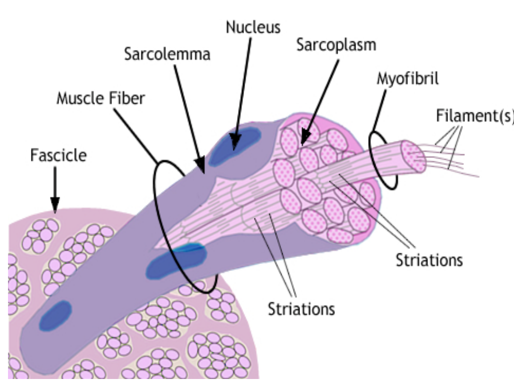

Figure 3. The sarcoplasm of the muscle cell is the location of glycolysis. Adapted from Structure of Muscle Cell, 2007.

continue (Powers, 2004). High lactate blood levels reflect the lactic acid accumulation in muscles as a result of this anaerobic process; these lactate levels are often used as indicators of athletic performance.

The final pathway used to produce ATP takes place within the mitochondria. When oxygen is present, the two molecules of pyruvate formed through glycolysis are converted into a two-carbon molecule (acetyl-CoA), which enters into the Krebs cycle. Numerous reactions within the Krebs cycle complete the oxidation of carbohydrates, proteins or fats and supplies electrons to be passed through the electron transport chain, providing energy for the ATP production (Powers, 2004). This complete pathway results in the production of 32 molecules of ATP (Krogh, 2005).

Various enzymes regulate these metabolic pathways, and as noted later, a variety of stimuli can affect these rate-limiting enzymes. It is important to note that the energy needed to perform exercise comes from both aerobic and anaerobic pathways simultaneously, not one and then the other. The time and intensity of exercise influences whether aerobic or anaerobic metabolism plays a larger role in energy production. There is a greater anaerobic ATP contribution in short-term, high-intensity exercise such as sprinting, while long-term activities have a greater aerobic ATP contribution. This interaction of aerobic/anaerobic energy production is illustrated in a simple short jog. When a runner takes off, the anaerobic ATP-PC system provides the necessary immediate energy. This system, which only provides enough energy for about five seconds, is quickly supported by ATP produced through glycolysis. As the runner reaches the two to three minute mark of his jog, 50% of his energy is a result of aerobic production. This percentage of aerobic/anaerobic continues to increase as time increases (Campbell, 1999).

The knowledge of these three metabolic pathways and the interaction between them is important when planning conditioning and training programs. Studies have shown that the oxidative capacity of the muscle cell is the most important biochemical characteristic in determining muscle function. A muscle's oxidative capacity is determined by its number of mitochondria, the amount of surrounding capillaries and the amount of myoglobin within the fiber. A greater number of mitochondria provide more sites for aerobic production of ATP; there are more places to utilize oxygen. A higher density of capillaries will ensure the muscle fiber receives adequate oxygen during contractions. Myoglobin acts as a shuttle, moving oxygen between the cell membrane to the mitochondria where it will be used. A greater amount of myoglobin will improve delivery of oxygen to the mitochondria. A high amount of these three factors will result in a more efficient muscle cell – one that is more fatigue resistant (Powers, 2004).

Studies conducted on elite athletes support this. The most common research studies done to determine performance levels include testing maximal oxygen uptake, blood lactate levels, mitochondrial enzyme levels and capillary density (Dalleck, 2007). Elite athletes consistently have higher maximal oxygen uptakes (VO_{2max}) than untrained individuals; in simple terms, the athletes use a greater percentage of the oxygen they take in than those who are untrained. VO_{2max} is a measure of the volume of oxygen (ml) one can use in one minute per kilogram of body weight while exercising at maximum capacity (Dalleck, 2007). Individuals perform a physical test to determine $VO_{2max.}$ Exercise intensity is increased while oxygen and carbon dioxide concentrations of inhaled and exhaled air are measured. VO_{2max} is reached when oxygen consumption stays constant despite an increase in workload (Dalleck, 2007).

Trained individuals also have an increased number of mitochondria within skeletal muscle; within these ATP-producing organelles, there are a greater number of mitochondrial enzymes. As noted above, this increase in mitochondria and mitochondrial enzymes creates an enhanced ability to generate energy through aerobic respiration, therefore producing a lower amount of lactate. Elite athletes and trained individuals also have increased capillary density around the muscles, helping to improve blood flow and oxygen supply to and from the exercising muscles. In addition, this increased capillary density helps to clear lactate more quickly (Powers, 2004). Research has revealed these physiological differences between trained and untrained individuals, but what causes these adaptations? What role does endurance training play in this process?

A Closer Look: Inside of a Contracting Skeletal Muscle

Intense exercise relies on the constant, quick contractions of skeletal muscles. Muscle fibers contract as a result of a complex process that shortens their myofibrils through the sliding of the actin filament over the mysosin filament. Two regulatory proteins, troponin and tropomyosin, control the interaction of myosin and actin filaments. These proteins are triggered by an increase in calcium within the cell; when a muscle is relaxed, there is a low Ca^{++} concentration. When a nerve impulse reaches the muscle cell, it releases stored calcium, which binds to troposin. This binding causes the removal of tropomyosin from the active sites on the actin filament. Cross-bridge attachments can now form between the actin and myosin filaments, allowing for sliding between the filaments and muscle contraction (Figure 4). These cross-bridges are powered by the breakdown of ATP. This contraction cycle is dependent upon ATP and Ca^{++}; if either of these is depleted, fatigue occurs (Powers, 2004).

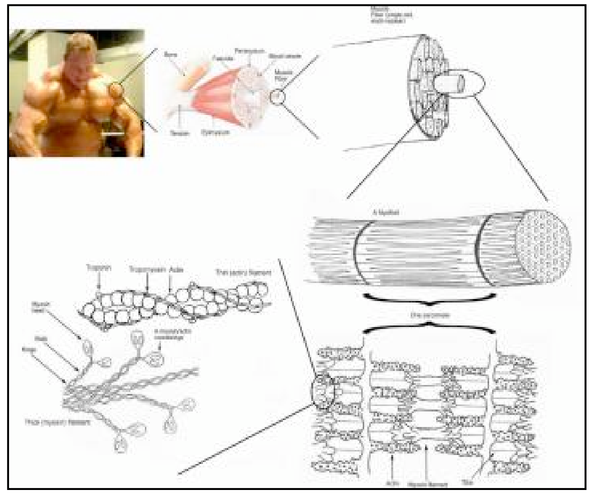

Figure 4. This look inside of a muscle cell shows the myosin and actin filaments within the myofibrils. Cross-bridges formed between the two filaments facilitate contractions. Adapted from HistoWiki, 2007.

This process of contraction occurs in all muscle fibers, although the time required for this process can vary. The speed at which a muscle fiber breaks down ATP determines the speed of muscle shortening or contraction. Muscle fibers are generally identified as one of three types: type I, a slow fiber, and types IIx and IIa, both types of fast fibers. Most muscle groups contain an equal mixture of slow and fast fibers. Exercise, genetics or hormone levels can all influence the percentage of fiber types within skeletal muscle (Powers, 2004). Type I fibers, or slow-twitch fibers, contain large numbers of mitochondria, have a higher myoglobin concentration and are surrounded by the most capillaries. This allows for a higher aerobic capacity and more resistance to fatigue. In contrast, fast-twitch IIx fibers contain a smaller number of mitochondria and are therefore less resistance to fatigue. However, they do have larger amounts of glycolytic enzymes and therefore have a greater anaerobic capacity as compared to Type I fibers (Powers, 2004).

Type IIa fibers fall in between the other two types, although they are classified as fast-twitch fibers. These fibers are highly adaptable; with endurance training, they have been shown to increase their oxidative capacity (number of mitochondria) to Type I levels (Gunning, 1991).

There is no significant difference in fiber type distribution between men and women, or across varying ages (Powers, 2004). The average person's muscular make-up ranges from about 47 to 53% slow fibers. Among successful elite athletes, sprinters have a higher percentage of fast-twitch fibers, while endurance athletes have a higher percentage of slow-twitch (Type I) fibers (see Figure 5, Powers 2004). However, it is important to note that a significant difference in fiber type exists even among the athletes. This illustrates that muscle fiber type alone does not dictate successful performance (Powers, 1992).

Subjects	% Type I (slow) fibers	% Type IIx and IIa (fast) fibers
Distance runners	70-80	20-30
Track sprinters	25-30	70-75
Non-athletes	47-53	47-53

Figure 5. The percentage of slow-twitch (Type I) and fast-twitch (Types IIx and IIa) muscle fibers varies among different athletes and individuals. Figure adapted from Powers, 2004.

The range of muscle fiber percentages begs the question, can endurance training cause changes in muscle fiber types? Recent research has shown that endurance training can produce a Type II to Type I shift within skeletal muscle. One such study, conducted on rabbits, showed a shift from fast to slow fibers involving sequential changes in enzyme activities, reduction of Ca^{++} and changes in RNA (Pette, 1984). These findings were supported by a more recent study using rats; ten weeks of endurance training showed a significant shift from Type IIx to Type I fibers. There was also a noted dose-response relationship; as exercise was increased from 30 to 90 minutes per day, there was a greater increase in fiber-type transformation (Demirel, 1999).

Recent Research: Identifying the Role of PGC-1α

In 2002, a team of researchers at the Dana Farber Cancer Institute announced a key finding: the discovery of PGC-1α, a molecule that appears to be the "chemical switch" in transforming fast-twitch into slow-twitch fibers (Lin, 2002). PGC-1α had previously been recognized as an abundant molecule within muscle cells that induces mitochondrial biogenesis (Lehman, 2000). This knowledge, coupled with the fact that muscle fiber type is largely determined by the amount of mitochondria present, inspired researchers to focus on the role of the PGC-1α molecule in fiber type conversion. Scientists first examined the expression of PGC-1α in various muscle types and found it was highly expressed in type I (slow) fibers. They next generated transgenic mice by placing PGC-1α DNA downstream of a MCK promoter sequence – a sequence that is primarily activated in type II (fast) fibers. They observed that PGC-1α protein levels were elevated in type II muscle fibers of the transgenic mice and identified an increased expression of mRNA for mitochondrial enzymes. The transgenic expression of PGC-1α also unexpectedly induced genes for myoglobin and troposin I, two molecules abundant in type I fibers (Lin, 2002).

The researchers next used metachromatic staining to distinguish between type 1, IIa and IIb fibers in both the transgenic line and the wild-type (control) muscle. The staining revealed 10% type I and 20% type IIa fibers within the plantaris muscle of the transgenic mouse; this muscle was almost entirely composed of type IIb fibers in the wild-type mouse (Lin, 2002). This finding further supported the hypothesis that PGC-1α was involved in the "switching" of type II fibers.

Muscles were next isolated and subjected to continuous electrical stimulation to test fatigue resistance; this electrical stimulation simulated the muscle contraction that occurs during exercise. In this study, the transgenic muscles were able to sustain continuous contraction longer than the control (wild type) muscles. This shows that PGC-1α expression correlated with a conversion toward a more aerobic state – a state usually associated with type I fibers because of their high mitochondrial concentration (Lin, 2002).

The researchers concluded PGC-1α was the main "switch" in muscle type conversion based upon the combined results of these experiments. The studies showed that PGC-1α is expressed in muscle rich in type 1 fibers, that PGC-1α elevation in type II fibers showed marked changes within the muscles and that PGC-1α stimulates genes linked to mitochondrial biogenesis and the expression of type I proteins, such as troposin I (Lin, 2002). It is still unknown, however, how physical exercise or nerve signals might control PGC-1α activity.

The Skeletal Muscle Cell: What Causes these Adaptations?

The adaptations occurring in skeletal muscles have been discussed in several instances – but what is it that causes these changes? The identification of PGC-1α was a major breakthrough to understand muscle fiber transformations. Overall, however, researchers have not yet found the answer; the mechanisms by which exercise modifies gene expression are still mostly unknown, though there are promising developments. Cellular muscle adaptations are classified as either acute or chronic. Acute adaptations refer to immediate responses in muscle cells, such as an increase in enzyme levels. Chronic exercise adaptations, however, refer to changes in muscle cells that continue for extended periods as a result of training (Hawley, 2002). The signaling mechanisms that trigger these chronic adaptations are the focus of much current research.

There are numerous possible factors that might induce cellular changes and result in these adaptations. “Exercise is a very complex physiological stimulus that challenges multiple biochemical and biophysical aspects of cellular function and therefore requires an appropriate control network” (Widegren, 2001). Some or many of the factors involved in exercise might trigger signaling mechanisms. These include increased blood flow, muscle contractions, energy depletion, increased lactate concentration, or lower pH within the muscle and/or blood (Widegren, 2001). All of these factors can cause muscle fatigue, disrupting the homeostasis of the cell. A major function of adaptation is to minimize this disruption of homeostasis during exercise (Booth, 1991). In addition, the release of autocrine and paracrine signals from muscles could also stimulate cell surface receptors and trigger changes. Recent research has focused on one type of signaling mechanism – the mitogen-activated protein kinase (MAPK) signaling cascade – as a possible mechanism for regulating these adaptations (Hawley, 2002).

Protein kinases are catalysts that facilitate the addition of a phosphate group to a protein; the phosphate group being accepted by the protein is transferred from an ATP molecule. A mitogen-activated protein kinase refers to a specific kinase, or enzyme, that is stimulated by something outside of the cell (for example, lower pH or increased blood lactate levels). When activated, the kinase catalyzes the phosphorylation of its specific protein target. This newly phosphorylated protein is now able to take part in another reaction, which might result in a product that takes part in a third reaction. This chain-like sequence of events is known as a signaling cascade.

There are a number of complicated signaling cascades at work in muscle cells. Recent work has focused on both the MAPK and the 5'-Adenosine Monophosphate-Activated protein kinase (AMPK) signaling cascades because of their association with increased transcriptional activity (Widegren, 2001). Several kinases found within the MAPK cascade have been linked to the phosphorylation of transcription factors. In addition, some of the factors associated with exercise (changes in intracellular calcium and mechanical stress) have been shown to stimulate MAPK cascades, making them a likely mechanism for muscle adaptations (Widegren, 2001).

Several kinases within the MAPK cascade have significant increases in activity during exercise (Hawley, 2002). Researchers have determined that one of these kinases is intensity-dependent; it has a greater rate of phosphorylation with higher intensity exercise. This increase of phosphorylation occurs only within the exercising muscle, pointing to local factors rather than systemic factors as triggers (Hawley, 2002).

The AMPK cascade has also been tied to muscle adaptations in response to exercise. Repeat activation of this cascade is now considered a possible reason for the increased mitochondrial oxidation enzyme activity in exercising muscle (Hawley, 2007). The AMPK cascade is triggered by changing Ca^{++} concentrations within the cell. During exercise, a muscle cell's Ca^{++} concentration increases, leading to a depletion of ATP and increase of adenosine monophosphate (AMP). The increased transformation of ATP to AMP activates the AMPK signaling cascade. The AMPK cascade has been linked to the regulation of many growth responses in skeletal muscle. Repeat, or chronic, activation of the AMPK increases the protein expression of glucose-transporter 4 (GLUT 4), a carrier protein that brings glucose into the cell (Hawley, 2007). The amount of GLUT 4 protein present in a cell limits the amount of glucose that can be brought into the cell and converted to energy. Higher GLUT 4 levels mean faster restoration of glucose levels after exercised-induced depletion of glucose, which is another characteristic of a highly trained athlete. The AMPK cascade has also been linked to the increase of mitochondria and oxidative enzymes (Hawley, 2007).

Although there is a large amount of recent research on signaling cascades, specifically the MAPK and AMPK cascades, there are also still many unknowns. "A big challenge for exercise biochemists … will be to directly link signaling events in skeletal muscle that occur during or after training to defined metabolic responses and specific changes in gene and protein expression that ultimately result in the phenotypic adaptations that are essential for improved endurance performance" (Hawley, 2007).

Implications for Training: The Link between Biochemistry and Performance

The link between these biochemical processes and accepted training practices is not always clear nor direct. Although we can see the scientific basis for many of today's accepted training programs, much of the recent work on signaling cascades does not yet have a direct application for athletes; it focuses on the individual mechanisms causing these adaptations, rather than the adaptations themselves. It is valuable, however, to review the common training programs for endurance athletes to see how science has influenced practice thus far and perhaps hypothesize about how it might evolve in the future.

The basic practice for any aspiring endurance athlete – a runner, for example – includes three types of training: long (slow) distance training, interval training, and high-intensity, continuous exercise (Powers, 2004). All of these exercise types employ the idea of overload; a muscle cell must be stressed above its normal level for change to occur. We might think of overload as running an extra mile. On a cellular level, these stressors are the same factors discussed as possible triggers for signaling cascades. Endurance athletes consistently increase their workload, building volume and continuously logging long distances over time. Science supports this; we now know that increased training leads to a higher VO_{2max}, a greater number of mitochondrial enzymes, a higher concentration of GLUT 4, and lower blood lactate levels. All of these adaptations are observable in elite athletes and lead to better performances.

If you examine an endurance athlete's training schedule further, you would notice some sets of high-speed interval training – quick, high intensity runs followed by recovery time. These sets of high-intensity exercise were once considered less important than long, slow distances, but recent research has shown high-intensity exercise appears to result in the same muscle adaptations caused by long runs, at least initially (Gibala, 2006). A group of Canadian exercise metabolism researchers compared the effects of low-volume sprint-interval training and high volume endurance training and found similar metabolic and performance adaptations in both subject groups (Gibala, 2006). Although this was the first standardized comparison of the two training strategies, the conclusion could have a profound impact on future training practices. Endurance athletes could potentially train with short distance, high intensity sets rather than high volume sets without compromising their performances.

It is evident that new scientific understandings have a great influence on training programs and performance. It is too early to tell how new developments with signaling cascades might affect athletic training programs, if at all. What will the new discoveries tell us? Will there be a positive application? One of the immediate reactions to the PGC-1α discovery was a question about the possible development of an athlete-enhancing drug that would activate the molecular "switch" and convert muscle fibers to Types I and IIa. Although scientists involved in the study discounted that idea, they did point to the possible creation of medicines that target degenerative muscle diseases (Research Matters, 2002). The possibilities for future applications of new knowledge are broad. As researchers study the effects of endurance training on a cellular level, new understandings will continue to influence training practices and shape athletic performance.

Works Cited

Adenosine Triphosphate (image). Downloaded from http://fig.cox.miami.edu/~cmallery/255/255metab/mcb2.24.ATP.jpg.

Booth, F., and Thomason, D. (1991). Molecular and cellular adaptation of muscle in response to exercise: Perspectives of various models. *Physiological Reviews* 71, 541-85.

Bowman, B. and Scott, M. (2003, February). Training Michael Phelps. http://www.swimmingworldmagazine.com/articles/swimtechnique/articles/200301-01st_art.asp.

Campbell, N., Mitchell, L., and Reece, J. (1999). *Biology*. New York: Addison Wesley Longman, Inc.

Dalleck, L. & Kravitz, L. Optimize Endurance Training. Retrieved Thursday, April 19, 2007, from www.unm.edu/~lkravitz/Article%20folder/optimizeendurance.html.

Demiral, H., Powers, S., Naito, H., Hughes, M., & Coombes, J. (1999). Exercise-induced alterations in skeletal muscle myosin heavy-chain phenotype: dose-response relationship. *Journal of Applied Physiology* 86, 1002-08.

Glycolysis (2007). Pearson Prentice Hall: the Biology Place. http://www.phschool.com/science/biology_place/biocoach/cellresp/glycolysis.html.

Gunning, P., and Hardeman, E. (1991). Multiple mechanisms regulate muscle fiber diversity. *FASEB Journal* 5, 3064-70.

Hawley, J. (2002). Adaptations of Skeletal Muscle to Prolonged, Intense Endurance Training. *Clinical and Experimental Pharmacology and Physiology* 29, 218-222.

Hawley, J and Spargo, F. (2007). Metabolic Adaptations to Marathon Training and Racing. *Sports Medicine* 37 (4/5), 328-331.

HistoWiki: Free Histology Encyclopedia (2007). Image downloaded from http://www.ihcworld.com/histowiki/fetch.php?w=360&h=&cache=cache&media=skeletal_muscle.jpg.

Gibala, M., Little, J., van Essen, M., Wilkin, G., Burgomaster, K., Safdar., A., et al. (2006). Short-term sprint interval versus traditional endurance training: similar initial adaptations in human skeletal muscle and exercise performance. *Journal of Physiology* 575 (3), 901-911.

Krogh, David. (2005). *Biology: A Guide to the Natural World.* New Jersey: Pearson Prentice Hall.

Lehman, J., Barger, P., Kovacs, A., Saffitz, J., Medeiros, D., & Kelly, D. (2000). Peroxisome proliferator-activated receptor coactivator-1 promotes cardiac mitochondrial biogenesis. *Journal of Clinical Investigation* 106, 847-856.

Lin, J., Wu, H., Tarr, P., Zhang, C., Wu, Z., Boss, O., et al. (2002). Transcriptional co-activator PGC-1 drives the formation of slow-twitch muscle fibers. *Nature* 418 (6899), 797-802.

Pette, D. (1984). Activity-induced fast-to-slow transitions in mammalian muscle. *Medicine and Science in Sports and Exercise* 16, 517-28.

Powers, S. (1992). Aging and respiratory muscle metabolic plasticity: effects of endurance training. *Journal of Applied Physiology* 72, 1068-73.

Powers, S. & Howley, E. (2004). *Exercise Physiology: Theory and Application to Fitness and Performance*. Boston: McGrawHill.

Scientists discover chemical switch that determines muscle fiber type. (2002). *Research Matters*. Retrieved Monday, July 16, 2007 from www.researchmattersharvard.edu/story.php?article_id=526.

Structure of a Muscle Cell (2007). Ivy Rose Holistic Health and the Human Body. Image downloaded from www.ivy-rose.co.uk/ Topics/Muscle_Cell.htm.

Widegren, U., Ryder, J.W., & Zierath, J.R. (2001). Mitogen-activated protein kinase signal transduction in skeletal muscle: effects of exercise and muscle contraction. *Acta Physiologica Scandinavia* 172, 227-38.

Endurance Training: The Science Behind the Grueling Workouts

Adapted to a seventh grade life science curriculum

Unit Description

In this unit, students will build upon their new understanding of cell structure and function by examining skeletal muscle from the cellular to the organism level. This unit is designed as a supplement/extension to the School District of Philadelphia 7th grade Core Curriculum: Cells, Heredity and Classification. Students will engage in web activities, simulations and experiments that allow them to understand the role of mitochondria within a muscle cell and connect it to exercise. Students will examine muscle fibers and the effect of stress on a group of muscles. They will evaluate various training programs and learn about the benefits of daily exercise. Finally, students will show their understanding of the unit through the completion of a self-directed final project. Students are presented with a choice of two final performance assessments: to create a nonfiction children's book or design a fitness program with a written defense. Each task requires students to show evidence of their understanding of fundamental ideas.

Unit Enduring Understandings:

1. The human body has many structural and functional levels.
2. Organisms are composed of cells that carry on the many functions necessary to sustain life. Specialized cells, such as muscle cells, work together to form larger systems.
3. In living organisms, there is a relationship between a part's structure and its function. A part's structure enables it to perform specific a function.
4. Organisms respond to internal and external cues on many levels, from the cellular level to the organism level. These responses allow the organism to survive.
5. Our behaviors affect our bodies in positive and negative ways.

Unit Essential Questions:

How is cellular activity related to what happens at the organism level?
Why are the mitochondria so important to our cells, particularly muscle cells?
How does exercise affect us on a cellular level?
Why do experts recommend 30 minutes of exercise each day?
How do our muscles work?

What will students need to know and be able to do (knowledge and skills):
Locate the mitochondria within a cell.
Explain the importance of mitochondria for the muscle cell.
Compare and contrast aerobic and anaerobic respiration.
List the different types of muscle and muscle fibers.
Describe simple muscle changes in response to exercise.
Evaluate a simple training program for effectiveness.
Explain good stress.
Identify examples of skeletal muscle.
Describe how our behaviors can affect our muscles.

Common Misconceptions

Students often hold preconceived beliefs about a topic that do not match what is known to be scientifically correct. It is extremely helpful to know what these preconceived ideas are before teaching a unit, as they can then be targeted through hands-on activities and direct instruction. According to a study published by the Michigan Science Teachers Association, students have a number of misconceptions about cells and the levels of organization. Students are usually confused about where cells belong in comparison to atoms and molecules (Berthelsen, 1999). Students often think that it is cells make up other things such as proteins and carbohydrates. This is understandable, given that cells are usually taught in isolation and introduced as the smallest unit of a living thing. Berthelsen (1999) also addresses the notion that only two kinds of cells exist – plant and animal. Students are generally introduced to cell structure through diagrams or cartoons of plant and animal cells, and it is easy to understand how this might surface later as a misconception. This research also points out student difficulty in understanding differences between cell division and enlargement and cell differentiation (Berthelsen, 1999).

Students also often misunderstand how systems work together. Rather than see the connection between body systems, students often believe that systems operate in isolation from each other (Human Anatomy, 2005).

The National Institute of Health [NIH] also addresses common misconceptions about the musculoskeletal systems. Students often think that muscles are only used for voluntary physical actions such as walking, running or jumping (NIH, 2005). It is important for students to recognize that skeletal muscle is not the only type of muscle we have; the smooth muscles found throughout our body and cardiac muscles of the heart are necessary for life functions. Students should understand that muscles are "hard at work," even during sleep. In addition, there are varying beliefs about the relationship between muscle and fat. Students (and adults) often believe that their muscles turn into fat if they stop exercising. This is not true; a person is born with a given amount of muscle cells. If he/she stops exercising, his/her muscle cells may decrease in size but they will not turn into fat (NIH, 2005).

Standards Assessed

Pennsylvania State Standards:
3.1.7A – Explain the parts of a simple system and their relationship to each other
3.1.7B - Identify different types of models and their functions
3.1.7 - Describe the effect of making a change in one part of a system on the system as a whole.
3.3.7B - Describe the cell as the basic structural and functional unit of living things.

- Identify the levels of organization from cell to organism.
- Compare life processes at the organism level with life processes at the cell level.
- Explain that cells and organisms have particular structures that underlie their functions.

National Standards:
Life Science: Content Standard C – Students should develop an understanding of the structure and function of living things

Unit Timeline and Overview

This unit requires approximately two weeks of daily classroom time (ten 45-90 minute sessions). All lessons should take place within a science classroom with access to computers and a classroom projector. Enduring understandings and essential questions for the unit will be posted in the classroom. Students will be informed of the final performance assessment at the start of the unit and be given time throughout the two-week period to work collaboratively on their projects.

Middle school students are always interested in their own bodies. Many of our students are athletes, dancers or cheerleaders, practicing daily to perfect their performances. This unit will begin with a concept walk that forces students to consider the connection between cells they have been learning about and the activities they enjoy.

Students will travel from station to station in groups, adding their thoughts and reactions to statements found on posters at each station. These poster statements will serve as a starting point for our explorations (see appendix). At the end of the unit, students will return to these posters and re-evaluate their answers, explaining how their understanding has deepened or changed.

In addition to the concept walk, students will also take a pre-unit assessment to determine prior factual knowledge. This pre-assessment will focus on the five questions required in the final project. Students will also set up an investigation about the effects of physical stress on muscles. Although this topic is covered toward the end of the unit, students will need to collect data during the entire two-week period. Students will start the investigation on day one and record their predictions and initial data.

The unit begins with an exploration of muscles on the cellular level. Students will review cell organelle structure and function by viewing Organelles in the Cytoplasm. A class discussion will focus on the importance of the mitochondria within the muscle cell. Students will continue to examine the mitochondria's role by viewing two short simulations/videos that focus on the organelle and its importance for exercise. Students will examine muscle cells under microscopes. Students will be responsible for their ongoing science notebooks during this unit, which will be used as an informal assessment. For this focus on the cellular level, students will also write a thank-you letter as the nucleus of a muscle cell to the mitochondria, explaining why the mitochondria are essential to the cell (creative writing exercise). Students will draw a diagram of the muscle cell, and identify a muscle cell under a microscope. A benchmark quiz, modeled after PSSA checkpoint questions, will be administered. Students will also construct an ongoing concept map (graphic organizer) on the classroom bulletin board. This map will begin with the terms muscle cell and mitochondria and will be added to throughout the unit, highlighting the connections between the levels of organization and knowledge gained from exploratory activities.

The next series of lessons in this unit focuses on the muscle tissue and system levels. Students will explore the structure of muscle fiber by comparing yarn and stewed meat. A whole class lesson following this activity will address specific muscle fiber types and their respective characteristics. Students will next dissect a chicken wing to study the connection between muscles and bones; this will serve as an introduction to muscle pairs. Students will next construct an arm model showing a pair of contracting and relaxing muscles. They will conduct an experiment to test whether muscle size and strength are related. After each activity, students will complete a written reflection and analysis, which will be used as assessments. A benchmark quiz, modeled after PSSA checkpoint questions, will be administered. Students will continue to add to the classroom concept map, showing the connection between one muscle cell (fiber) and a group of muscle fibers working together. They will add the terms muscle pair, contracting muscle and relaxing muscle and show the connection between these terms.

The final series of lessons addresses the system and organism levels. Students will build upon their knowledge by examining how muscles work together to perform common sports functions, such as kicking a soccer ball. A local track coach will visit the class and discuss training techniques for sprinters and long distance runners. Students will use real data to investigate the role of resistance training on muscle mass and construct graphs to determine a relationship. In addition to exploring the effects of exercise, students will learn about anabolic steroids, reading and discussing both a factual article and a current newspaper editorial. Students will evaluate a training program for effectiveness, and brainstorm suggestions for given scenarios. As they work through the activities in this section, students will continue to revisit essential questions and the class concept map.

The final portion of this unit includes an analysis of the two-week stress experiment, a unit reflection and a synthesis of unit understandings in the form of a final performance assessment. Students will write a formal report following their two-week "Good Stress" conditioning experiment. Students will review the statements they wrote in response to concept walk prompts at the start of the unit. They will re-evaluate their positions, changing answers if necessary, and write an explanation of why or how their view has shifted. Finally, students will demonstrate understanding through the development and presentation of either a nonfiction children's book or a fitness program and written defense. During periodic group planning meetings, students will have the opportunity to collaborate and conduct additional research on their position. In addition to the written portion, students will present their projects to their classmates. Those students who created a children's book will share their projects with the neighboring elementary school children. Students will also complete an end-of-unit traditional assessment for factual understanding.

Experiences
This section includes a more detailed description of the activities mentioned above.

Good Stress – an ongoing activity
Students will conduct a two-week experiment to test the effects of physical stress on muscles. On Day One, students will measure and record the number of times they can complete a simple hand activity in a given amount of time. They will do this exercise for five minutes every day. After two weeks, students will test the results of their conditioning by completing the same test and comparing results. They will draw conclusions about conditioning in sports and training programs based on their evidence.
Adapted from National Biomedical Research Institute: Muscles and Bones.

Organelles in the Cytoplasm (Streaming Video)

Students will reflect on previous lessons about cell organelle structure and function. They will view the short Organelles in the Cytoplasm video, which shows a variety of real cells (not cartoons!) and organelles within the cell. After watching the simulation, students will discuss the role of the mitochondria and brainstorm what kind of cells might require the most mitochondria, and why.

Adapted from Teacher's Domain: Muscles and Mitochondria.

Mitochondrion Flyover/Powerhouse of the Cell (streaming videos)

While viewing these two short videos, students review the structure and function of the mitochondria within the cell. After viewing the Mitochondrion Flyover, students will draw a mitochondrion in detail, labeling all the parts and writing a brief paragraph explaining how the structure of the mitochondrion relates to its function.

The second clip, Powerhouse of the Cell, shows the connection between different types of exercise and the role of mitochondria in muscle cells. This video will serve as an introduction to many of the following activities and give students some background information before a guest speaker visit. Students will be introduced to the different types of muscle fiber and physical activities linked to each type. Class discussion questions would include:

> What causes the number of mitochondria in a cell to increase?
> How are a sprinter's muscles different from a long-distance runner?
> Which type of cell would you predict to have more mitochondria, a heart cell or a skin cell? Why?
> *Adapted from Teacher's Domain: Muscles and Mitochondria.*

Under the Microscope – lab activity
Students will use microscopes to observe a variety of muscle cells. Students will draw

and label initial observations. These observations will be used a basis for future lessons about skeletal muscle cell structure.

Examining Muscle Fibers – lab
Students will compare and contrast the structure of yarn to the observed structure of a piece of cooked stew meat. Students will test the strength of the muscle fibers in the meat by pulling it in various directions. This exploration will be followed by a whole-class discussion on muscle fibers and fiber types.
Adapted from National Biomedical Research Institute: Muscles and Bones.

Winging It – lab
Students will work in groups to dissect a chicken wing. After removing the skin, they will use an identification sheet to find the different structures within, focusing on the muscles. They will experiment with trying to flap the wing; this will help them to see the connection between the two muscles within the wing.
Adapted from STC/MS Human Body Systems: The Musculoskeletal System – An Overview.

The Power of Togetherness – Creating Arm Models
Students will construct a model arm in order to understand how bones and muscles work together to create movement. They will be challenged to figure out how to show muscles working in pairs to bend and straighten the arm.
Adapted from National Biomedical Research Institute: Muscles and Bones.

Muscle Size and Strength – lab
Students will determine if there is a relationship between the size and strength of their arm muscles. Students will measure the size of their biceps, triceps and forearm muscles, and then measure the strength of the muscles using a scale (see appendix for procedures). They will use this data to determine the average strength of the muscles.
Adapted from STC/MS Human Body Systems: The Musculoskeletal System – An Overview.

Anatomy of a Kick – activity
In this activity, students investigate the opposing actions of muscles. This class will begin with a discussion and diagram of the six main muscle groups of the leg and foot. After this, one student will demonstrate a kicking motion, while the others try to determine the order in which the same six muscle groups contract. Students will learn that muscles produce movement by contracting and that opposing muscles are required to move an arm/leg in opposing directions. This is another application of how muscles work.
Adapted from National Institute of Health: Looking Good, Feeling Good From the Inside Out.

Just Ask the Coach! – classroom visit
A track coach will visit to share his training practices for sprinters and long-distance runners. Students will compare and contrast the differences between the two programs, using what they have learned to support why one training program is more effective for a sprinter than the other.

The Effects of Exercise – data analysis
(also known as: How do we know this, anyway?)
In this activity, students will use real data to understand the effects of resistance training on muscles. This study was conducted using rats as model systems – an important point for students to understand. The data collected shows resistance training causes an increase in muscle mass, but that a decrease in muscle mass occurs after training ends. Students will graph the given data and analyze the results, drawing conclusions about the influence of training on muscle mass.
Adapted from National Institute of Health: Looking Good, Feeling Good From the Inside Out.

The Problems with Steroids
Students will read a background article about anabolic steroids as well as a recent article about steroid use among today's elite athletes. Students will make an informative poster about the danger of steroid use.

Exercise Evaluation
Students will revisit the training programs presented by our visiting track coach. They will reevaluate these programs given their new understandings of how muscles work. Using these training programs as a guide and their experiences thus far, students will give exercise recommendations for certain scenarios. Scenarios include: what kind of exercise program would you recommend for someone who can only do one pushup? Does your friend need to make gains in strength or endurance? What specific exercises would you recommend? How often should your friend exercise? How will he know if he is making any progress?

Unit Final Performance Task
I have found that students often perform at higher levels when they are given a choice of how they show their understanding. In this unit, students are presented with a choice of two final performance assessments. Each task requires students to show evidence of their understanding of fundamental ideas (outlined in standards below). Although this unit includes two performance assessment options, students will be encouraged to consider other ways of showing understanding, provided they address fundamental ideas. Creativity is always welcome!

Goal

Students will show their understanding of the structure and function of muscle cells and the effect of behavior on muscles. They will show evidence of the connection between muscles and exercise. Students will choose one of two scenarios and products to show this understanding (fitness program and defense or children's book).

Roles

(a) In this performance, students will assume the role of scientific fitness instructors or sports coaches attempting to sell a fitness/dance/exercise program.
(b) In this performance, students will assume the role of a nonfiction children's book author.

Audience

(a) The audience is a group of health conscious students who are looking for a scientifically based exercise program. This audience may vary in accordance to students' proposed product; i.e., a student group project aimed to train for a race would target runners, while a dance video would target dancers.
(b) The audience is a group of younger children (approximately third grade).

Situation

(a) The fitness industry and sports world are competitive markets. Athletes striving for better performances and those individuals looking for a healthy lifestyle want to make sure they are choosing the correct program that will bring them results. How does a scientific understanding of cells, organs and systems support your fitness program? What is happening on a cellular level as you are exercising?
(b) Childhood obesity is a growing problem in the United States. It is essential that children learn the reasons why daily exercise is so important. What does exercise do for your body? This book will address these issues on a kid-friendly level.

Product

(a) The final product will be an exercise plan, program or video that addresses a specific fitness goal and a written defense of your program. Your goal may be general (get in shape) or specific (train for an upcoming 100-m dash).
(b) The final product will be a children's science book focused on the connection between exercise and muscles.

Standards

The standards for both of these options take into account the method of presenting information (Is this book on the level of third grade students? Does this fitness program and defense appeal to the targeted audience?). Each product must fully address the following questions: What are muscles made of? What do they do? How do they work? How do our behaviors affect our muscles? How do we keep them healthy? Each product must include realistic, scientifically based recommendations for a healthy lifestyle.

Teacher Resources

Basic Histology – Skeletal Muscle (n.d.). Retrieved Monday, July 30, 2007, from http://www.pathguy.com/histo/061.htm.
This site provides a variety of muscle cell images and student-friendly background information about what each image shows. These images can be used in a whole class setting or made available for as a student resource outside of class.

Many of the experiences included in this unit were adapted from established curricula. An example of one of these lessons – in its original form – is included in the appendix. These lessons are all available online at the websites listed in the Works Cited section of this paper.

Works Cited

Berthelsen, B. (1999). Students Naïve Conceptions in Life Science. MSTA Journal, 44 (1), 13-19. http://www.msta-mich.org. Retrieved Monday, August 6, 2007, from http://homepage.mac.com/vtalsma/syllabi/2943/handouts/misconcept.html#cells.

National Space Biomedical Research Institute (2000). Muscles and Bones. Available at http://www.bioedonline.org/resources/files/TG_muscles.pdf.

National Institute of Health. (2005). Looking Good, Feeling Good: From the Inside Out. Teacher's Guide: Information about the Musculoskeletal System. http://science.education.nih.gov/supplements/nih6/Bone/guide/info_musculo_skin-a.htm.

Science and Technology Concepts for Middle Schools: Human Body Systems (2000). Burlington, North Carolina: Carolina Biological Supply Company.

Sweetland, R.D. (2005). Human Anatomy Misconceptions. http://www.huntel.net/rsweetland/science/misconceptions/humanAnatomy.html

Teachers' Domain (2004). Muscles and Mitochondria. http://www.teachersdomain.org/resources/tdc02/sci/life/cell/mitochondria/index.html.

Wiggins, G. & McTighe, J. (2005). Understanding by Design. New York: Prentice Hall.

Appendix

Concept Walk Activity

A concept walk serves as an introductory activity for a unit of study. Students activate prior knowledge by responding to given statements and questions posted around the classroom. I have found the concept walk activity to be an excellent way to jumpstart student interest and curiosity at the start of the unit. Students travel in small groups to each station, responding to the prompt with examples, thoughts or their own questions. As they travel from one station to another, they also read what others before them have written and show agreement with check marks. Concept walk prompts should focus on the main ideas of the unit and encourage discussion or debate within student groups. It is helpful to display these posters so they are visible throughout the unit. At the end of the unit, students return to their initial statements and thoughts and evaluate them to assess how their understanding has changed over the course of the unit.

The following is a list of possible concept walk prompts for this unit:

- What does the statement “form matches function” mean to you? Can you think of any examples that illustrate this?
- Why might muscle cells contain a large number of mitochondria?
- True/False: All exercise is the same. Support your answer.
- True/False: All muscle is the same. Support your answer.
- List all the parts of your body where you might find muscle cells.
- What jobs do our muscles do within our body?
- It can be helpful to examine something on several different levels, such as the cellular and the tissue level. Respond to this statement.