Chapter 8

EXERCISE PHYSIOLOGY

OUTLINE

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Metabolic and Hemodynamic Continua
Energy
    Anaerobic Production of ATP
    Aerobic Production of ATP
The Cardiorespiratory System
    Thermoregulation
Summary

OBJECTIVES

1. Explore exercise physiology as a discipline of kinesiology.
2. Distinguish activities based on metabolic considerations.
3. Understand basic principles related to anaerobic and aerobic production of energy.
4. Understand how the cardiovascular and pulmonary systems are integrated with aerobic metabolic processes.
5. Understand the importance of thermoregulation during exercise.

Exercise physiology is the study of the function of the body under the stress of *acute* and *chronic* exercise. It is equally concerned with how the body responds to the intense demands placed on it by physical activity and the changes that occur in the body as individuals regularly participate in exercise training (1).

Physical activity takes many forms. Activities as diverse as a slow stroll, raking leaves, a mile run at a fast pace, a dock worker's day-long labor, an Olympic weightlifter's 200 kg snatch lift, an elite bodybuilder's grueling three-hour workout, and a marathoner's 26.2-mile run are but a few examples of the activities to which the principles of exercise physiology can be applied. These diverse forms of physical activities require our bodies to make varying degrees of physiological adjustments. The role of the exercise physiologist is to examine specific responses in an attempt to delineate the alterations made with acute exercise to better understand the chronic adaptations that occur with exercise training.

The term *acute* refers to the performance of a single bout of exercise. This may take a few seconds (running a 40-yard dash) or many hours (competing in an ultramarathon race). Exercise physiologists investigate how the body makes internal adjustments in the face of massive disruptions to homeostasis occurring with exercise stress.

The study of acute responses represents only half of what is of interest in exercise physiology. Of concern also are the adaptive processes to chronic exercise stress. The term *chronic* refers to a length of time over which changes take place in different physiological systems during exercise training. These changes, or adaptations, generally can be interpreted as an improvement in the body's function at rest and during submaximal and maximal exercise.

Using the framework of acute responses and chronic adaptations, the exercise physiologist applies the knowledge gained from the basic sciences to problems in exercise physiology, thereby gaining insights into how the body functions during the stress of exercise. This can then be used as a basis for developing the best training practices to enhance athletic performance or improve health, two areas of special interest to the exercise physiologist.

METABOLIC AND HEMODYNAMIC CONTINUA

The differences in the acute responses and chronic adaptations among physical activities are often astounding. For example, it is possible to classify all exercises, athletic activities, and general physical activities on continua based on the two key physiological perturbations to exercise—*metabolic* and *hemodynamic* responses. In terms of metabolic responses, exercises can range from those that require the anaerobic production of energy in the cell to those that require the aerobic production of energy. In terms of hemodynamic responses, exercises can range from those that impose a volume load on the heart to those that impose a pressure load.

The metabolic continuum illustrates physical activities as energetic events (Figure 8.1). Activities are placed in a time frame that depicts the duration of the maximal effort during the event. The descriptors power, speed, and endurance are intensity factors with the greatest intensity (and shortage duration) being on the power end of the continuum and the lowest intensity (and longest duration) on the endurance end. Power and speed events are anaerobic, that is, they do not require the production of adenosine triphosphate (ATP) via oxygen metabolism to fuel the event. The further an event moves along the continuum toward the right, the more it relies on oxygen metabolism and the longer will be the duration of the event or exercise. Therefore, endurance events are aerobic, requiring oxygen for the production of ATP.

Track and field events are ideal examples of the use of these descriptors. For instance, the shotput requires all-out effort from the first instance of movement to displace the shot with as much force and distance as possible.

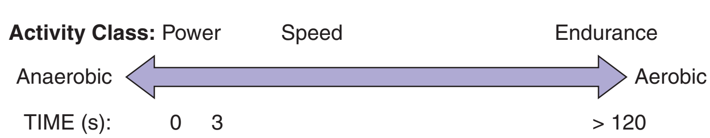

Figure 8.1. *Metabolic continuum.*

The event is over in less than 3 seconds. Other examples of power activities are Olympic weightlifting (single, maximal lifts) and running up a short flight of stairs. From an energetics standpoint, the fuel used for events classed in the power category is resting stores of phosphagens, particularly ATP and creatine phosphate (CP).

Speed events require a slightly longer time period. Examples of speed events are sprints (100 and 200 meters) and longer runs (400 meters). Weightlifting performed as a bodybuilding routine involving many repetitions per bout also qualifies as a speed event since the time frame during which the performer lifts is longer, but not approaching the endurance end of the continuum. Events and exercises of this nature rely on glycogen stores in the muscles to fuel maximal performance of the activity, which results in the production of lactic acid. Lactic acid buildup is what sets the boundary for duration of the maximal effort during speed events.

Endurance events are at the extreme right end of the continuum and are of much longer duration than both power and speed events. However, endurance activities are not very intense, allowing the production of ATP largely through aerobic metabolism. The 1500-meter run and runs of much longer duration are in this category. It must be noted that activities are not mutually exclusive in a metabolic sense; no one activity relies solely on a single energy system.

Sometimes placing an event or activity or sport on the metabolic continuum to determine the main way ATP is supplied to the contracting muscle can be tricky. For example, is soccer play aerobic or anaerobic? What about basketball? The answer to those questions depends on the action of the performer. If the play is of low intensity, as is sometimes the case, aerobic production of ATP predominates. If, however, an athlete steals the ball and there is a fast break to the goal, the anaerobic production of ATP predominates. So how would such an athlete train? The answer is that training should employ a combination of methods to ready the athlete for the various rigors of the sport.

It can be seen then that some activities fall in a "gray" zone with the energy output dependent on both anaerobic and aerobic sources. Generally, the shorter the activity, the greater is the contribution of anaerobic energy production. Conversely, the longer the activity, the greater is the contribution of aerobic energy production. The type of training program adopted to improve performance in an activity or sport event depends heavily on where the activity falls on the continuum.

An important concept related to the metabolic continuum and the type of exercise training employed is *specificity*. To maximize benefits, training should be carefully matched to an athlete's specific performance needs. Physiological adaptations produced from exercise training are highly specific to the nature of the training activity. Because of this principle, athletes should avoid certain kinds of training regimens, since the adaptations they receive from them may run counter to their performance requirements. For example, a power performer would not want to train with long distance jogging because the physiological adaptations gained from that form of exercise would tend to weaken his performance in the power event or sport.

Another example is the classic misconception that weight training will produce aerobic or cardiovascular benefits. The reasons why this is false are physiological and biochemical in nature and relate to the fact that specific kinds of adaptations (i.e., the aerobic benefits supposedly produced by weight training) follow only if there is a demand made on the bioenergetic processes and the physiological systems thought to be adapting. Cardiovascular benefits do not follow weight training because weightlifting does not sufficiently engage aerobic bioenergetic pathways.

Exercise can also be classified on a hemodynamic continuum (Figure 8.2). The degree to which an activity promotes blood movement (volume load) and the amount of blood pressure produced (pressure load) by the activity are important considerations when attempting to understand acute responses.

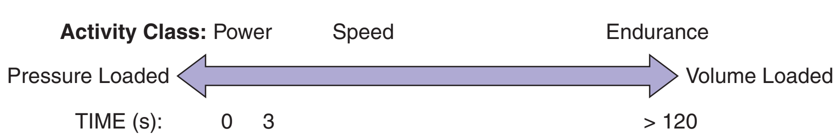

Figure 8.2. *Hemodynamic continuum.*

Hemodynamic refers to the circulation of blood and encompass the forces restricting or promoting its circulation. Exercises that promote a great deal of blood movement are the endurance forms. These exercises are also associated with moderate elevations in blood pressure and are classified under the volume load heading. In typical aerobic or endurance exercise, the heart is loaded or stressed by pumping a great deal of blood volume through the circulation. There is a necessary link between aerobic metabolism (the metabolic continuum) and blood flow (the hemodynamic continuum). When an exercise is primarily aerobic, the hemodynamic response is largely one that promotes large blood flow. In contrast, those exercises that restrict blood movement, as in resistance forms (weightlifting), are also the ones that lead to a sharp increase in blood pressure. The heart is said to be pressure loaded in this class of exercise. While resistance exercise promotes moderate increases in blood movement, the amount of blood flow during resistance exercise is still very limited in comparison to volume load exercise. Therefore, pressure load exercises also are said to be largely anaerobic. Weightlifting is a perfect example of a pressure load exercise.

Activities, exercises, and sports events will fall at some point along the continua, but a few can be placed at either extreme. The concept of metabolic and hemodynamic continua is extremely useful in helping the coach or personal trainer design the best exercise training programs for clients. With knowledge of where a sport event or exercise falls on the continua, it becomes a matter of designing an exercise program that stresses training in the time frame of the event. For those sports events that are somewhere in the middle of the metabolic continuum, a mixed training program is needed.

ENERGY

Understanding energy conversion in the cell is vital for a sound understanding of muscular activity. The most rudimentary understanding of movement can be reduced to the study of the biochemical processes that release bound energy, converting it to free energy that is involved at any moment in all biological processes. Energy is the ability to perform work. Work and energy are directly related; as work increases, so does the transfer of energy from one form to another.

Different forms of energy are important in biological processes. The following are a few examples:

- Skeletal and heart muscle contraction, metabolic processes: chemical energy
- Nerve conduction: electrical energy
- Maintenance of body temperature: thermal energy

The laws of thermodynamics dictate energy conversions. The first law states that energy conversions result in no lost energy. This is the law of conservation of energy—energy is neither created nor destroyed, but is converted from one form to another.

The body's bioenergetic systems are part of the thermal processes that govern life on the entire planet, the sun being the ultimate source of energy for life. The massive amount of thermonuclear energy on the sun is released during fusion reactions, which then irradiates the earth where it drives the reactions of photosynthesis, the process that makes carbohydrates in plants (Figure 8.3).

The energy from one reaction (energy releasing—*exergonic*) is transformed to another form (energy absorbing—*endergonic*). Exergonic and endergonic reactions are coupled. In the example of photosynthesis radiant energy from fusion reactions (exergonic) on the sun is transformed to chemical energy in the form of carbohydrates (endergonic) on earth. The same coupling of energy-releasing and energy-conserving reactions takes place in our cells with muscle contraction (an endergonic process) being the ultimate outcome.

Energy for movement comes from energy-rich nutrients in the form of carbohydrates, fats, and proteins. These three energy nutrients are broken down during digestion to their constituent building-block molecules that enter the body from the digestive tract and are processed by the liver for storage and usage. These building-block molecules are rich in potential energy that is available to be converted to free energy for future muscular work. The energy bound in the building-block molecules, however, cannot be directly used by the

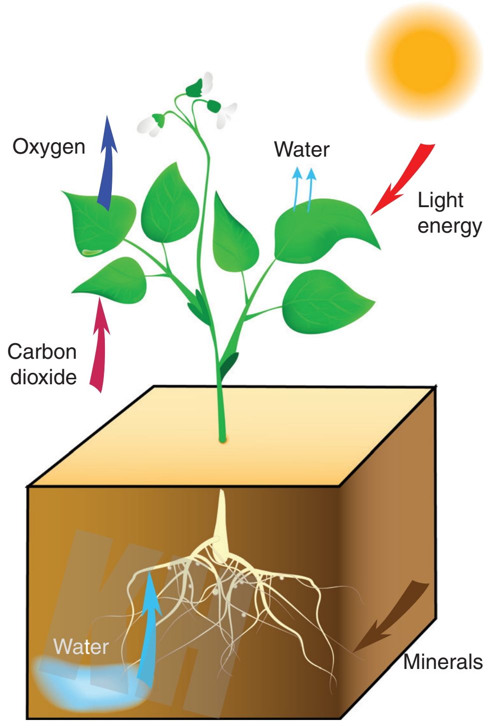

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Figure 8.3. *The exergonic process on in the sun is nuclear fusion, which gives off energy in the form of the light and heat. Plants capture this energy and use it to build carbohydrates and other chemical compounds. Since the sun is releasing energy, its reaction is exergonic, and since plants are storing this energy, their reaction is endergonic.*

contracting muscle. It must first be converted to another chemical form that can then become the direct source of energy for muscle contraction.

Metabolism is the sum of the chemical processes that convert energy from indirect sources (the energy nutrients) to the source that can be used directly to do muscular activity. Another way to state this is that metabolism is the sum of all catabolic and anabolic reactions. Catabolism is the process of breaking down large energy nutrient molecules to their smaller constituent building blocks. In this process a transfer of energy takes place.

Anabolism is the process whereby smaller biomolecules are built up to larger biomolecules (glucose to glycogen, for example). An input of free energy is necessary to produce these kinds of reactions, making them energy-requiring reactions. For movement to occur, catabolic (energy releasing—exergonic) processes are linked with anabolic (energy trapping—endergonic) processes for the purpose of producing another high-energy product that then becomes the direct donor of free energy for muscular activity. This high-energy compound is ATP.

The subsequent breakdown of ATP releases its bound energy, converting it to free energy, which is then used for all of the energy-requiring processes in our cells, including muscle contraction. How ATP is created in the cell to power muscular activity is one of the major topics in the study of exercise physiology. As we have seen, the processes that produce ATP can proceed by anaerobic or aerobic means. These metabolic pathways are controlled by mechanisms inside the cell that regulate energy storage. All of this activity is precisely integrated for the most efficient production of ATP for a given sport activity or exercise.

Anaerobic Production of ATP

ATP can be produced without involving the cellular mechanisms that involve oxygen. The anaerobic production of ATP is a very important means of powering movement and makes possible a greatly expanded repertoire of activities. Table 8.1 provides examples of activities that are powered by the anaerobic production of ATP divided into power and speed activities. Without the anaerobic production of ATP, activities such as a sprinting or heavy weightlifting would not be possible. What makes power and speed activities possible is the rapid production of ATP in the cell by means of anaerobic metabolic pathways.

Table 8.1. Examples of the Time Course of Anaerobic Sport Events and Bodybuilding Training

Activity	Power	Speed	Duration (s)
Weight Training (Olympic Style)	X		< 5
Track and Field Throwing Events	X		< 10
100 m sprint	X		
200 m sprint		X	< 20
Weight Training (Bodybuilding)		X	> 30
400 m run		X	< 45

The phosphagen system is the first and simplest anaerobic metabolic pathway, so named because it uses two important high energy phosphate compounds stored in muscles in small quantities. The release of energy from ATP upon its breakdown causes muscle fibers to shorten (contraction). Every cell in the body contains a quantity of ATP and other high-energy phosphates. These quantities are very small, and because the high energy phosphates cannot be supplied from other areas of the body to the muscle, ATP must be continuously remade in muscle and every other cell. The *energy charge* of the cell, therefore, is directly related to ATP concentration—low ATP concentration means low energy charge and vice versa. A central role of metabolism is to guarantee that the cell is properly charged by the transfer of bound energy in the form of the energy nutrients to ATP, a process called *phosphorylation*.

Because anaerobic activities are highly intense, they require a very rapid re-supply of ATP for the rate of muscle contraction, and therefore the activity, to be sustained. Aerobic activities are much less intense, which means ATP production can proceed slowly through the coordinated integration of both cellular and cardiopulmonary system interactions.

To understand these differences more fully, it is important to introduce the concept of metabolic power versus metabolic capacity. A metabolic pathway is powerful if it has the ability to rapidly supply ATP during highly intense activity. Therefore, power relates to the rapidity of the pathway to produce ATP. Capacity, however, refers to the ability to make large quantities of ATP. Power and capacity are inversely related. Metabolic pathways that are the most powerful also have the least capacity, and vice versa. The anaerobic pathways are far more powerful than the aerobic pathways, but have a very limited capacity for ATP production.

ATP is referred to as the *energy currency* of the cell, because the free energy released from its breakdown powers cellular functions, including muscular contraction. However, since the concentration of ATP is very low in muscle, it is possible to deplete it rapidly in highly intense exercise. The depletion rate of ATP during intense activity would be much greater if it were not for creatine phosphate (CP) serving as a reservoir of phosphate units. The breakdown CP sustains ATP concentrations by the donation of the phosphate group from CP to ADP during the simultaneous breakdown of ATP. The breakdown of CP serves to sustain ATP levels in the muscle until the CP reservoir is itself depleted. When the reservoir is depleted, ATP concentration decreases precipitously, and so does the power output of the activity. In essence, the runner in a 200-meter run cannot complete the event at 40-meter sprint velocities, because of rapidly declining ATP concentrations. Muscle cells, in effect, run out of energy (ready ATP supply) and sprint velocity necessarily falls off. Without the presence of the next anaerobic metabolic pathway a 200-meter run could not be completed with much intensity of effort at all, and neither could anaerobic activities of longer duration such as the 400-meter run.

Two hundred meter sprints and races of longer distances can be completed in a very intense fashion due to the fact that our muscles have the capability to break down glucose to produce ATP in intense activity. The breakdown of glucose is termed *glycolysis*. During intense activity, longer than 10 to 15 seconds, exercising muscles rely more and more on glycolysis to pick up where the phosphagen system left off. This has very important implications, because without glucose breakdown during intense activity we would have to severely curtail our running velocity before we finished our 200-meter sprint. In effect, our range of anaerobic activities would be limited to those activities that could be completed with a very high intensity of effort before our reservoir of creatine phosphate ran out, which is only a few seconds. We would not be able to engage in the speed activities (intense activities that are more enduring than the power activities, but of much shorter duration than the endurance activities). Fortunately, the glycolytic pathway provides an adequate backup.

According to the concept of power versus capacity, glycolysis, while capable of supplying ATP very rapidly, is less powerful than the phosphagen system. One reason for this is that glycolysis is a far more complicated metabolic pathway. It involves the use of eleven enzymes, whereas the phosphagen system needs only two to produce ATP.

Remember that when power is low, capacity is high. This means that the capacity of glycolysis to produce ATP is much greater than the phosphagen system. The reason for this is that there is a lot more energy reserve stored as glucose, so much so that its storage quantity is not a limiting factor for intense activity. This means that glycolysis will be limited or forced to cease during intense activity prior to glucose being depleted in the cell. Recall that the reason ATP production via creatine phosphate breakdown stopped was that creatine phosphate exists in very limited quantities in muscle. These concepts make glycolysis an ideal backup to the phosphagen system in producing ATP anaerobically, greatly increasing our range of anaerobic activities.

The cell's capacity for glycolysis is crucial beyond the initial 10 to 15 seconds of very intense activity and up to approximately 90 seconds. However, there is a limit to the ability of glycolysis to sustain ATP production in intense activity. This limitation is brought about by the end product of glycolysis during intense activities, lactic acid. When glucose is metabolized in muscle during intense activity, lactic acid, formed in the last of 11 reactions, increases in concentration in the muscle and spills over in the blood circulating through the muscle. Since this is an acid buildup, the pH of the cell significantly decreases to the point at which muscle contraction begins to be compromised due to at least two reasons. First, the buildup of acid in the muscle cell causes any further chemical breakdown of glucose to be hampered by decreasing the activity of the enzymes responsible for glucose breakdown. Second, as the watery medium of the muscle cell (the sarcoplasm) becomes more acidic, the ability of the muscle to continue to contract forcibly is reduced. The net result of this is that exercise intensity (i.e., running speed) must be reduced.

Lactic acid is a fatiguing substance and in this respect its buildup is detrimental. However, the ability of the cell to form lactic acid early in intense activity is actually what provides the cell with the capability to continue to make ATP rapidly. Therefore, lactic acid can be seen as necessary initially and detrimental later in intense activity.

Aerobic Production of ATP

When exercise is at an intensity level that can be maintained continuously for long periods of time, ATP is produced in muscles through cellular respiration, a process that uses oxygen. In terms of power versus capacity, the aerobic production of ATP has by far the least power. It is not capable of providing ATP rapidly. In turn, the capacity of this system far exceeds the anaerobic systems. Glycolysis releases only approximately 5% of the energy in the glucose molecule when its final product is lactic acid. When the exercise intensity is lower, the rest of this energy is liberated by cellular processes that are located in the mitochondria. Glucose breakdown continues in the mitochondria during activity that can be extended for long periods of time.

The processes of cellular respiration are very complex, involving the integration of cellular aerobic metabolism with several organ systems designed to coordinate fuel (energy nutrient) and oxygen delivery to the working muscles. Cellular respiration involves five separate metabolic pathways in the breakdown of the two main energy nutrients (triglyceride and glucose) used during steady-state (endurance) exercise.

The breakdown of triglycerides is termed *lipolysis*, a process that liberates fatty acids from the triglyceride molecule. This takes place primarily in adipose tissue. The fatty acids are released to the blood and transported to muscle cells where they are metabolized. The breakdown of fatty acids is termed *beta-oxidation*. In this process acetyl-CoA is formed. Other pathways involved in the aerobic production of ATP are the Krebs cycle and the electron transport chain.

Beta oxidation and glycolysis are coordinated in that both funnel their end products to the respiratory mechanisms inside the mitochondria. Beta-oxidation ends in the formation of acetyl-CoA. Unlike the form of glycolysis that runs during intense activity, ending in lactic acid buildup, the form of glycolysis that proceeds during endurance activity ends in the formation of pyruvate. Pyruvate is placed into the mitochondria where it is also converted to acetyl-CoA. Therefore, acetyl-CoA is referred to as the *common degradation product*, because it is derived from both carbohydrate and fat catabolism. In the aerobic production of ATP during endurance-types of activities, both glucose and fats are metabolized simultaneously with common end products entering cellular respiration in the mitochondria.

The aerobic production of ATP is far more complicated, because these reactions involve many separate metabolic pathways each with many enzyme steps that are located in different parts of the cell and the body. For instance, fatty acids are mobilized from fat cells during lipolysis and are catalyzed via beta oxidation in muscle during exercise. Muscle stores of triglycerides are also used. Recall that both anaerobic pathways were located in the sarcoplasm of the muscle fiber and had relatively few steps. This allowed ATP to be produced very rapidly for quick muscular activity. Thus, power was increased at the expense of capacity. In the aerobic system this is turned around, with the advantage now toward capacity. Also, now that fat is being utilized as a fuel substrate, the energy source is almost unlimited. This great increase in capacity, however, comes at the expense of decreases in power.

In many ways the Krebs cycle can be considered the beginning of the aerobic system, since it is the point of entry for all metabolic intermediate compounds that serve as fuel substrate to be completely broken down in cellular respiration. Starting in the Krebs cycle these compounds are further broken down to form additional energy-rich carrier molecules—nicotinamide adenine dinucleotide (NADH) and flavin adenine dinucleotide (FADH). These high-energy carrier molecules funnel hydrogen ions to the inner mitochondrial wall where the electron transport chain makes large quantities of ATP molecules in a process called *oxidative phosphorylation* (as opposed to substrate level phosphorylation when ATP was formed during glycolysis).

The Krebs cycle is also significant because it is the process whereby carbon dioxide is produced. The aerobic system is aptly named since a regular supply of oxygen is needed in the mitochondria to serve as a final repository for the hydrogen atoms that are stripped off of the energy nutrients during metabolism. With enough oxygen, NADH, and FADH present, oxygen serves as the final acceptor of hydrogen atoms as these atoms are passed along a series of intermediate acceptors. Throughout this process ATP is generated, and metabolic water is produced. This process, therefore, utilizes the oxygen that we breathe in and deliver to the working muscles. In this process oxygen is said to be consumed. In the next section the physiological systems that deliver oxygen to the muscles where it is extracted from blood and used in aerobic metabolism are examined. The ATP supplied to the muscles provides the energy for contraction to occur.

THE CARDIORESPIRATORY SYSTEM

Major organ systems must provide an adequate supply of oxygen to meet the demand contracting muscles have for oxygen during endurance exercise. The organ system that absorbs oxygen from the atmosphere and into blood is the pulmonary system. The cardiovascular system then delivers oxygen carried by the blood to the working muscles and all other organ systems. The heart and lungs are controlled to precisely match the increased metabolic demand for oxygen that occurs with exercise. These systems work as a unit to maintain oxygen and carbon dioxide homeostasis in the body.

The integration of the pulmonary and cardiovascular systems in the delivery, extraction, and utilization of oxygen can be depicted by an equation that expresses the relationship between three important variables: oxygen consumption, cardiac output, and the arteriovenous oxygen difference. The blood delivered depends on the size of the cardiac output (the volume of blood circulated per minute). The amount of oxygen extracted depends in large part by the ability of the muscles to absorb and utilize oxygen. The three variables are shown in the equation below.

$$\begin{array}{rcl} \text{Oxygen Consumption} = \text{Cardiac Output} & & \text{Arteriovenous Oxygen Difference} \\ \text{(Utilization)} = \text{(Amount Delivered)} & \times & \text{(Amount Extracted)} \\ \text{Central Factor (Heart)} & & \text{Peripheral Factor (Tissues)} \end{array}$$

There is an immediate need to meet the increased demand for oxygen with an adequate supply during endurance exercise. Heart rate and strength of cardiac contractions increase so that the cardiac output closely matches any level of oxygen consumption. The increased strength of cardiac contractions produces a greater cardiac stroke volume. Cardiac output is the product of heart rate and stroke volume. These factors result in an increase in the delivery of blood to the working muscles, and constitute the central factor (pertaining to the heart itself) for the increase in oxygen consumption that occurs with exercise. The increased delivery of blood is accomplished not only by an increase in blood flow (cardiac output), but by the massive redistribution of blood away from areas that do not participate in producing movement (the gastrointestinal tract, bone, skin) and toward the working muscles (where the greatest demand is). The increase in cardiac output, heart rate, and oxygen consumption during endurance activities is proportional to exercise intensity. For instance, both cardiac output and oxygen consumption increase in a step-by-step fashion as walking or running rate increases. However, during weightlifting, a resistance exercise that requires the anaerobic production of ATP, oxygen consumption is much lower for a given level of heart rate.

Second, as exercise intensity increases more oxygen is extracted from the blood as the blood passes through the capillaries of the working muscles. This can be measured as a larger difference between the oxygen content of the arteries feeding the muscles and oxygen content of the veins leaving the muscles. This greater difference in the oxygen content of arteries versus veins constitutes the peripheral (away from the heart) factor for the increase in oxygen consumption that occurs with exercise.

Third, the increase in oxygen consumption with exercise results from an increase in pulmonary ventilation. Pulmonary ventilation is the bulk flow of air into and out of the lungs. Upon the initiation of exercise the rate and depth of breathing increase, which results in an increase in pulmonary ventilation. As the exercise intensity during endurance activity increases, more air is passed in and out of the lungs. The increased rate at which the lungs are ventilated allows more oxygen to be delivered to the working muscles.

Thermoregulation

Mammals are classified as homeothermic, meaning that regardless of the state of the external environment, they must maintain internal body temperatures within narrow limits for survival. This is often quite challenging when faced with extremes of temperatures. One of the functions of the cardiovascular system is to remove heat from the body. This function is especially important during aerobic exercise, because of the large amount of heat produced and subsequently trapped in the body.

Part of the energy liberated during aerobic exercise is used to perform useful work. However, this portion of the energy expenditure is relative small (only about 20%–30%). This means that the remaining part of the energy produced is stored as heat and must be eliminated to maintain core temperature within reasonable levels. If this is not done adequately, the result may be some form of heat illness or possibly even death.

When aerobic exercise is performed in environmental conditions that are favorable (low to moderate air temperature and relative humidity), the body's ability to thermoregulate is sufficient to keep core temperature increases to a minimum. The increase in core temperature is linked to exercise intensity (as the percentage of maximal oxygen consumption). Exercise at 50% maximal oxygen consumption would mean a core temperature increase of only 1°C. This represents a successful thermoregulatory effort.

If environmental conditions are at the extremes of temperature, relative humidity, or both, thermoregulation is much harder to accomplish. The result of exercising in environmental extremes is an increased core temperature and a reduced work output. The reduced work output is a direct result of the extra burden placed on the cardiovascular system, which must not only supply oxygen to the working muscles to sustain the work output, but now it has an even more important role in delivering heat to the superficial regions of the body to dissipate the heat. This would have the direct effect of reducing maximal oxygen consumption and reducing exercise performance. In this case two areas of the body are competing for same cardiac output: the muscles to sustain the exercise intensity and the skin to dissipate the heat being carried by the blood. As the skin region receives more of the cardiac output, there is of necessity a reduction in endurance performance.

The ability to adequately dissipate the extra heat produced during aerobic exercise depends on the evaporative transfer of heat to the environment as water is vaporized from the respiratory passages and from the surface of the skin. Evaporation of water (sweat) off the skin is especially important since it represents the major way heat is removed from the body during exercise, except in hot, humid environments. Anything that retards this process will hinder exercise performance and carries a certain amount of risk to the exercising subject.

Evaporation is aided when the vapor pressure gradient from the skin surface to the air is large. This occurs when the relative humidity of the air is low. In this condition sweat easily evaporates to air that is relatively more dry than the skin. As water evaporates from the skin, heat is also transferred to the surroundings, and the body is cooled. Exercising in conditions of low relative humidity is, therefore, desirable. This problem is also independent of environmental temperatures since deaths have occurred in high humidity conditions even when temperatures have been moderate.

Inappropriate clothing greatly retards the evaporation of sweat from the skin. Different types of clothing are more effective in setting up a microenvironment around the skin than others, resulting in evaporation being retarded even when the outside environmental conditions are favorable. Certain types of athletic wear are specifically designed to provide a vapor barrier that completely stops the evaporative cooling process.

One of the most important things that can be done when exercising in a hot environment is to drink enough water. Studies have shown that water replacement is very effective in keeping the increase in core temperature seen with aerobic exercise to a minimum. When water balance (water intake that matched water loss) is maintained core body temperature increases are minimal.

SUMMARY

Exercise physiology is the science of how the body functions during exercise and sports activities and how the body adapts to chronic exercise training. The scope of exercise physiology covers both acute and chronic exercise responses and adaptations and includes the study of activities that can be placed on metabolic and hemodynamic continua. Exercise physiology is the study of how the body utilizes energy from the standpoint of cellular mechanisms to a systems approach. In this chapter the major organ systems supporting energy-transferring processes were briefly featured to show the integration of these systems with cellular mechanisms in the production of energy.

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