## Motor behaviour

Motor behaviour is the HMS response to internal and external environmental stimuli. The study of motor behaviour examines the manner by which the nervous, skeletal, and muscular systems interact to produce skilled movement using sensory information from internal and external environments. Studying motor behaviour represents the collective study of motor control, motor learning, and motor development (Schmidt & Lee, 1999).

Motor control is the ability to initiate and correct purposeful controlled movements and involves mechanisms used by the central nervous system to assimilate and integrate sensory information with previous experiences (Newton, 2003; Rose, 1997). Motor control is concerned with the central nervous system structures that are involved with motor behaviour to produce movement (Rose, 1997).

Motor learning is the use of these processes through practice and experience, leading to a relatively permanent change in one’s capacity to produce skilled movements (Schmidt & Wrisberg, 2000). Anytime a new physical skill is learned and practiced, motor learning is occurring.

Motor development is then defined as the cumulative changes in motor behaviour, over time, throughout the life span (Gabbard, 2008). Essentially, individuals’ motor development represents every physical ability they have learned over their lifetime, from rolling over for the first time as an infant to performing complex movements for athletic competition as an adult and beyond.

**Motor control**

To move in an organized and efficient manner, the HMS must exhibit precise control over its collective segments. This segmental control is an integrated process involving neural, skeletal, and muscular components to produce appropriate motor responses. This process—and the study of these movements—is known as motor control and focuses on the involved structures and mechanisms used by the central nervous system to integrate internal and external sensory information with previous experiences to produce a skilled motor response.

Motor control is concerned with the neural structures that are involved with motor behavior and how they produce movement (Coker, 2004; Nordin et al., 2017; Rose, 1997; Schmidt & Wrisberg, 2000). Essentially, motor learning and development are required for an individual to have proper motor control. Fitness professionals play a key role in the development of their clients’ motor control through proper instruction during exercise and fitness endeavours.

**Muscle synergies**

One of the most important concepts in motor control is that muscles are recruited by the nervous system in groups, known as muscle synergies (Newton, 2003; Rose, 1997; Singh et al., 2018). There is never a time where only one single muscle is activated alone. This makes controlling movement more efficient by allowing muscles and joints to operate as functional units (Bizzi & Cheung 2013).

Muscle synergies represent the interworking relationship between agonist and synergist muscle roles for a given movement pattern. Through the practice of proper exercise technique and form, these synergies become more fluent and automated. Table 7-3 explores muscle synergies for some common gym exercises.

TABLE 7-3 Muscle Synergies for Common Exercises

| **Exercise** | **Muscle Synergies** |
| --- | --- |
| Squat | Agonists: quadriceps, gluteus maximus Synergist: hamstrings complex Stabilizer: transverse abdominis |
| Shoulder press | Agonists: deltoids Synergist: triceps brachii Stabilizers: rotator cuff |
| Bench press | Agonist: pectoralis major Synergists: triceps brachii, anterior deltoid Stabilizer: rotator cuff |
| Seated row | Agonist: latissimus dorsi Synergists: posterior deltoid, biceps brachii Stabilizers: rotator cuff |

**Proprioception**

Mechanoreceptors collectively feed the nervous system with a form of sensory information known as proprioception. Proprioception uses information from the mechanoreceptors (i.e., muscle spindles, Golgi tendon organs, and joint receptors) to provide information about body position, movement, and sensation as it pertains to muscle and joint force (Newton, 2003). Proprioception is a vital source of information that the nervous system uses to gather information about the environment to produce the most efficient and precise movement.

For example, proprioceptive input may provide a runner with a cue to contract the ankle muscles to avoid an inversion injury. Research has demonstrated that although proprioception may help prevent injury, it is altered after injury. This means that many of today’s health club members may have altered proprioception as a result of past injuries. This provides a rationale for the inclusion of both core and balance training to enhance one’s proprioceptive capabilities.

TRY THIS

Sit in a chair with your eyes closed. Next, raise your right arm above your head. Then, move your arm in a small circular motion five times. Stop and open your eyes.

How were you able to understand what your arm was doing? You couldn’t see, smell, taste, hear, or touch your right arm as it moved, but somehow you were able to internally sense what your arm was doing. This internal sensation is proprioception at work.

**Sensorimotor integration**

Sensorimotor integration is the ability of the nervous system to gather and interpret sensory information and to select and execute the proper motor response (Biedert, 2000; Drury, 2000; Janda & Va Vrova, 1996; Levangie et al., 2019; Rose, 1997). The definition implies that the nervous system ultimately dictates movement. It is important to recognize that nervous system function includes both central and peripheral nervous systems as well as their integration with the musculotendinous structures and inert tissues (ligament and capsule).

For example, during an exercise, the muscle is activated and movement occurs. Movement occurs as a result of neural input to the muscle from the nervous system. Further to this point, the movement that occurs may activate the muscle receptors as well as the receptors in the joint itself, both providing feedback to the nervous system and influencing movement.

Sensorimotor integration is effective as long as the quality of incoming sensory information is good (Janda & Va Vrova, 1996; Levangie et al., 2019). Individuals who train using improper form will develop improper sensory information delivered to the central nervous system, leading to movement compensations and potential injury. It is, therefore, important to create properly designed exercise programs and encourage clients to train with correct techniques at all times. For example, if an individual consistently performs a chest press while rounding and elevating the shoulders, it can lead to altered length-tension relationships of muscles, altered force-couple relationships, and altered arthrokinematics, ultimately leading to shoulder injury.

**Motor learning**

Motor learning is the integration of motor control processes, with practice and experience, leading to a relatively permanent change in the capacity to produce skilled movements (Levangie et al., 2019; Rose, 1997; Schmidt & Lee, 1999). The study of motor learning looks at how movements are learned and retained for future use. Motor learning occurs when practicing to ride a bike, throw a baseball, play the piano, and every other physical task the body can possibly learn to perform.

In all cases, proper practice and experience will lead to a permanent change in one’s ability to perform a movement efficiently. For a movement to occur repeatedly, sensory information and sensorimotor integration must be used to aid the HMS in the development of permanent neural representations of motor patterns, a process referred to as feedback. Essentially, the nervous system learns from repeated activity, and newer movements often take more time to be refined or mastered.

**Feedback**

Feedback is the use of sensory information and sensorimotor integration to aid the HMS in developing permanent neural representations of motor patterns. Feedback allows for efficient movement, which is achieved through two different forms of feedback: internal (or sensory) feedback and external (or augmented) feedback.

Internal feedback

Internal feedback is the process whereby the body uses sensory information to reactively monitor movement and the environment. It comes primarily from internal biological structures (mechanoreceptors) in the body relaying information via the autonomic nervous system. Internal feedback acts as a guide, steering the HMS to the proper force, speed, and amplitude of movement patterns for a given situation.

It is important to instruct clients to use proper form when exercising to ensure that the incoming sensory feedback is correct information, allowing for optimal sensorimotor integration. For example, during a hamstring stretch, the exerciser can feel when a stretch has reached a tolerable limit and chooses to stop further movement to avoid overstretching.

External feedback

External feedback refers to the information provided by an external source, including a Certified Personal Trainer, video recording, mirror, or heart rate monitor, to help supplement internal feedback to produce more efficient motor learning. External feedback provides clients with another source of information that allows them to associate whether the achieved movement pattern was “good” or “bad” with what they are feeling internally.

Two major forms of external feedback are knowledge of results and knowledge of performance (Rose, 1997; Schmidt & Lee, 1999; Schmidt & Wrisberg, 2000; Swinnen, 1996). *Knowledge of results* is used after the completion of a movement to help inform a client about the outcome of the performance. Effective use and application of knowledge of results involves both the fitness professional and the client’s participation. An example of knowledge of results is a fitness professional telling clients that their squats looked “good” followed by asking the clients whether they could “feel” or “see” their good form.

By getting clients involved with the knowledge of results, they increase their awareness and augment other forms of sensory feedback, leading to more effective exercise technique. Knowledge of results can be done after each repetition, after a few repetitions, or after the set is completed. As clients become increasingly familiar with the desired technique of a movement, knowledge of results from the fitness professional can be offered less frequently. When knowledge of results is implemented, it improves neuromuscular efficiency as well (Swinnen, 1996).

*Knowledge of performance* provides information about the quality of the movement during an exercise. An example would be noticing that a client’s feet were excessively externally rotated

and the knees were adducting during a squat, and then asking the client whether they felt or looked different during those repetitions. Knowledge of performance gets the client involved in their own sensory process. Knowledge of performance should be offered less frequently as the client becomes more proficient (Swinnen, 1996).

These forms of external feedback allow for the identification of performance errors and help improve effective performance outcomes in the future. They are also an important component of motivation. Furthermore, they provide the client supplemental sensory input to help create an awareness of the desired action. It is important that clients not become dependent on external feedback, especially from a fitness professional, because this may detract from their responsiveness to internal sensory input or internal motivation (Rose, 1997; Schmidt & Lee, 1999; Schmidt & Wrisberg, 2000; Swinnen, 1996). Excessive use of external feedback can negatively affect sensorimotor integration and motor learning and, ultimately, movement patterns.

## Introduction to exercise metabolism and bioenergetics

The human body needs a constant supply of energy to function properly. Those energy requirements can change, and exercise places unique demands on the body’s ability to supply energy. In addition to increasing energy demand, exercise also requires the body to handle additional metabolic by-products.

The food we eat contains carbohydrates, proteins, and fats, which are needed by our cells to produce energy and function properly. The energy stored in these food sources, through a series of chemical reactions, is converted to a high-energy compound called adenosine triphosphate (ATP), which serves as the main form of energy in the human body (Figure 8-1). The role of energy metabolism during exercise involves understanding how energy is supplied, which energy systems are used during exercise, how quickly energy can be supplied, and how cells generate ATP.

### Bioenergetics and metabolism

Energy metabolism, or bioenergetics, is the study of how energy is transformed through various biochemical reactions. Energy is required to sustain life, support exercise, and pro­mote recovery from physical activity or structured exercise. The term metabolism refers to all the chemical reactions that occur in the body to maintain itself. As mentioned earlier, the main sources of chemical energy for humans are carbohydrates, fats, and protein. Exercise metabolism refers to the examination of bioenergetics as it relates to the unique physiological changes and demands placed on the body during exercise.

**Introduction to the law of thermodynamics**

The body is an intact (i.e., closed) system. Like all other systems in nature, the body must follow the first law of thermodynamics, which states that energy can neither be created nor destroyed, only recycled or converted from one form into another. In humans, this is referred to as the concept of energy balance. Put briefly, the energy entering the body in the form of macronutrients and coming out of the body is always accounted for by changes in mass (i.e., a person’s scale weight). If someone consistently expends more energy than they consume, that person will lose mass (weight). If someone consistently consumes more energy than they expend, that person will gain mass (weight). Therefore, all of the energy someone consumes is either used to perform bodily functions or stored within the body (typically as body fat).

GETTING TECHNICAL

Carbon In – Carbon Out

All life on earth is carbon-based, meaning that carbon is the element that primarily gives living things their physical mass. The “energy” contained in food is located within the molecular bonds that connect carbon and other elements in various ways to form carbohydrate, protein, and fat molecules (i.e., the edible forms of organic matter). Other elements in organic matter—such as oxygen, phosphorous, nitrogen, and hydrogen— have little to no contribution to physical mass. Water, which does contribute to a living thing’s *scale weight*, is contained *within* the physical mass (i.e., inside cells and blood); it is not part of it. When organic matter is consumed by an animal, molecular bonds are broken and reformed numerous times during metabolism—converting the source macronutrients into numerous intermediate forms of organic matter—on the way to forming the ATP molecules that muscles and organs use directly as their “energy currency” to power function.

Energy is stored in the human body in the same way it is contained within food—in the molecular bonds of carbohydrate (glucose and glycogen), fat (body fat), and protein (muscle and other soft tissues) structures. Per the first law of thermodynamics, a body’s mass increases when it consumes more energy than it uses because that energy must be physically contained within the molecular bonds of carbon-based organic matter. Simply put, if energy isn’t used, it is stored away for later, and there can be no energy stored away for later without the accompanying increase in carbon-based body mass to contain that energy.

Body mass is then lost in only one specific way. As metabolism works to convert both food and bodily stores (i.e., glycogen and fat) to ATP for use, carbon dioxide (CO2) is formed as the main waste product. Other than physically removing tissue through surgery, exhaling CO2 is the only way carbon is removed from the body. As the body exhales CO2, the energy contained within the CO2’s carbon-oxygen molecular bonds is released back into the external environment where it is taken up by plants and entered back into the greater food supply. Energy is never created or destroyed; it is just transferred from one form of carbon-based organic matter to another. In the human body’s case, energy starts as food, is then converted to various forms within the body during metabolism, and is finally released back to the environment as CO2 during exhalation.

**Fuel for energy metabolism**

Dietary food provides energy to sustain life and support physical activity, but not directly; it first must be broken down by the digestive system into smaller by-products called substrates. Proteins (more specifically, chains of amino acids), carbohydrates, and fats constitute the main substrates used to transfer metabolic energy to be used for all types of cellular activity and life (Becker & Smith, 2006; Gleeson, 2005; Kalish et al., 2012; Maughan, 2005). Since all energy substrates are forms of organic matter, many can be converted from one to the other within the body depending on what is needed. For example, the body can convert carbohydrate-based foods to fat molecules in order to store energy for later use. However, a small selection of substrates cannot be created internally in this manner and must be consumed in the diet. Those nutrients we must eat to live healthily are termed *essential*.

**Glucose and glycogen**

Glucose is one of the main sources of energy, particularly for brain function and higher-intensity activity. Glucose can be made in the body from other substrates (fats and amino acids), but a large majority of our daily glucose needs come from consuming carbohydrate-based foods. Carbohydrates are consumed and broken down into glucose through digestion. Glucose is then absorbed and transported in the blood, where it circulates until it enters cells and is either used to make ATP or is stored for later. When it is stored, it is stored as string molecules in a branched structure called glycogen. Glycogen is stored in the liver and muscle cells and can be broken down rapidly to provide energy when there is not enough free glucose in the blood.

Glucose makes a relatively small contribution to overall energy production during rest or low-intensity exercise. The brain always requires glucose to function, but fats are what primarily fuel the body when it is not active.

As the intensity of an activity increases, the body transitions from using mostly fat as fuel to using mostly glucose to provide energy. This is because glucose can be used much faster than fat and can also be metabolized without oxygen, whereas using fat for fuel always requires oxygen.

As activity intensity increases, the usage of carbohydrate as an energy source becomes 50%, and the usage of fat becomes 50%. This metabolic marker is referred to as ventilatory threshold 1 (VT1). This will be an important concept to keep in mind during cardiorespiratory assessment and programming, especially as it pertains to maximizing both fat loss goals and performance goals for clients. As exercise intensity increases further to maximal levels, ventilatory threshold 2 (VT2) is reached (Ballweg et al., 2013; Foster et al., 2008). VT2 represents the point where activity is so intense that glucose is providing virtually all of the energy for the activity, as fats metabolize too slowly to keep up with maximal demands. If the supplies of glucose and glycogen run out, a person would not be able to continue exercising at maximal intensity and he or she will have to reduce effort to a point where fat usage is once again possible, commonly referred to as hitting a wall. This is part of why some athletes use “energy gels” and other carbohydrate supplements during prolonged strenuous training and in competition.

**Free fatty acids**

An equally important source of energy are fats, also known as lipids. This energy source is particularly important during rest and lower-intensity activity (i.e., below VT1). The chemical (or substrate) form in which most fats exist in food (as well as in the body) is called triglyceride (Gleeson, 2005; Kalish et al., 2012). Triglycerides, more commonly referred to as free fatty acids when they are in the blood stream, are derived directly from fats contained in foods or are made by the body to store excess energy when more food is consumed than is needed to support activity.

Before cells can use consumed fat or stored body fat as a fuel source, it first needs to be broken down into free fatty acids. Free fatty acids are then used exclusively in the aerobic metabolic pathway to produce ATP. One of the benefits of having fat as a fuel source is that even relatively lean people still have a large supply stored on their body, which can be broken down into triglycerides and used for energy during prolonged, lower-intensity physical activity and exercise. Any time an individual is exercising at an intensity below VT1, free fatty acids are the primary fuel source.

STRETCH YOUR KNOWLEDGE

For conversion purposes, 1 lb (~0.5 kg) of body fat equals around 3,500 calories of stored energy. For example, a lean 150 lb (~68 kg) person with 10% body fat would still have roughly 15 lb (~6.8 kg) of fat stored away throughout their body. That is roughly 52,500 calories!

**Amino acids**

The third fuel source is protein, which is made up of long chains of “building block” substances called amino acids. Humans use 20 different amino acids to assemble bodily proteins. Of these 20 amino acids, nine are called essential amino acids, which means that the body cannot synthesize them on its own and they must be consumed in the diet.

The other 11 amino acids are called nonessential amino acids, which means that they can be synthesized by the body (from consumed carbohydrate or fat substrates) as long as overall nutrition intake is adequate.

When a person consumes protein, it is broken down into its component amino acids. Those amino acid building blocks will then, ideally, be used to synthesize human bodily proteins that build up muscle and repair cellular machinery. However, the amino acids from dietary protein can also supply energy for ATP production if carbohydrate and fat sources are low. This situation should happen rarely to “spare protein,” which is why adequate carbohydrate intake is important, especially after intense exercise; therefore, glycogen stores get replenished from the carbohydrate source, and amino acids can fulfill their main postexercise role: build and repair muscle.

Protein rarely supplies much energy during exercise and, in many descriptions, is ignored as a significant fuel source for energy metabolism (Mitchell et al., 2016; Phillips, 2017). During a negative energy balance, amino acids are used to assist in energy production and can come from protein that was eaten or from the breakdown of muscle tissue itself in extreme cases, like starvation or when exercising at extremely high intensities for long periods of time (for example, with Olympic marathon runners). Before amino acids can be used to make ATP, they are further broken down and then recombined into either glucose through a process called gluconeogenesis or ketone bodies through a process called ketogenesis (Maughan, 2005; McArdle et al., 2010).

**Ketone bodies**

Ketone bodies is the name collectively used to refer to three molecules—acetone, acetoacetic acid, and beta-hydroxybutyric acid—that can be anaerobically metabolized similar to glucose. These molecules are produced by the liver as a by-product of the breakdown of fatty acids or through the conversion of ketogenic amino acids. The human body does not have the ability to store these molecules, so they are only used acutely to produce energy and are not stored for later like glycogen (Miller et al., 2018). Even though the body does primarily run on free fatty acids during low-intensity activity and rest, it still needs carbohydrate substrates to properly function. So, when carbohydrate stores run low, ketone bodies are produced and used alongside gluconeogenic glucose to help make up for the deficiency. During this metabolic state, the body is said to be in ketosis. Ketone levels can increase in the human body in several ways:

* By restricting overall calories to very low levels
* By following very low-carbohydrate diets (e.g., ketogenic diet)
* By consuming exogenous ketones
* When there is a lack of insulin produced (type 1 diabetes) or substantial insulin resistance (type 2 diabetes)

In most cases, when humans engage in the previous dietary habits 1–3, their ketone levels can increase to approximately 0.5–1.5 millimoles per liter (mmol/L) of blood, which is known as nutritional ketosis. This is a different physiological state than what is known as ketoacidosis, which mostly occurs in diabetic individuals. For most people, ketones make up a small portion of the energy-producing substrates in the human body, even in nutritional ketosis. However, there is some research studying the effect of ketosis and ketone-producing diets, such as ketogenic diets, for exercise performance (LaFountain et al., 2019; Volek et al., 2016).

### Energy and mechanical work

To perform mechanical work, the body needs fuel, which is broken down through a series of chemical reactions to provide energy. Recall the first law of thermodynamics and how energy cannot be created or destroyed. The only way new energy enters the earth’s ecosystem is from the sun. Plants convert the sun’s energy to food and food provides animals (including humans) with energy to perform cellular and mechanical functions (Kalish et al., 2012; Maughan, 2005). Essentially, the human body is an organic machine that can turn chemical energy into mechanical work. Interestingly, about 40% of the energy released during metabolism is actually used for cellular work, such as a cell creating more molecules; the remainder is released as heat (McArdle et al., 2010). This is analogous to a car engine that uses gasoline (a chemical) to produce work and heat.

HELPFUL HINT

ATP for the body is like gasoline for a car, in that it is the specific fuel substrate that burns best in the engine. The food we eat is like crude oil; it contains all the necessary chemical energy, but it must be processed into a form that our “engines” (mitochondria in cells) can use. Metabolism essentially represents the body’s internal “oil refinery.” It processes the “crude” input (i.e., macronutrients) into something that can be specifically used by the cells for fuel (i.e., ATP).

**Energy systems**

Adenosine triphosphate is the primary energy-providing molecule in the human body. It is a complex molecule made up of a nitrogenous base (adenine), a sugar molecule (ribose), and three phosphate groups. Specifically, the energy that the body gets from ATP is stored in the chemical bonds that hold the three phosphates together. When these chemical bonds are broken, energy from one of the phosphates is released for mechanical work (such as performing muscle contraction), leaving behind another molecule called adenosine diphosphate (ADP) and an extra phosphate group (Figure 8-2).

ADP is then left free in the cell, waiting to be converted back to ATP when enough energy substrates from food or bodily stores are available. Even though it takes numerous complicated physiological processes and chemical reactions to get there, all the useable energy from the food we eat and from stores in the body has the same end goal of making more available ATP.

The human body has several ways to generate ATP from ADP, which is a process called phosphorylation. The three main ways that phosphorylation is reached are known as the three metabolic pathways:

1. ATP-PC system
2. Glycolytic system (glycolysis)
3. Oxidative system (oxidative phosphorylation)

Depending on the intensity of an activity, each of the systems will shift in priority as to which is primarily supplying ATP; however, there is rarely a time where only one or another is active by itself. All three systems work together to fulfil the body’s total energy demand. The energy systems do not turn on and off in a linear fashion; rather, they operate more like dimmer switches. As the intensity of activity changes, the energy systems dynamically adjust in relation to one another to ensure energy needs are met. Even though one energy system might be contributing more than the others given a specific intensity of activity, the other two are still contributing in the background in some fashion.

This is best shown when looking at a graph of how the energy systems respond when the body is asked to perform a maximally intense activity for a long duration (Figure 8-3), such as running a few laps around a track at the fastest pace possible (hypothetically assuming the same maximal pace can be maintained for a few minutes). Recall that at rest and during low-intensity activity, free fatty acids provide most of the energy via the oxidative system. Then, when intensity increases (e.g., going from a standstill to an all-out sprint), the oxidative system cannot keep up, and the anaerobic processes kick into gear.

For the first 10–15 seconds, as the body transitions from low to high intensity, the ATP-PC system provides the most energy. As the ATP-PC begins to exhaust and taper off, glycolysis is already ramping up to take over the majority of the energy production duties, which it can support for around 2 minutes. And all the while, the oxidative system is ramping up, contributing greater and greater amounts until it eventually becomes the primary source of ATP production. The better a person’s cardiorespiratory fitness is, the more efficiently the oxidative system can support higher levels of intensity without having to rely as heavily on anaerobic processes.

When intensity continues long enough that the oxidative system can no longer support the activity, there is no other option but to slow down, rest, and recover (i.e., the point beyond VT2 commonly known as hitting a wall).

HELPFUL HINT

The contribution of all three energy systems must always add up to 100%. There is never a time where one is completely “turned off.” Even when the oxidative system is primarily supplying energy for a long-lasting intense activity, the other systems are working to replenish so they can again support increased bursts of intensity when needed.

**ATP-PC**

The first of the ATP-generating metabolic pathways is known as the ATP-PC system, or the phosphagen or the phosphocreatine system (Figure 8-4). The body naturally creates stores of phosphocreatine by breaking down and converting certain amino acids. This system is the simplest and fastest way to generate more ATP. Essentially, it works by taking ADP left over from a previous muscle contraction and adds a phosphate taken from a phosphocreatine (PC) molecule, rapidly creating available ATP at the site where it needs to be used. This process does not require oxygen, which is why the ATP-PC energy pathway is considered anaerobic.

The ATP-PC system provides energy for primarily high-intensity, short-duration bouts of activity. This can be seen in strength and power forms of training in which very heavy loads are used with only a few repetitions or during short sprinting efforts. When activity rapidly intensifies, the small amounts of free ATP in the muscle tissue and the ATP-PC system can supply energy for only 10 to 15 seconds before running out (Wells et al., 2009). This system is activated at the onset of any increase in activity intensity because of its ability to produce energy very rapidly in comparison with the other systems. However, PC stores run out faster than they can be replenished, at which point other methods of ATP production must pick up the slack.

**Glycolysis**

As PC stores begin to exhaust, a slightly slower (but still relatively rapid) anaerobic energy system is ramping up. This is the first step in the chemical breakdown of glucose in a process referred to as glycolysis (Figure 8-5). The process of glycolysis turns free blood glucose or stored glycogen into pyruvate and ATP. Glycolysis takes place in the cytoplasm of an animal cell (Figure 8-6). This anaerobically created ATP can then be used directly the same way as the ATP created by the ATP-PC system. This system can produce a significantly greater amount of energy than the ATP-PC system, but it is a bit slower to ramp up to its full ATP production capabilities. However, it lasts longer, with a capacity of approximately 30 to 60 seconds of duration, which can be increased by several seconds through the use of high-intensity styles of training (Burke et al., 2011; Wells et al., 2009).

Most people have enough free glucose in the blood and stored glycogen to fuel anaerobic glycolysis for many repeated bursts, such as a sprint workout or a session of high-intensity interval training (Maughan, 2005). However, for most people, those carbohydrate sources run out after around 1 hour of sustained activity, which is why carbohydrate drinks or gels are helpful to keep the body performing at its best when an event lasts longer than 60 minutes.

Glycolysis is directly linked with the oxidative system by the pyruvate by-product that is created. It can be treated in two different ways depending on whether or not there is oxygen present. If there is oxygen available, the pyruvate is further broken down, enters the oxidative system, and leads to the creation of additional ATP. If oxygen cannot be delivered fast enough, the pyruvate will be converted into a molecule called lactate, which contributes to the “burn” felt during strenuous exercise as it accumulates in muscle tissue (the accumulation of CO2 in muscle tissue at a rate faster than it can be removed also factors into the burning feeling).

GETTING TECHNICAL

What Is Lactic Acid?

During periods of high-intensity exercise, ATP is needed faster than oxygen can be delivered by the cardiorespiratory system. Therefore, the body relies mostly on the ATP-PC system and glycolysis for energy when intensities push toward maximal levels. As pyruvate accumulates in an anaerobic environment, it is quickly converted to lactate, releasing a free hydrogen ion in the process.

These hydrogen ions contribute to a decrease in muscle pH, which is known as acidosis. This acidosis can lead to some of the feelings of pain and fatigue associated with intense exercise because the hydrogen ions that lower pH can interfere with muscle contraction. Because of this, tissue pH shifts toward becoming acidic; the lactate and hydrogen ions produced during anaerobic glycolysis are often collectively termed *lactic acid*.

However, lactate is not a true “waste product” in the same way as CO2. Once it has been removed from soft tissue cells and enters the bloodstream, instead of being removed from the body, it is processed by the liver in a separate metabolic process called the Cori cycle. During the Cori cycle, ATP is used to convert lactate in the opposite direction back to pyruvate and subsequently glucose (Cori & Cori, 1929). This glucose is then released back into the bloodstream to be used again. Because of this, the Cori cycle is highly important in helping keep the body’s pH balanced.

**The oxidative system**

The most complex of the three energy systems is the oxidative system—a process that uses oxygen to convert food substrates into ATP (Figure 8-7). This process is called oxidative phosphorylation, and it is defined as an aerobic process because it needs oxygen to complete the reactions. There are three substrates that are used in the oxidative system: free fatty acids, the pyruvate created during glycolysis, and amino acids that have undergone deamination.

Oxidative phosphorylation uses a series of chemical reactions leading to the end result of creating ATP and carbon dioxide. This pathway includes two sets of reactions. Both sets occur in cellular organelles called the mitochondria (Figure 8-8). The first set of reactions is called the citric acid cycle (CAC), also known as the Krebs cycle, which leads to the creation of a few ATP molecules and the waste product of carbon dioxide. During this stage, electrons are freed for use in the next set of reactions known as the electron transport chain (ETC), which uses those electrons to drive a complex series of reactions that create the most ATP.

The oxidative system is what the body primarily relies on for the majority of low- to moderate-intensity activity. While anaerobic processes last anywhere from a few seconds to a few minutes, aerobic metabolism can sustain the body indefinitely, just at increasingly lower intensity levels (Kalish et al., 2012). As a person’s cardiorespiratory fitness improves (i.e., the ability to deliver oxygen to the cells), so does the oxidative energy system’s ability to support higher intensity levels without having to preferentially activate the anaerobic processes.

**Oxidative metabolism of different macronutrients**

Whether carbohydrate, fat, or protein substrates are being used, they all must be broken down to the same substance, called acetyl coenzyme A (acetyl CoA), before they can enter the CAC (Gleeson, 2005). Acetyl CoA provides a common starting point for the enzymes used in the CAC, which removes the electrons from this molecule and transports the negatively charged electrons along with positively charged hydrogen ions to the ETC. These electrons and hydrogens are stored inside the mitochondria and then used to provide the energy that converts ADP into ATP.

To use fat substrates for aerobic energy production, the fat (e.g., triglycerides) must first be converted into free fatty acids and then further broken down to acetyl CoA in a process called beta-oxidation. Fat molecules are large, energy dense, and more complex than carbohydrates, which is why fat metabolism is slower and cannot keep up with high-intensity energy demands. Even though fat oxidation is slow, one fatty acid molecule can net significantly more ATP than glucose. For example, when one molecule of the fatty acid palmitate is fully metabolized, it yields 129 ATP.

Unlike the initial anaerobic metabolism of glucose, using fat as an energy source always requires oxygen. The rate at which a person can break down fat depends on the number of mitochondria in the muscle cell and the amount of oxygen delivered by the blood (Gleeson, 2005). Athletes and well-conditioned people tend to have more mitochondria in their muscle cells than sedentary individuals and are therefore better at breaking down fat (Nielsen et al., 2016).

Finally, if there is a lot of carbohydrate (glucose) available, the body will use some of that instead, which will decrease the total amount of fat used to make ATP.

If oxidative phosphorylation is starting from a carbohydrate food source, it must first be broken down into glucose and then converted to pyruvate through glycolysis. Essentially, not only is glycolysis its own anaerobic energy system, but it is also the first step in the aerobic metabolism of glucose. When there is enough oxygen present, pyruvate is not converted to lactate. Instead, it is further broken down to acetyl CoA and enters the CAC. The complete metabolism (anaerobic and aerobic) of a single glucose molecule produces between 35 and 40 ATP (McArdle et al., 2010). Additionally, if both carbohydrates and fats are depleted to the point that amino acids are being relied on directly for energy (e.g., during extreme starvation), they are also broken down and metabolized aerobically.

GETTING TECHNICAL

Amino acids are very rarely deaminated and converted to acetyl CoA directly for oxidative phosphorylation. Most of the time, when amino acids are called on as an energy source, they are first converted to glucose or ketone bodies via gluconeogenesis and ketogenesis. Those converted substrates then enter their respective carbohydrate- or fat-based metabolic pathways.

#### Electron transport chain

The ETC is a vastly complex process that occurs in the inner mitochondrial membrane after the CAC has removed the electrons from acetyl CoA. In this process, protein complexes create a gradient of stored hydrogen ions that allow the electrons freed by the CAC to move through them. When ATP levels fall and ADP levels rise, the hydrogen gradient is “harvested” by a protein called ATP synthase to turn ADP and oxygen into ATP and water (Everman et al., 2011). As a result of this efficient handling of the molecules, the ETC can generate a relatively large amount of ATP with minimal waste products.

**Energy during exercise**

Any form of exercise can be defined by two factors: intensity and duration. These key factors are inversely related, meaning that as intensity goes up, duration must go down. Figure 8-9 illustrates the relationship of these factors; lifting weights for very a short duration with a high intensity is illustrated at point A, running 400 meters is shown at point B, while distance running for a long duration at a lower intensity is at point C. Essentially, the more intense the effort, the shorter the possible duration of the activity will be. Identifying where an exercise is located within this relationship helps define the exercise’s predominate energy system.

At higher intensities (above VT1), carbohydrates will provide more of the energy to make ATP compared to fat because carbohydrates (glucose) can be broken down quickly via glycolysis. Lower-intensity activities (below VT1) will rely mostly on fat oxidation to provide ATP. As the exercise intensity increases to levels over VT1, the body will dynamically shift to relying more on blood glucose and stored glycogen (Romijn et al., 1993). Then, at any point in an activity when a quick burst of energy is needed, the ATP-PC system will provide a large contribution for the short, intense effort. Essentially, all three systems are in a constant state of flux, readily adapting to meet 100% of the body’s energy needs for the entire range of activity intensities.

**Metabolism during steady-state exercise**

The bioenergetics of exercise can be indirectly measured in a laboratory using various modes of exercise (e.g., treadmill or cycle ergometer). Other physiologic functions can be measured as well, including heart rate, blood pressure, and exercise load or work output. Measurements made for the purpose of assessing exercise metabolism are typically made during periods of steady-state. Steady-state aerobic exercise, as the term suggests, is aerobic exercise performed at a constant pace (intensity). For example, steady-state exercise could be described as walking or jogging at a consistent pace for 1 mile.

The entire energy requirements of steady-state exercise is visualized in Figure 8-10. It begins with a person straddling a treadmill belt set at a steady light jogging pace (Figure 8-10, segment A). At the start of exercise (i.e., when the person jumps on the belt and goes from no activity to jogging), aerobic metabolic pathways are too slow to meet the initial demands, so the body relies on the ATP-PC cycle and glycolysis to make up the demand, known as an O2 deficit (represented by the first shaded area, Figure 8-10, segment B).

Gradually, the rate of aerobic ATP production increases, and less and less energy needs to be derived from anaerobic sources. At this point a few minutes into the steady-state effort, oxidative metabolic processes are able to catch up and take over most ATP production duties. Once that point has been reached, the energy demand of the exercise is being met through aerobic means (Figure 8-10, segment C). That primarily aerobic state would essentially continue indefinitely, limited only by the exerciser’s muscular endurance and fitness level.

Then, when the person in the example steps off the treadmill, the energy demands start falling back to baseline quickly (Figure 8-10, segment D) and then more slowly (Figure 8-10, segment E), but the oxygen consumption remains elevated for a few minutes to keep generating ATP aerobically. This shaded area is often referred to as excess postexercise oxygen consumption, or EPOC (McArdle et al., 2010; Wells et al., 2009). The purpose of EPOC is to produce additional ATP (above and beyond what is needed for recovery) to help reestablish baseline levels of ATP and PC and to assist with clearing metabolic waste products. Once the ATP and PC levels have been restored and other physiologic processes have returned to normal, oxygen consumption will have returned close to baseline, and immediate recovery will be mostly complete.

**Metabolism during intermittent work**

During intermittent exercise, this same energy production pattern as steady-state exercise occurs, just multiple times across a workout with each change in intensity. Just like the example in Figure 8-10, when an exerciser has to increase intensity, most of the energy needs come from anaerobic metabolism (Burke et al., 2011; Romijn et al., 1993; Wells et al., 2009). When intensity is decreased, there is a continued period of high, but briefly elevated, oxygen consumption in an attempt to recover quickly to be ready for the next bout of higher-intensity work. Essentially, intermittent work cycles between Figure 8-10, segments B and D, create repeated periods of EPOC without allowing the aerobic processes to fully take over as seen in Figure 8-10, segment C.

If the prior bout of high-intensity work is less than 1 minute, meaning it was primarily fueled by the ATP-PC system, the recovery period will also be about 1 minute or slightly less. If the period of high-intensity work is longer, such as in repeated interval training, the recovery period should have a similar 1-to-1 ratio of work-to-rest time (Daniels, 2014). Recovery is an aerobic event to set ATP-PC concentrations back toward normal and eliminate metabolic waste products. Therefore, even though interval training workouts and athletic competitions are quite often not steady-state efforts, participants really do need to have periods of training that address improving aerobic energy production to perform and recover optimally.

**Estimating fuel contribution during activity**

At lower intensities, the body is using primarily fat for fuel, which results in a lot of ATP being produced, some oxygen being used, and relatively less carbon dioxide being produced. As the exercise intensity increases, the rate at which ATP needs to be produced increases, so more oxygen needs to be delivered to the mitochondria. This causes an increase in breathing volume (i.e., the length and depth of breaths) and is a hallmark of reaching VT1. However, as exercise intensity continues to increase, aerobic metabolism of fat cannot be used to create ATP fast enough, so the body shifts to relying on glucose for fuel via glycolysis (Romijn et al., 1993).

This change in fuel source also means that more carbon dioxide will be produced, which needs to be exhaled. As a result, breathing rate must increase, not only to deliver more oxygen but now also to exhale the increasing amounts of carbon dioxide being produced. This point, where breathing becomes rapid enough that talking is extremely difficult to impossible, marks VT2.

In summary, at VT1, a person needs to take in more air to supply more oxygen to the mitochondria to help support the oxidative metabolism of free fatty acids. Then, at VT2, a person is relying primarily on anaerobic metabolism, and the body becomes more focused on exhaling carbon dioxide and trying to recover anaerobically, so expiration becomes more forceful making it difficult to talk. Because of this, fitness professionals can use a “talk test” to help determine if a client is working aerobically or anaerobically. This concept is discussed more in Chapter 11. Table 8-1 and Figure 8-11 outline how each of the energy systems contribute to overall energy demand.

TABLE 8-1 Characteristics of the Three Energy Systems

|  | **ATP-PC** | **Glycolysis** | **Oxidative** |
| --- | --- | --- | --- |
| Fuel Substrate | Phosphocreatine (PC) | Stored glycogen and/or blood glucose | Pyruvate and free fatty acids |
| Intensity Supported | High | Moderate to high | Low to moderate |
| Onset of Maximal ATP Production | 1 sec | 5-10 sec | 2-3 min |
| Time to Exhaustion of the System | 10-15 sec | 30-60 sec | Theoretically unlimited |
| Ultimate Limiting Factor(s) | Depletion of ATP-PC stores | Lactate and CO2 accumulation | Insufficient oxygen, heat accumulation, muscle fatigue |

**The myth of the “fat-burning zone”**

There is another way of thinking about exercise intensity that has been misinterpreted: the concept of the so-called fat-burning zone. The thought is that people burn more fat at lower-intensity exercise because that easy work relies primarily on the oxidation of free fatty acids and does not require getting energy quickly from carbohydrates. Although it is true that lower-intensity activity relies more on fat as a fuel substrate than glucose, the end result is a little more complex and needs to be viewed from the perspective of a full 24-hour day.

When considering fat burning, it is important to think of both the intensity of an activity and the total duration of that activity. Lower-intensity activities do use a higher percentage of fat as a fuel, but they do not burn a lot of calories unless performed for a very long time. However, while moderate- and high-intensity activities might have a higher percentage of energy coming from carbohydrates, they are burning more total calories in a given time. Table 8-2 compares the differences in calorie expenditure between 20 minutes of exercise at low and moderate intensities. This essentially busts the myth of the fat-burning zone so often advertised on commercial cardio equipment; with 24 hours in a day, total calorie burn matters more for body composition than preferentially training the oxidative system for a short workout.

As seen in Table 8-2, the exerciser burned a higher percentage of fat (70%) when performing low-intensity work as compared to moderate-intensity exercise (50%). However, the *total* number of fat calories was greater when exercising at a moderate-intensity (60 calories) versus low-intensity exercise (42 calories).

This means that when weight loss is the goal, the average individual with only 1 hour of time per day to exercise will see better results with a moderate- to higher-intensity type of workout. He or she will burn more calories during the higher-intensity workout, which will contribute to a greater number of total daily calories burned. On the other hand, if an individual has the ability to do so, lower-intensity activity performed for many hours at a time—such as very long hikes out in nature—would, in fact, net a greater fat burn than 60 minutes of interval training performed by someone who otherwise sits at a desk all day.

TABLE 8-2 Comparing Energy Expenditures

| **Example Exercise Programs** | **Fat Calories Expended** | **Carbohydrate Calories Expended** | **Total Calories Expended** |
| --- | --- | --- | --- |
| 20 minutes, low intensity | 42 (70%) | 18 (30%) | 60 |
| 20 minutes, moderate intensity | 60 (50%) | 60 (50%) | 120 |

### Daily energy needs

When daily food intake is matched to energy needs, people are said to be in energy balance, which allows them to maintain a stable body weight. However, when energy intake is higher than needed to support the total daily energy requirements, it can lead to an increase in body weight. Similarly, if individuals eat less than they need to support their daily energy requirements, they will lose weight as the body fuels itself from its internal stores. Individuals who are over their ideal weight will need to either decrease daily energy intake and/or increase daily activity to achieve their ideal weight. Conversely, people who want to gain muscle mass need to increase their daily energy intake beyond what is being used. The amount of daily energy individuals need is also impacted by their age, sex, pregnancy, existing muscle mass, hormone function, medication use, and genetic factors. As a result, individual daily energy needs vary tremendously across the population.

**Total Daily Energy Expenditure**

The total number of calories that a person expends in a day is called the total daily energy expenditure (TDEE). Calories are the basic unit of energy that is provided by food. Scientifically speaking, 1 Calorie (also referred to as a kilocalorie (kcal)) is the amount of energy needed to raise the temperature of 1 kilogram of water by 1º Celsius. But more importantly from a health and fitness perspective, calories (as commonly written on food labels) represent the units of energy that come from the food we use to stay alive, maintain body functions, move, and exercise.

STRETCH YOUR KNOWLEDGE

A calorie (lowercase c) is a unit of energy and is defined as the amount of heat energy required to raise the temperature of 1 gram of water 1º Celsius. A kilocalorie (kcal, sometimes written as Calorie with an uppercase C) is equal to 1,000 calories. Although not scientifically correct, calories (as written on food labels) and kilocalories are used interchangeably in everyday language all around the world; however, food calories are technically kilocalories.

The number of calories that each person expends in a day varies tremendously. The calories that are burned throughout the day are used for a variety of processes besides exercise, including maintenance of the resting metabolic rate (RMR), digestion and absorption of food, and general activities ranging from walking to the mailbox to typing on a keyboard. Because heat is a by-product of processing macronutrient substrates for energy, the “burning of calories” is more specifically termed *thermogenesis*. With that in mind, energy used for exercise is called exercise activity thermogenesis (EAT), energy used to digest food is called the thermic effect of food (TEF), and energy used for all the other daily movements and activities a person performs is called nonexercise activity thermogenesis (NEAT). The combination of RMR, EAT, TEF, and NEAT combine to form TDEE.

**Resting metabolic rate**

The RMR is the number of calories that the body uses at complete rest to function (e.g., pumping blood, breathing, fueling the brain, organ functioning). Simply put, RMR is the minimum energy expenditure (i.e., number of calories needed) to keep a person alive. This number can vary considerably among individuals, but people with more muscle mass tend to have a higher RMR because muscle is a more active user of ATP than other bodily tissues. RMR accounts for around 70% of TDEE, with activity (EAT + NEAT) and TEF making up the remainder of the daily energy expenditure (Trexler et al., 2014) (Figure 8-12).

GETTING TECHNICAL

One of the best methods to measure RMR is via indirect calorimetry, a process that uses expired gasses (CO2) to predict energy expenditure. However, the equipment to do this is not widely available, so there are several equations that can be used to estimate RMR, including the Harris-Benedict, Miflin St. Jeor, and Katch-McArdle methods. There are also many online calculators that have been developed that incorporate one or more prediction equations in an attempt to improve the accuracy.

However, when compared to measuring RMR through indirect calorimetry, all prediction equations tend to underestimate RMR, especially for muscular people and clinical populations (Joseph et al., 2017; Zanella et al., 2018). Also, prediction equations to determine RMR work poorly in people with obesity, so caution should be used when estimating RMR via a prediction equation when working with obese clients (Madden et al., 2016; Spears et al., 2009).

**Thermic effect of food**

TEF is the number of calories that are expended to break down the components of a meal (Secor, 2009). In other words, it takes energy (calories) to digest food. On average, around 7–10% of the calories contained in foods go toward their own digestion and absorption. In general, protein results in a higher TEF, meaning it takes more calories to break down protein foods compared to carbohydrates or fats.

**Energy expended during physical activity**

While most of the energy (calories) that a person burns during the day is due to the basic metabolic processes that sustain life, any type of activity or exercise also burns calories and therefore raises TDEE. Physical activity can be broken down into two categories: structured, purposeful exercise (EAT) and nonexercise activities (NEAT), such as cleaning the house or shopping for groceries. Exercise can increase energy expenditure both during the activity itself and afterward via increased metabolic rate and recovery processes.

The utilization of 1 liter of oxygen during aerobic activity requires 5 kcal (calories) of energy, so longer-duration or higher-intensity aerobic activities can burn a considerable number of calories. The physical activity level (PAL) has been quantified as the total daily energy expenditure divided by the resting energy expenditure (Westerterp, 2013). The physical activity level quantifies a person’s activity level by comparing the number of calories burned while active to the amount burned while sedentary. Some evidence suggests that the ideal physical activity level ratio for a sustainable lifestyle ranges from 1:1–2:5, which peaks during reproductive age and declines somewhat later in life (Westerterp, 2013).

GETTING TECHNICAL

Another way that activity is sometimes quantified is by metabolic equivalent (MET). One MET is equal to 3.5 mL of oxygen consumed per kilogram of body weight per minute (3.5 mL O2/kg per min), which is the average resting metabolic rate for the greater population (McArdle et al., 2010). A moderate-intensity activity might require 5 METs (5 times RMR, or 17–18 mL/kg per min), and a very high-intensity activity might require 9 or more METs (9 times RMR or >30 mL/kg per min).

**Nonexercise activity thermogenesis**

NEAT refers to the burning of calories from activity that occurs independent of structured, planned exercise. Factors like standing instead of sitting, fidgeting, shivering, and daily tasks, such as walking to the parking lot and doing household chores, are all components of NEAT. NEAT levels can vary tremendously across populations and may contribute up to 20% of TDEE in people who have nonsedentary jobs (e.g., manual labor). Some research has suggested that certain individuals have greater inherent tendency to perform NEAT—such as people who fidget more—and that higher levels of daily NEAT may be protective against obesity (Levine, 2007; Villablanca et al., 2015). While some people may be more predisposed to unconsciously engage in NEAT than others, anyone can choose to incorporate more NEAT into their day by including things like using a standing desk, parking farther away in the parking lot, pacing while on the phone, and taking the stairs instead of the elevator.