CHAPTER 3 STUDY GUIDE

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The Three Energy Systems (Bioenergetics)

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Chapter Overview

This chapter study guide provides an overview of bioenergetics and the three energy systems as they relate to training and sport. Bioenergetics is the study of the flow of energy within biological systems, specifically focusing on how macronutrients (carbohydrates, proteins, and fats) are converted into usable forms of energy, primarily adenosine triphosphate (ATP). Understanding bioenergetics is crucial for designing effective training programs because it explains how energy is supplied for different types of exercise and how training can modify these energy transfer processes to enhance performance. Without a sufficient supply of ATP, muscle activity and growth would not be possible. This information is important for coaches and practitioners as they design effective strength and conditioning programs to prepare athletes to meet the physiological and metabolic demands of their sport.

Students should use this document as a study guide and to reinforce concepts found in the text. The questions at the end of the document can be used to check understanding and ensure that both key facts and overarching themes are understood.

Key Themes:

The central theme of the chapter is the **metabolic specificity of exercise and training**. This concept emphasizes that understanding how energy is produced and transferred in biological systems is crucial for designing effective training programs tailored to the specific demands of an athletic event or activity.

The chapter defines **bioenergetics** as the flow of energy in a biological system, primarily involving the conversion of macronutrients (carbohydrate, protein, and fats) into usable forms of energy.

Adenosine Triphosphate (ATP) and its Role:

- **ATP** is the immediate source of energy for muscular activity and growth.
- ATP is composed of adenosine and three phosphate groups.
- The breakdown of ATP to yield energy is called **hydrolysis**, catalyzed by **ATPase** enzymes.
- "Without an adequate supply of ATP, muscular activity and muscle growth would not be possible."
- ATP is a **high-energy molecule** storing large amounts of energy in its chemical bonds.
- Muscle cells store limited amounts of ATP, necessitating constant replenishment.

Biological Energy Systems:

Human skeletal muscle utilizes three basic energy systems to replenish ATP:

1. **Phosphagen System:**
    - Provides ATP primarily for **short-term, high-intensity activities** (e.g., resistance training, sprinting).
    - Highly active at the start of all exercise.

- Relies on the hydrolysis of ATP and the breakdown of **creatine phosphate (CP)**, catalyzed by **creatine kinase**.
- CP donates a phosphate to ADP to replenish ATP.
- "The creatine kinase reaction provides energy at a high rate; however, because CP is stored in relatively small amounts, the phosphagen system cannot be the primary supplier of energy for continuous, long-duration activities."
- Skeletal muscle CP concentrations are typically 4-6 times higher than ATP.
- The **adenylate kinase (myokinase) reaction** (2ADP -> ATP + AMP) can also rapidly replenish ATP and produces AMP, a powerful stimulant of glycolysis.
- Control is largely governed by the **law of mass action**, where reactant concentrations drive reaction direction.
- Type II (fast-twitch) muscle fibers contain higher CP concentrations than Type I (slow-twitch) fibers, potentially allowing faster ATP replenishment in these fibers during anaerobic exercise.

2. **Glycolysis:**

- Breakdown of **carbohydrate (glycogen or glucose)** to resynthesize ATP.
- Occurs in the **sarcoplasm**.
- Involves multiple enzymatic reactions, resulting in a slower ATP resynthesis rate than the phosphagen system, but with a much higher capacity due to larger glycogen and glucose stores.
- **Pyruvate**, the end product of glycolysis, can be converted to **lactate** or shuttled into the **mitochondria**.
- **"Anaerobic glycolysis" (Fast Glycolysis):** Pyruvate converted to lactate. Faster ATP resynthesis but limited duration due to H+ production and decreased pH.
- **"Aerobic glycolysis" (Slow Glycolysis):** Pyruvate enters mitochondria for the Krebs cycle. Slower ATP resynthesis but longer duration if oxygen is sufficient.
- The fate of pyruvate depends on cellular energy demands. High demand favors lactate conversion for rapid ATP. Lower demand and sufficient oxygen favor mitochondrial entry.

3. **Lactate Formation:** Catalyzed by lactate dehydrogenase. Lactate is the product, not lactic acid, at physiological pH.
    - "Although the muscular fatigue experienced during exercise often correlates with high tissue concentrations of lactate, lactate is not the cause of fatigue... Proton (H+) accumulation during fatigue reduces the intracellular pH, inhibits glycolytic reactions, and directly interferes with muscle's excitation–contraction coupling."
    - This pH decrease is termed **metabolic acidosis**.
    - Lactate can be used as an energy substrate (Type I and cardiac muscle) or converted to glucose in the liver via the **Cori cycle**.
    - Blood lactate increases with exercise intensity and depends on muscle fiber type, duration, training status, and initial glycogen levels.
    - Peak blood lactate occurs ~5 minutes post-exercise.
    - Active recovery and training (aerobic and anaerobic) lead to faster lactate clearance.
    - Trained individuals have lower blood lactate at absolute workloads but higher blood lactate during maximal exercise.
4. **Energy Yield of Glycolysis:** ATP is resynthesized via **substrate-level phosphorylation**.
    - Starting with blood glucose: Net 2 ATP.
    - Starting with muscle glycogen: Net 3 ATP.
    - **Control of Glycolysis:** Stimulated by high ADP, Pi, ammonia, slight pH decrease, and AMP. Inhibited by markedly lower pH, ATP, CP, citrate, and free fatty acids.
    - Key regulatory enzymes (rate-limiting steps) are **hexokinase**, **phosphofructokinase (PFK)**, and **pyruvate kinase**. These are subject to **allosteric regulation** (feedback regulation).
5. **Lactate Threshold (LT):** Exercise intensity at which blood lactate begins an abrupt increase above baseline. Represents increased reliance on anaerobic mechanisms. Occurs at 50-60% V.O2max in untrained and 70-80% in trained.
    - **Onset of Blood Lactate Accumulation (OBLA):** Second increase in lactate accumulation rate, typically at 4 mmol/L.
    - Training at or above LT/OBLA shifts these thresholds to higher intensities.

6. **Oxidative (Aerobic) System:**
    - Primary source of ATP at **rest and during low-intensity activities**.
        - Uses primarily **carbohydrate and fats** as substrates. Protein contributes minimally except during prolonged starvation or exercise (>90 minutes).
        - At rest: ~70% ATP from fats, 30% from carbohydrate.
        - As intensity increases: Shift to carbohydrate.
        - During prolonged, submaximal work: Gradual shift back to fats and protein.
        - Occurs in the **mitochondria**.
    - **Glucose and Glycogen Oxidation:** Pyruvate enters mitochondria, converted to acetyl-CoA, which enters the **Krebs cycle**.
        - Krebs cycle oxidizes substrates and produces indirect ATP (via GTP) and electron carriers (NADH, FADH2).
        - NADH and FADH2 transport hydrogen atoms to the **Electron Transport Chain (ETC)**.
        - The ETC uses NADH and FADH2 to rephosphorylate ADP to ATP (**oxidative phosphorylation**), with oxygen as the final electron acceptor.
        - One NADH yields 3 ATP, one FADH2 yields 2 ATP.
        - Total ATP from one glucose: ~38 (from blood glucose) or ~39 (from muscle glycogen).
        - Oxidative phosphorylation accounts for >90% of ATP synthesis.
    - **Fat Oxidation:** Triglycerides are broken down into free fatty acids and glycerol. Free fatty acids enter mitochondria and undergo **beta oxidation**, forming acetyl-CoA and hydrogen protons.
        - Acetyl-CoA enters the Krebs cycle, hydrogen atoms go to the ETC.
        - Fat oxidation yields hundreds of ATP per molecule, demonstrating a vast capacity for ATP synthesis.
    - **Protein Oxidation:** Amino acids can be converted to glucose (**gluconeogenesis**), pyruvate, or Krebs cycle intermediates to produce ATP.

    - Contributes minimally (<3%) during short-term exercise but 3-18% during prolonged activity.
    - Branched-chain amino acids are major ones oxidized in skeletal muscle.
    - Nitrogenous waste includes urea and small amounts of ammonia (toxic, associated with fatigue).
  - **Control of the Oxidative System:** The rate-limiting step in the Krebs cycle is catalyzed by **isocitrate dehydrogenase**, stimulated by ADP and inhibited by ATP. Also influenced by NAD+ and FAD2+ availability and succinyl CoA accumulation. The ETC is inhibited by ATP and stimulated by ADP.

Energy Production Rate and Capacity:

- There is an **inverse relationship** between an energy system's maximum rate of ATP production and its capacity (total ATP produced).
- **Phosphagen System:** Highest rate, lowest capacity. Supplies ATP for high-intensity, short-duration activities (e.g., 100m dash).
- **Glycolytic System:** Moderate rate and capacity. Supplies ATP for moderate- to high-intensity activities of short to medium duration (e.g., 400m dash).
- **Oxidative System:** Slowest rate, greatest capacity. Supplies ATP for low-intensity, long-duration activities (e.g., marathon).
- Table 3.2 provides general guidelines for primary energy systems used based on event duration and intensity.
- "At no time, during either exercise or rest, does any single energy system provide the complete supply of energy." Contribution is primarily based on intensity, secondarily on duration.

Substrate Depletion and Repletion:

- Depletion of energy substrates (phosphagens, glucose, glycogen, lactate, free fatty acids, amino acids) can reduce energy production and lead to fatigue.
- Fatigue is frequently associated with **phosphagen** and **glycogen** depletion.
- **Phosphagens:**
  - More rapidly depleted during high-intensity anaerobic exercise.

    - CP can decrease 50-70% in short, intense exercise and be almost completely depleted in very intense exercise to exhaustion.
    - ATP may decrease slightly or up to 50-60% during fatigue.
    - Complete ATP resynthesis occurs within 3-5 minutes post-exercise.
    - Complete CP resynthesis occurs within 8 minutes post-exercise.
    - Repletion is largely aerobic.
    - Effects of training on phosphagens are less understood; some evidence suggests increased resting concentrations with aerobic and resistance training, and decreased depletion rates at absolute submaximal workloads with aerobic training.
- **Glycogen:**
    - Limited stores in muscle (300-400g) and liver (70-100g).
    - Resting concentrations influenced by training and diet. Anaerobic and aerobic training can increase resting muscle glycogen with appropriate nutrition.
    - Depletion rate is related to exercise intensity. Muscle glycogen is more important in moderate/high intensity, liver glycogen in low intensity and longer duration.
    - Above 60% V.O2max, muscle glycogen becomes increasingly important; some muscle cells can be completely depleted.
    - Long-term exercise (>90 minutes) at higher intensities can lead to decreased blood glucose due to liver glycogen depletion, potentially causing hypoglycemia.
    - Very high-intensity, intermittent exercise (resistance training) can cause substantial muscle glycogen depletion (20-60%) even with few sets.
    - While phosphagens may limit high-resistance/low-repetition resistance exercise, muscle glycogen may limit workouts with many sets and high total work.
    - Rate of glycogenolysis during resistance exercise depends on intensity. Total depletion is similar regardless of intensity for equal total work.
    - Repletion of muscle glycogen is optimal with carbohydrate ingestion (0.7-3.0 g/kg body weight every 2 hours post-exercise).
    - Complete muscle glycogen repletion can take 24 hours with sufficient carbohydrate; longer if exercise includes high eccentric components (muscle damage).

Bioenergetic Limiting Factors in Exercise Performance:

- Understanding limiting factors is important for designing training programs to delay fatigue and enhance performance.
- Possible limiting factors include **glycogen depletion**, **metabolic acidosis (increased muscle hydrogen ions)**, increased intracellular inorganic phosphate, ammonia accumulation, increased ADP, and impaired calcium release.
- Glycogen depletion can limit both long-duration (aerobic) and repeated, high-intensity (anaerobic) exercise.
- Metabolic acidosis limits contractile force in resistance training, sprinting, and other anaerobic activities.

Oxygen Uptake and Aerobic/Anaerobic Contributions:

- **Oxygen uptake (consumption):** Measure of ability to take in, deliver, and use oxygen.
- During low-intensity exercise, oxygen uptake increases until a **steady state** is reached (oxygen demand = consumption).
- At the start of exercise, energy is partially supplied anaerobically due to slow aerobic system response, creating an **oxygen deficit**.
- Post-exercise oxygen uptake remains elevated (**EPOC - Excess Postexercise Oxygen Consumption**) to restore the body. EPOC is influenced by factors like replenishing oxygen stores, ATP/CP resynthesis, increased body temperature, circulation, ventilation, triglyceride-fatty acid cycling, protein turnover, and energy efficiency changes.
- Anaerobic mechanisms provide much of the energy if intensity is above maximal oxygen uptake.
- Generally, as anaerobic contribution increases, exercise duration decreases.
- Table 3.5 shows anaerobic contributions are primary up to ~60 seconds of maximal sustained effort, after which aerobic metabolism becomes primary.

Metabolic Specificity of Training:

- Using appropriate **exercise intensities and rest intervals** allows "selection" of specific primary energy systems for training.
- This leads to more efficient and productive training regimens tailored to the metabolic demands of the sport.

- Examples of sports involving intermittent high-intensity bouts interspersed with rest include American football, basketball, and hockey.
- **Interval Training:** Uses predetermined intervals of exercise and rest (**work-to-rest ratios**) to emphasize bioenergetic adaptations for efficient energy transfer.
    - Allows more work at higher intensities with less fatigue compared to continuous training.
    - Table 3.6 provides general guidelines for work-to-rest ratios based on the energy system being stressed (e.g., Phosphagen: 1:12 to 1:20; Fast glycolysis: 1:3 to 1:5; Oxidative: 1:1 to 1:3).
    - Shorter, high-intensity exercise requires greater work-to-rest ratios for phosphagen repletion. Longer duration, lower intensity tasks can have longer work intervals and smaller ratios.
- **High-Intensity Interval Training (HIIT):** Brief repeated bouts of high-intensity exercise with intermittent recovery periods.
    - Efficient for cardiopulmonary, metabolic, and neuromuscular adaptations.
    - Considered highly effective for improving physical performance.
    - Involves a high-intensity work phase and a lower-intensity recovery phase (duty cycle).
    - Key variables to manipulate include intensity and duration of both work and recovery phases.
    - To optimize adaptations, HIIT sessions should maximize time spent at or near V.O2max.
    - Benefits include increased V.O2max, proton buffering, glycogen content, anaerobic thresholds, time to exhaustion, and time-trial performance.
    - HIIT can provide performance and physiological adaptations equivalent to long, slow endurance training in a time-efficient manner.
    - Design considerations include periodization and the number of HIIT sessions, especially when combined with other training.
- **Combination Training (Cross-Training):** Adding aerobic endurance training to anaerobic athletes' programs.
    - Postulated to enhance recovery due to reliance on aerobic mechanisms.

- Some studies show endurance fitness is related to power recovery.
- However, aerobic endurance training **may reduce anaerobic performance capabilities**, particularly for high-strength, high-power performance.
- Possible mechanisms for hindering strength development include increased training volume leading to overtraining risk, chronically lower muscle glycogen, decreased rapid voluntary activation, and fiber type transition to slow-twitch fibers.
- Conversely, some studies suggest anaerobic training (strength training) can improve low- and high-intensity exercise endurance without hindering metabolic parameters (V.O2max) in highly trained athletes.
- "Thus, it appears that extensive aerobic endurance training to enhance recovery from anaerobic events is not necessary and may be counterproductive in most strength and power sports."

Strength and conditioning professionals need to understand that designing productive training programs requires understanding how energy is produced during different exercise types and how training can modify energy production. The dominant energy system is primarily determined by exercise intensity and secondarily by duration. Metabolic responses and adaptations are regulated by exercise characteristics (intensity, duration, recovery). Applying the principle of metabolic specificity through appropriate exercise selection, intensities, and rest intervals is key to enhancing athletic performance.

Chapter Themes Reflection

Now that you've read through the chapter utilizing this study guide to help retain the key points, would you be able to articulate answers to the following questions in your own words?

- [ ] Respond to each question in your own words first
- [ ] Check your answer against the response
- [ ] Note any deficiencies in your response and revisit key sections of the study guide
- [ ] Now, rephrase the answer again in your own words

What is bioenergetics and why is it important in exercise and training?

Bioenergetics is the study of the flow of energy within biological systems, specifically focusing on how macronutrients (carbohydrates, proteins, and fats) are converted into usable forms of energy, primarily adenosine triphosphate (ATP). Understanding bioenergetics is crucial for designing effective training programs because it explains how energy is supplied for different types of exercise and how training can modify these energy transfer processes to enhance performance. Without a sufficient supply of ATP, muscle activity and growth would not be possible.

What is ATP and how is it replenished in muscle cells during exercise?

ATP (adenosine triphosphate) is the primary energy currency of the body. It's a molecule composed of adenosine and three phosphate groups, storing energy in its chemical bonds. When one molecule of ATP is broken down (hydrolyzed) in the presence of water, it releases energy for muscle contractions and other biological work, producing adenosine diphosphate (ADP), inorganic phosphate (Pi), and a hydrogen ion (H+). Muscle cells have three basic energy systems to replenish ATP: the phosphagen system, glycolysis, and the oxidative system.

Describe the three basic energy systems in muscle cells and how they contribute to ATP production.

The three basic energy systems are:

- **Phosphagen System:** This system provides ATP for short-term, high-intensity activities like resistance training and sprinting. It relies on the hydrolysis of ATP and the breakdown of creatine phosphate (CP) to rapidly resynthesize ATP. The phosphagen system is highly active at the start of all exercise regardless of intensity but is limited by the relatively small stores of CP.
- **Glycolysis:** This system breaks down carbohydrate (glycogen or glucose) to resynthesize ATP. While slower than the phosphagen system, it has a higher capacity due to larger carbohydrate stores. Glycolysis occurs in the sarcoplasm and can proceed with pyruvate being converted to lactate (sometimes called anaerobic glycolysis) or shuttled into the mitochondria (sometimes called aerobic glycolysis).
- **Oxidative System:** This is the primary source of ATP at rest and during low-intensity activities, using primarily carbohydrates and fats. Protein can also contribute, especially during prolonged exercise. This system involves glycolysis leading to the Krebs cycle and

the electron transport chain within the mitochondria, requiring oxygen as the final electron acceptor. It has the lowest rate of ATP production but the greatest capacity.

How do exercise intensity and duration influence which energy system is primarily used?

There is an inverse relationship between exercise intensity and duration in determining the primary energy system used. Short-duration, high-intensity activities rely heavily on the phosphagen system and fast glycolysis for rapid ATP production. As the duration of exercise increases and the intensity decreases, the reliance shifts towards slow glycolysis and the oxidative system, which can produce larger amounts of ATP over time, albeit at a slower rate. However, it's important to note that all three energy systems are active to some degree at any given time.

What is the lactate threshold (LT) and onset of blood lactate accumulation (OBLA), and how are they affected by training?

The lactate threshold (LT) is the exercise intensity at which blood lactate begins to increase abruptly above baseline levels, indicating a greater reliance on anaerobic metabolism. The onset of blood lactate accumulation (OBLA) is a second point of inflection where blood lactate concentration reaches 4 mmol/L. These thresholds can be used as markers of the anaerobic threshold. Training, particularly at or above the LT or OBLA, can shift these thresholds to higher exercise intensities. This shift is likely due to adaptations such as reduced catecholamine release and increased mitochondrial content, allowing athletes to perform at higher percentages of their maximal oxygen uptake with less lactate accumulation.

How do phosphagen and glycogen stores get depleted and repleted during and after exercise?

During high-intensity anaerobic exercise, phosphagen (ATP and CP) concentrations can decrease significantly, particularly CP which can be almost completely depleted during very intense exercise to exhaustion. ATP concentrations may also decrease but are largely maintained by CP depletion and other energy sources. Complete resynthesis of ATP typically occurs within 3-5 minutes after exercise, while CP resynthesis can take up to 8 minutes, primarily through aerobic metabolism.

Muscle glycogen depletion is related to exercise intensity, with higher intensities leading to faster depletion. Muscle glycogen is more important during moderate- and high-intensity exercise, while liver glycogen is more important during low-intensity exercise and as duration increases. High-intensity intermittent exercise can also cause substantial muscle glycogen depletion. Glycogen repletion is optimal with sufficient post-exercise carbohydrate ingestion (0.7-3.0 g/kg body weight every 2 hours), potentially achieving complete replenishment within 24 hours, though more time may be needed after exercise causing significant muscle damage.

What are some bioenergetic factors that can limit exercise performance?

Several bioenergetic factors can limit maximal exercise performance:

- **Phosphagen Depletion:** Depletion of ATP and CP can directly limit the ability to sustain high-intensity efforts.
- **Glycogen Depletion:** Running out of muscle and liver glycogen can limit the availability of carbohydrates for both anaerobic and aerobic metabolism, particularly during prolonged or repeated high-intensity exercise.
- **Metabolic Acidosis:** Accumulation of hydrogen ions (H+), primarily from ATP hydrolysis, reduces intracellular pH (metabolic acidosis). While lactate itself does not cause acidosis, the reduced pH inhibits glycolytic enzymes and interferes with muscle contraction, contributing to fatigue.
- **Other Factors:** Increased intracellular inorganic phosphate (Pi), ammonia accumulation, increased ADP, and impaired calcium release from the sarcoplasmic reticulum have also been implicated in muscular fatigue.

How can training programs be designed to be metabolically specific to an athletic event?

Training programs can be designed to target specific energy systems by manipulating exercise intensity and rest intervals. This is known as metabolic specificity of training.

- **Interval Training:** Using predetermined work and rest periods allows for greater work to be performed at higher intensities with less fatigue compared to continuous training. The work-to-rest ratio can be adjusted to emphasize different energy systems (e.g., short, high-intensity intervals with long rest for the phosphagen system; longer, moderate-intensity intervals with shorter rest for glycolysis).

- **High-Intensity Interval Training (HIIT):** This involves brief, repeated bouts of very high-intensity exercise with intermittent recovery. HIIT is effective for improving both cardiopulmonary and metabolic adaptations, particularly increasing the time spent at or near maximal oxygen uptake. Manipulating variables like the intensity and duration of work and recovery phases, number of cycles and sets, and rest between sets allows for precise metabolic targeting.
- **Combination Training:** While some aerobic endurance training might enhance recovery (which relies on aerobic mechanisms), excessive aerobic training can negatively impact anaerobic performance capabilities, particularly for strength and power athletes. Specific anaerobic training can also improve aerobic power and recovery markers. Therefore, for anaerobic sports, extensive aerobic training may not be necessary and could be counterproductive; careful consideration is needed when combining different training modalities.

Glossary of Key Terms

- **Adenosine diphosphate (ADP):** A molecule composed of adenosine and two phosphate groups; formed by the hydrolysis of ATP.
- **Adenosine monophosphate (AMP):** A molecule composed of adenosine and one phosphate group; formed by the further hydrolysis of ADP.
- **Adenosine triphosphatase (ATPase):** An enzyme that catalyzes the hydrolysis of ATP, releasing energy.
- **Adenosine triphosphate (ATP):** The main energy currency of the cell; stores and releases energy for biological work through hydrolysis.
- **Adenylate kinase reaction:** A single-enzyme reaction that rapidly replenishes ATP by combining two molecules of ADP to form ATP and AMP.
- **Aerobic:** Processes that require the presence of oxygen.
- **Aerobic glycolysis:** Glycolysis where pyruvate is shuttled into the mitochondria for further oxidation through the Krebs cycle and electron transport chain. Also referred to as slow glycolysis.
- **Allosteric activation:** Occurs when an "activator" molecule binds to a regulatory enzyme at a site other than the active site, increasing its turnover rate.

- **Allosteric inhibition:** Occurs when an end product binds to a regulatory enzyme at a site other than the active site, decreasing its turnover rate.
- **Anabolism:** The synthesis of larger molecules from smaller molecules, which requires energy. Building-up processes.
- **Anaerobic:** Processes that do not require the presence of oxygen.
- **Anaerobic glycolysis:** Glycolysis where pyruvate is converted to lactate in the sarcoplasm. Also referred to as fast glycolysis.
- **Beta oxidation:** A series of reactions in the mitochondria where free fatty acids are broken down to form acetyl-CoA and hydrogen protons.
- **Bioenergetics:** The flow of energy in a biological system; primarily concerns the conversion of macronutrients into biologically usable forms of energy.
- **Branched-chain amino acid:** Amino acids with a branched side chain (leucine, isoleucine, valine); major amino acids oxidized in skeletal muscle.
- **Calcium ATPase:** Enzyme that catalyzes ATP hydrolysis for pumping calcium into the sarcoplasmic reticulum.
- **Catabolism:** The breakdown of large molecules into smaller molecules, associated with the release of energy. Breaking-down processes.
- **Combination training:** Combining aerobic endurance training with anaerobic training. Also referred to as cross-training in this context.
- **Cori cycle:** The process where lactate produced in the muscle is transported in the blood to the liver and converted to glucose.
- **Creatine kinase:** The enzyme that catalyzes the synthesis of ATP from creatine phosphate and ADP in the phosphagen system.
- **Creatine phosphate (CP):** A high-energy phosphate molecule that provides a phosphate group to ADP to replenish ATP; also called phosphocreatine (PCr).
- **Cytochrome:** A series of electron carriers in the electron transport chain.
- **Depletion:** The reduction in the concentration of energy substrates during exercise.
- **Electron transport chain (ETC):** A series of electron carriers in the mitochondria that uses NADH and $FADH_2$ to rephosphorylate ADP to ATP.

- **Endergonic reaction:** Reactions that require energy, such as anabolic processes and muscle contraction.
- **Energy:** The capacity to do work.
- **Energy substrate:** Molecules that provide starting materials for bioenergetic reactions, including phosphagens, glucose, glycogen, lactate, free fatty acids, and amino acids.
- **Excess postexercise oxygen consumption (EPOC):** The oxygen uptake above resting values used to restore the body to the preexercise condition. Also known as oxygen debt or recovery O2.
- **Exergonic reaction:** Energy-releasing reactions, generally catabolic.
- **Fast glycolysis:** See anaerobic glycolysis.
- **Flavin adenine dinucleotide (FADH2):** A molecule produced in the Krebs cycle that transports hydrogen atoms to the electron transport chain.
- **Gluconeogenesis:** The formation of glucose from noncarbohydrate sources, such as lactate and amino acids.
- **Glycogenolysis:** The breakdown of glycogen into glucose.
- **Glycolysis:** The breakdown of carbohydrate (glycogen or glucose) to resynthesize ATP.
- **Glycolytic:** Related to glycolysis.
- **High-intensity interval training (HIIT):** Exercise regimen involving brief repeated bouts of high-intensity exercise with intermittent recovery periods.
- **Hydrolysis:** The breakdown of a molecule by adding water, such as the hydrolysis of ATP.
- **Inorganic phosphate (Pi):** A phosphate molecule that is not bound to an organic molecule.
- **Interval training:** Method using predetermined intervals of exercise and rest periods to emphasize bioenergetic adaptations for efficient energy transfer.
- **Krebs cycle:** A series of reactions that continues the oxidation of substrates from glycolysis and produces ATP indirectly; also known as the citric acid cycle or tricarboxylic acid cycle.
- **Lactate:** The end product of anaerobic glycolysis; formed from pyruvate.
- **Lactate threshold (LT):** The exercise intensity at which blood lactate begins an abrupt increase above the baseline concentration.

- **Lactic acid:** Often mistakenly used to describe the end result of anaerobic glycolysis; due to physiological pH, lactate is the actual product.
- **Law of mass action:** States that the concentrations of reactants or products in solution will drive the direction of the reactions.
- **Mass action effect:** The influence of reactant and product concentrations on the rate of enzyme-mediated reactions.
- **Metabolic acidosis:** An exercise-induced decrease in intracellular pH.
- **Metabolic specificity:** The principle that training adaptations are largely regulated by exercise characteristics such as intensity, duration, and recovery intervals.
- **Metabolism:** The total of all catabolic (exergonic) and anabolic (endergonic) reactions in a biological system.
- **Mitochondria:** Specialized cellular organelles where the reactions of aerobic metabolism occur.
- **Myokinase reaction:** See adenylate kinase reaction.
- **Myosin ATPase:** The enzyme that catalyzes ATP hydrolysis for muscle crossbridge recycling.
- **Near-equilibrium reactions:** Reactions that proceed in a direction dictated by the concentrations of the reactants due to the law of mass action.
- **Nicotinamide adenine dinucleotide (NADH):** A molecule that transports hydrogen atoms to the electron transport chain; produced during glycolysis and the Krebs cycle.
- **Onset of blood lactate accumulation (OBLA):** The exercise intensity at which the concentration of blood lactate reaches 4 mmol/L.
- **Oxidative phosphorylation:** The resynthesis of ATP in the electron transport chain.
- **Oxidative system:** The primary source of ATP at rest and during low-intensity activities, using carbohydrate and fats as substrates; occurs in the mitochondria.
- **Oxygen debt:** See excess postexercise oxygen consumption (EPOC).
- **Oxygen deficit:** The anaerobic contribution to the total energy cost of exercise at the start of an exercise bout.

- **Oxygen uptake:** A measure of a person's ability to take in, deliver, and use oxygen during exercise.
- **Phosphagen system:** The energy system that provides ATP primarily for short-term, high-intensity activities; relies on ATP hydrolysis and creatine phosphate breakdown.
- **Phosphocreatine (PCr):** See creatine phosphate (CP).
- **Phosphofructokinase (PFK):** A regulatory enzyme in glycolysis and the rate-limiting step of the pathway.
- **Phosphorylation:** The process of adding an inorganic phosphate (Pi) to another molecule.
- **Pyruvate:** The end product of glycolysis.
- **Rate-limiting step:** The slowest step in a metabolic pathway that controls the overall rate of the pathway.
- **Repletion:** The restoration of energy substrates during recovery from exercise.
- **Slow glycolysis:** See aerobic glycolysis.
- **Sodium-potassium ATPase:** Enzyme that catalyzes ATP hydrolysis for maintaining the sarcolemmal concentration gradient after depolarization.
- **Substrate-level phosphorylation:** The direct resynthesis of ATP from ADP during a single reaction in metabolic pathways.
- **Wet muscle:** Muscle that has not been desiccated.
- **Work-to-rest ratio:** The ratio of the duration of the exercise interval to the duration of the rest or recovery interval in interval training.

Test Your Understanding

This section is designed to test your ability to **recall, explain, and apply** key concepts from the chapter without relying on notes.

Before you begin:

☐ Answer each question fully and thoughtfully using your own words.

☐ After responding to the short answer quiz, review the answers on the last page of this section carefully to identify any gaps in your understanding.

- [ ] After responding to the essays, check against the relevant section from the *Essentials* text.

Remember: Mastery comes from the ability to explain concepts clearly, not just recognize them.

Short Answer Quiz

Answers provided on the last page of this section

1. What are the three basic energy systems used to replenish ATP in human skeletal muscle?
2. Explain the primary role of the phosphagen system during exercise.
3. How does glycolysis contribute to ATP resynthesis?
4. What are the two possible fates of pyruvate following glycolysis, and what determines which path it takes?
5. What is the difference between substrate-level phosphorylation and oxidative phosphorylation?
6. Define the lactate threshold (LT) and the onset of blood lactate accumulation (OBLA).
7. Describe the primary function of the oxidative system during exercise.
8. How does the intensity and duration of exercise influence which energy system is primarily used?
9. What is EPOC, and what are some of the factors that contribute to it?
10. What is metabolic specificity of training, and why is it important for designing training programs?

Essay Format Questions

Answers will vary. Check against relevant section from the *Essentials* text.

1. Compare and contrast the three basic energy systems (phosphagen, glycolysis, and oxidative) in terms of their rate and capacity for ATP production, primary substrates used, and typical exercise durations and intensities they support.
2. Discuss the role of lactate in energy metabolism during exercise. Explain how it is formed, its relationship to metabolic acidosis, and how it is cleared from the body.
3. Explain the concept of bioenergetic limiting factors in exercise performance. Provide examples of how depletion of specific substrates or accumulation of metabolic byproducts can contribute to fatigue during different types of exercise.

4. Describe the metabolic specificity of training. How can understanding the energy system demands of a sport be used to design effective interval training and high-intensity interval training (HIIT) programs, including considerations for work-to-rest ratios?
5. Analyze the potential benefits and drawbacks of combination training (aerobic endurance training combined with anaerobic training) for strength and power athletes. Discuss the proposed mechanisms behind the interference effect and provide examples of how it might impact performance.

Short Answer Quiz Key

1. The three basic energy systems are the phosphagen system, glycolysis, and the oxidative system. These systems work together to continuously resynthesize ATP for muscle activity.
2. The phosphagen system provides ATP primarily for short-term, high-intensity activities like resistance training and sprinting. It relies on the hydrolysis of ATP and the breakdown of creatine phosphate to rapidly replenish ATP stores.
3. Glycolysis is the breakdown of carbohydrate (glycogen or glucose) to resynthesize ATP. It occurs in the sarcoplasm and can proceed without the direct involvement of oxygen, although the rate of ATP resynthesis is slower than the phosphagen system.
4. Pyruvate can be converted to lactate in the sarcoplasm (anaerobic glycolysis) or shuttled into the mitochondria (aerobic glycolysis/Krebs cycle). The energy demands within the cell determine the fate of pyruvate; high demand favors lactate formation for faster ATP resynthesis.
5. Substrate-level phosphorylation is the direct resynthesis of ATP from ADP during a single reaction in metabolic pathways like glycolysis. Oxidative phosphorylation refers to the resynthesis of ATP in the electron transport chain using energy derived from NADH and FADH2.
6. The lactate threshold (LT) is the exercise intensity where blood lactate begins to increase abruptly above baseline. The onset of blood lactate accumulation (OBLA) is a second, higher intensity where blood lactate reaches a concentration of 4 mmol/L.
7. The oxidative system is the primary source of ATP at rest and during low-intensity, long-duration activities. It uses carbohydrate, fats, and to a lesser extent protein as substrates to produce a large amount of ATP through the Krebs cycle and electron transport chain.

8. Exercise intensity is the primary determinant of which energy system is primarily used. High-intensity activities rely on the phosphagen system and fast glycolysis, while low-intensity, long-duration activities rely on the oxidative system. Duration is a secondary factor.
9. EPOC stands for Excess Postexercise Oxygen Consumption. It is the oxygen uptake above resting levels after exercise, used to restore the body to its pre-exercise state, and factors include replenishing oxygen and phosphagen stores, increased temperature, and metabolic processes.
10. Metabolic specificity of training involves designing training programs with appropriate exercise intensities and rest intervals to target and enhance specific primary energy systems used in a particular sport or activity. This leads to more efficient and productive training regimens by mirroring the metabolic demands of the event.

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