chapter

3

Bioenergetics of Exercise and Training

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Chapter Objectives

- Explain the basic energy systems available to supply ATP during exercise
- Understand lactate accumulation, metabolic acidosis, and cellular manifestations of fatigue
- Identify patterns of substrate depletion and repletion during various exercise intensities
- Describe the bioenergetic factors that limit exercise performance

(continued)

Chapter Objectives *(continued)*

- Develop training programs that demonstrate metabolic specificity of training
- Explain the metabolic demands of and recovery from interval training, high-intensity interval training, and combination training to optimize work-to-rest ratios

Key Terms

- **bioenergetics:** The flow of energy in a biological system; the conversion of macronutrients into biologically usable forms of energy.
- **catabolism:** The breakdown of large molecules into smaller molecules, associated with the release of energy.
- **anabolism:** The synthesis of larger molecules from smaller molecules; can be accomplished using the energy released from catabolic reactions.

(continued)

Key Terms *(continued)*

- **exergonic reactions:** Energy-releasing reactions that are generally catabolic.
- **endergonic reactions:** Require energy and include anabolic processes and the contraction of muscle.
- **metabolism:** The total of all the catabolic or exergonic and anabolic or endergonic reactions in a biological system.
- **adenosine triphosphate (ATP):** Allows the transfer of energy from exergonic to endergonic reactions.

Biological Energy Systems

- **Three basic energy systems exist in muscle cells to replenish ATP:**
  - Phosphagen system
  - Glycolysis
  - Oxidative system

(continued)

Biological Energy Systems *(continued)*

- **Phosphagen system**
  - Provides ATP primarily for short-term, high-intensity activities (e.g., resistance training and sprinting) and is active at the start of all exercise regardless of intensity
  - Creatine kinase catalyzes the synthesis of ATP from CP and ADP

(continued)

Biological Energy Systems *(continued)*

- **Phosphagen system**
  - ATP stores
    - The body does not store enough ATP for exercise.
    - Some ATP is needed for basic cellular function.
    - The phosphagen system uses the creatine kinase reaction to maintain the concentration of ATP.
    - The phosphagen system replenishes ATP rapidly.

(continued)

Biological Energy Systems *(continued)*

- **Phosphagen system**
  - Control of the phosphagen system
    - Law of mass action: The concentrations of reactants or products (or both) in solution will drive the direction of the reactions.

(continued)

Biological Energy Systems *(continued)*

- **Glycolysis**
  - The breakdown of carbohydrates—either glycogen stored in the muscle or glucose delivered in the blood—to resynthesize ATP

Biological Energy Systems

- **Glycolysis**
  - The end result of glycolysis (pyruvate) may proceed in one of two directions:

    (1) Pyruvate can be converted to lactate.

    - ATP resynthesis occurs at a faster rate but is limited in duration.
    - This process is sometimes called *anaerobic glycolysis* (or *fast glycolysis*).

(continued)

Biological Energy Systems *(continued)*

- **Glycolysis** ***(continued)***

  (2) Pyruvate can be shuttled into the mitochondria.

  - When pyruvate is shuttled into the mitochondria to undergo the Krebs cycle, the ATP resynthesis rate is slower, but it can occur for a longer duration if the exercise intensity is low enough.
  - This process is often referred to as *aerobic glycolysis* (or *slow glycolysis*).

(continued)

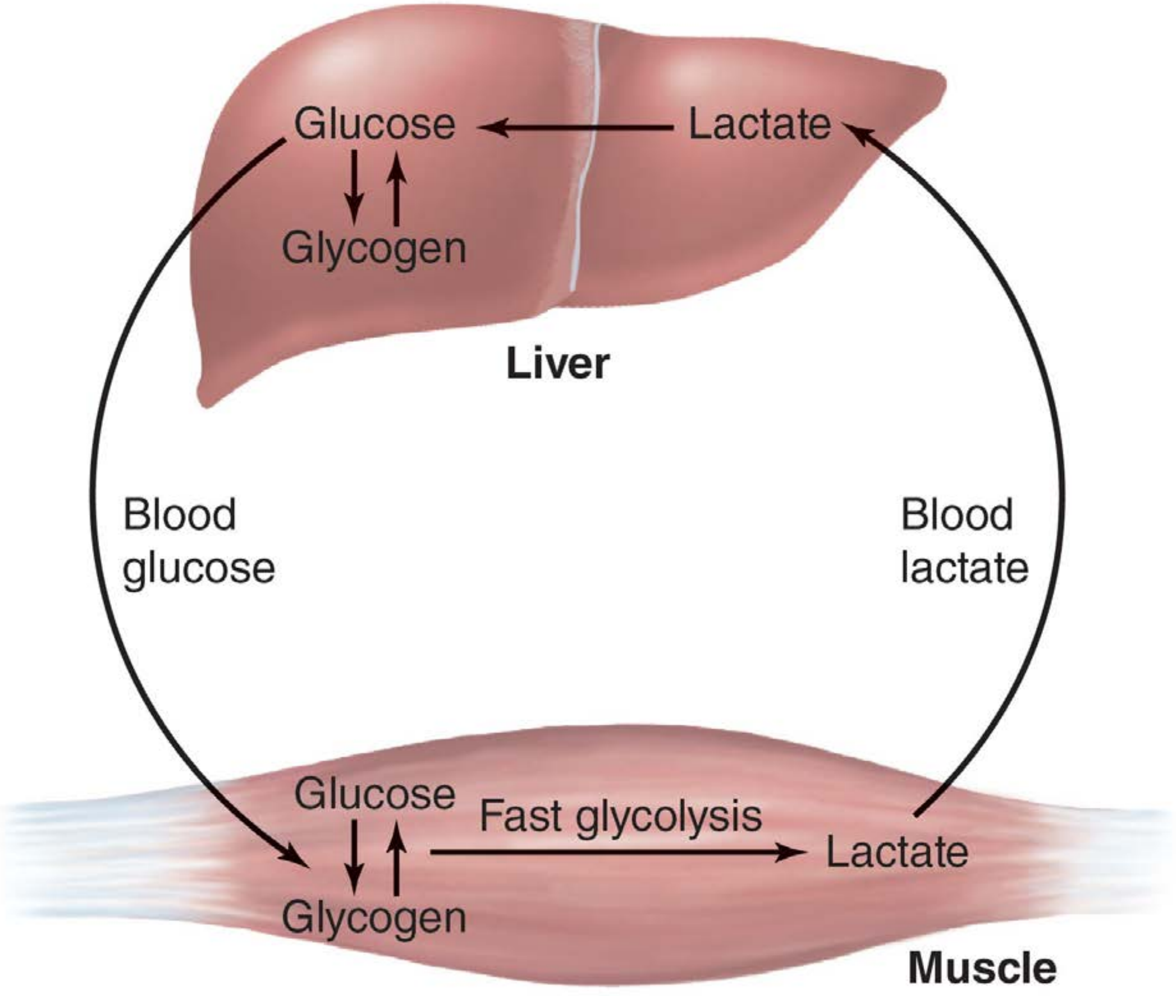
Biological Energy Systems *(continued)*

- **Glycolysis**
  - Formation of lactate
    - The formation of lactate from pyruvate is catalyzed by the enzyme lactate dehydrogenase.
    - The end result is *not* lactic acid.
    - Lactate is *not* the cause of fatigue.
    - Glucose + 2P_i + 2ADP $\rightarrow$ 2Lactate + 2ATP + H_2O

Cori Cycle

- **Figure 3.3 (next slide)**
  - Lactate can be transported in the blood to the liver, where it is converted to glucose.
  - This process is referred to as the *Cori cycle*.

Figure 3.3



Glucose
Lactate
Glycogen
Liver
Blood
glucose
Blood
lactate
Glucose
Fast glycolysis
Lactate
Glycogen
Muscle

Biological Energy Systems

- **Glycolysis**
  – The Krebs cycle
    - Pyruvate that enters the mitochondria is converted to acetyl-CoA.
    - Acetyl-CoA can then enter the Krebs cycle.
    - The NADH molecules enter the electron transport system, where they can also be used to resynthesize ATP.

(continued)

Biological Energy Systems *(continued)*

- **Glycolysis**
  - Energy yield of glycolysis
    - Glycolysis from one molecule of blood glucose yields a net of two ATP molecules.
    - Glycolysis from muscle glycogen yields a net of three ATP molecules.

(continued)

Biological Energy Systems *(continued)*

- **Glycolysis**
  - Lactate threshold and onset of blood lactate
    - Lactate threshold (LT) represents an increasing reliance on anaerobic mechanisms.
    - LT is often used as a marker of the anaerobic threshold.

Key Term

- **lactate threshold (LT):** The exercise intensity or relative intensity at which blood lactate begins an abrupt increase above the baseline concentration.

Biological Energy Systems

- **Glycolysis**
  - Lactate threshold and onset of blood lactate
    - LT begins at 50% to 60% of maximal oxygen uptake in untrained individuals and at 70% to 80% in aerobically trained athletes.
    - OBLA is a second increase in the rate of lactate accumulation.
    - It occurs at higher relative intensities of exercise.
    - It occurs when the concentration of blood lactate reaches 4 mmol/L.

(continued)

Biological Energy Systems *(continued)*

- **The oxidative (aerobic) system**
  - Primary source of ATP at rest and during low-intensity activities
  - Uses primarily carbohydrates and fats as substrates

(continued)

Biological Energy Systems *(continued)*

- **Glucose and glycogen oxidation**
  - Metabolism of blood glucose and muscle glycogen begins with glycolysis and leads to the Krebs cycle.
  - NADH and $FADH_2$ molecules transport hydrogen atoms to the electron transport chain, where ATP is produced from ADP.

Biological Energy Systems

- **Fat oxidation**
  - Triglycerides stored in fat cells can be broken down by hormone-sensitive lipase. This releases free fatty acids from the fat cells into the blood, where they can circulate and enter muscle fibers.

(continued)

Biological Energy Systems *(continued)*

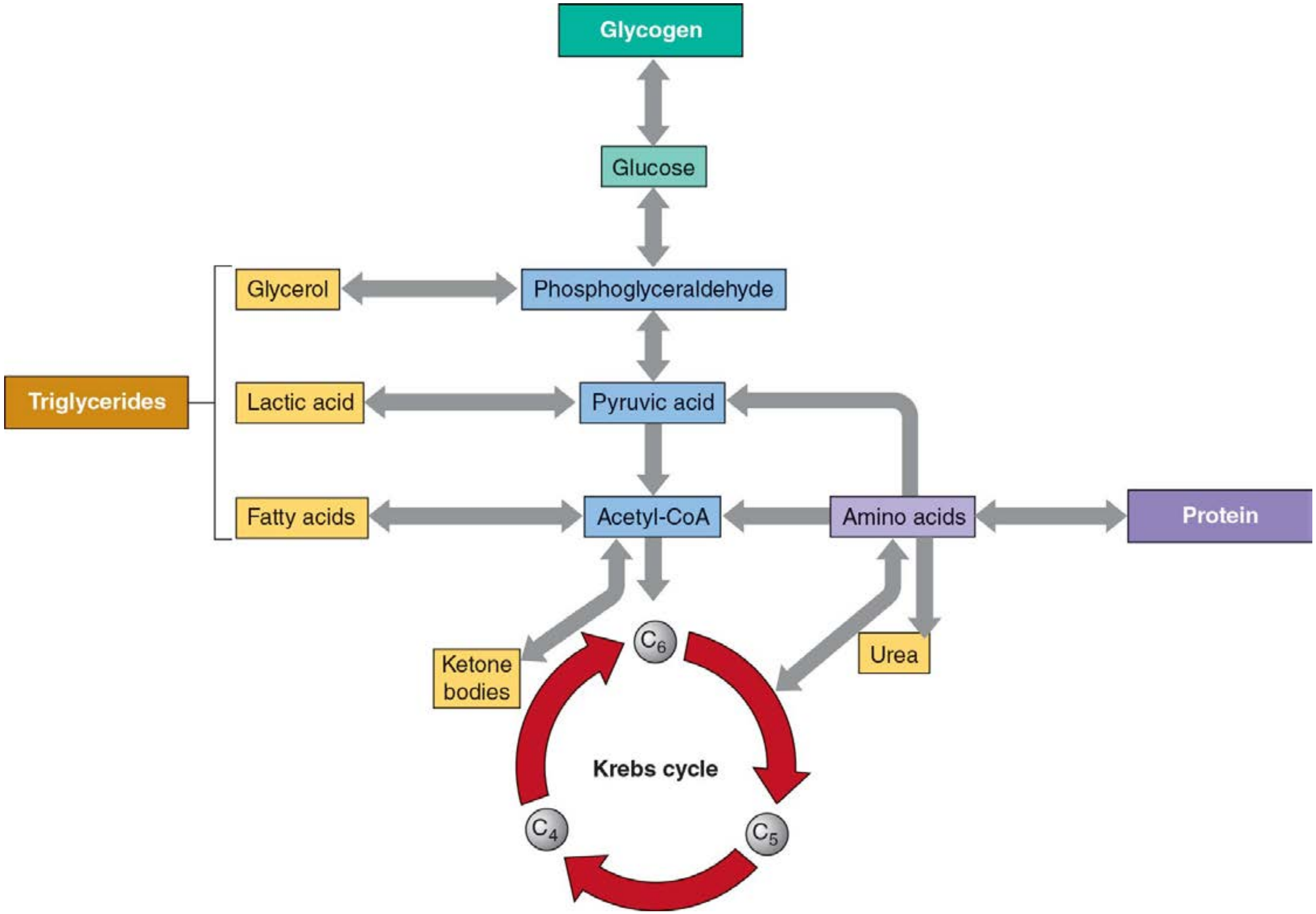
- **Protein oxidation**
  - Protein is not a significant source of energy for most activities.
  - Protein is broken down into amino acids, and the amino acids are converted into glucose, pyruvate, or various Krebs cycle intermediates to produce ATP.

(continued)

Metabolism of Fat, Carbohydrate, and Protein

- **Figure 3.8 (next slide)**
  - The metabolism of fat and that of carbohydrate and protein share some common pathways. Note that all are reduced to acetyl-CoA and enter the Krebs cycle.

Figure 3.8



Glycogen
Glucose
Glycerol
Phosphoglyceraldehyde
Triglycerides
Lactic acid
Pyruvic acid
Fatty acids
Acetyl-CoA
Amino acids
Protein
Ketone bodies
Urea
C_6
Krebs cycle
C_4
C_5

Table 3.2

TABLE 3.2 Effect of Event Duration and Intensity on Primary Energy System Used

Duration of event	Intensity of event	Primary energy system
0-6 s	Extremely high	Phosphagen
6-30 s	Very high	Phosphagen and fast glycolysis
30 s to 2 min	High	Fast glycolysis
2-3 min	Moderate	Fast glycolysis and oxidative system
>3 min	Low	Oxidative system

The relationships between duration, intensity, and primary energy systems used assume that the athlete strives to attain the best possible performance for a given event.

Key Point

- The extent to which each of the three energy systems contributes to ATP production depends primarily on the intensity of muscular activity and secondarily on the duration. At no time, during either exercise or rest, does any single energy system provide the complete supply of energy.

Substrate Depletion and Repletion

- **Phosphagens**
  - Creatine phosphate can decrease markedly (50-70%) during the first stage (5-30 seconds) of high-intensity exercise and can be almost eliminated as a result of very intense exercise to exhaustion.

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Substrate Depletion and Repletion *(continued)*

- **Phosphagens**
  - Postexercise phosphagen repletion can occur in a relatively short period; complete resynthesis of ATP appears to occur within 3 to 5 minutes, and complete creatine phosphate resynthesis can occur within 8 minutes.

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Substrate Depletion and Repletion *(continued)*

- **Glycogen**
  - The rate of glycogen depletion is related to exercise intensity.
    - At relative intensities of exercise above 60% of maximal oxygen uptake, muscle glycogen becomes an increasingly important energy substrate; the entire glycogen content of some muscle cells can become depleted during exercise.

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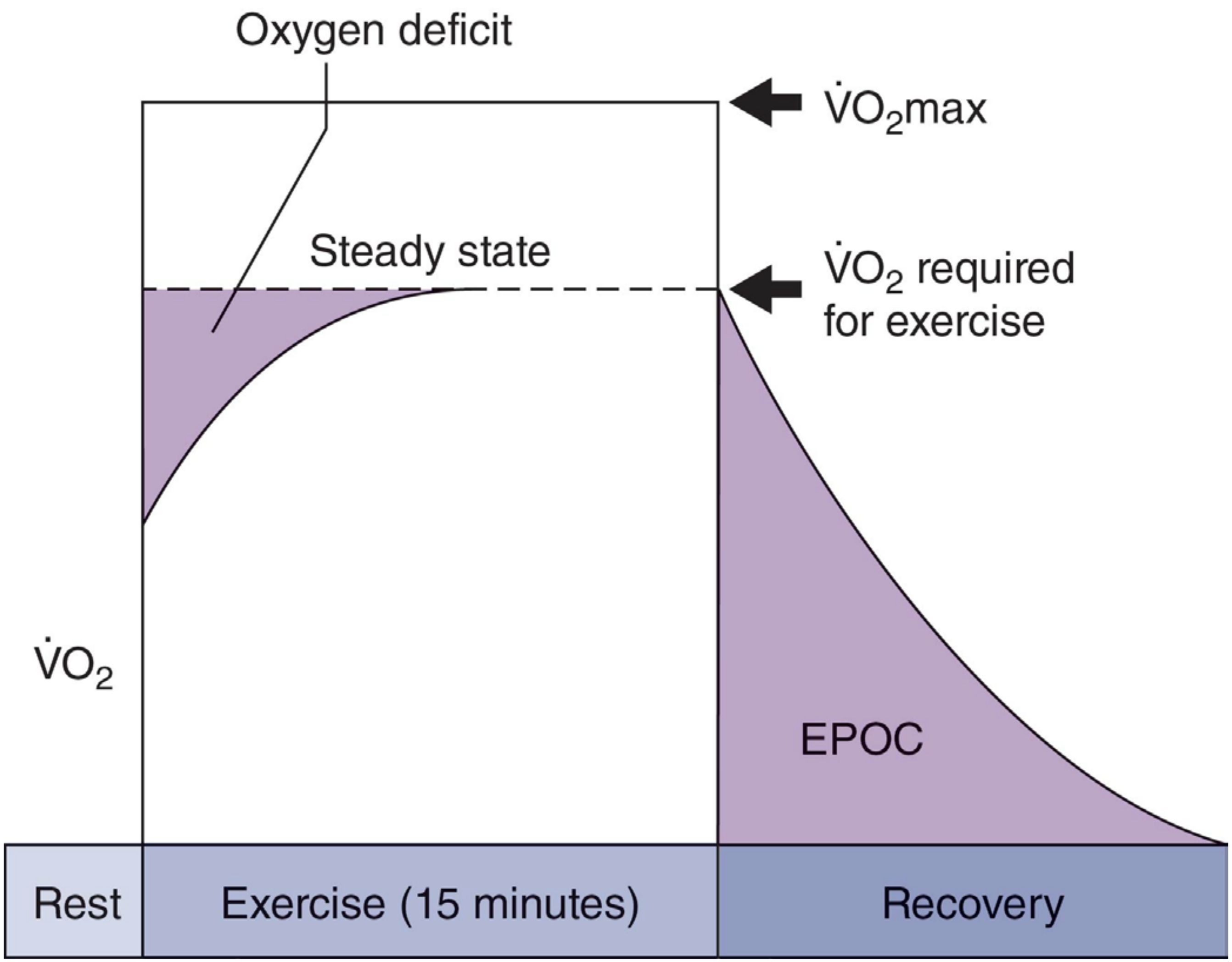
Substrate Depletion and Repletion *(continued)*

- **Glycogen**
  - Repletion of muscle glycogen during recovery is related to postexercise carbohydrate ingestion.
    - Repletion appears to be optimal if 0.7 to 3.0 g of carbohydrate per kilogram of body weight is ingested every 2 hours following exercise.

Low-Intensity, Steady-State Exercise Metabolism

- **Figure 3.9 (next slide)**
  - 75% of maximal oxygen uptake ($\dot{V}O_2max$)
  - EPOC = excess postexercise oxygen consumption
  - $\dot{V}O_2$ = oxygen uptake

Figure 3.9



Oxygen deficit
$\dot{V}O_2max$
Steady state
$\dot{V}O_2$ required
for exercise
$\dot{V}O_2$
EPOC
Rest
Exercise (15 minutes)
Recovery

Key Term

- **excess postexercise oxygen consumption (EPOC):** Oxygen uptake above resting values used to restore the body to the preexercise condition; also called postexercise oxygen uptake, oxygen debt, or recovery O_2.

Metabolic Specificity of Training

- **Interval training**
  - Emphasizes bioenergetic adaptations for a more efficient energy transfer within the metabolic pathways by using predetermined intervals of exercise and rest periods.
    - Much more training can be accomplished at higher intensities
    - Difficult to establish definitive guidelines for choosing specific work-to-rest ratios

Table 3.6

TABLE 3.6 Using Interval Training to Train Specific Energy Systems

% of maximum power	Primary system stressed	Typical exercise time	Range of work-to-rest period ratios
90-100	Phosphagen	5-10 s	1:12 to 1:20
75-90	Fast glycolysis	15-30 s	1:3 to 1:5
30-75	Fast glycolysis and oxidative	1-3 min	1:3 to 1:4
20-30	Oxidative	>3 min	1:1 to 1:3

Metabolic Specificity of Training

- **High-intensity interval training (HIIT)**
  - Brief repeated bouts of high-intensity exercise with intermittent recovery periods to elicit cardiopulmonary, metabolic, and neuromuscular adaptations
  - Cumulative duration and intensity of active portions should equate to several minutes above 90% of $\dot{V}O_2max$

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Metabolic Specificity of Training *(continued)*

- **High-intensity interval training (HIIT)**
  - Suggested work-to-rest ratios >1:1
  - When used in conjunction with other training sessions, may result in greater stress and risk of injury

(continued)

Metabolic Specificity of Training *(continued)*

- **Combination training**
  – Adds aerobic endurance training to the training of anaerobic athletes in order to enhance recovery (because recovery relies primarily on aerobic mechanisms)
  – May reduce anaerobic performance capabilities, particularly high-strength, high-power performance

(continued)

Metabolic Specificity of Training *(continued)*

- **Combination training**
  - Can reduce the gain in muscle girth, maximum strength, and speed- and power-related performance
  - May be counterproductive in most strength and power sports