3

Bioenergetics of Exercise and Training
Chapter Objectives

• Understand the terminology of bioenergetics and metabolism related to exercise and training.
• Discuss the central role of ATP in muscular activity.
• Explain the basic energy systems present in human skeletal muscle.
• Recognize the substrates used by each energy system.
• Develop training programs that demonstrate an understanding of bioenergetics and metabolism.
Energy: the capacity to do work

Bioenergetics: converting fats, proteins, and carbs into a biological usable form of energy

Catabolism: the breaking down of large molecules to smaller molecules

Anabolism: the building up of smaller molecules to larger molecules

Exergonic reactions: reactions that release energy

Endergonic reactions: reactions that require energy

Metabolism (sum of all anabolic and catabolic reactions)

Adenosine triphosphate (ATP): high energy phosphate used by cells to release energy and do cellular work

Adenosine diphosphate (ADP): molecule that combines with inorganic phosphate to form ATP
Chemical Structures of ATP and ADP

- Energy stored in the chemical bonds of adenosine triphosphate (ATP) is used to power muscular activity. The hydrolysis of ATP breaks the terminal phosphate bond, releases energy, and leaves ADP, an inorganic phosphate ($P_i$), and a hydrogen ion ($H^+$).
The replenishment of ATP in human skeletal muscle is accomplished by three basic energy systems:

- (1) phosphagen (ATP-CP)
- (2) glycolytic (lactate)
- (3) oxidative (aerobic).
Biological Energy Systems

• 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
Biological Energy Systems

• 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 phosphate/creatine kinase reaction to maintain ATP concentration.
    • The phosphagen system replenishes ATP rapidly.
  – 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.
Myosin ATPase & Creatine Kinase Reactions

Reactants

- ATP
- ADP + Creatine phosphate
- ATP + Creatine

Products

- ADP + P_i + Energy

Myosin ATPase & Creatine kinase are rate limiting enzymes in the phosphagen system.
Biological Energy Systems

• Glycolytic (Lactate) System
  – The breakdown of carbohydrates—either glycogen stored in the muscle or glucose delivered in the blood—to resynthesize ATP
  – The end result of glycolysis (which is pyruvate) may proceed in one of two directions:
Biological Energy Systems

1) Pyruvate can be converted to lactate.
   • ATP resynthesis occurs at a faster rate but is limited in duration.
   • This process is also called anaerobic glycolysis (or fast glycolysis).

2) Pyruvate can be shuttled into mitochondria and enter Krebs Cycle.
   • ATP resynthesis rate is slower, but it can occur for a longer duration if exercise intensity is low enough.
   • This process is often referred to as aerobic glycolysis (or slow glycolysis).
Figure 2.2

Rate limiting enzyme

Blood glucose (6 carbon) → Muscle glycogen

- ATP
- ADP

(Glycolysis)

- Hexokinase
- Phosphofructokinase [PFK]

Fructose-6-phosphate → Fructose-1,6-bisphosphate

Dihydroxyacetone phosphate → Glyceraldehyde-3-phosphate (3 carbon)

Glyceraldehyde-3-phosphate (3 carbon) → Electron transport chain

1,3-bisphosphoglycerate

- ADP
- ATP

3-phosphoglycerate → 2-phosphoglycerate

Phosphoenolpyruvate

- ADP
- ATP

Pyruvate → Lactate

Electron transport chain

Fast Glycolysis

Slow Glycolysis

Slow Glycolysis

Fast Glycolysis

Krebs cycle (mitochondria)
Biological Energy Systems

• Glycolysis
  – Formation of Lactate
    • The formation of lactate from pyruvate is catalyzed by the enzyme lactate dehydrogenase.
    • The end result is *not* lactic acid, but rather lactate.
    • Lactate does *not* cause muscle fatigue, but rather the H+ associated with lactate causes pH to ↓, which may:
      – a) inhibit glycolytic reactions (such as enzymatic turnover rate)
      – b) inhibit calcium binding to troponin
      – c) interfer with cross-bridge re-cyling
Buffers Minimize Drop in Muscle pH But Not Enough

- pH <6.9 inhibits glycolytic enzymes, ATP synthesis
- pH = 6.4 prevents further glycogen breakdown

eg, 200 m Sprint

Muscle pH

Recovery (min)

0 5 10 15 20 25 30 35
Lactate can be transported in the blood to the liver, where it is converted to glucose.

80-90% of glycogen in the body is stored in skeletal muscle (approx 350-600 g, which increases with training)

10-20% of glycogen in the body is stored in the liver (approx 60-90 g)
Lactate as an Energy Substrate

Blood lactate can also be used as an energy substrate by the heart and skeletal muscle, especially Type I fibers. In cardiac and skeletal muscle, lactate removed from the blood can be converted to pyruvate, which can then be transformed to acetyl-CoA and enter Krebs Cycle and contribute to oxidative metabolism.
Biological Energy Systems

• 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.
Biological Energy Systems

• Glycolysis
  – Control of Glycolysis
    • Stimulated by high concentrations of ADP, P_i, and by a slight decrease in pH and AMP
    • Inhibited by ATP, CP, citrate, free fatty acids, and markedly lower pH
    • Also affected by rate limiting enzymes, such as phosphofructokinase
Biological Energy Systems

• Glycolysis
  – Lactate Threshold and Onset of Blood Lactate
    • Lactate threshold (LT): The exercise intensity or relative intensity at which blood lactate begins an abrupt increase above the baseline concentration. It represents an increasing reliance on anaerobic mechanisms.
    • LT is often used as a synonymous term with anaerobic threshold.
Lactate Threshold (LT) and Onset of Blood Lactate Accumulation (OBLA)

- OBLA (occurs at 4 mmol/L and at higher intensities)
- LT (occurs at 50-60% VO2max in untrained and 70-80% VO2max in Trained)

Lactate production and clearance in equilibrium
Biological Energy Systems

• The Oxidative (Aerobic) System
  – Requires molecular oxygen
  – Primary source of ATP at rest and during relatively low-intensity activities
  – Uses primarily carbohydrates and fats as substrates, except in long duration aerobic events greater than 1.5-2 hrs (eg, marathons), where protein is used as a substrate to a much higher extent).
    • Protein is broken down into amino acids, and the amino acids are converted into glucose, pyruvate, or various Krebs cycle intermediates to produce ATP.
The oxidative (hydrogen removal) metabolism of blood glucose and muscle glycogen begins with glycolysis. If oxygen is present in sufficient quantities the end product of glycolysis, pyruvate, is not converted to lactic acid but is transported to the mitochondria, where it is taken up and enters the Krebs Cycle, or citric acid cycle, and then passed along to the electron transport chain (ETC) – this is termed slow glycolysis.
## Table 2.1

Total Energy Yield From the Oxidation of One Glucose Molecule

<table>
<thead>
<tr>
<th>Process</th>
<th>ATP production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow glycolysis:</td>
<td></td>
</tr>
<tr>
<td>Substrate-level phosphorylation</td>
<td>4</td>
</tr>
<tr>
<td>Oxidative phosphorylation:</td>
<td>6</td>
</tr>
<tr>
<td>2 NADH (3 ATP each)</td>
<td></td>
</tr>
<tr>
<td>Krebs cycle (2 rotations through the Krebs cycle per glucose):</td>
<td></td>
</tr>
<tr>
<td>Substrate-level phosphorylation</td>
<td>2</td>
</tr>
<tr>
<td>Oxidative phosphorylation:</td>
<td>24</td>
</tr>
<tr>
<td>8 NADH (3 ATP each)</td>
<td></td>
</tr>
<tr>
<td>Via GTP:</td>
<td>4</td>
</tr>
<tr>
<td>2 FADH$_2$ (2 ATP each)</td>
<td></td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td><strong>40</strong></td>
</tr>
</tbody>
</table>

*Glycolysis consumes 2 ATP (if starting with blood glucose), so net ATP production is 40 – 2 = 38. This figure may also be reported as 36 ATP depending on which shuttle system is used to transport the NADH to the mitochondria. ATP = adenosine triphosphate; FADH$_2$ = flavin adenine dinucleotide; GTP = guanine triphosphate; NADH = nicotinamide adenine dinucleotide.*

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Biological Energy Systems

• The Oxidative (Aerobic) System
  – 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.
    • Some free fatty acids come from intramuscular sources.
    • Free fatty acids enter the mitochondria, are broken down and form acetyl-CoA and hydrogen protons (beta oxidation), then enter Kreb’s cycle and the ETC.
<table>
<thead>
<tr>
<th>Process</th>
<th>ATP production</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 molecule of glycerol</td>
<td>22</td>
</tr>
<tr>
<td>*18-carbon fatty acid metabolism:</td>
<td>441</td>
</tr>
<tr>
<td>147 ATP per fatty acid</td>
<td></td>
</tr>
<tr>
<td>× 3 fatty acids per triglyceride molecule</td>
<td></td>
</tr>
<tr>
<td>Total:</td>
<td>463</td>
</tr>
</tbody>
</table>

*Other triglycerides that contain a different number of carbons will yield more or less ATP.*

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Biological Energy Systems

• The Oxidative (Aerobic) System
  – Kreb’s Cycle
    • The function of Krebs cycle is to remove hydrogen's from various substrates in the cycle using NAD and FAD as hydrogen carriers, thus forming NADH and FADH. Hydrogen, by virtue of the electrons they possess, contain the potential energy in the food molecules. This energy is then used in the ETC to rephosphorylate ADP to ATP.
Krebs Cycle

Aerobic Metabolism of Carbohydrates, Fats, and Proteins
Krebs Cycle
Aerobic Metabolism of Carbohydrates, Fats, and Proteins
Pairs of hydrogen electrons from NADH or FADH are passed down a series of electron carriers known as cytochromes (Cyt). During this process energy is released at three different sites to form 3 mol ATP for each NADH and 2 mol ATP for each FADH.

The process of ATP production in the ETC is referred to as Oxidative Phosphorylation, with the ETC being the final stage of ATP production. The oxidative system, beginning with glycolysis, then Krebs cycle, and finally the ETC, yields 38 mol ATP with the degradation of one mol glucose (39 mol ATP for one mol glycogen). Oxygen is the final hydrogen acceptor, forming $\text{H}_2\text{O}$. 

Figure 2.6
Electron Transport Chain

ADP$+P_i$  NADH  FAD$^2+$  CoQ  Cyt b  ADP$+P_i$  FADH$_2$  CoQ  Cyt b  ADP$+P_i$  Cyt $c_1$  Cyt $c_1$  Cyt c  ADP$+P_i$  Cyt c  Cyt c  Cyt a  ADP$+P_i$  Cyt a  Cyt a  Cyt $a_3$  ADP$+P_i$  Cyt $a_3$  H$_2$O  $\frac{1}{2}$O$_2$
Summary of Events for Oxidative (Aerobic) System

Food intake

Fats (triglycerides)
  Free fatty acids + Glycerol
  Lipolysis
  Lipogenesis
  FFA pool

Carbohydrates
  Glucose
  Lipogenesis
  Glycogen synthesis
  Glucose pool
  Glycogen stores

Proteins
  Amino acids
  Protein breakdown
  Body protein
  Protein synthesis

Metabolism

Gluconeogenesis
  Minimal contribution
Summary of Events for Aerobic and Anaerobic Systems

Proteins
- Liver glycogen
- Amino acids
- Pyruvate
- Lactic acid

Carbohydrates
- Glucose absorbed at the intestine
- Liver glycogen
- Glucose
- Pyruvate
- Lactic acid

Adipose tissue
- Lipids stored in adipose tissue
- Glycerol + fatty acids

Energy supply
- Glucose
- Glycolysis (anaerobic)
- Pyruvate
- Lactic acid
- Acetyl CoA
- Oxidative phosphorylation and citric acid cycle (aerobic)

Energy demand
- Glycogen
- Exercise
- Contraction
- Myosin ATPase
- Ca-ATPase
- Relaxation
- ADP + P_i
- ATP + creatine
- Creatine - P (PCr) + ADP

Krebs Cycle and ETC
- Muscle fiber
- Blood
- O_2
- CO_2
- Gas exchange at the lungs: O_2 - CO_2
Biological Energy Systems

• Energy Production and Capacity
  – In general, there is an inverse relationship between a given energy system’s maximum rate of ATP production (i.e., ATP produced per unit of time) and the total amount of ATP it is capable of producing over a long period.
  – As a result, the phosphagen energy system primarily supplies ATP for high-intensity activities of short duration, the glycolytic system for moderate- to high-intensity activities of short to medium duration, and the oxidative system for low-intensity activities of long duration.
<table>
<thead>
<tr>
<th>Duration of event</th>
<th>Intensity of event</th>
<th>Primary energy system(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-6 seconds</td>
<td>Extremely high</td>
<td>Phosphagen</td>
</tr>
<tr>
<td>6-30 seconds</td>
<td>Very high</td>
<td>Phosphagen and fast glycolysis</td>
</tr>
<tr>
<td>30 seconds to 2 minutes</td>
<td>High</td>
<td>Fast glycolysis</td>
</tr>
<tr>
<td>2-3 minutes</td>
<td>Moderate</td>
<td>Fast glycolysis and oxidative system</td>
</tr>
<tr>
<td>&gt;3 minutes</td>
<td>Low</td>
<td>Oxidative system</td>
</tr>
</tbody>
</table>

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.

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### Table 2.4

**Rankings of Rate and Capacity of ATP Production**

<table>
<thead>
<tr>
<th>System</th>
<th>Rate of ATP production</th>
<th>Capacity of ATP production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphagen</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Fast glycolysis</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Slow glycolysis</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Oxidation of carbohydrates</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Oxidation of fats and proteins</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>

*Note: 1 = fastest/greatest; 5 = slowest/least.*

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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.
  – 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.
Substrate Depletion and Repletion

• **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.
Substrate Depletion and Repletion

• **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 kg of body weight is ingested every 2 hours following exercise.
<table>
<thead>
<tr>
<th>Exercise</th>
<th>ATP and creatine phosphate</th>
<th>Muscle glycogen</th>
<th>Liver glycogen</th>
<th>Fat stores</th>
<th>Lower pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marathon</td>
<td>1</td>
<td>5</td>
<td>4-5</td>
<td>2-3</td>
<td>1</td>
</tr>
<tr>
<td>Triathlon</td>
<td>1-2</td>
<td>5</td>
<td>4-5</td>
<td>1-2</td>
<td>1-2</td>
</tr>
<tr>
<td>5,000 m run</td>
<td>1-2</td>
<td>3</td>
<td>3</td>
<td>1-2</td>
<td>1</td>
</tr>
<tr>
<td>1,500 m run</td>
<td>2-3</td>
<td>3-4</td>
<td>2</td>
<td>1-2</td>
<td>2-3</td>
</tr>
<tr>
<td>400 m swim</td>
<td>2-3</td>
<td>3-4</td>
<td>3</td>
<td>1</td>
<td>1-2</td>
</tr>
<tr>
<td>400 m run</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>4-5</td>
</tr>
<tr>
<td>100 m run</td>
<td>5</td>
<td>1-2</td>
<td>1</td>
<td>1</td>
<td>1-2</td>
</tr>
<tr>
<td>Discus</td>
<td>2-3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Repeated snatch exercise at 60% of 1RM (10 sets)</td>
<td>4-5</td>
<td>4-5</td>
<td>1-2</td>
<td>1-2</td>
<td>4-5</td>
</tr>
</tbody>
</table>

Note: 1 = least probable limiting factor; 5 = most probable limiting factor.
Low-Intensity, Steady-State Exercise Metabolism

- **Oxygen deficit**

- **Steady state**
  
  75% of maximal oxygen uptake (VO2max)
  EPOC = excess postexercise oxygen consumption
  VO2 = oxygen uptake

- **VO2max**

- **VO2 required for exercise**

<table>
<thead>
<tr>
<th>Rest</th>
<th>Exercise (15 minutes)</th>
<th>Recovery</th>
</tr>
</thead>
</table>

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80% of max power output
The required VO2 is the oxygen uptake that would be required to sustain the exercise if such an uptake were possible to attain. Because it is not possible, the oxygen deficit lasts for the duration of the exercise.
Purpose of EPOC – Restore Homeostasis:

- Resynthesis of ATP and CP stores
- Resynthesis of glycogen from lactate (gluconeogenesis)
- Oxygen resaturation of myoglobin
- Oxidize lactate in energy metabolism
- Restore $O_2$ to blood and muscle
- Decrease elevated body temperature, HR, and ventilation
- Decrease blood levels of catecholamines and hormones
<table>
<thead>
<tr>
<th></th>
<th>0-5 s</th>
<th>30 s</th>
<th>60 s</th>
<th>90 s</th>
<th>150 s</th>
<th>200 s</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Exercise intensity (% of maximum power output)</strong></td>
<td>100</td>
<td>55</td>
<td>35</td>
<td>31</td>
<td>Not available</td>
<td>Not available</td>
</tr>
<tr>
<td><strong>Contribution of anaerobic mechanisms (%)</strong></td>
<td>96</td>
<td>75</td>
<td>50</td>
<td>35</td>
<td>30</td>
<td>22</td>
</tr>
<tr>
<td><strong>Contribution of aerobic mechanisms (%)</strong></td>
<td>4</td>
<td>25</td>
<td>50</td>
<td>65</td>
<td>70</td>
<td>78</td>
</tr>
</tbody>
</table>
Metabolic Specificity of Training

- The use of appropriate exercise intensities and rest intervals allow for the “selection” of specific energy systems during training and results in more efficient and productive regimens for specific athletic events with various metabolic demands.
Metabolic Specificity of Training

• Interval Training
  – Interval training is a method that 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
Using High Intensity Interval Training to Train Specific Energy Systems

<table>
<thead>
<tr>
<th>% of Max Power</th>
<th>Primary System Stressed</th>
<th>Typical Exercise Time</th>
<th>Range of Exercise-to-Rest Period Ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>90-100 Phosphagen</td>
<td>5-10 s</td>
<td>1:12 to 1:20</td>
<td></td>
</tr>
<tr>
<td>75-90 Fast Glycolysis</td>
<td>15-30 s</td>
<td>1:3 to 1:5</td>
<td></td>
</tr>
<tr>
<td>30-75 Fast Glycolysis and Oxidative</td>
<td>1-3 min</td>
<td>1:3 to 1:4</td>
<td></td>
</tr>
<tr>
<td>20-35 Oxidative</td>
<td>&gt;3 min</td>
<td>1:1 to 1:3</td>
<td></td>
</tr>
</tbody>
</table>
Metabolic Specificity of Training

• Combination Training
  – Combination training integrates aerobic and anaerobic training, thus uses multiple energy systems
    • May be counterproductive in most strength and power athletes (in done, off season is best time) by reducing anaerobic performance capabilities, particularly high-strength, high-power performance
    • May reduce gains in muscle girth, maximum strength, and speed- and power-related performance
    • May be beneficial in aerobic athletes as long as over-training does not occur