Presentation 2:
Bioenergetics of Exercise and Training

by:
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MULTIMEDIA SYMPOSIUM OVERVIEW

This multimedia symposium was developed for the specific purpose of providing individuals who sit for the Certified Strength and Conditioning Specialist® (CSCS®) certification exam with a review of facts, concepts, and theories that are relevant to strength training and conditioning.

You are encouraged to simultaneously listen and watch the symposium video presentation, view the PowerPoint® slide show, follow along in the presentation outline, and add your own notes in the spaces within the outline (more paper may be necessary).

To maximize the value of the multimedia symposium when preparing for the CSCS exam, you may find it helpful to first study the Essentials of Strength Training and Conditioning (2nd edition) text. Further, candidates who perform well on the CSCS exam typically have considerable practical experience in strength training and conditioning athletes (e.g., designing programs, teaching proper exercise technique, performing testing sessions) and a strong academic background in the exercise sciences (i.e., anatomy, physiology, biomechanics, etc.). For additional suggestions for preparing for the CSCS exam, go to www.nsca-cc.org.

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• While comprehension of the information provided by the multimedia symposium should certainly increase the likelihood of passing the CSCS certification exam, it does not guarantee a successful performance. The questions on the CSCS exam are developed from numerous resources in addition to the multimedia symposium.
I. Introduction

A. Basic definitions

1. Energy

2. Bioenergetics

3. Catabolism

4. Anabolism

5. Exergonic reactions

6. Endergonic reactions

7. Metabolism

8. ATP

B. An illustration of metabolism (Figure 1)
II. Biological Energy Systems

A. Three energy systems to replenish ATP
   1. Phosphagen system
   2. Glycolytic system
   3. Oxidative system

B. All energy systems are active at any given time

C. The extent of contribution
   1. Primary
   2. Secondary

III. Phosphagen System

A. Primary functions
   1. Provide ATP for high intensity activities lasting 0-6 seconds (up to 20-30 seconds)
   2. Other names for this energy system
   3. Active at the start of all exercise, regardless of intensity
B. Three primary reactions (Figure 2)

1. Hydrolysis of ATP $\rightarrow$ ADP + inorganic phosphate + energy

2. Resynthesis of ATP
   a. ADP + creatine phosphate $\rightarrow$ ATP + creatine

3. Also to resynthesize ATP
   a. 2 ADP $\rightarrow$ ATP + AMP

C. Enzymes used to hydrolyze ATP: Myosin ATPase, Sodium-potassium (Na\(^+\)-K\(^+\)) ATPase, and Calcium (Ca\(^{++}\)) ATPase

D. Creatine kinase and myokinase reactions are near-equilibrium reactions: the concentrations of the reactants will drive the direction of the reactions
IV. Glycolytic System

A. Primary functions

1. Carbohydrate (CHO) breakdown to produce ATP in the cytoplasm (i.e., sarcoplasm of a muscle cell)

2. Provides energy primarily for moderate to high intensity activities: for 30 seconds up to 2-3 minutes of activity in a hypoxic cellular environment
B. Glycolysis (Figure 3)

1. Begin with one molecule of glucose-6-phosphate (G-6-P) via the hexokinase reaction
   
   a. If from blood glucose, 1 ATP is needed to phosphorylate the blood glucose molecule to keep it from leaving the cell
   
   b. If from muscle glycogen, ATP is not yet needed (1 ATP is saved)
2. Phosphofructokinase (PFK) reaction
   a. Costs 1 ATP to create fructose-1,6-bisphosphate
   b. The “rate limiting” step or reaction of glycolysis

3. So far, the processes are “priming” the 6-carbon molecule (chain) to split into two 3-carbon molecules (i.e., glyceraldehyde-3-phosphate or G-3-P)

4. Reduction of NAD⁺ (i.e., to reduce the relative proportion of oxygen): when a hydrogen ion (H⁺) is added to NAD⁺, it is reduced to NADH

5. 2 types of ATP phosphorylation (i.e., 2 ways to produce ATP) : ATP is actually produced, not used (which is what has occurred up to this point):
   a. Substrate level phosphorylation: ATP molecules are synthesized (from ADP) during the breakdown of glyceraldehyde-3-phosphate (G-3-P) at two specific reactions (as shown in Figure 3, page 7)
   b. Oxidative phosphorylation: NADH and FADH₂ are oxidized in the electron transport chain to produce ATP (discussed in section E)

6. For each of the two G-3-P molecules (i.e., the right and left sides of Figure 3, page 7) 2 ATP and 1 NADH are created (4 ATP and 2 NADH total)

7. After pyruvate is created, glycolysis may proceed in one of two directions:
   a. Fast glycolysis (anaerobic glycolysis): pyruvate is reduced to lactic acid, providing ATP at a fast rate
   b. Slow glycolysis (aerobic glycolysis): pyruvate is transported to the mitochondria (to the Krebs Cycle) for use in the oxidative system
8. Summary (net total energy production)
   a. 2 ATP (-2 + 4 = 2) from blood glucose
   b. 3 ATP (-1 + 4 = 3) from muscle glycogen

C. Fate of pyruvate (primarily determined by energy demands within the cell)
   1. High rate of energy demand
      a. Insufficient oxygen present
      b. Fast glycolysis
      c. Example

   2. Low rate of energy demand
      a. Sufficient oxygen present
      b. Slow glycolysis
      c. Example

D. Lactic acid vs. lactate
   1. Lactic acid
      a. Corresponding hydrogen (H⁺) accumulation
      b. Negative feedback
         i. Calcium (Ca²⁺) release from sarcoplasmic reticulum
         ii. Actomyosin formation
iii. Glycolytic enzyme activity

c. Results in fatigue

2. Lactate (converted from lactic acid via a bicarbonate buffer; lactate reflects lactic acid production and clearance)
   a. Not believed to be fatigue-producing
   b. Energy substrate
      i. Gluconeogenesis: the formation of CHO from a non-CHO source
      ii. Cori cycle (from the muscle to the liver and back to the muscle)

E. Energy yield of glycolysis (Figure 3, page 7)
   1. From glucose: 2 ATP
   2. From muscle glycogen: 3 ATP
   3. With slow glycolysis, 2 NADH are transported to the mitochondria where they each produce 3 ATP (total of 6 ATP) via oxidative phosphorylation

V. Oxidative System

A. Primary function: provide ATP for low intensity activities lasting longer than 3 minutes

B. Substrates
   1. CHO
   2. Fats
3. Proteins

C. Location

D. Krebs Cycle (Figure 4); also called the “Citric Acid Cycle” or the “Tricarboxylic Acid Cycle (TCA Cycle)”

1. Pyruvate (from slow glycolysis) enters into the Krebs Cycle; the 3-carbon (chain) pyruvate becomes a 2-carbon (chain) acetyl-CoA; the extra carbon that is removed combines with $O_2$ to make carbon dioxide ($CO_2$) which is later exhaled
2. Reduce 1 NAD\(^+\) to NADH (creates 3 more ATP in the ETC; see section E)

3. 2-carbon (chain) acetyl-CoA combines with oxaloacetate (a 4-carbon chain) to produce citrate (a 6-carbon chain)

4. Citrate gets recycled into oxaloacetate—follow the circle in Figure 4, page 11 clockwise—(the 6-carbon chain gets recycled into a 4-carbon chain) and:
   a. The 2 removed carbons combine with oxygen to create CO\(_2\) (the primary by-product of the Krebs Cycle)
   b. NAD\(^+\) is reduced 3 times, and FAD\(^{++}\) is reduced once, which results in oxidative phosphorylation (ATP production) in the ETC (see section E)
   c. Substrate level phosphorylation creates 1 ATP (indirectly through GTP; see section B.5.a. for more details on substrate level phosphorylation)

5. Isocitrate dehydrogenase is the “rate limiting” step or reaction in the Krebs Cycle

6. NOTE: all of the above reactions occur TWICE for each 6-carbon glucose

E. NADH and FADH\(_2\) molecules are transported to the Electron Transport Chain (ETC) in the mitochondria to produce ATP (Figure 5) via oxidative phosphorylation

   1. The NADH (reduced NAD\(^+\)) and FADH\(_2\) (reduced FAD\(^{++}\)) molecules phosphorylate ADP or ATP

   2. The H\(^+\) ions are passed down a series of electron carriers to form a H\(^+\) ion (proton) concentration gradient to synthesize ATP with ATP synthase from [ADP + inorganic phosphate]
3. NAD\(^+\) and FAD\(^{++}\) differ in the ability to produce ATP (Figure 5, page 12)
   a. 1 reduced NAD\(^+\) produces 3 ATP
   b. 1 reduced FAD\(^{++}\) produces 2 ATP

4. Oxygen serves as the terminal electron receptor/acceptor; used to create the primary by-product of the ETC: water

F. Total energy yield of oxidation of 1 blood glucose molecule

<table>
<thead>
<tr>
<th>PROCESS</th>
<th>ATP PRODUCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Slow glycolysis</strong></td>
<td></td>
</tr>
<tr>
<td>—Substrate level phosphorylation</td>
<td>4</td>
</tr>
<tr>
<td>—Oxidative phosphorylation: 2 reduced NAD(^+) (3 ATP each)</td>
<td>6</td>
</tr>
</tbody>
</table>

| Krebs Cycle (occurs twice for each glucose molecule) |                |
| —Substrate level phosphorylation (GTP)              | 2              |
| —Oxidative phosphorylation:                         |                |
| —8 reduced NAD\(^+\) (3 ATP each)                   | 24             |
| —2 reduced FAD\(^{++}\) (2 ATP each)                | 4              |
| *Total (gross): 40                                  |                |
| *Total (net): 38*                                   |                |

*Glycolysis consumes 2 ATP (if starting with glucose), so net ATP production is 40: 2 = 38. If start with glycogen, net ATP production is 40: 1 = 39.

G. Fat oxidation (Figure 4, page 11)

1. Free fatty acids enter the mitochondria and undergo beta oxidation

2. Beta oxidation results in the formation of acetyl-CoA

3. ATP is produced both from substrate level phosphorylation and oxidative phosphorylation

4. Adaptations to training
   a. Increase in muscle mitochondrial content
b. Spares CHO for use by the central nervous system

c. Helps prevent a substantial drop in intracellular pH

5. Total energy yield of oxidation of 1 triglyceride molecule

<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>—147 ATP per fatty acid (3 fatty acids per</td>
<td>441</td>
</tr>
<tr>
<td>triglyceride molecule)</td>
<td></td>
</tr>
<tr>
<td>Total:</td>
<td>463*</td>
</tr>
</tbody>
</table>

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

H. Protein oxidation (Figure 4, page 11)

1. Amino acids can be broken down and converted into glucose, pyruvate and various Krebs Cycle intermediates (Figure 4, page 11)

2. Gluconeogenesis
*A simplified summary of fat, CHO and protein metabolism (Figure 6)*
VI. Energy Production and Capacity

A. There is an inverse relationship between the rate and the capacity of the phosphagen, glycolytic, and oxidative systems to supply ATP (Table 1)

B. The extent to which the energy systems contribute to the energy being produced is primarily determined by the intensity and secondarily by the duration of the exercise (Table 2) (When the speaker describes Table 2, know that he is looking a different version of what is shown here. Also, by mistake, the speaker describes the duration of the phosphagen system as “between 60 and 30 seconds” — it should be “between 6 and 30 seconds.”)
VII. Substrate Depletion and Repletion

A. Energy substrates used to produce ATP

1. Phosphagen

2. Glycogen

3. Glucose

4. Lactate

5. Free fatty acids

6. Amino acids

B. Phosphagen and ATP

1. Depletion
   a. Creatine phosphate (CP) stores can decrease 50-70% in the first 5-30 seconds; virtually eliminated as a result of high intensity exercise
   
   b. ATP stores do not decrease more than 60% even with very intense exercise

2. Repletion
   a. Post-exercise resynthesis of ATP can occur within 3-5 minutes; CP up to 8 minutes
   
   b. Most post-exercise phosphagen resynthesis is accomplished through aerobic mechanisms
c. Current work:rest ratio recommendations (Table 3)

<table>
<thead>
<tr>
<th>Percent of maximum power</th>
<th>Primary energy system stressed</th>
<th>Typical exercise time</th>
<th>Work:rest ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>90-100</td>
<td>Phosphagen</td>
<td>5-10 seconds</td>
<td>1:12 to 1:20</td>
</tr>
<tr>
<td>75-90</td>
<td>Fast glycolysis</td>
<td>15-30 seconds</td>
<td>1:3 to 1:5</td>
</tr>
<tr>
<td>30-75</td>
<td>Fast glycolysis and oxidative</td>
<td>1-3 minutes</td>
<td>1:3 to 1:4</td>
</tr>
<tr>
<td>20-35</td>
<td>Oxidative</td>
<td>&gt;3 minutes</td>
<td>1:1 to 1:3</td>
</tr>
</tbody>
</table>

C. Glycogen

1. Depletion
   a. Rate of breakdown increases with intensity
   b. Selective glycogen depletion can cause early fatigue without total depletion

2. Repletion
   a. Post-exercise CHO ingestion (if inadequate, post-exercise glycogen resynthesis is impaired)
GLOSSARY OF TERMS

**Adenosine triphosphate (ATP)**—principle energy compound in most cells; energy is stored in the phosphate bonds

**Aerobic**—occurring in the presence of oxygen

**Anaerobic**—occurring in the absence of oxygen

**Beta oxidation**—series of reactions that results in the formation of acetyl-CoA from free fatty acids

**Bioenergetics**—flow of energy in a biological system

**Creatine phosphate**—high energy compound in cells used to regenerate ATP

**Electron Transport Chain (ETC)**—a series of reactions in mitochondria that converts hydrogen ions into carbon dioxide and water, and produces ATP

**Endergonic**—energy consuming

**Exergonic**—energy releasing

**Flavin adenine dinucleotide (FADH$_2$)**—a coenzyme; an electron carrier in energy metabolism

**Glycolysis**—breakdown of glucose

**Inorganic phosphate**—released during the hydrolysis of ATP

**Krebs Cycle**—a series of reactions in mitochondria that produces reduced electron (FADH$_2$ and NADH) carrier for the ETC

**Metabolism**—total of all catabolic/exergonic and anabolic/endergonic reactions in a biological system

**Mitochondria**—site of aerobic energy production

**Nicotinamide adenine dinucleotide (NADH)**—a coenzyme; an electron carrier in energy metabolism

**Oxidative phosphorylation**—process of the ETC in which inorganic phosphate is added to ADP (adenosine diphosphate) to form ATP (adenosine triphosphate) with oxygen serving as the final electron acceptor
PRESENTATION REFERENCES


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<td>F2</td>
<td>Reactions in the Phosphagen System</td>
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