Physiological Responses to Acute and Chronic Exercise
A Review

Working Definitions

• Physical activity
  – body movt. that is produced by the contraction of skel. muscl. that substantially increases energy expenditure

• Exercise
  – a type of PA that is structured and often performed for enjoyment or to improve physical fitness

• Physical fitness
  – a set of attributes that relates to the ability to perform PA

Components of Physical Fitness

1. Cardiorespiratory Endurance
   – VO2max, exercise time
   – Important for most diseases
2. Musculoskeletal fitness
   – Strength, endurance,
   – Particularly relevant for neuromuscular care, also cardiac and others
3. Body Weight and body composition
   – Type 2 Diabetes, obesity
4. Flexibility
   – neuromuscular, diabetes, cardiac…
5. Neuromuscular relaxation
   – stress
Aerobic or Endurance Exercise

- O₂ utilization.
- Endurance exercise training.
- The body responds with physiologic adaptations
- Causing a host of health benefits.
- These adaptations are thought to be important for the rehabilitation of individuals with disease.

Acute Dynamic Exercise

How The Body Responds

Aerobic Exercise-Acute Response

- increased VO₂, VCO₂ and CO
- VO₂ increases with WR
- VO₂ is the product of CO and peripheral O₂ extraction
- FICK EQUATION:
  \[ \text{VO}_2 = \text{Cardiac output} \times \text{C(a-v)O}_2 \]
  - Cardiac output = HR x SV
- Which one changes during exercise?
- What about with training?
VO$_2$max and the Fick Equation

$\dot{V}O_2$max = (HR x SV) x (arterial $O_2$ - venous $O_2$)

How do different diseases influence these factors?

Workrate vs VO$_2$

Cardiovascular Responses

Normal individual

$VO_2$ = Cardiac output x (a-v $O_2$ difference)

<table>
<thead>
<tr>
<th></th>
<th>Rest</th>
<th>Moderate exercise</th>
<th>Maximal exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO (L/min)</td>
<td>5.0</td>
<td>17.0</td>
<td>25.0</td>
</tr>
<tr>
<td>SV (ml)</td>
<td>71</td>
<td>117</td>
<td>131</td>
</tr>
<tr>
<td>HR (bpm)</td>
<td>70</td>
<td>145</td>
<td>190</td>
</tr>
<tr>
<td>VO$_2$ (l/min)</td>
<td>0.3</td>
<td>2.0</td>
<td>3.4</td>
</tr>
</tbody>
</table>

How will disease influence these values?
Distribution of CO

<table>
<thead>
<tr>
<th>Tissue</th>
<th>L/min</th>
<th>%</th>
<th>Tissue</th>
<th>L/min</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart</td>
<td>0.2</td>
<td>4</td>
<td>Heart</td>
<td>1.0</td>
<td>4</td>
</tr>
<tr>
<td>Skin</td>
<td>0.3</td>
<td>6</td>
<td>Skin</td>
<td>0.6</td>
<td>2</td>
</tr>
<tr>
<td>Brain</td>
<td>0.7</td>
<td>14</td>
<td>Brain</td>
<td>0.9</td>
<td>4</td>
</tr>
<tr>
<td>Liver</td>
<td>1.3</td>
<td>27</td>
<td>Liver</td>
<td>0.5</td>
<td>2</td>
</tr>
<tr>
<td>Kidneys</td>
<td>1.1</td>
<td>22</td>
<td>Kidneys</td>
<td>1.1</td>
<td>1</td>
</tr>
<tr>
<td>Skel.muscl.</td>
<td>1.0</td>
<td>20</td>
<td>Skel.muscl.</td>
<td>21.0</td>
<td>84</td>
</tr>
<tr>
<td>Other</td>
<td>0.4</td>
<td>7</td>
<td>Other</td>
<td>0.8</td>
<td>3</td>
</tr>
<tr>
<td>TOTAL</td>
<td>5.0</td>
<td>100</td>
<td>TOTAL</td>
<td>25.0</td>
<td>100</td>
</tr>
</tbody>
</table>

Rowell, 1993

Pulmonary System

- Lunges are the gateway for metabolism
  - External respiration must match internal respiration
  - $\frac{\text{VCO}_2}{\text{VO}_2} = \text{RER} (0.7 \text{ to} 1.0)$
- $V_e$ (L/min) = ventilatory rate x tidal volume
- $V_e$ is regulated by the brain stem
  - Regulated by PO$_2$, PCO$_2$, pH and temperature

What might happen if someone has lung disease?

Breathing Mechanics

- Exercise increases $f$ and $V_T$ until about 70%VO$_2$max
- Work of breathing can range from 5% of VO$_2$ at rest to 20% of VO$_2$max during maximal exercise
- What do you think pulmonary disease will do to the work of breathing?
- Do normal individuals have pulmonary limits to exercise
- What about in lung disease?
What Is the Ventilatory Threshold?

Methods for Determining VT

- A rise in ventilatory equivalents for O₂ (VE/VO₂)
  - Can occur during hyperventilation
- A steady or slowly falling ventilatory equivalent for CO₂
- Constant or slowly rising PETCO₂
- Plot VCO₂ against VO₂ and identify the breakpoint
What is the Lactate Threshold?

• “LT represents the highest steady state exercising intensity an athlete can maintain for prolonged periods of time (> 30 minutes).” The Bike Doc

• “It so happens that lactate doesn’t just build up gradually the faster we run. What happens is that it builds slowly to a certain point then all of a sudden it increases dramatically. The point where it increases dramatically is called the anaerobic (without oxygen) or lactate threshold.”

• “The point at which lactate begins to increase exponentially is called the lactate threshold.”

Method for Determining LT

• The VO\textsubscript{2} or power that blood lactate shows a “systematic” increase
  – \( > 2.0 \text{ mM} \)
  – \( > 4.0 \text{ mM} \)
Metabolic Responses to Acute Exercise

Substrate Flux
- What fuels are important during exercise?
- How do you measure fuel utilization?
- What influences fuel selection?

Metabolic Responses
- Whole body energy expenditure increases from 10-20 fold from rest to maximal exercise
- High energy phosphate bonds (ATP, creatine phosphate) in muscle
- Muscles utilize predominately carbohydrate and fat
### Metabolic Responses

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Approx total fuel reserve</th>
<th>Estimated period for which fuel store would provide energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adipose TG</td>
<td>16,000 kcal</td>
<td>7,143 Minutes of marathon running</td>
</tr>
<tr>
<td>Liver glycogen</td>
<td>90 g</td>
<td>18</td>
</tr>
<tr>
<td>Muscle glycogen</td>
<td>350 g</td>
<td>71</td>
</tr>
<tr>
<td>Blood and extra fluids</td>
<td>20 g</td>
<td>4</td>
</tr>
</tbody>
</table>

Newsholme and Start, 1973

How would diabetes and obesity influence these?

#### Fuel Utilization- Influence of Exercise Duration

![Graph showing fuel utilization over time](image)

#### Fuel Utilization- Influence of Exercise Intensity

![Graph showing fuel utilization at different intensities](image)

Romijn et al. 1993
Physiological Adaptations To Aerobic Training

Review of Cardio-Respiratory and Metabolic Responses

Physiologic Adaptations

- Training and subsequent exercise bouts
- Maximal aerobic power (VO$_2$max) is the single best indicator of the cardiorespiratory system’s functional capacity
  - Tends to increase about 15% in normal individuals
- Increase in VO$_2$max appears to be caused equally by peripheral (O$_2$ extraction) and central (cardiac output) adaptations

\[ \text{VO}_2\text{max} = (SV \times HR) \times (\text{arterial} - \text{venous oxygen}) \]

What adaptations occur that are beneficial for persons with disease?
**VO₂max and Training**

\[ \dot{V}O_2\text{max} = (HR \times SV) \times (\text{arterial } O_2 - \text{venous } O_2) \]

- **Central Adaptations (HR x SV)**
  - Aerobic training increases cardiac output:
    - Does not change or may even lower HRmax
    - Increases resting, submax and max SV
    - Increases "preload" or plasma volume (aldosterone and antidiuretic hormone levels ↑ cause renal retention of water and plasma protein levels to ↑ fluid retention)
    - Increases LV filling time and LV volume
    - Increases LV size and wall thickness
    - Decreases TPR or “afterload” by reducing SNS vasoconstriction on arterioles

**Central Adaptations To Training- Summary**

- ↑ Stroke volume
- ↑ End diastolic volume (preload)
- ↓ Contractility
- ↓ Total peripheral resistance
- ↑ Plasma volume
- ↑ Filling time and venous return
- ↑ Ventricular volume

*Note: HR x SV = CO
# Note: also described as CaO₂-CvO₂
Peripheral Adaptations (A-VO$_2$ difference)

- Aerobic training:
  - Increases blood volume but not Hb concentration (i.e. O$_2$ content is unaffected) *
  - Decrease venous PO$_2$
  - Increases mitochondrial density and size
  - Increases oxidative enzyme activity
  - Increases capillary density and myoglobin levels (O$_2$ shuttle)
  - Shift from fast-twitch white (type IIb) to fast twitch red (type IIa)

Slow (type I fibers)  |  Fast red (type IIa) ← Fast white (type IIb)
More oxidative    |  Less oxidative

Aerobic Training on VO$_2$
Summary of Factors

<table>
<thead>
<tr>
<th>Factor</th>
<th>Rest</th>
<th>Submaximal exercise</th>
<th>Max exercise</th>
</tr>
</thead>
<tbody>
<tr>
<td>VO$_2$</td>
<td>No change (↑)</td>
<td>No change (↑)</td>
<td>Increase</td>
</tr>
<tr>
<td>HR</td>
<td>Decrease</td>
<td>Decrease</td>
<td>Decrease</td>
</tr>
<tr>
<td>SV</td>
<td>Increase</td>
<td>Increase</td>
<td>Increase</td>
</tr>
<tr>
<td>CO</td>
<td>No change</td>
<td>No change</td>
<td>Increase</td>
</tr>
<tr>
<td>Myocardial O$_2$ demand</td>
<td>Decrease</td>
<td>Decrease</td>
<td>No change</td>
</tr>
<tr>
<td>Ventilation</td>
<td>No change</td>
<td>Decrease</td>
<td>Increase</td>
</tr>
<tr>
<td>Arterial-venous O$_2$</td>
<td>No change</td>
<td>No change</td>
<td>Increase</td>
</tr>
<tr>
<td>Blood lactate concentration</td>
<td>No change</td>
<td>No change</td>
<td>Increase</td>
</tr>
<tr>
<td>Muscle BF</td>
<td>No change</td>
<td>No change</td>
<td>Increase</td>
</tr>
<tr>
<td>Splanchnic blood flow</td>
<td>No change</td>
<td>No change</td>
<td>No change</td>
</tr>
<tr>
<td>SBP</td>
<td>Decrease</td>
<td>Decrease</td>
<td>No change</td>
</tr>
<tr>
<td>DBP</td>
<td>Decrease</td>
<td>Decrease</td>
<td>No change</td>
</tr>
</tbody>
</table>

Cardiorespiratory Adaptations

Hoffman 1999 HK pub
Case study-metabolic response to exercise in the trained state

- Bruce a 35 year old doctor decides to improve his body composition and “metabolism” by starting an endurance exercise program. His father is a type 2 diabetic and Bruce’s BMI is 29. His waist circumference is 95cm.
  - What metabolic changes can be expected once he completes 6 weeks of ex therapy?
    • Rest
    • Exercise
  - How will the hormonal response to exercise differ for Bruce once he is in the trained” state?
  - What anthropometric changes should we expect?

Metabolic Adaptations

- Smaller accumulation in muscle and blood lactate at the same absolute and relative exercise intensity
  - Decreased lactate production (blood flow, more O₂ utilization)?
  - Increased lactate removal and disposal (blood flow, metabolism?)
- Reduced reliance on carbohydrate (CHO) as a fuel at the same absolute and relative exercise intensity
  - Spares muscle glycogen (delays fatigue)
- Increased reliance on fat as a fuel
  - Muscle TG?

Metabolic Adaptations- Fuel Utilization

Jeukendrup et al. 1997

Jeukendrup et al. 1997

Jeukendrup et al. 1997
Metabolic Adaptations

Hormones

• What are they?
• What do they do?
• What happens to them during acute exercise?
• What happens to them with training?

Hormonal Adaptations

• Influence energy balance, fluid/electrolyte balance, circulation, reproduction/growth, pain…
• Training adaptations for the same absolute intensity:
  – Reduces plasma EPI and NOREPI levels
    • Maximal exercise EPI levels are actually increased however
  – Increases glucagon secretion during exercise
  – Delays GH, cortisol secretion
  – May augment beta-endorphin release
• Reduces plasma insulin levels at rest
  • but increases muscle insulin sensitivity
Other Training Adaptations

• Thermoregulatory - lowers sweating threshold, limits the rise in core temperature, higher blood volume allows for heat dissipation
• Neurological - enhance motor unit recruitment, coordination/economy, central motor drive
• Adaptations to bone and connective tissue (bone mass, bone density, strengthen ligaments and tendons)
• Psychological adaptations

Factors Affecting Adaptations to Endurance Exercise Training

• Initial level of fitness
  – Those who are less fit increase their VO₂max by a greater amount
    • Athletes may increase only 2-3%
    • Healthy active young individuals may increase ~10%
    • Inactive individuals with CHD may increase ~50%
• Genetics (may contribute to 25-50% of the variation)
  – Monozygous twins have very similar VO₂max
  – Is it your mitochondria?
  – Is it your blood volume?

Factors Affecting Adaptations to Endurance Exercise Training

• Age
  – VO₂max tends to peak at 15-20 years then declines ~10% per decade (about 5% is related to inactivity)
Physiological Adaptations To Strength Training

Strength Training

• Important component to many rehab programs
• Strength may be defined conceptually as “the ability of skeletal muscle to develop force for the purpose of providing stability and mobility within the musculoskeletal system, so that functional movement can take place” (Harris and Watkins 1993)
  – i.e. the amount of force that can be generated by skel. muscl.
• Operational definition: “the magnitude of the torque exerted by a muscle(s) in a single maximal isometric contraction of unrestricted duration (Enoka 1994)”
• Traditionally, use high load, low repetition formulas to increase strength
Types of Muscle Contractions

• Contraction of a muscle generates force:
  – Concentric contraction  force developed exceeds the magnitude of the external force, causing shortening
  – Isometric contraction  force developed is equal to external force
  – Eccentric contraction  force developed is less than exertional force, causing lengthening

Factors Influencing Strength

• Age
  – Strength decreases with age
  – Muscle mass loss, # of units decrease (Type II)
  – Sensory and motor conduction velocities decrease
  – Decrease reaction time

• Disuse and Immobilization
  – Bed rest, space flight cause a decrease in muscle mass
  – Altered metabolism (phosphocreatine, glycogen, enzymes)
  – Decreased capillary density
  – Neuromuscular activity (coordination and muscle tone)
  – Loss of both Type I and Type II x-sectional area

Factors Influencing Strength

• Musculoskeletal Trauma
  – Causes atrophy and decreased performance
  – Pain and inflammation impair function
  – Decreased tensile strength during healing (re-injury)

• Training
  – Muscles and neuromotor mechanisms are extremely adaptable to stresses of activity
  – Must be of sufficient intensity and frequency to challenge the physiologic components of the muscle
  – Increases neuronal activity and causes hypertrophy of individual fibers
  – Increases stiffness of non-contracting components (more efficient)
Principles of Strength Training

Several methods (consider status, functional goals)

• Overload
  – Must be challenged beyond current force capabilities (threshold)

• Specificity
  – Training effects are specific to the mode of exercise stressed imposed on the exercising muscle

• Cross training
  – Overcome limitation of specificity (use isometric, concentric, eccentric as well as endurance components)

• Reversibility
  – Muscles must remain specifically challenged to maintain benefits

Adaptations to Strength Conditioning

<table>
<thead>
<tr>
<th>Physiologic adaptations</th>
<th>Positive changes in impairments</th>
<th>Positive changes in function</th>
<th>Quality of life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased motor unit recruitment</td>
<td>Strength-force production</td>
<td>Balance and coordination</td>
<td>Athletic performance</td>
</tr>
<tr>
<td>Synchronization of motor unit discharge</td>
<td>Increase bone mass</td>
<td>Gait</td>
<td>Job performance</td>
</tr>
<tr>
<td>Hypertrophy</td>
<td>Body composition</td>
<td>Activities of daily living</td>
<td>Social activity</td>
</tr>
<tr>
<td>Increased fiber size</td>
<td>Reaction time</td>
<td></td>
<td>Sense of well-being</td>
</tr>
<tr>
<td>Remodeling of muscle proteins</td>
<td>Immune function</td>
<td></td>
<td>Improvements in disease/disorders</td>
</tr>
<tr>
<td>Increasing in size and number of myofibrils</td>
<td>Cardio-pulmonary status</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increase in sarcomeres</td>
<td>Metabolism</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hyperplasia?</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increased tensile strength of connective tissue</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

What is Endurance?

• The time or number of contractions at a sustained load
Training Flexibility

Flexibility

• A largely ignored
• Limited scientific literature
• Definition:
  – Flexibility is the range of motion of a joint or series of joints
  – Assessment of length-tension relationship of muscles as they are lengthened
  – Influenced by muscles, tendons, ligaments, and bony structures.
• Dynamic (or ballistic) vs static stretches

Responses to Chronic Stretch

• Presumably, increasing fiber length increases joint ROM
• Increases sarcomere number (20–25% in cat model) but decreases sarcomere length (11–16%) (Tarbary et al. 1972)
• Stretching in animal models show changes in viscoelastic properties of muscle (Taylor et al. 1990)
  – Stress relaxation
    • Stretching the muscle to 10% greater than its initial length and immediately releasing it causes decreases in tension required to stretch
  – Creep response
    • Muscle stretched to a given tension (and held for 30 sec) then released and stretched again and released...caused a creep in the length generated
Joint Range of Motion Required for Activities of Daily Living

<table>
<thead>
<tr>
<th>Joint</th>
<th>ROM</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elbow</td>
<td>120° flexion</td>
<td>Eating, personal hygiene</td>
</tr>
<tr>
<td>Shoulder</td>
<td>45° flexion, 90° abduction, 20° external rotation</td>
<td>Eating, personal hygiene</td>
</tr>
<tr>
<td>Ankle</td>
<td>10° dorsiflexion, 20° plantar flexion</td>
<td>Walking</td>
</tr>
<tr>
<td>Knee</td>
<td>60° flexion</td>
<td>Walking</td>
</tr>
<tr>
<td>Hip</td>
<td>90° flexion</td>
<td>Stair climbing</td>
</tr>
<tr>
<td></td>
<td>30° flexion</td>
<td>Walking</td>
</tr>
<tr>
<td></td>
<td>50° flexion</td>
<td>Sitting</td>
</tr>
</tbody>
</table>

How Much Stretch Time Is Required?

- Bany and Irion (1974) compared static hamstring stretching for 15 sec, 30 sec and 60 sec
  - 15 sec did not improve flexibility
  - 30 and 60 sec both improved flexibility to the same extent
- Frequency of one stretching program per week may be sufficient to maintain flexibility after training program but stretching 3-5 x/week further improved flexibility (Wallin et al. 1985)
Basic Stretching Prescription

- Static stretching or contractions against a passive stretch (proprioceptive neuromuscular facilitation)
- Avoid ballistic stretching
- 3x per week to as much as daily to improve flexibility
- Perform stretches 3 times and hold for 15-30 seconds