

EXERCISE PHYSIOLOGY

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OBJECTIVES

Upon completion of this lecture, participants will be able to:

- Identify the training response to aerobic and anaerobic training.
- Recognize the benefits of appropriate resistive training.
- Summarize the importance of flexibility training.
- Define muscle fiber types.
- Understand current concepts regarding delayed onset muscle soreness.
- Discuss lactate kinetics and how they apply to the athlete.
- Understand the benefits of exercise for the treatment and/or prevention of several chronic diseases.

OUTLINE

Muscle anatomy and physiology
Energy Systems
Adaptations to Exercise

MUSCLE CONTRACTION

Muscles

- Muscle cells (myofibers)
 - Long, cylindrical multinucleated cells
 - Cell membrane = sarcolemma
 - Cytoplasm = sarcoplasm
- Connective tissue
 - Endomysium surrounds each cell, continuous with sarcolemma
 - Perimysium surrounds bundles of muscle cells (fascicles)
 - Epimysium covers the outer surface of the muscle
- Tendons
 - Connect muscle to bone periosteum
- Innervation
 - Each muscle cell innervated by a single α -motor neuron
 - Each α -motor neuron can innervates multiple muscle cells
 - Motor Unit = single α -motor neuron and all of the muscle cells it innervates
 - All cells of motor unit contract together (ie: all or nothing)

MUSCLE CONTRACTION

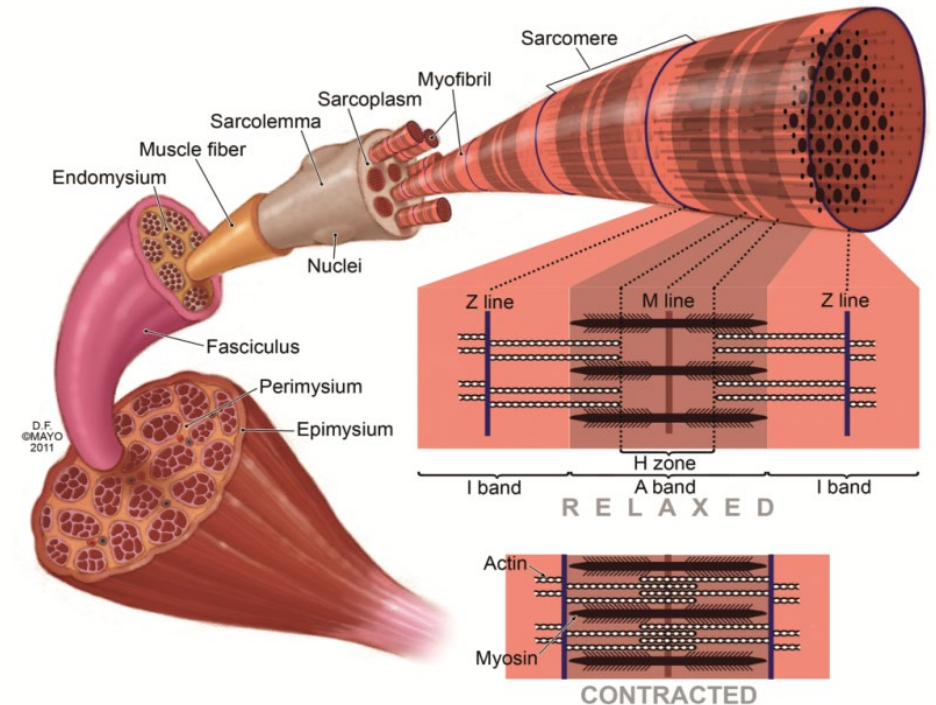
Myofibrils

- Contractile units of muscles
- Found in the sarcoplasm
- 2 myofilaments
 - Thick filaments (myosin)
 - Globular head, which can form cross bridges with actin
 - Surrounded by 6 actin
 - Thin filaments (actin)
 - 2-stranded double helix structure
 - Surrounded by 3 myosin

MUSCLE CONTRACTION

Sarcomere = the smallest contractile unit in skeletal muscle

- **Z-line**
 - Ends of the sarcomere
 - Actin attaches to Z-line
- **M-line**
 - Middle of sarcomere
 - Myosin attaches to M-line
- **A (dark)-band**
 - Contain myosin and actin
- **I (light)-band**
 - Contains only actin
 - Gets smaller during muscle contraction
- **H-zone**
 - Middle of the A-band
 - Only contains myosin
 - Gets smaller during muscle contraction



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MUSCLE CONTRACTION

Sarcomere at rest

- Low calcium in the sarcoplasm
- Tropomyosin/troponin cover myosin binding sites on actin

Sarcomere during contraction

- Alpha-motor neuron releases acetylcholine
- Sarcolemma depolarizes, depolarization transmitted to interior of myofiber by transverse tubules (T-tubules)
- Intra-cellular calcium released from sarcoplasmic reticulum
- Calcium binds to troponin
 - Tropomyosin has conformational change
 - Uncovers myosin binding sites on actin filament
- Myosin head attaches to actin, flexes, dissociates from actin, then resets to original position
- 1 ATP required for myosin head to attach to actin and flex, and 1 to dissociate from actin and reset (ie: **2 ATP required for muscle contraction**)

MUSCLE FIBER TYPE

2 main fiber types

- Type I
 - Slow twitch-oxidative
- Type II
 - Fast twitch-glycolytic
 - 2 sub-types
 - Type IIa = fast twitch-oxidative glycolytic
 - Type IIx = fast twitch-glycolytic

RECRUITMENT

Henneman Size Principle

- Smaller, lower threshold motor neurons recruited first
 - Innervate Type I muscle cells
- Larger, higher threshold motor neurons recruited if more force is required
 - Innervate Type II muscle cells

Exception:

- Type II muscle cells are recruited first in high-velocity (e.g. plyometric) activities

ENERGY SYSTEMS

3 Primary Energy Systems

- ATP-phosphocreatine
- Anaerobic (glycolytic)
- Aerobic (oxidative)

All 3 energy systems are constantly utilized, but the percentage each contributes to energy production changes based upon the activity.

ENERGY SYSTEMS

ATP-phosphocreatine

- Main energy system for maximal exercise lasting up to 30 seconds
- Provides P to ADP to reform ATP
- Catalyzed by enzyme creatine kinase
- Most of the phosphocreatine can be regenerated after 3 minutes of rest

ENERGY SYSTEMS

Anaerobic energy system

- Primary energy source for exercise lasting 1-3 minutes
- Metabolism of glucose to pyruvate via glycolysis
- No oxygen is required
- Produces 2 ATP if it begins with a glucose or 3 ATP if it begins with glycogen
- In the presence of oxygen, pyruvate proceeds to the aerobic energy system for further metabolism
- However, pyruvate is created faster than it can be metabolized, so it is reversibly converted to lactate in order to prevent excess pyruvate accumulation
 - Facilitated by a low-oxygen environment
- Rate limiting step of glycolysis catalyzed by phosphofructokinase

ENERGY SYSTEMS

Aerobic energy system

- Primary energy source for sustained exercise lasting greater than 3 minutes
- Occurs in mitochondria via oxidative phosphorylation
- Oxidative phosphorylation has 2 parts
 - Krebs cycle (by product is carbon dioxide)
 - Electron transport chain (by product is water)
- Produces 36 ATP per glucose molecule
- Net ATP from glycolysis and oxidative phosphorylation is 38 (beginning with glucose) or 39 (beginning with glycogen)

ENERGY SYSTEMS

Aerobic energy system

- Fat also metabolized in the mitochondria
 - Triglycerides broken down into glycerol and 3 free fatty acids by lipolysis
 - Free fatty acids enter the mitochondria and are converted to acetyl coenzyme A through β -oxidation
 - Acetyl coenzyme A metabolized by the Krebs cycle and electron transport chain
 - Net ATP produced from free fatty acid metabolism is far greater than for glucose (e.g., 129 ATP for 1 palmitic acid molecule)

CARDIOVASCULAR RESPONSE TO EXERCISE

Linear increase in heart rate (HR) relative to intensity

- $HR_{max} = 220 - \text{age} \pm 20$

Stroke volume (SV) initially increases, then plateaus due to limited diastolic filling time

Cardiac output (CO) = $HR * SV$

- Increase in CO related to low to moderate intensity exercise due to increases in both HR and SV
- Increase in CO related to high intensity exercise nearly completely due to increased HR

Cardiac Drift

- During prolonged aerobic exercise, there is a gradual increase in HR and decrease in SV for any given work load
- Due to decreased blood volume from sweating and opening of skin capillary beds for heat dispersion

CARDIOVASCULAR RESPONSE TO EXERCISE

Oxygen consumption/uptake (VO_2)

- $\text{VO}_2 = \text{CO} * (\text{O}_{2a} - \text{O}_{2v})$

Maximal Oxygen Consumption/Uptake ($\text{VO}_{2\text{max}}$)

- $\text{VO}_{2\text{max}} = \text{CO}_{\text{max}} * (\text{O}_{2a} - \text{O}_{2v})$

Linear relationship between VO_2 and CO

- CO is major determinant of aerobic exercise capacity

VO_2 is trainable due to increases in SV and oxygen extraction, and lower resting HR

LACTATE KINETICS

At rest and during low-intensity exercise

- Blood lactate levels are low and remain relatively constant

As activity intensity increases

- Lactate gradually begins to accumulate

If exercise intensity continues to increase

- Anaerobic metabolism becomes the predominant energy source
- Lactate produced faster than it can be cleared
- This point is called the Lactate or Anaerobic Threshold
- Usually occurs at 4 mmol/L of blood lactate
- Untrained individuals = 50-60% VO_2max
- Trained individuals = 80-90% VO_2max
- Lactate threshold is trainable
- Lactate is a by product of glycolysis and is converted back to pyruvate, which is an energy substrate
- Lactate does not appear to cause the “muscle burn” associated with exercise

RESPIRATORY RESPONSE TO EXERCISE

Initial rapid increase in ventilation

- Predominantly due to increased tidal volume

Brief plateau, then gradual rise until steady state is achieved

- Predominantly due to increased respiratory rate

Submaximal exercise = linear relationship between ventilation and VO_2

ENDOCRINE RESPONSE TO EXERCISE

Testosterone

- Increases after resistance exercise
 - Enhanced by:
 - Shorter rest periods (1 min rather than 3 min)
 - Less intensity but higher volume (10 rep maximum [RM] rather than 5 RM)
 - Exercise lasting longer than 20 min
- Anaerobic exercise also temporarily increases testosterone levels
- Endurance athletes have lower than normal resting testosterone levels

ENDOCRINE RESPONSE TO EXERCISE

Growth hormone

- Increases after resistance exercise, and is enhanced by similar patterns of exercise as discussed for testosterone
- Also increases following aerobic exercise

Insulin concentrations

- Decrease during exercise
- Increase for 20-60 minutes immediately following exercise
- Prolonged increase in insulin sensitivity following exercise

Cortisol levels

- Increase after resistance training and prolonged aerobic exercise above 70% of maximal oxygen uptake

IMMUNE SYSTEM RESPONSE TO EXERCISE

Reduced

- Mucosal IgA
- Leukocyte counts
- Natural killer cell numbers
- Incidence of infections in previously sedentary individuals

Increased

- URI's in endurance athletes

ADAPTATIONS TO EXERCISE

Aerobic Exercise

- Increased:
 - Resting and maximal SV
 - Left ventricular wall thickness, internal diameter, and mass (eccentric hypertrophy)
 - Blood volume
 - Initially, mainly increased plasma volume due to increased ADH and aldosterone levels
 - Later due to increased plasma volume and number of red blood cells
 - More increase in plasma volume than red blood cells = pseudoanemia
 - Muscular capillary density
 - Size and number of mitochondria
 - Oxidative enzymes
 - Fatty acid transport across the sarcolemma
 - Fat metabolism (ie: glycogen sparing)
 - Arterial oxygen extraction
 - Arteriovenous oxygen difference
 - Rate of pyruvate metabolism due to increased oxidative enzymes
 - Fiber type conversion from Type IIx to Type IIa (after 2 weeks of exercise)

ADAPTATIONS TO EXERCISE

Aerobic Exercise

- Decreased:
 - Resting and submaximal exercise HR
 - Systolic and diastolic blood pressures
 - Glycogen/glucose metabolism (ie: glycogen sparing)
 - Decreased lactate production
- No Change:
 - Lactate buffering
 - Resting CO

ADAPTATIONS TO EXERCISE

Anaerobic Exercise

- Increased:
 - Intra-muscular anaerobic enzymes (e.g. phosphofructokinase, phosphorylase, and lactate dehydrogenase)
 - Lactate buffering capacity
 - +/- oxidative enzymes
 - +/- creatine kinase and myokinase

ADAPTATIONS TO EXERCISE

Resistance Exercise

- Muscle cell hypertrophy
 - Takes 6-8 wks
 - Due to an increase in sarcomeres
 - Predominantly Type II muscle cells
- Strength gains prior to 6 wks due to:
 - Improved motor unit recruitment
 - Suppression of self-protective reflexes

No substantial evidence supporting muscle cell hyperplasia in humans

ADAPTATIONS TO EXERCISE

Resistance Exercise

- Fiber type conversion begins after 2 weeks
 - Type IIx to Type IIa (similar to changes with aerobic exercise)
- Endurance exercise does not enhance strength gains from resistance exercise, but resistance exercise does improve endurance exercise performance

ADAPTATIONS TO EXERCISE

Resistance Exercise

- Increases:
 - Left ventricular wall thickness and mass (no change in internal diameter)
 - Bone mineral density
 - Ligament and tendon strength
 - Collagen content
 - Anaerobic energy stores (glycogen, phosphocreatine, ATP)
 - Anaerobic enzymes
- Decreases:
 - Capillary and mitochondrial density (larger increase in muscle cross-sectional area than in capillary and mitochondrial content)

ADAPTATIONS TO EXERCISE

Flexibility

- 3 main techniques
 - Static
 - Hold muscle in stretched position for a specified period of time (e.g. 30 sec)
 - Easy and safe
 - Minimal muscle spindle activation
 - Ballistic
 - Bouncing motion
 - Activates muscle spindles/stretch reflex
 - As effective as static stretching, but more painful and higher potential for injury
 - Proprioceptive neuromuscular facilitation (PNF)
 - Contracting a muscle (agonist or antagonist) to facilitate the stretch
 - Utilizes reflexes to facilitate the stretch
- Effectiveness
 - PNF > static = ballistic

ADAPTATIONS TO EXERCISE

Factors that influence flexibility

- Bony anatomy of a joint
- Muscles, fascia, tendons, and ligaments that cross a joint
- Increased age
 - Fibrocartilaginous replacement of degenerative muscle fibers
 - Increased adhesions
 - Calcium deposits
- Gender
 - Females > flexibility than males, primarily due to pelvic structure and hormonal differences
- Activity level
 - Active people > flexibility than sedentary people

ADAPTATIONS TO EXERCISE

Force required to maintain a sustained stretch decreases due to:

- Acute
 - Musculotendinous viscoelastic properties
- Chronic
 - Increased number of sarcomeres

Chronic stretching also increases pain tolerance to stretching

ADAPTATIONS TO EXERCISE

Static stretching performed immediately prior to strength, power, agility, and speed activities can inhibit performance

Dynamic stretching does not appear to have the same inhibitory effects

(Peck et al *Cur Sports Med Reports* 2014)

DELAYED ONSET MUSCLE SORENESS

Due to high-force, unaccustomed eccentric (and occasionally isometric in an extended position) muscle contractions

- Theory: few motor units during eccentric contraction = higher force per area

Begins 6-12 hours after exercise, peaks 2-3 days post-exercise, and resolves 5-7 days post-exercise

DELAYED ONSET MUSCLE SORENESS

Eccentric muscle contraction causes:

- Disruption of sarcomere Z-lines called “Z-line streaming”
- Sarcolemma damage
- Intra-cellular calcium release
- Activation of calcium dependent proteolytic enzymes
- Degrade the damaged sarcomere z-lines
- Circulating neutrophil concentrations increase within a few hours of the injury
- Creatine kinase leaks from muscle cells into plasma and attracts monocytes within 6-12 hours
- Monocytes transform into macrophages and phagocytose damaged structures
- Macrophages release prostaglandin PGE2, which sensitize Type III and IV nerve endings
- Mast cells also are attracted to the area and release histamine
- Tissue edema, hyperthermia, and further nerve sensitization occurs
- Monocyte/macrophage concentrations peak 48 hours post-injury
- Oxygen free radicals produced throughout the process causing secondary tissue damage

DELAYED ONSET MUSCLE SORENESS

Prevention

- “Repeated bout effect”: bout of eccentric is isometric exercise prevents subsequent DOMS from the same exercise for 4-12 weeks (Hyldahl RD et al. Sports Sci Rev 2017)
- Cherry juice??
 - Anti-oxidant and anti-inflammatory properties
 - Ingestion of 355 ml of tart cherry juice bid x 7 days prior to exercise and day of exercise
 - Reduced pain, inflammatory markers post-exercise (Kuehl J Int Soc Sports Nutr 2010, Kuehl Med Sport Sci 2012)

Treatment

- NSAIDs, acetaminophen, heat, ice, rest, massage, electrical stimulation

KEY POINTS

2 ATP required for muscle contraction

2 ATP produced in glycolysis (3 if start from glycogen), 36 from oxidative phosphorylation, 38 total for both (39 if start from glycogen)

Far more ATP produced with triglyceride metabolism than glucose metabolism

Glycogen sparing, eccentric hypertrophy are adaptations to aerobic conditioning

Cardiac drift = increased HR at same work level with extended exercise

Rate limiting step of glycolysis = phosphofructokinase

Strength gains < 6 wks = neuromuscular, > 6 wks = hypertrophy

Lactate is an energy substrate, doesn't cause "muscle burn"

Reduced mucosal IgA with heavy aerobic exercise = increased risk of URI's, but with less intense exercise, have no increased risk of URI's

Best prevention strategy for DOMS = repeat bout effect

THANK YOU



THANK YOU

