Chapter 3

Neuromuscular Responses and Adaptations to Exercise

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Chapter 3
What You Will Learn in this Chapter

• Anatomy and Physiology
  • Basic physiologic concepts concerning neuromuscular responses & adaptations to exercise
  • Basic terminology related to neuromuscular responses & adaptations to exercise

• Applied Concepts
  • Strategies to improve exercise performance by optimizing neuromuscular responses & specific adaptations to training
  • Concepts of neuromuscular integration aimed at learning to optimize exercise performance.
Neuromuscular Integration: Central Command

• A feed-forward set of neural signals coming from motor cortex (brain)
  • Activates cardiovascular control centers

• This activation rapidly
  • Diminishes parasympathetic control of heart
    • Increasing HR
  • Increases sympathetic outflow to heart & vasculature
    • Increasing HR & regulating BP
Neuromuscular Integration (Key Structures)

• **Somatic nerves (axons)**
  - Nerves that directly control muscles
    • *Motor neurons* (nerves)

• **Motor neurons (nerves)**
  - Axons that possess a motor function that enclose nucleus

• **Cell bodies**
  - Body of nerve cell
Neuromuscular Integration (Key Structures)

- **Motor cortex**
  - Outer layer of brain that contains cell bodies & axons of motor nerves

- **Axons (motor neurons)**
  - Carry nerve impulses away from the cell body.

- **Dendrites**
  - Carry nerve impulses toward the cell body
Animation: Skeletal Muscle Innervation
The Anatomy of a Neuron

**Key Structures**
- Nucleus
- Axon
- Axon Terminal
- Dendrites
- Glia (support cells)

**Other Terminology**
- Neurotransmitters (chemicals)
- Synapse (junction)
- Receptors (molecules)
Motor Neuron Innervating Skeletal Muscle

Fig 3.1
The Neuromuscular Junction

Fig 3.2

1. An action potential in a motor neuron is propagated to the axon terminal (terminal button).
2. This local action potential triggers the opening of voltage-gated Ca²⁺ channels and the subsequent entry of Ca²⁺ into the terminal button.
3. Ca²⁺ triggers the release of acetylcholine (ACh) by exocytosis from a portion of the vesicles.
4. ACh diffuses across the space separating the nerve and muscle cells and binds with receptor-channels specific for it on the motor end plate of the muscle cell membrane.
5. This binding brings about the opening of these nonspecific cation channels, leading to a relatively large movement of Na⁺ into the muscle cell compared to a smaller movement of K⁺ outward.
6. The result is an end-plate potential. Local current flow occurs between the depolarized end plate and the adjacent membrane.
7. This local current flow opens voltage-gated Na⁺ channels in the adjacent membrane.
8. The resultant Na⁺ entry reduces the potential to threshold, initiating an action potential, which is propagated throughout the muscle fiber.
9. ACh is subsequently destroyed by acetylcholinesterase, an enzyme located on the motor end-plate membrane, terminating the muscle cell's response.
Animation: Skeletal Muscle Innervation
The CNS and Brain

- **Anatomy of central nervous system (CNS):**
  - Consists of brain & spinal cord
- **Brain has 6 major areas:**
  1. Cerebrum
  2. Cerebellum
  3. Diencephalon
  4. Midbrain
  5. Pons
  6. Medulla
- **Integration of the Motor Nerves with the Muscle Is Required for Muscle Contraction and Relaxation**
Major Areas of the Human Brain
The Spinal Cord and Nerves

- **Spinal Cord divided into 2 areas:**
  - Central gray areas
  - Surrounding white matter

- **Afferent nerve fibers**
  - Carrying sensory information from periphery back to the brain; will enter spinal cord via dorsal (back) side

- **Motor nerves**
  - Leave spinal cord on ventral (front) side
Motor Control

Fig 3.3

The CNS is constantly apprised of muscle length and tension and other peripheral events via pathways conveying afferent input, so it can program coordinated, purposeful skeletal muscle activity.

Motor movement is controlled by input to the motor neurons from afferent neuron terminals at the level of the spinal cord, the primary motor cortex, via the corticospinal motor system, and brain stem nuclei, which serve as the final link in the complex, multineuronal motor system involving many regions of the brain.

KEY
- Pathways conveying afferent input
- Corticospinal motor system
- Multineuronal motor system
Key Neuromuscular Structures

- **Muscle spindles**
  - Receptors in connective tissue capsules located between muscle fibers

- **Golgi tendon organs (GTOs)**
  - Respond to tension within muscle by inhibiting agonist muscles (contracting) & facilitating antagonist (relaxing) muscles during contraction

- **Myotendinuous Junction**
  - The region between the bone and the tendon.
Skeletal Muscle Receptors

(a) Muscle spindle

- Alpha motor neuron axon
- Gamma motor neuron axon
- Afferent neuron axons
- Primary (annulospiral) endings of afferent fibers
- Secondary (flower-spray) endings of afferent fibers
- Extrafusal ("ordinary") muscle fibers

(b) Golgi tendon organ

- Skeletal muscle
- Afferent fiber
- Golgi tendon organ
- Collagen
- Tendon
- Bone

Capsule
Intrafusal (spindle) muscle fibers
Contractile end portions of intrafusal fiber
Noncontractile central portion of intrafusal fiber
Function of Muscle Spindles

Fig 3.4
Reflexes

• Involve four components:

1. Receptor located in muscle
2. Gamma afferent neurons arising from receptor & synapse in gray matter of spinal cord
3. Alpha motor neurons exiting from cell bodies within spinal cord
4. Muscle fibers of motor unit
The Patellar Tendon Reflex
Three Layers of Protein (Muscle)
Levels of Organization in a Skeletal Muscle

(a) Relationship of a whole muscle and a muscle fiber

(b) Relationship of a muscle fiber and a myofibril

(c) Cytoskeletal components of a myofibril

(d) Protein components of thick and thin filaments
Skeletal Muscle

**Structural Hierarchy**

- Muscles are made up of
  - Muscle fascicles, muscle fibers, & myofilaments of actin & myosin arranged as a series of sarcomeres
- Muscle fiber is surrounded by double membrane:
  - Inner membrane = plasma membrane
  - Outer membrane = basement membrane
- **Satellite (stem) cells** are located between the two membranes
Sacromere

- When viewed under an electron microscope
  - Myofibrils within muscle fiber appear striated
- Striations result from
  - Different light properties associated with actin & myosin proteins
- Interaction between contractile & regulatory proteins of individual sarcomeres
  - Forms the functional (contractile unit) of the muscle
  - Defined as the Z-line to Z-line
  - Pulls together and releases during contraction (sliding filament theory)
Sarcomere
Sliding Filament and Cross-bridge Cycling Theory of Contraction

- **This theory describes how**
  
  - Actin & myosin move in relation to each other to shorten the length of sarcomere (contraction)
  
  - Because sarcomeres are connected in series with each other, muscle fiber also contracts

- **Crossbridge Cycle**
  
  - Repetitive, 4-step cycle that attaches myosin to actin using ATP & its breakdown to ADP + Pi + E
  
  - Pi represents inorganic phosphate
  
  - E represents energy
Oxygen ($O_2$) Delivery

For simplicity, only two capillary beds within two organs are illustrated.
Muscle Training Methods

Isotonic Exercise

Isometric Exercise

Isokinetic Exercise
Muscle Contractions

1. **Isometric, or static**
   - Contraction is when muscle develops force but its length does not change

2. **Isotonic**
   - **Concentric contraction**
     - When muscle develops force by causing length of muscle to shorten
   - **Eccentric contraction**
     - When muscle develops force & external force causes muscle to lengthen

3. **Isokinetic** – Accomplished at same speed of contraction throughout the complete range of motion (equal force and controlled speed)
The Length-Tension Relationship

(a) Range of length changes that can occur in the body

- A: Maximal tension
- B: Tetanic tension
- C: Resting tension
- D: Minimal tension

Percent maximal (tetanic) tension

<table>
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<th>100%</th>
<th>130%</th>
<th>170%</th>
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<tr>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>50%</td>
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Muscle fiber length compared with resting length

- Shortened muscle
- Stretched muscle

(b) Graph showing change in muscle length (in.)

- Resting length
- Voluntary force curve

Max tension (units)

<table>
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<th>Change in muscle length (in.)</th>
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<tr>
<td>0.5</td>
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Electromyography (EMG)

• Recording is obtained by using
  • Electrodes on the surface of or needle electrodes placed in belly of skeletal muscle
  • It measures & integrates electrical activity of the active action potentials of muscle

• During its contraction
  • A linear relation between force of contraction & amount of EMG activity has been demonstrated
Electromyography (EMG)

- Amount of EMG activity
  - Greater during shortening
    - Concentric or positive contractions
  - Than during lengthening
    - Eccentric or negative contractions
Mechanical Efficiency (ME)

- Can be calculated as a
  - Ratio of external work (W) performed divided by extra Energy (E) required to perform the work above the resting energy (e)
- This ratio is expressed as a percentage

- Summarized in the following equation:
  - \( \% ME = \frac{W}{E - e} \times 100 \)
Motor Unit

• Body’s fundamental structural unit that functionally integrates
  • Neural activity with
  • Skeletal muscle contraction
Comparison of Motor Unit Recruitment

(a) Recruitment of small motor units

(b) Recruitment of large motor units
Muscle Fiber Type Distribution

Key:
S = sprinters
P = power jumpers and throwers
MD = middle distance runners
LD = long distance runners
Histochemistry & Immunocytochemistry

- **Histochemistry**
  - Chemistry of identifying living tissues by using different stains that can be identified by light microscopy or electron microscopy
  - It is used to identify different fiber types

- **Immunocytochemistry**
  - A technique using chemical reaction that occurs between proteins & its antibodies within a cell
  - Can be identified by imaging techniques
    - Such as confocal or fluorescence microscopy
Muscle Fiber Types

• **Type I**
  - A *slow-twitch* muscle fiber that is classified by histochemistry or immunocytochemistry as a *slow oxidative red fiber*
  - With light microscopy appears *pinky-red*

• **Type Ila**
  - A *fast-twitch fiber* with a higher oxidative capacity
  - Appears *pinky-red* with light microscopy
Muscle Fiber Types

- **Type IIb**
  - A *fast-twitch fiber* has low oxidative capacity
  - Appears *pale white* with light microscopy

- **Type IIx**
  - Muscle fiber that is *only* rats
  - Appears to have high oxidative capacity
  - Resists fatigue
Metabolic Pathways For Muscle Contraction and Relaxation

During muscle contraction, ATP is split by myosin ATPase to power cross-bridge stroking. Also, a fresh ATP must bind to myosin to let the cross bridge detach from actin at the end of a power stroke before another cycle can begin.

During relaxation, ATP is needed to run the Ca$^{2+}$ pump that transports Ca$^{2+}$ back into the lateral sacs of the sarcoplasmic reticulum.

The metabolic pathways that supply the ATP needed to accomplish contraction and relaxation are:

1. Transfer of a high-energy phosphate from creatine phosphate to ADP (immediate source);
2. Oxidative phosphorylation (the main source when O$_2$ is present), fueled by glucose derived from muscle glycogen stores or by glucose and fatty acids delivered by the blood; and
3. Glycolysis (the main source when O$_2$ is not present). Pyruvate, the end product of glycolysis, is converted to lactate when lack of O$_2$ prevents the pyruvate from being further processed by the oxidative phosphorylation pathway.
Overload

• A training program designed around overload principle results in:
  • Increased skeletal muscles size (hypertrophy)
    • Requires an increase in muscle protein accumulation
  • Increase their strength

This can occur if:
1. Protein synthesis increases above protein degradation
2. Protein degradation decreases below protein synthesis
3. A combination of both

• Hyperplasia
Specific Adaptations of Fiber Types

- If an individual uses only weight-training exercises in a 6-month training program:
  - Both type I & type II fibers increase their cross-sectional area
  - However, type II fibers increase 10% greater than type I fibers
Specific Adaptations of Fiber Types

- Increases in cross-sectional area of fibers are due to:
  - Increases in protein content
  - Result in a 2% increase in cell volume
  - However, increase in cell volume results in
    - 11% decrease in capillary density
    - 1% decrease in mitochondrial density
Neuromuscular Adaptations to Strength Training

- Increases in motor cortex input that allows for greater neural control and increased force production
- Increase in muscle recruitment (more motor units) increasing force production
- Increases in neural firing rates and timing and coordination of recruitment that increases the rate of force production
- Reduction in the inhibitory functions like the Golgi tendon organs allowing for increased force production, motor unit synchronization, and cross-training (education) that helps balance force production between both sides of the body
Skeletal Muscle Adaptations to Strength Training

- Increases in muscle fiber size and cross-sectional size (muscle mass) that allows for increase in muscular strength
- Increases in myosin heavy chain protein and hypertrophy after early training changes associated with neural adaptations that allow for increases in muscular strength
- No change or decreases in capillary densities and decreases in mitochondrial densities, which are associated with decreased oxidative capacity and reduced changes in aerobic power
- Increases in ATP, creatine phosphate, glycogen stores, fuel mobilization, and anaerobic enzyme activity that allow for improved energy utilization and muscular endurance
- Potential increases in ligament, tendon, collagen, and bone strength with decrease in body fat and increases in lean weight that can enhance functional health and may reduce falls (particularly in the elderly)

Table 3.3  p. 93
Comparison of Absolute Endurance and Strength Developed by Different Exercise Regimens

A
High Repetitions (15-30)
Low Weights (40-50% of 1 RM)

B
Moderate Repetitions (6-14)
and Weights (60-70% of 1 RM)

C
Low Repetitions (1-5)
And Heavy Weights (90%+ of 1 RM)
Training for Endurance

- Endurance exercise training generally follows
  - Same underlying principles of overload, frequency, intensity, & duration (see Ch 2)

- However, if you only want the health benefits
  - Overload principle can be ignored
  - Frequency, intensity, & duration of exercise training can be maintained
Overloading the Skeletal Muscle during Exercise

- Long Slow Distance (LSD)
- Speed Play
- Interval Training
- Plyometrics
- Core Strength
- Pilates
- Stability Exercise Balls
Interval Training

- Idea of using timed speed runs over distances
- **For example:**
  - 100 m in 12 sec, 200 m in 30 sec, 300 in 45 sec, & 400 m in 60–70 sec
- At completion of speed run
  - Athlete walks or jogs back to beginning of speed run while measuring HR
- When the HR recovers to < 120 bpm
  - Athlete repeats speed run & recovery walk/jog/rest paradigm
Plyometrics

• **Objective**
  • Generate greatest amount of force in the shortest time (power)

• **Solid strength base is necessary**

• **Popular in sports that require powerful movements**
  • Examples – bench hops, push-ups, etc.

• **Relatively high injury risk**
Core Strength Training

- “Core”
  - Trunk and pelvis
- Core muscles
  - Abdominal muscles, hip muscles, and spinal muscles
- Core strength training
  - Objective
    - Train abdominal and lower back muscles in unison
The Pilates training system was originally developed in the 1920s by German physical therapist Joseph Pilates.

This training technique emphasizes controlled breathing, correct spinal and pelvic alignment, and concentration on smooth, flowing movements.

A series of exercises will help to strengthen the body’s core muscle groups while at the same time promote graceful movements and flexibility.

Stability Exercise Balls

- Designed to develop
  - Abdominal
  - Hip
  - Chest
  - Spinal muscles
- Characteristics of ball choice
- Wide range of exercises
Overloading the Skeletal Muscle during Exercise

- These training techniques result in
  - Increasing capacity to deliver oxygen
  - Improving capacity of muscle’s metabolic machinery & its neuromuscular coordination

- Improving one’s aerobic capacity is beneficial
  - Speed & power athletes
  - Endurance athletes

- The higher one’s aerobic capacity & muscular endurance, the easier it is to recover from
  - Intermittent short time training
  - Highly intense bursts of energy output
Endurance and Myoplasticity

- **Periodization:** before & during competitive season
  - Athlete uses interval training and LSD & speed-play training in a cyclical manner
    - Peaking
    - Tapering
    - Recovering
Endurance and Myoplasticity

- Major changes occur
  - Amount of mitochondrial proteins present within cell oxidative enzymes
  - Increase mitochondrial density
  - Increase mitochondrial capacity
Muscular Factors Associated with Muscular Fatigue During Exercise

1. ATP/CP (CP; utilization & resynthesis)

2. Muscle glycogen (depletion & resynthesis)

3. Glucose availability

4. Accumulation or depletion of metabolites
   (lactate/H+, Mg2+, ADP, Pi, ammonia [NH₃], Ca+, & reactive oxygen species)
Physiologic Factors Related to Muscle Fatigue

Central fatigue
- ↓ CBF and CA
- ↑ ROS → ↓ NO → ↑ SNS outflow
- ↓ Motor nerve outflow

Muscular fatigue
- ↓ LBF
- ↓ ATP/CP
- ↓ Glycogen to zero
- ↓ Myoneural function
- ↓ Glucose availability
- ↑ $H^+$, $Na^+$, $Ca^{2+}$
- ↑ Myokines (IL6) and ROS
- ↑ Blood temperature
- ↑ Central sympathetic activity

Respiratory modulators
- ↑ EIAH
- ↓ $HbO_2$ sat
- ↑ Work of breathing
- + Intrathoracic pressures
- ↑ Respiratory muscle fatigue
- ↑ ROS
- ↑ Resp. muscle ischemia
Delayed Onset Muscle Soreness (DOMS)

What type of activities result in DOMS?

1. Eccentric muscle contractions
   - Running or walking downhill

2. High-intensity exercise
   - Clients are unaccustomed, which results in damage to muscle structure

3. Overstretching or tearing of muscle connective tissues
Delayed Onset Muscle Soreness (DOMS)

What are some commonly reported factors associated with DOMS?

1. Inflammatory reaction of muscles
2. Edema (swelling) after cellular inflammation
3. Secondary chemical damage from cellular inflammation
Recovery from DOMS

Strenuous Exercise

Structural damage to muscle cells

Calcium leaks out of sarcoplasmic reticulum

Protease activation—results in breakdown of cellular proteins

Inflammatory response

Edema and pain

Recovery

Adaptation

Neural Theory
Changes in nervous system

Connective Tissue Theory
Increased intramuscular connective tissue

Cellular Theory
Cellular changes that strengthen and protect muscle fibers

Repeated bout of exercise

Less muscle damage
Muscle Cramps Remain a Mystery

• Exact physiologic cause of muscle cramps is unknown, but they are most likely associated
  • Dehydration
  • Disruptions in electrolyte balance and/or CHO stores

• Strategies to Reduce or Eliminate Cramping:
  • Regular conditioning
  • Proper hydration for the environmental conditions
  • Reducing intensity & duration of exercise training program at the beginning of program
  • Stretching muscle groups prone to cramping
The End

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