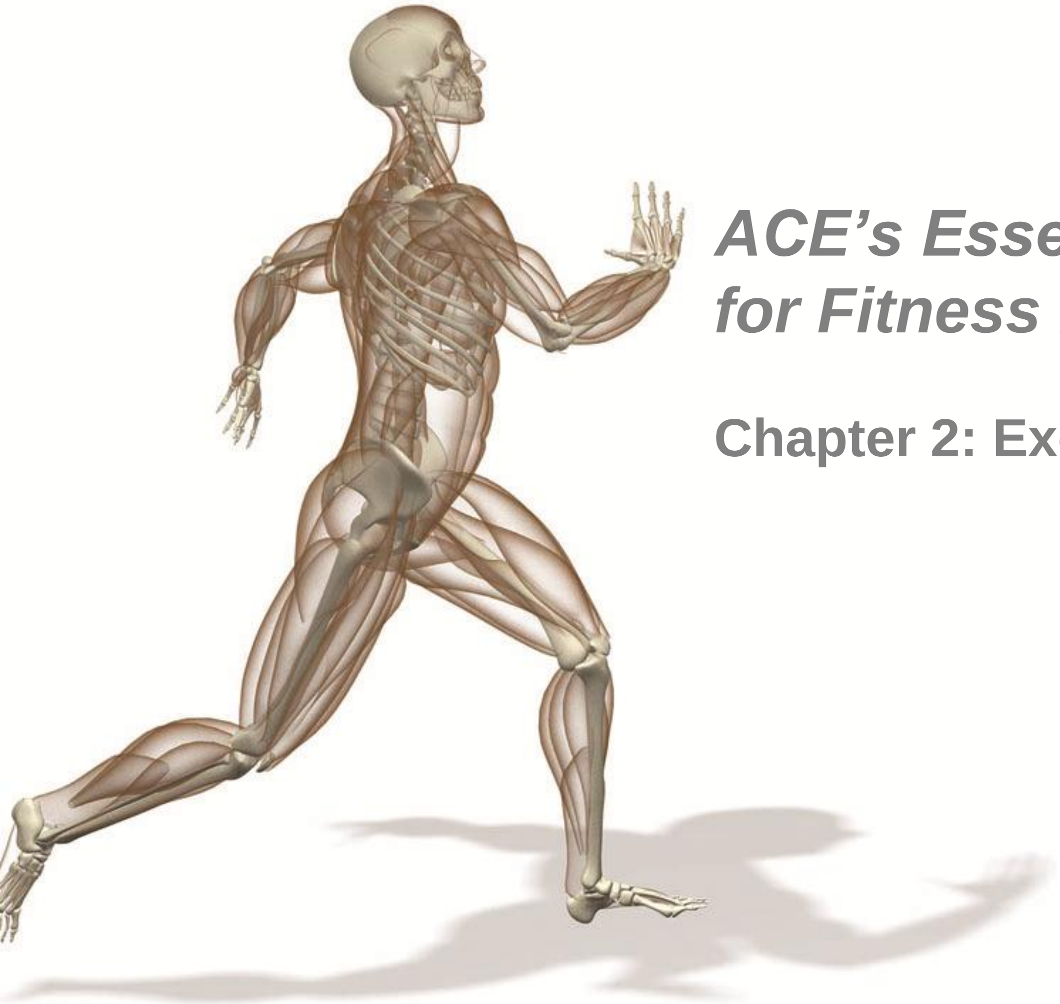


ACE's Essentials of Exercise Science for Fitness Professionals

Chapter 2: Exercise Physiology

AMERICAN COUNCIL ON EXERCISE

Learning Objectives

- This chapter covers how the body responds to the demands of exercise at the cellular level and the physiological adaptations that occur with specific training programs.
- Upon completion of this chapter, you will be able to:
  - List the components of fitness
  - Describe the physiology of the cardiorespiratory system
  - Explain the aerobic and anaerobic energy pathway systems
  - Describe the acute and chronic responses to aerobic training
  - Explain the physiological adaptations to strength training
  - List some of the hormonal responses to exercise
  - Take into account environmental considerations during exercise

Introduction

- Exercise physiology is the study of how the body responds to acute and chronic demands.
- Benefits of regular exercise include:
  - Improved cardiovascular function
  - Lowered systolic and diastolic blood pressure
  - Decreased body weight and fat mass
  - Improved lipid profile
  - Improved glucose control
  - Decreased anxiety and depression
- 30 minutes a day of moderate-intensity exercise is recommended for reducing the risk of lifestyle diseases.

Physical Fitness

- Components of physical fitness
  - Muscular strength
  - Muscular endurance
  - Cardiorespiratory endurance (aerobic fitness)
  - Flexibility
  - Body composition

Physiology of the Cardiorespiratory System

- For muscles to contract, they need energy in the form of adenosine triphosphate (ATP).
- The cardiorespiratory system is responsible for the three basic processes to produce this energy:
  - Get oxygen into the blood (oxygen-carrying capacity)
  - Deliver oxygen to the muscles (oxygen delivery)
  - Extract the oxygen from the blood to form ATP (oxygen extraction)
- Oxygen-carrying capacity is affected by two primary factors:
  - The ability to adequately ventilate the alveoli in the lungs
  - The hemoglobin concentration in the blood

Oxygen Delivery

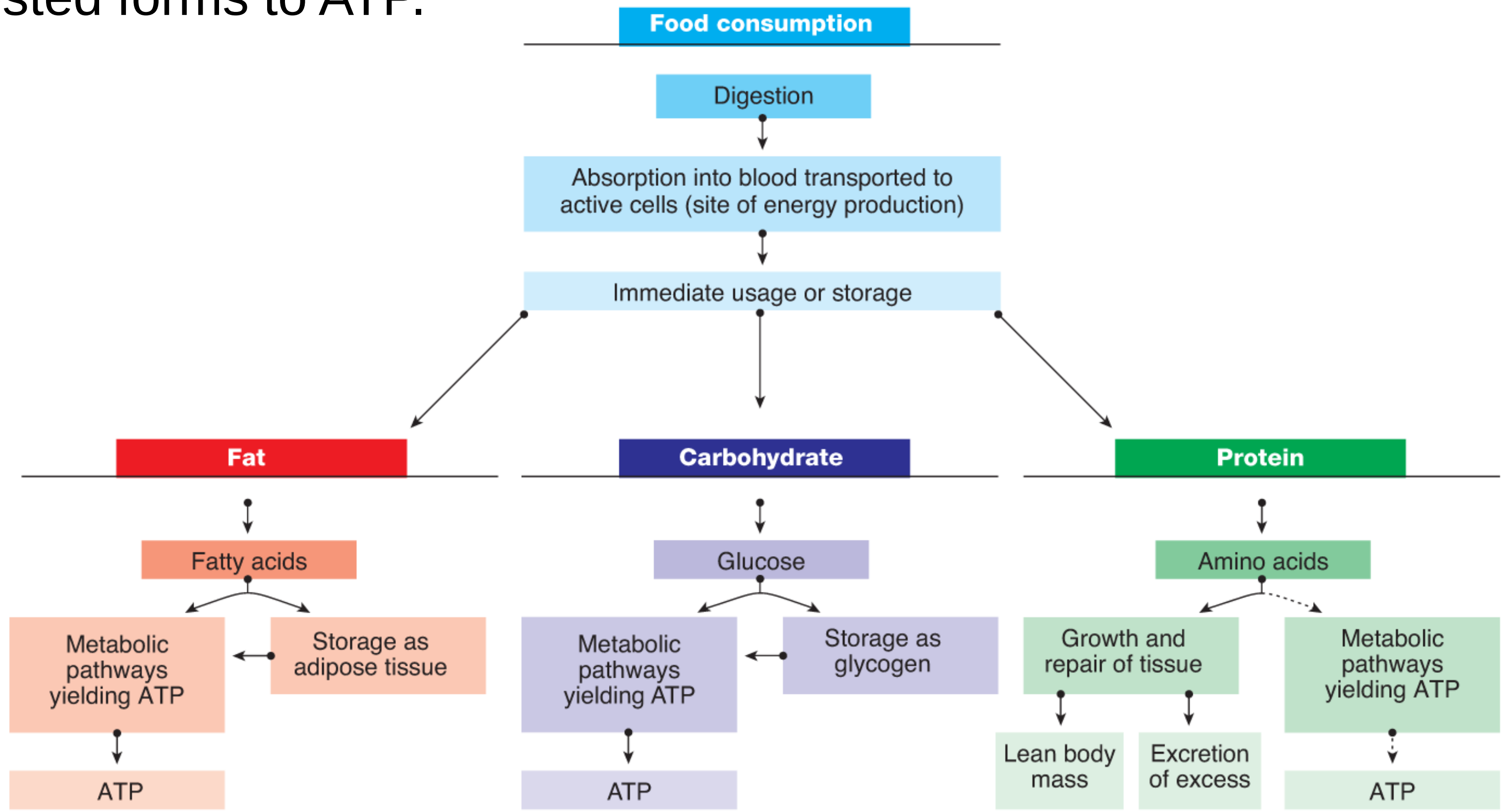
- Oxygen delivery is a function of cardiac output (the quantity of blood pumped per minute).
  - Cardiac output (Q) = Stroke volume (SV) x Heart rate (HR) (in beats per minute)
    - Stroke volume is the amount of blood pumped during each heartbeat.
- Cardiac output increases due to increases in both SV and HR.
  - HR typically increases in a linear fashion up to maximal levels.
  - SV increases to about 40–50% of maximal capacity, and then plateaus.

Oxygen Extraction

- Oxygen extraction from the blood at the cellular level depends on muscle-fiber type and the availability of specialized oxidative enzymes.
  - Slow-twitch muscle fibers are specifically adapted for oxygen extraction and utilization.
  - Aerobic production of ATP occurs in the mitochondria of the cells.
  - The circulatory system increases blood flow to the active muscles and decreases blood flow to non-active areas such as the viscera, allowing a higher concentration of O_2 to be extracted.

Supplying the Body With Energy

- The body's cells require energy in the form of ATP.
- The figure below breaks down the conversion of foods from their ingested forms to ATP.



Note: ATP = Adenosine triphosphate

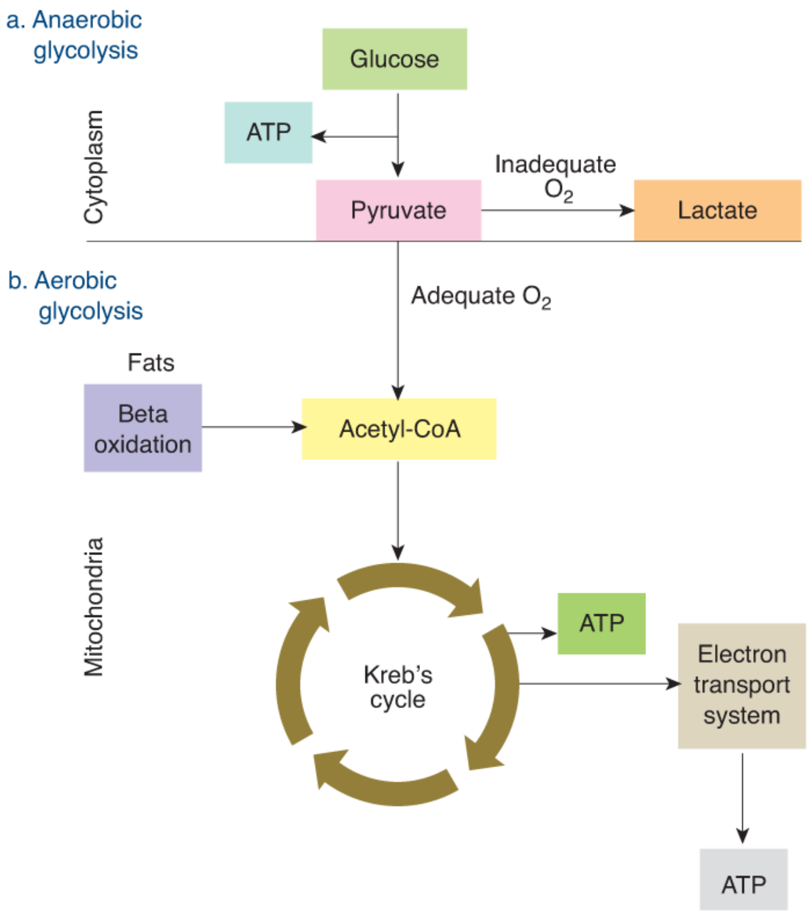
Energy Systems Available During Exercise

- There are three primary energy systems that supply the body with ATP during exercise.

1. Phosphagen system (anaerobic)
   - Involves the breakdown of creatine phosphate (CP) and stored ATP to resynthesize ATP for immediate use
2. Anaerobic glycolysis
   - Involves the breakdown of glucose and glycogen to form ATP
3. Aerobic glycolysis
   - When sufficient oxygen is available, more ATP can be produced via the breakdown of carbohydrates and fat.
   - The aerobic metabolism of fat yields larger amounts of ATP compared to glucose (fat = 9 kcal/gram; carbohydrate = 4 kcal/gram).
   - Because carbohydrate metabolism requires less oxygen than fat metabolism, the body will use more glucose and less fat for energy as exercise intensity increases.

Breakdown of Fat and Glucose Metabolism

- The figure below illustrates the pathway of glucose (anaerobic and aerobic oxidation) and fat (beta oxidation) in their conversion to ATP.



Respiratory Exchange Ratio

- The respiratory exchange ratio (RER) is the ratio of carbon dioxide produced relative to the amount of oxygen consumed.
  - RER = Carbon dioxide/Oxygen consumed
  - RER is a marker for the proportion of fat or carbohydrate being used for fuel at different intensities during steady-state exercise.
  - At rest, the average RER is 0.75, meaning that the body is burning approximately 85% fat and 15% carbohydrate.
  - As intensity increases, so does RER, meaning a larger percentage of carbohydrate is being burned and a lesser percentage of fat.
  - The use of RER has been linked to a common misconception that low-intensity exercise is the best way to lose more weight because it burns more fat.

Oxygen Consumption

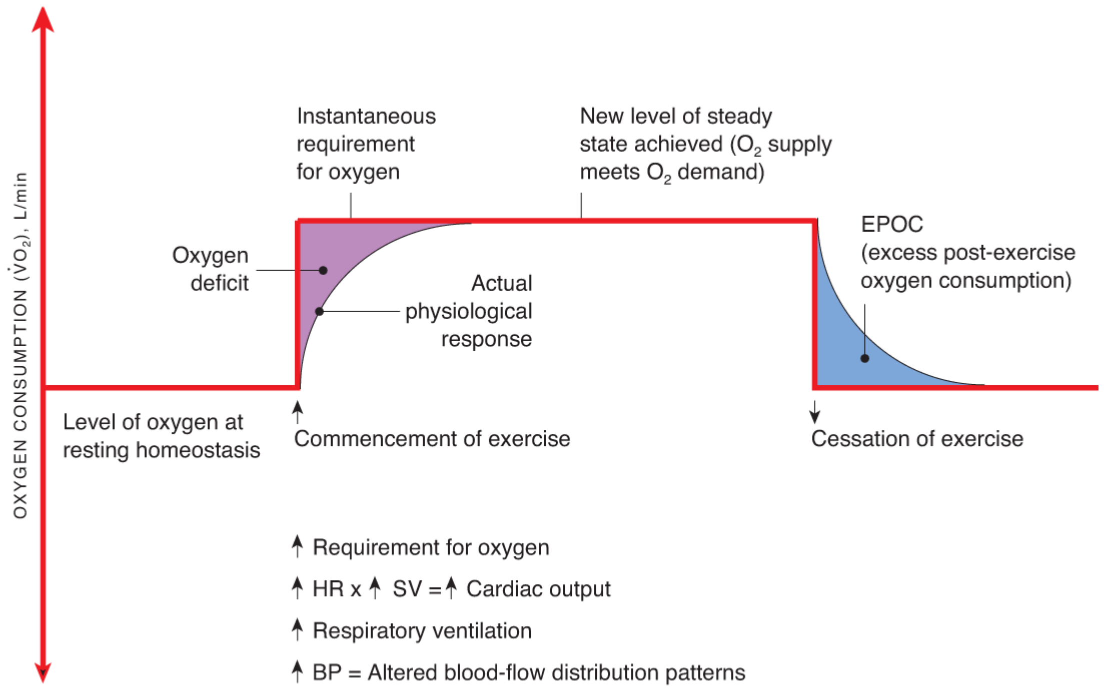
- The more oxygen a person can take in, deliver, and utilize, the more work he or she can perform.
- VO_2max refers to one's maximal oxygen consumption.
  - It is expressed in either "relative" terms (mL/kg/min) or "absolute" terms (L/min).
- Relative VO_2max allows for comparisons between individuals.
- Absolute VO_2max is used to determine caloric expenditure during specific activities.
  - Approximately 5 kcal of energy are burned for every liter of oxygen consumed.

Oxygen Consumption During Aerobic Exercise

- As soon as aerobic exercise begins, the sympathetic nervous system stimulates an increase in cardiac output and the release of epinephrine and norepinephrine.
- It takes two to four minutes for the body to meet the increased metabolic demand of oxygen.
  - During this time, the anaerobic energy systems take over.
- When the cardiorespiratory system has fully taken over, a new level of steady-state oxygen consumption is achieved.

Return of Oxygen to Resting Levels

- After exercise, oxygen levels slowly return to resting levels.
- Cardiac output, blood pressure, and ventilation return to resting levels.
- Oxygen consumption slowly declines, but remains elevated above resting level.
  - Excess post-exercise oxygen consumption (EPOC)



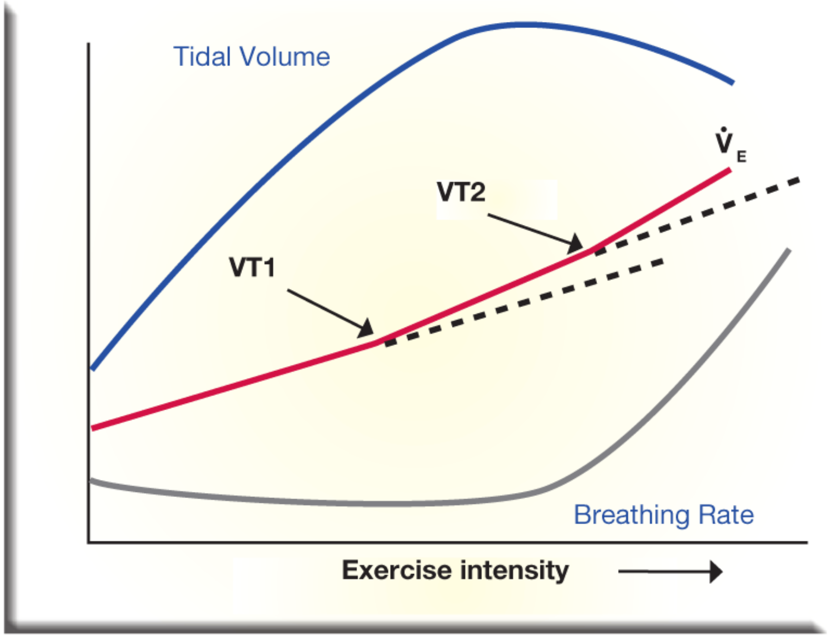
Note: HR = Heart rate; SV = Stroke volume; BP = Blood pressure

Anaerobic Threshold

- The anaerobic threshold (AT) is reached when exercise intensity increases above steady-state aerobic metabolism and anaerobic production of ATP occurs.
- When the AT is crossed, exercise can only be sustained for a few minutes before hyperventilation begins to occur.
  - Lactate accumulates progressively in the blood and the oxygen deficit and corresponding EPOC are extremely high.
  - At this point, the body attempts to rid excess CO_2 (a by-product of acid metabolites).
  - The increase in respiration is called the second ventilatory threshold (VT2).
    - VT2 is an indirect indicator of AT.

Ventilatory Threshold

- There are two distinct changes in breathing patterns during incremental exercise: the first ventilatory threshold (VT1) and the second ventilatory threshold (VT2).
- VT1 occurs as soon as blood lactate begins to accumulate and the body needs to rid itself of excess CO_2 through increased respiration.
  - It is the first point at which it becomes noticeably more difficult to speak.
- VT2 occurs as blood lactate rapidly increases with intensity, and represents increased hyperventilation past the need to rid the body of excess CO_2.
  - Also known as the lactate threshold (LT) and respiratory compensation threshold (RCT)
  - Speaking is definitely not comfortable at this intensity.



Note: VT1 = First ventilatory threshold; VT2 = Second ventilatory threshold; $\dot{V}_E$ = Minute ventilation

Training Levels

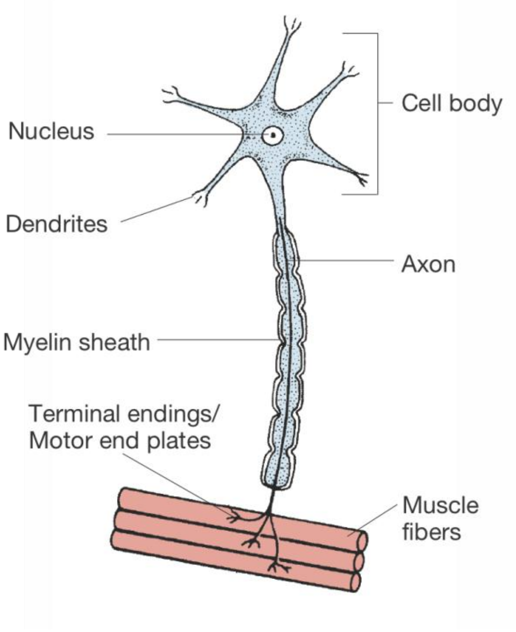
- VT1 and VT2 are used to develop training programs for both serious athletes and beginning exercisers.
  - Serious athletes perform approximately 70–80% of their training intensities below VT1, <10% between VT1 and VT2, and 10–20% above VT2.
  - For beginning exercisers, VT1 may serve as an appropriate upper limit of exercise intensity.

Chronic Training Adaptations to Exercise

- SAID principle (specific adaptation to imposed demands)
- Examples include:
  - Improved cardiac output efficiency (increased SV and lower HR) (aerobic training)
  - Increase in respiratory capacity (aerobic training)
  - Increase in maximal oxygen consumption (aerobic training)
  - Increase in bone density (weightbearing exercise)
  - Improved control of blood glucose and lipids (physical activity)
  - Maintained or improved lean body mass (weightbearing activity)
  - Decreased depression and anxiety (physical activity)
  - Higher quality of life (physical activity)

Neuromuscular Physiology

- Nerves are made up of neurons (nerve cells), of which there are two types:
  - Sensory neurons
  - Motor neurons
- Motor neurons connect (synapse) with the muscle at a neuromuscular junction (motor end plate).
- A motor unit is made up of one motor neuron and all of the muscle cells it innervates.
- The number of muscle cells a motor neuron innervates depends on the precision and accuracy required of that muscle.



Muscle-fiber Types: Fast Twitch

- Fast-twitch (FT) muscle fibers
  - Utilize primarily the phosphagen and anaerobic glycolysis energy systems
  - Specialized for anaerobic metabolism
  - FT motor units innervate more muscle fibers, allowing greater force production.

Muscle-fiber Types: Slow Twitch

- Slow-twitch (ST) muscle fibers
  - Well equipped for oxygen delivery
  - High number of oxidative enzymes
  - High number of mitochondria; aerobic glycolysis and fatty-acid oxidation
  - Used for low-intensity, longer-duration activities (e.g., walking, jogging, and swimming)
  - Usually more abundant in fatigue-resistant muscles (e.g., postural muscles)

Muscle-fiber Distribution

- Muscle-fiber distribution is largely determined by genetics.
  - Most people have about equal percentages of FT and ST fibers.
  - Persons better at low-intensity endurance activities may have a larger percentage of ST fibers.
  - Persons better at high-intensity, sudden bursts of activity probably have a larger percentage of FT fibers.
  - “Intermediate” fiber types have a high capacity for both fast anaerobic and slow aerobic movements, and are adaptable based upon the training stimulus.

Muscle-fiber Response to Training

- All three muscle-fiber types are highly trainable.
  - Adapt to the specific demand placed on them
  - Muscle-fiber types are recruited sequentially in response to force generation: ST then FT
  - FT muscle fibers are more closely related to the hypertrophy (increase in size) of fibers in response to a strength program.
  - Muscular endurance training is specific to both ST and FT fibers and motor units.

The Endocrine System

- The endocrine system is responsible for releasing hormones from glands into the circulation.
- These hormones act on specific receptors to perform a number of functions in the body, including:
  - Regulating cellular metabolism
  - Facilitating the cardiovascular response to exercise
  - Facilitating transport across cell membranes (e.g., insulin)
  - Inducing secretory activity (e.g., ACTH and cortisol)
  - Modulating protein synthesis

Hormonal Response to Exercise

- Hormones are necessary to help the body make acute and chronic adaptations to exercise.
- Growth hormone (GH)
  - Secreted by the anterior pituitary gland
  - Facilitates protein synthesis
  - Mediated by insulin-like growth factors

Hormonal Response to Exercise (cont.)

- Antidiuretic hormone (ADH)
  - Also called vasopressin
  - Secreted by the posterior pituitary gland
  - Reduces urinary excretion of water in response to the dehydrating effects of sweat during exercise
- Epinephrine and norepinephrine
  - Collectively called the catecholamines
  - Secreted by the adrenal medulla as part of the sympathetic response to exercise
  - Two major roles:
    - Increase cardiac output (increase HR and contractility)
    - Stimulate glycogen breakdown in the liver (glycogenolysis)

Hormonal Response to Exercise (cont.)

- Aldosterone and cortisol
  - Secreted by the adrenal cortex
  - Aldosterone limits sodium excretion in urine to maintain electrolyte balance.
  - Cortisol promotes protein and triglyceride breakdown to aid in maintaining blood glucose.
- Insulin and glucagon
  - Secreted by the pancreas (specifically, the islets of Langerhans)
  - Insulin is active when blood glucose levels are high to move glucose from the blood to the tissues.
  - Glucagon is active when blood glucose is low to stimulate glucose release from the liver.

Hormonal Response to Exercise (cont.)

- Testosterone and estrogen
  - Testosterone (male sex hormone) is secreted by the testes.
    - Responsible for masculine characteristics and muscle-building (anabolic) effects
  - Estrogen (female sex hormone) is secreted by the ovaries.
    - Responsible for feminine characteristics and bone formation and maintenance
    - May play a role in amenorrhea and the female athlete triad

Exercising in the Heat

- In addition to exercising in a hot, humid environment, other factors can cause heat overload.
  - Poor hydration prior to exercise
  - Overdressing
  - Overweight and obesity
- During exercise, the internal heat load is brought to the skin's surface to be cooled via the secretion of water by the sweat glands (evaporation).
  - The goal (given favorable environmental conditions) is to prevent body temperature from rising more than 2 to 3º F.
  - When the ability to dissipate heat is compromised, injuries occur.

Physiological Responses to Exercising in the Heat

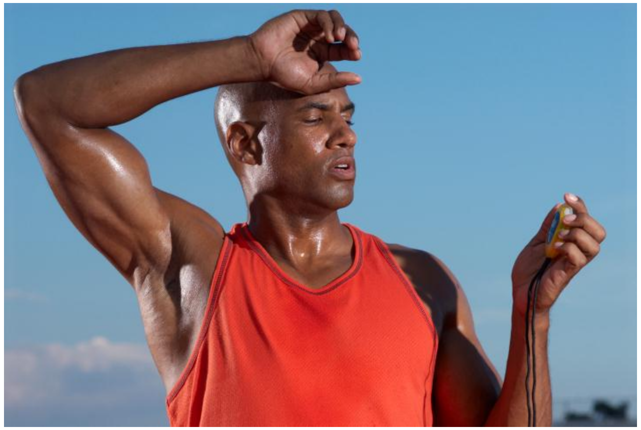
- Dissipating internal body heat is more difficult in the heat, resulting in a higher heart rate than normal at any level of exercise to maintain cardiac output.
- A hot, humid environment is the most stressful environment for exercising and poses the risk of heat exhaustion and heat stroke.

Heat Exhaustion and Heat Stroke

	Signs and Symptoms	Treatment
Heat Exhaustion	Weak, rapid pulse Low blood pressure Headache Nausea Dizziness General weakness Paleness Cold clammy skin Profuse sweating Elevated body core temp (≤104° F or 40° C)	Stop exercising Move to a cool, ventilated area Lay down and elevate feet 12–18 inches Give fluids Monitor temperature
Heat Stroke	Hot, dry skin Bright red skin color Rapid, strong pulse Labored breathing Elevated body core temp (≥105° F or 41° C)	Stop exercising Remove as much clothing as feasible Try to cool the body immediately in any way possible (wet towels, ice packs/baths, fan, alcohol rubs) Give fluids Transport to emergency room immediately

Safety in the Heat

- The heat index, as presented on the next slide, provides guidelines for when exercise is safe and when it should be avoided.
- Considerations for exercising in the heat:
  - Begin gradually
  - Always wear lightweight, well-ventilated clothing
  - Avoid impermeable or non-breathable garments
  - Replace body fluids as they are lost
  - Record daily body weight
  - Air movement is critical for adequate cooling



Heat Index

Heat Index

	Actual Thermometer Reading (°F) (°C given in parentheses)										
	70 (21)	75 (24)	80 (27)	85 (29)	90 (32)	95 (35)	100 (38)	105 (41)	110 (43)	115 (46)	120 (49)
Relative Humidity	**Equivalent or Effective Temperature* (°F) (°C given in parentheses)**										
0	64 (18)	69 (21)	73 (23)	78 (26)	83 (28)	87 (31)	91 (33)	95 (35)	99 (37)	103 (39)	107 (42)
10	65 (18)	70 (21)	75 (24)	80 (27)	85 (29)	90 (32)	95 (35)	100 (38)	105 (41)	111 (44)	116 (47)
20	66 (19)	72 (22)	77 (25)	82 (28)	87 (31)	93 (34)	99 (37)	105 (41)	112 (44)	120 (49)	130 (54)
30	67 (19)	73 (23)	78 (26)	84 (29)	90 (32)	96 (36)	104 (40)	113 (45)	123 (51)	135 (57)	148 (64)
40	68 (20)	74 (23)	79 (26)	86 (30)	93 (34)	101 (38)	110 (43)	123 (51)	137 (58)	151 (66)	
50	69 (21)	75 (24)	81 (27)	88 (31)	96 (36)	107 (42)	120 (49)	135 (57)	150 (66)		
60	70 (21)	76 (24)	82 (28)	90 (32)	100 (38)	114 (46)	132 (56)	149 (65)			
70	70 (21)	77 (25)	85 (29)	93 (34)	106 (41)	124 (51)	144 (62)				
80	71 (22)	78 (26)	86 (30)	97 (36)	113 (45)	136 (58)					
90	71 (22)	79 (26)	88 (31)	102 (39)	122 (50)						
100	72 (22)	80 (27)	91 (33)	108 (42)							

*Combined index of heat and humidity and what it feels like to the body

How to Use Heat Index

1. Locate temperature across top
2. Locate relative humidity down left side
3. Follow across and down to find Equivalent or Effective Temperature
4. Determine Heat Stress Risk on chart at right

Note: This Heat Index chart is designed to provide general guidelines for assessing the potential severity of heat stress. Individual reactions to heat will vary. In addition, studies indicate that susceptibility to heat disorders tends to increase among children and older adults. Exposure to full sunshine can increase Heat Index values by up to 15° F.

Apparent Temperature	Heat Stress Risk with Physical Activity and/or Prolonged Exposure
90–105 (32–41)	Heat cramps or heat exhaustion *possible*
106–130 (41–54)	Heat cramps or heat exhaustion *likely* Heat stroke *possible*
131–151 (54–66)	Heat stroke *highly likely*

Exercising in the Cold

- The excessive loss of body heat can lead to a generalized vasoconstriction and conditions such as hypothermia, frostbite, and increased blood pressure.
- Strong wind can accelerate heat loss.
  - The windchill index, which is presented on the following next, provides guidelines for determining if exercise is safe.
- Considerations for exercising in the cold:
  - Wear several layers so that garments can be removed or replaced as needed
  - Allow for adequate ventilation of sweat
  - Wear garments made of materials that allow the body to give off body heat during exercise and retain body heat during inactivity
  - Replace body fluids in the cold, just as in the heat
  - Monitor body weight over several days

Windchill Factor Chart

Windchill Factor Chart

Actual Thermometer Reading (°F) (°C given in parentheses)												
Estimated wind speed (in mph) (km/h given in parentheses)	50 (10)	40 (4)	30 (-1)	20 (-7)	10 (-12)	0 (-18)	-10 (-23)	-20 (-29)	-30 (-34)	-40 (-40)	-50 (-46)	-60 (-51)
Equivalent or Effective Temperature (°F) (°C given in parentheses)												
calm	50 (10)	40 (4)	30 (-1)	20 (-7)	10 (-12)	0 (-18)	-10 (-23)	-20 (-29)	-30 (-34)	-40 (-40)	-50 (-46)	-60 (-51)
5 (8)	48 (9)	37 (3)	27 (-3)	16 (-9)	6 (-14)	-5 (-21)	-15 (-26)	-26 (-32)	-36 (-38)	-47 (-44)	-57 (-49)	-68 (-56)
10 (16)	40 (4)	28 (-2)	16 (-9)	4 (-16)	-9 (-23)	-24 (-31)	-33 (-36)	-46 (-43)	-58 (-50)	-70 (-57)	-83 (-64)	-95 (-71)
15 (24)	36 (2)	22 (-6)	9 (-13)	-5 (-21)	-18 (-28)	-32 (-36)	-45 (-43)	-58 (-50)	-72 (-58)	-85 (-65)	-99 (-78)	-112 (-80)
20 (32)	32 (0)	18 (-8)	4 (-16)	-10 (-23)	-25 (-32)	-39 (-39)	-53 (-47)	-67 (-55)	-82 (-63)	-96 (-71)	-110 (-79)	-124 (-87)
25 (40)	30 (-1)	16 (-9)	0 (-18)	-15 (-26)	-29 (-34)	-44 (-42)	-59 (-51)	-74 (-59)	-88 (-67)	-104 (-76)	-118 (-83)	-133 (-92)
30 (48)	28 (-2)	13 (-11)	-2 (-19)	-18 (-28)	-33 (-36)	-48 (-44)	-63 (-53)	-79 (-62)	-94 (-70)	-109 (-78)	-125 (-87)	-140 (-96)
35 (56)	27 (-3)	11 (-12)	-4 (-20)	-20 (-29)	-35 (-37)	-51 (-46)	-67 (-55)	-82 (-63)	-98 (-72)	-113 (-81)	-129 (-89)	-145 (-98)
40 (64)	26 (-3)	10 (-12)	-6 (-21)	-21 (-29)	-37 (-38)	-53 (-47)	-69 (-56)	-85 (-65)	-100 (-73)	-116 (-82)	-132 (-91)	-146 (-99)
[Wind speeds greater than 40 mph (64 km/h) have little additional effect.]	**GREEN**				**YELLOW**				**RED**			
	LITTLE DANGER (for properly clothed person). Maximum danger of false sense of security.				INCREASING DANGER Danger for freezing of exposed flesh				GREAT DANGER			

Exercising at Higher Altitudes

- At moderate-to-high altitudes, the partial pressure of oxygen in the air is reduced.
- Acclimatization (physiological adaptation to an unfamiliar or unaccustomed environment) begins in a couple weeks, but it may take several months to fully acclimatize.
  - Gradually increase exercise intensity over several days.
  - Increase warm-up and cool-down periods.
  - Take frequent exercise breaks at a lower intensity.

Altitude Sickness

- The higher the altitude, the greater the risk.
- Altitude sickness can be avoided by proper acclimatization.
- Signs and symptoms of altitude sickness include:
  - Shortness of breath
  - Headache
  - Lightheadedness
  - Nausea

Exercising in Air Pollution

- Inhaled air pollutants (e.g., smog) negatively affect the body and performance.
- The overall physiological effects depend on:
  - The amount of pollutant in the air
  - The length of exposure
  - The amount of air breathed
- Exercising early in the morning and avoiding high-traffic areas can help minimize exposure.

Age

- Generally, exercise performance improves from puberty until young adulthood, followed by a slow decline.
  - If a person maintains activity levels, performance can be preserved into the early 30s, but inevitably declines beyond age 60.
  - Individuals who are sedentary and over the age of 45 (for males) and 55 (for females) should avoid high-intensity activity the first several weeks to decrease the risk of triggering a heart attack.

Gender

- The relative amounts of testosterone (in males) and estrogen (in females) account for specific variances in males and females and their physiological response to exercise.
- Outside of the hormone-attributed differences, men and women have very similar responses to exercise.

Pregnancy

- Weight gain, change in body shape, and the diversion of part of the cardiac output to the developing baby can affect exercise performance.
- Exercise performance will decrease as the pregnancy progresses.
  - Exercise intensity and duration should be reduced to maintenance levels during pregnancy, as guided by comfort.
  - Current research does not support the traditional concerns about hyperthermia and circulatory diversion.
- It is not recommended to engage in intense training or competitions or to reduce body fat during pregnancy.

Summary

- In response to exercise, a series of physiological adaptations (acute and chronic) occur specific to the encountered stress.
- This chapter covered:
  - Physical fitness
  - Physiology of the cardiorespiratory system
  - Energy systems available during exercise
  - Anaerobic and ventilatory thresholds
  - Chronic training adaptations to exercise
  - Neuromuscular physiology
  - The hormonal response to exercise
  - Exercise in the heat and cold, at high altitudes, and in the presence of air pollution