

Exercise Physiology

FIFTH EDITION

Energy, Nutrition, and
Human Performance



William-D. McArdle
Frank I. Katch
Victor L. Katch



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William D. McArdle

Professor Emeritus, Department of Family, Nutrition,
and Exercise Science
Queens College of the City of New York
Flushing, New York

Frank I. Katch

Professor, Department of Exercise Science
University of Massachusetts
Amherst, Massachusetts

Victor L. Katch

Professor, Division of Kinesiology
Department of Movement Science
Associate Professor, Pediatrics
University of Michigan
Ann Arbor, Michigan

Editor: Pete Darcy
Managing Editor: Karen Gulliver
Marketing Manager: Christen DeMarco
Production Editor: Lisa JC Franko
Compositor: Graphic World
Printer: RR Donnelley & Sons

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Baltimore, Maryland 21201-2436 USA

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Oxygen Deficit in the Trained and Untrained

Trained and untrained individuals attain similar steady-rate oxygen consumption values. The endurance-trained person, however, reaches steady rate more rapidly with a smaller oxygen deficit than the untrained (Fig. 7.3), sprint-power athletes, and cardiac patients.^{24,36,42,51} Consequently, the aerobically trained person consumes a greater total amount of oxygen during steady-rate exercise and, presumably, the anaerobic component of exercise energy transfer becomes proportionately smaller. *A facilitated rate of aerobic metabolism in the early stages of exercise may result from a more rapid increase in overall blood flow (cardiac output) and/or a disproportionately large regional blood flow to active muscle complemented by training-induced cellular adaptations. Many of these adaptations increase cellular capacity to generate ATP aerobically (see Chapter 21).*



INTEGRATIVE QUESTION

Respond to a student who asks: “At what exercise level does the body switch to anaerobic energy metabolism?”

Maximal Oxygen Consumption

Figure 7.5 depicts oxygen consumption during a series of constant-speed runs up six progressively steeper hills. The laboratory simulates these hills by increasing the elevation of a treadmill or step bench or increasing the resistance to pedaling a bicycle ergometer. Each successive hill requires a greater energy output that places an additional demand on the capacity for aerobic ATP resynthesis. During the first several hills, oxygen consumption increases rapidly, with each new steady-rate value in direct proportion to exercise severity. The

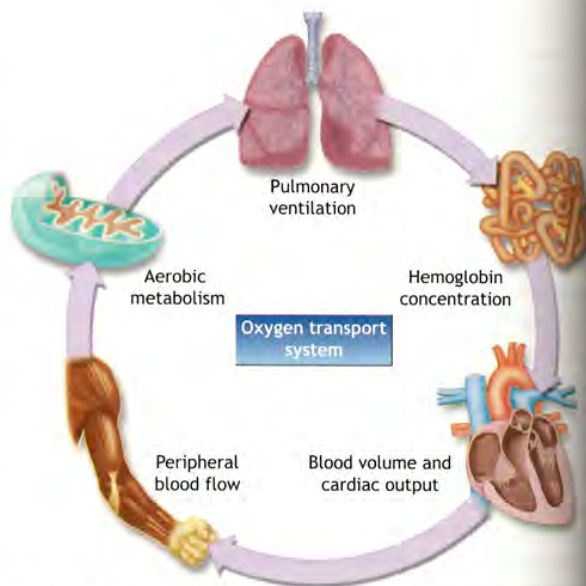


FIGURE 7.6 • The oxygen transport system. The physiologic significance of $\dot{V}O_{2\max}$ relates to its dependence upon the functional capacity and integration of systems required for oxygen supply, transport, delivery, and use.

runner maintains speed up the two last hills, but oxygen consumption does not increase as rapidly or to the same extent as with the previous hills. No increase in oxygen consumption occurs during the run up the last hill. *The region in which oxygen consumption plateaus or increases only slightly with additional increases in exercise intensity represents the maximal oxygen consumption—also called maximal oxygen uptake, maximal aerobic power, aerobic capacity, or, simply, $\dot{V}O_{2\max}$.* Performing more-intense exercise results only from energy transfer in glycolysis, with a resulting lactate accumu-

FIGURE 7.5 • Attainment of maximal oxygen consumption ($\dot{V}O_{2\max}$) while running up hills of increasing slope. $\dot{V}O_{2\max}$ occurs in the region where further increases in exercise intensity produce a less-than-expected increase (or no increase) in oxygen consumption. The dots represent measured values of oxygen consumption while running up each of the hills.



lation. Under these conditions, the runner soon becomes exhausted and unable to continue.

The $\dot{V}O_{2\max}$ provides a quantitative measure of a person's capacity for aerobic ATP resynthesis. This makes the $\dot{V}O_{2\max}$ an important determinant of the ability to sustain high-intensity exercise for longer than 4 or 5 minutes. Attainment of a high $\dot{V}O_{2\max}$ has important physiologic meaning in addition to its role in sustaining energy metabolism. High aerobic power requires the integrated and high-level response of diverse physiologic support systems illustrated in Figure 7.6. In subsequent chapters, we discuss various aspects of $\dot{V}O_{2\max}$, including its physiologic significance, measurement, and role in exercise performance and cardiovascular health.

Fast- and Slow-Twitch Muscle Fibers

Extracting about 20 to 40 mg of tissue (the size of a grain of rice) during surgical biopsy gives exercise physiologists the means to study functional and structural characteristics of human skeletal muscle. Two distinct types of muscle fiber exist in humans. A **fast-twitch (FT)**, or **type II**, fiber has two primary subdivisions, type IIa and type IIb, each possessing rapid contraction speed and high capacity for anaerobic ATP production in glycolysis. The type IIa fiber also possesses somewhat higher aerobic capacity. Type II fibers become active during change-of-pace and stop-and-go activities like basketball, soccer, and ice hockey. They also contribute increased force output when running or

cycling up a hill while maintaining a constant speed or during all-out effort requiring rapid, powerful movements that depend almost exclusively on energy from anaerobic metabolism.

The second fiber-type, the **slow-twitch (ST)**, or **type I**, muscle fiber, generates energy primarily through aerobic pathways. This fiber possesses a relatively slow contraction speed compared with its fast-twitch counterpart. Its capacity to generate ATP aerobically intimately relates to numerous large mitochondria and high levels of enzymes required for aerobic metabolism, particularly fatty acid catabolism. Slow-twitch muscle fibers primarily sustain continuous activities requiring a steady rate of aerobic energy transfer. Fatigue in prolonged running is associated with glycogen depletion in the leg muscles' type I and type IIa muscle fibers.^{2,31} This selective glycogen depletion pattern also occurs in the arms of wheelchair-dependent athletes during extended periods of exercise.⁶² More than likely, the predominance of slow-twitch muscle fibers greatly contributes to high blood lactate thresholds observed among elite endurance athletes.^{47,61} Figure 7.7 illustrates the muscle fiber type composition of two athletes in sports that rely on distinctly different energy systems that would be favored by a specific fiber type predominance. For the 50-m sprint swim champion, type II fibers represent nearly 80% of the total muscle fibers, whereas the endurance cyclist possesses 80% type I fibers. From a practical perspective, most sports require relatively slow, sustained muscle actions interspersed with short bursts of powerful effort (e.g.,

IN A PRACTICAL SENSE

►► INTERPRETING $\dot{V}O_{2\max}$ —ESTABLISHING CARDIOVASCULAR FITNESS CATEGORIES

Cardiovascular fitness reflects the maximal amount of oxygen consumed during each minute of near-maximal exercise. These values for maximal oxygen consumption, or $\dot{V}O_{2\max}$, generally are expressed in milliliters of oxygen per kg of body mass per minute ($\text{mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$). Individual values can range from about $10 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ in cardiac patients to 80 or $90 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ in world-class runners and cross-country skiers. Men and women distance runners, swimmers, cy-

clists, and cross-country skiers generally attain $\dot{V}O_{2\max}$ values nearly double those of sedentary persons (see Fig. 11.8).

Researchers have measured the $\dot{V}O_{2\max}$ of thousands of individuals of different ages. The average values and respective ranges for men and women of different ages establish category values to classify individuals for cardiovascular fitness. The table presents a five-part classification based upon data from the literature.

CARDIOVASCULAR FITNESS CLASSIFICATIONS

GENDER	AGE	POOR	FAIR	AVERAGE	GOOD	EXCELLENT
Men	≤29	≤24.9	25-33.9	34-43.9	44-52.9	≥53
	30-39	≤22.9	23-30.9	31-41.9	42-49.9	≥50
	40-49	≤19.9	20-26.9	27-38.9	39-44.9	≥45
	50-59	≤17.9	18-24.9	25-37.9	38-42.9	≥43
	60-69	≤15.9	16-22.9	23-35.9	36-40.9	≥41
Women	≤29	≤23.9	24-30.9	31-38.9	39-48.9	≥49
	30-39	≤19.9	20-27.9	28-36.9	37-44.9	≥45
	40-49	≤16.9	17-24.9	25-34.9	35-41.9	≥42
	50-59	≤14.9	15-21.9	22-33.9	34-39.9	≥40
	60-69	≤12.9	13-20.9	21-32.9	33-36.9	≥37

Focus on Research

An Important Measure of Cardiorespiratory Functional Capacity

Mitchell JH, et al. The physiological meaning of the maximal oxygen intake test. J Clin Invest 1958;37:538.

► In the 1920s, A. V. Hill and colleagues—and in latter years other scientists—considered maximal oxygen consumption ($\dot{V}O_{2\max}$) the single best measure of cardiorespiratory capacity. Hill asserted that $\dot{V}O_{2\max}$ “was physiologically restricted owing to the limitation of the circulatory and respiratory systems.” This assertion, however, had not been tested experimentally because the interplay among physiologic parameters had not yet been established. Mitchell and coworkers directly examined the relationships among $\dot{V}O_{2\max}$ and various cardiovascular–pulmonary measures to objectify the physiologic significance of $\dot{V}O_{2\max}$.

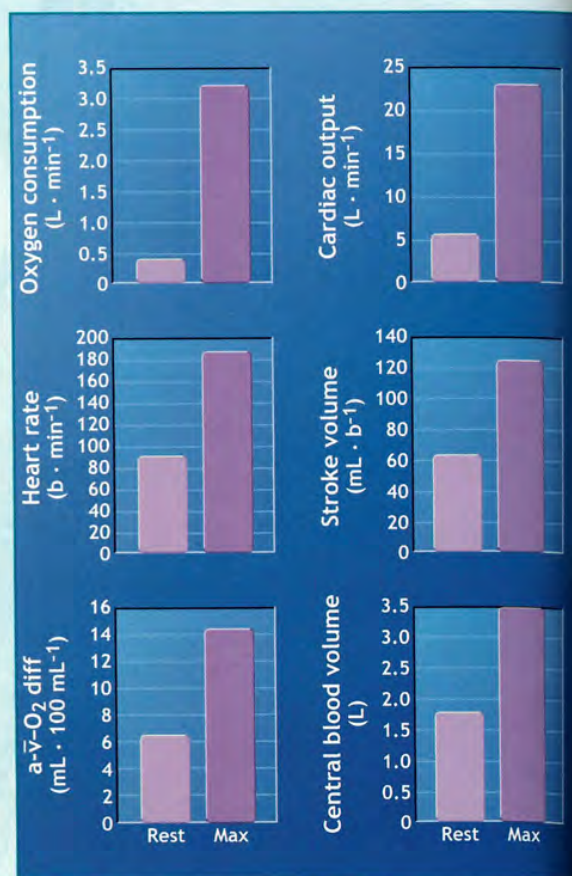
Sixty-five men performed graded, discontinuous treadmill exercise to $\dot{V}O_{2\max}$. Subgroups ran in several different protocols to volitional exhaustion. Measurements included cardiac output and $a-\bar{v}O_2$ difference by the dye dilution technique, blood gas pressures, and central blood volume. Two significant findings emerged that related to test methodology: First, $\dot{V}O_{2\max}$ provides a highly reproducible measure of aerobic capacity “if rigid criteria for determining the point at which the maximal value has been attained are applied.” The reproducibility of test scores (i.e., test–retest reliability coefficient) for 15 subjects was $r = 0.92$, with a standard error of measurement of $\pm 7\%$ for determining an individual's maximal value. Second, a “peaking over” or “plateauing” criterion (when relating oxygen consumption to exercise intensity) provided an important conceptual standard to establish attainment of $\dot{V}O_{2\max}$ in diverse forms of exercise as follows:

Plots of oxygen intake against workload for the entire material showed that, until a maximal value was attained, oxygen intake rose 142 ± 44 mL with each increase in workload. If the rise was less than 142 minus 88 (twice the standard deviation), or 54 mL, the final value was accepted as the maximal intake, the assumption being that the subject had attained his true maximal value or had reached the beginning of a plateau and could not increase his intake very much more.

The physiologic findings from this study endorsed the view that the $\dot{V}O_{2\max}$ depended almost exclusively on the functional capacity of the cardiovascular system (cardiac output and $a-\bar{v}O_2$ difference) and not accommodation of left ventricular output by the peripheral vascular bed. No significant change occurred in arterial oxygen pressure from rest to heavy work; the slight arterial desaturation often observed in heavy exercise resulted from a blood pH decrease and the resulting Bohr effect on hemoglobin saturation. Maintenance of high arterial oxygen pressures during heavy exer-

cise argued against the possibility that pulmonary factors provided a “weak link” in limiting $\dot{V}O_{2\max}$. In essence, the researchers maintained that in healthy individuals an adequate arterial oxygen diffusion gradient always exists from the alveoli to the blood and from the blood to active tissues.

This study confirmed the importance of $\dot{V}O_{2\max}$ to indicate central circulatory function (cardiac capacity) and, to a lesser degree, the capacity of peripheral or local factors as reflected by the $a-\bar{v}O_2$ difference. This and subsequent research by other laboratories firmly established $\dot{V}O_{2\max}$ as a “benchmark” to quantify cardiovascular functional capacity and aerobic fitness.



Magnitude of changes in cardiovascular dynamics (arteriovenous oxygen difference, heart rate, oxygen consumption, stroke volume, and blood volume) in 15 normal subjects, between rest and exercise at the maximal oxygen consumption.

The "Training-Sensitive Zone"

One can determine maximum exercise heart rate immediately after several minutes of all-out effort in a specific form of exercise. This exercise intensity requires considerable motivation and stress—a requirement certainly inadvisable for adults without medical clearance, particularly individuals predisposed to coronary heart disease. Consequently, people should consider themselves average and use the **age-predicted maximum heart rates** presented in Figure 21.19.

Although individuals of a specific age possess varying HR_{max} values, the inaccuracy resulting from individual variation ($\pm 10 \text{ b} \cdot \text{min}^{-1}$ standard deviation for any age-predicted HR_{max}) has little influence in establishing effective training for healthy people. *Maximum heart rate computes as 220 minus the person's age in years, with values independent of race or gender in children and adults.*^{94,123,124}

$$HR_{max} = 220 - \text{age (y)}$$

The decrease in maximum heart rate with age probably results from reduced sympathetic output from the medulla and age-related changes in the inherent characteristics of the SA node.¹⁸⁶ Although this formula represents a convenient rule of thumb, it does not determine a specific person's maximum heart rate. Within normal variation, the maximum heart rate of 95% (± 2 standard deviations) of 40-year-old men and women ranges between 160 and 200 $\text{b} \cdot \text{min}^{-1}$. Figure 21.18 also depicts the "training-sensitive zone" in relation to age.

Aerobic system conditioning occurs as long as exercise heart rate remains within this zone.

A 40-year-old woman or man who wants to train at moderate intensity but still achieve the threshold level would select a training heart rate equal to 70% of age-predicted HR_{max} or a target exercise heart rate of $126 \text{ b} \cdot \text{min}^{-1}$ (0.70×180). Then, using progressive increments of light-to-moderate exercise, the person achieves a walking, jogging, or cycling intensity that produces this heart rate. To increase training to 85% of maximum, exercise intensity must increase to produce a heart rate of $153 \text{ b} \cdot \text{min}^{-1}$ (0.85×180).

RUNNING VERSUS SWIMMING AND OTHER FORMS OF UPPER-BODY EXERCISE. Estimation of HR_{max} requires an adjustment when using swimming or other upper-body exercises for training.⁶⁰ Maximum heart rate during these exercise modes averages about $13 \text{ b} \cdot \text{min}^{-1}$ lower than in running for trained and untrained men and women.^{66,135,138} This difference probably results from less feed-forward stimulation from the motor cortex to the medulla, in addition to less feedback stimulation from the smaller, active upper-body muscle mass. In swimming, the horizontal body position and cooling effect of the water may also contribute to a lower HR_{max} .

Establishing the appropriate exercise intensity for swimming and upper-body exercise requires subtracting $13 \text{ b} \cdot \text{min}^{-1}$ from the age-predicted HR_{max} in Figure 21.19. Consequently, a 30-year-old person who swims at 70% HR_{max} should select a swimming speed that produces a heart rate of

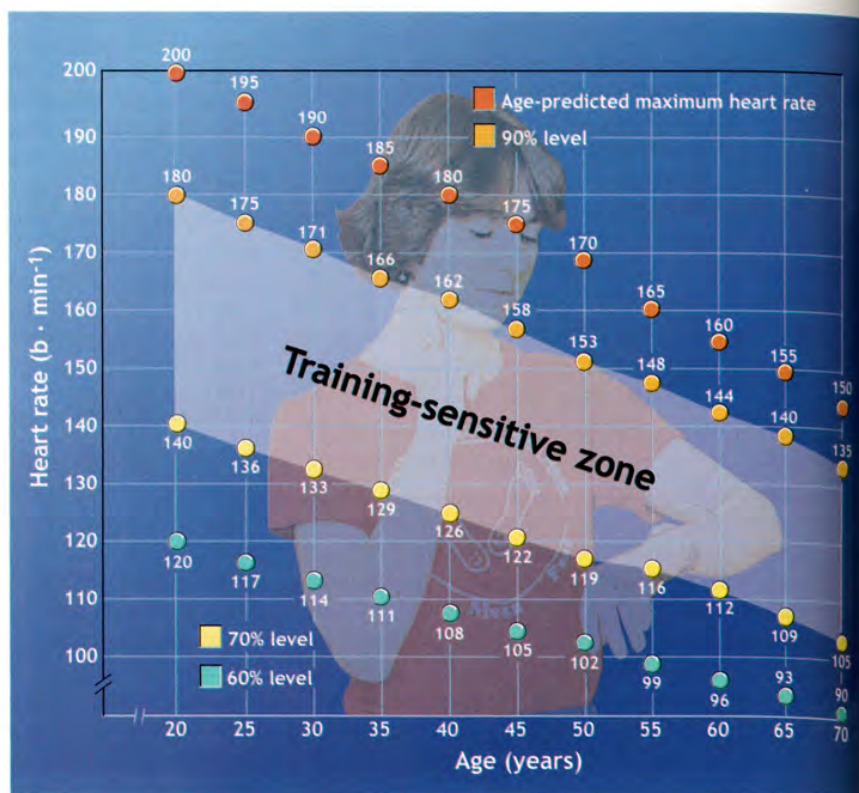


FIGURE 21.18 • Maximal heart rates and the training-sensitive zone for use in aerobic training of men and women of different ages.

FIGURE 21.1
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Sports Exer

$124 \text{ b} \cdot \text{min}^{-1}$ ($0.70 \times [190 - 13]$). This more accurately represents the appropriate threshold training heart rate for swimming. Without the appropriate heart rate adjustment, a prescription of upper-body exercise based on $\%HR_{\max}$ in leg exercise results in *overestimation* of the appropriate threshold training heart rate.

Is Less-Intense Training Effective?

The often-cited recommendation of 70% $HR_{\max}$ as a training threshold for aerobic improvement represents a *general guideline* for effective yet comfortable exercise. The actual lower limit may depend on the participant's initial exercise capacity and current state of training. In addition, older and less fit, and sedentary, overweight men and women show training thresholds closer to 60% $HR_{\max}$, which corresponds to about 45% $\dot{V}O_{2\max}$.⁶⁴ Twenty to 30 minutes of continuous exercise at the 70% $HR_{\max}$ level stimulates a training effect; exercise at the lower intensity of 60% for 45 minutes also proves beneficial. *Generally, a longer exercise duration offsets a lower exercise intensity.*

Train at a Perception of Effort

In addition to oxygen consumption, heart rate, and blood lactate as indicators of exercise intensity, one also can use the **rating of perceived exertion (RPE)**.^{19,183} With this psychophysiologic approach, the exerciser rates on a numerical scale (**Borg scale**, after researcher Gunnar Borg who developed this scaling system) perceived feelings in relation to the

RPE Scale	Equivalent $\%HR_{\max}$	Exercise Intensity $\%VO_{2\max}$
6		
7 Very, very light		
8		
9 Very light		
10		
11 Fairly light	52-66	31-50
12		
13 Somewhat hard	61-85	51-75
14		
15 Hard	86-91	76-85
16	92	85
17 Very hard		
18		
19 Very, very hard		

FIGURE 21.19 • The Borg scale (and accompanying estimates of relative exercise intensity) for obtaining the RPE during exercise. (Modified from Borg GA. Psychological basis of physical exertion. *Med Sci Sports Exerc* 1982;14:377.)

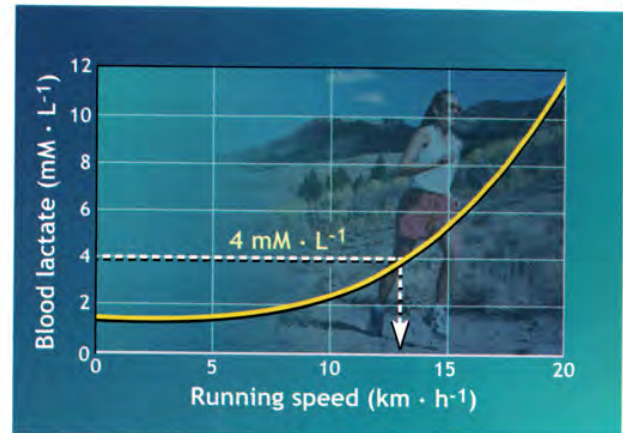


FIGURE 21.20 • Blood lactate concentration in relation to running speed for one subject. At a lactate level of $4.0 \text{ mM} \cdot \text{L}^{-1}$, the corresponding running speed was approximately $13 \text{ km} \cdot \text{h}^{-1}$. This speed establishes the subject's initial training intensity.

exertion level. Monitoring and adjusting RPE during exercise is a relatively easy and effective means to prescribe exercise on the basis of an individual's perception of effort that coincides nicely with objective measures of physiologic/metabolic strain ($\%HR_{\max}$, $\% \dot{V}O_{2\max}$, blood lactate concentration). Exercise levels corresponding to higher levels of energy expenditure and physiologic strain produce higher RPE ratings. For example, an RPE of 13 or 14 (exercise that feels "somewhat hard;" Fig. 21.19) coincides with about 70% $HR_{\max}$ during cycle ergometer and treadmill exercise; an RPE between 11 and 12 corresponds to exercise at the lactate threshold for trained and untrained individuals.¹⁹⁹ The RPE effectively establishes and regulates an exercise prescription for exercise intensities corresponding to blood lactate concentrations of 2.5 mM (RPE ≈ 15) and 4.0 mM (RPE ≈ 18) during a 30-minute treadmill run in which subjects self-regulated exercise intensity.²¹⁷ Individuals learn quickly to exercise at a specific RPE. In this sense, the axiom "listen to your body" becomes apropos.

Train at the Lactate Threshold

Exercising at or slightly above the lactate threshold provides effective aerobic training, with the higher exercise levels producing the greatest benefits, particularly for fit individuals.^{122,235} Figure 21.20 illustrates determination of the appropriate exercise level by plotting exercise intensity (e.g., running speed) in relation to blood lactate level. In this example, the running speed that produced a blood lactate concentration at the 4-mM level (OBLA) represented the recommended training intensity. While many coaches use the 4-mM blood lactate level as the optimal aerobic training intensity, no convincing evidence yet exists to justify this particular blood lactate level as "ideal." Regardless of the specific blood lactate level chosen for endurance training, the blood lactate-exercise intensity relationship should be evaluated periodically and the exercise intensity adjusted as aerobic fitness im-



FIGURE 31.2 • Disability-adjusted life expectancy rankings (an estimate of healthy life expectancy) of populations of selected countries as assessed by the World Health Organization. Of all countries surveyed, the US ranked 24th with Japan ranked at the top.

► PART 1 • Physical Activity in the Population

PHYSICAL ACTIVITY EPIDEMIOLOGY

Epidemiology involves quantifying factors that influence the occurrence of illness to better understand, modify, and/or control a disease pattern in the general population. The specific field of **physical activity epidemiology** applies the general research strategies of epidemiology to study physical activity as a health-related behavior linked to disease and other outcomes.

Terminology

Physical activity epidemiology applies specific definitions to characterize behavioral patterns and outcomes of the groups under investigation. Relevant terminology includes the following:

- **Physical activity:** Body movement produced by muscle action that increases energy expenditure
- **Exercise:** Planned, structured, repetitive, and purposeful physical activity
- **Physical fitness:** Attributes related to how well one performs physical activity
- **Health:** Physical, mental, and social well-being, not simply absence of disease
- **Health-related physical fitness:** Components of physical fitness associated with some aspect of good health and/or disease prevention (Fig. 31.3)
- **Longevity:** Length of life

Within this framework, physical activity becomes a generic term, with exercise its major component. Similarly, the definition of health focuses on the broad spectrum of well-being that ranges from complete absence of health (near death) to the highest levels of physiologic function. Such de-

finitions often challenge our ability to measure and quantify health and physical activity objectively. However, they do provide a broad perspective to study the role of physical activity in health and disease.

The trend in physical fitness assessment during the past 25 years deemphasizes tests that stress motor performance and athletic fitness (i.e., speed, power, balance, and agility). Instead, current assessment focuses on functional capacities, related to overall good health and disease prevention. The four most common components of **health-related physical fitness** are aerobic and/or cardiovascular fitness, body composition, abdominal muscular strength and endurance, and lower back and hamstring flexibility (see “In a Practical Sense”).

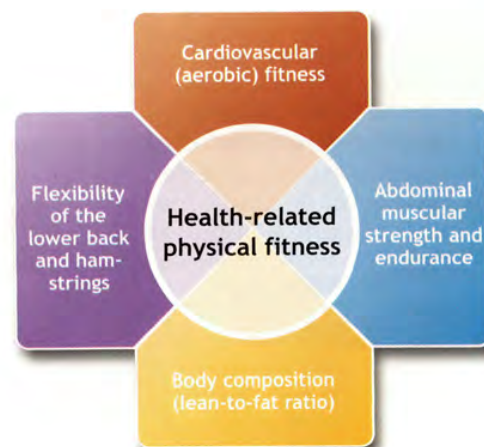


FIGURE 31.3 • Health-related physical fitness components.



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Get the power and authority of McArdle, Katch, and Katch, world-class specialists in exercise, energy, and exercise nutrition in this new edition of Exercise Physiology. The extensive revision of this masterpiece combines the strengths of previous editions with content updates. The Fifth Edition is a must for building a strong academic foundation in nutrition, energy transfer, and exercise training.

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