SECTION 2

ERGONOMIC HAZARDS AND REPETITIVE STRAIN INJURIES

LEARNING OBJECTIVES

- Be able to define key terms.
- Apply introductory anthropometric design principles in work design using appropriate data and allowances.
- Understand the fundamentals of various systems in the body, including the skeletal, skeletal muscular, neuromuscular, respiratory, circulatory, and metabolic systems.
- Estimate energy requirements for walking and lifting.
- Understand the importance of aerobic work design.
- Be able to estimate oxygen consumption or uptake.
- Understand localized muscle fatigue, general physiologic and mental fatigue, and be able to identify possible control measures.
- Apply introductory work design principles to minimize fatigue and enhance performance.
- Understand work schedules and circadian rhythms.

APPLIED SCIENCE AND ENGINEERING: WORK PHYSIOLOGY

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WORK PHYSIOLOGY IS the study of physiological information about humans and how to apply that information in the evaluation and design of work. The term physiology is defined as the study of the processes and functions of an organism—in this case, the human organism. The realm of work physiology (including anthropometry for this chapter) includes: body systems (skeletal, skeletal muscular, neuromuscular, respiratory, circulatory, and metabolic), thermal stress, evaluation of cardiovascular capacity, fatigue, and work design. Work physiology and anthropometry can help the practicing safety professional to minimize occupational injuries while providing a safer workplace and improving productivity.

ANTHROPOMETRY

Definition and Use

The term *anthropometry* literally means *the measure of humans*. From a practical standpoint, the field of anthropometry is the science of measurement and the art of application that establishes the physical geometry, mass properties, and strength capabilities of the human body (Roebuck 1995). Anthropometric data are fundamental in the fields of work physiology (Åstrand and Rodahl 1986), occupational biomechanics (Chaffin, Andersson, and Martin 1999), and ergonomics/work design (Konz and Johnson 2004). Anthropometric data are used in the evaluation and design of workstations, equipment, tools, clothing, personal protective equipment, and products, as well as in biomechanical models and bioengineering applications.

Anthropometric Data

It is a fundamental concept of nature that humans come in a variety of sizes and proportions. Because there is a reasonable amount of useful anthropometric data available, it is usually not necessary to collect measurements on a specific workforce. The most common application involves design for a general occupational population. Some selected anthropometric data (body dimensions) are shown in Table 1. These data were collected on seminude subjects in rigid, erect postures; therefore, certain allowances must be applied for most practical uses. For shoe height, add 1 inch; for shoe weight, add 2 pounds; and for clothing weight, add 1 pound (Marras and Kim 1993). People rarely work in rigid, erect postures, so allowance for slumping may be appropriate for standing (subtract 1 inch) and sitting positions (subtract up to 1.5 inches) (Pheasant and Haslegrave 2006). For a comprehensive source of anthropometric data, Pheasant and Haslegrave (2006) and Roebuck (1995) provide extensive information about statistical aspects, data collection methods, gender differences, ethnic differences, and aging trends.

Anthropometric Design Principles

There are three general anthropometric design principles useful in the design of workspaces. Each design principle is described with its advantages and disadvantages.

1. **Design for Average.** With the *design for average* principle, you design a workspace for the average-sized person, or a one-size-fits-all approach. This is a commonly used approach by designers without knowledge of population variability and is generally not recommended. Another reason it is commonly used is it is normally the least-cost method. For example, a designer might design a standing workstation for light assembly work at the average standing elbow height for the 50th percentile male and female:

TABLE 1

Body Dimensions (Inches) of Seminude U.S. Adult Civilians

	Percentile						Standard Develop Fem	Standard Develop Male
	5th Fem	5th Male	50th Fem	50th Male	95th Fem	95th Male		
Heights (above floor)								
Height (standing)	60.1	64.8	64.1	69.1	68.4	73.5	2.50	2.63
Eye height	55.7	60.2	59.7	64.3	63.8	68.6	2.46	2.59
Shoulder height	48.9	52.8	52.5	56.8	56.4	60.9	2.28	2.44
Elbow height	36.5	39.2	39.3	42.2	42.3	45.4	1.76	1.89
Knuckle height[1]	26.4	27.6	28.7	30.1	31.1	32.7	1.46	1.61
Sitting Heights (above seat)								
Height (sitting)	31.3	33.6	33.5	36.0	35.8	38.3	1.37	1.40
Eye height	27.0	28.9	29.1	31.2	31.3	33.4	1.31	1.35
Shoulder height	20.0	21.6	21.9	23.5	23.8	25.4	1.13	1.17
Elbow height	6.9	7.2	8.7	9.1	10.4	10.8	1.06	1.07
Thigh height	5.5	5.9	6.3	6.6	7.1	7.5	0.48	0.50
Popliteal height (above floor)	13.8	15.5	15.3	17.1	16.9	18.8	0.93	0.98
Depths								
Forward reach (thumbtip)	26.6	29.1	28.9	31.5	31.4	34.1	1.43	1.54
Buttock-knee distance (sitting)	21.3	22.4	23.2	24.3	25.2	26.3	1.17	1.18
Buttock-popliteal distance (sitting)	17.3	18.0	19.0	19.7	20.8	21.5	1.05	1.05
Weight (lb)[2]			139.2	182.3				

[1]From Abraham, Johnson, and Najjar (1979)

[2]From Marras and Kim (1993)

(Unless otherwise noted, adapted from Kroemer, Kroemer, and Kroemer-Elbert 2001, p. 27)

[(39.3 + 42.2) ÷ 2] + 1 – 1 = 40.75 inches above floor level. (Remember to add 1 inch for shoe sole allowance and to subtract 1 inch for standing slump.)

The problem with the one-size-fits-all approach is that it fails to accommodate people at both ends of the population, specifically the shortest females and the tallest males. The shortest females forced to work at this assembly workstation will find the surface too high and may develop shoulder discomfort. The tallest males will find the surface too low and may develop low back or neck discomfort. If these discomforts lead to injuries and workers' compensation claims, then this will not be the least-cost method from a systems viewpoint.

2. **Design for Extreme.** The *design for extreme* principle is very useful in specific circumstances when it make sense to design a dimension at an extreme end of the distribution and, because of its function, the entire distribution is accommodated. Here are a few examples:
    - A doorway is designed so that extremely tall males and extremely broad people can fit through it. For example, an interior doorway may be designed to be 36 inches wide and 80 inches tall. Both these dimensions exceed the 99th percentile for height and body breadth. A doorway designed for the 50th percentile person would present problems, especially since there are life safety code and emergency egress concerns at play here.
    - If reach distances are designed for the shortest female to reach, then all will be accommodated. Do not design for fingertip reach, but for thumbtip reach, as this is more functional.
    - This principle should also be applied in general for strength requirements, with some precautions. If the weaker person has the strength capability for the task, then all will be accommodated. In some cases, this may set the strength requirement lower than practical and perhaps economically infeasible, so use reasonable judgment. Normally the people in the weakest tail of the strength distribution will self-select out of jobs with moderate to high strength requirements.
3. **Design for Range.** *Designing for the range* normally means designing an adjustable workspace. Returning to the standing workstation for light assembly, an adjustable-height workstation might be designed to accommodate elbow heights ranging from the 5th percentile female to the 95th percentile male, or 37.5 to 46.4 inches. Now the potential shoulder, neck, and low back discomfort discussed earlier may have been eliminated. Adjustability is one of the keys to effective ergonomic design. The adjustability function and features will come at a greater initial investment, but the potential increases in productivity, worker comfort, and reduced risk of workers' compensation claims will make this a favorable investment.

Most companies are not likely to initially practice the design for range principle in their workplaces because they fail to look at the economic advantage. Also, OSHA is not likely to include designing for range in regulations, so most companies will ignore this principle. However, it is important to note that this principle makes good economic sense and will improve productivity and worker satisfaction.

Practical Application of Anthropometric Data

As stated earlier, anthropometric data are useful in work physiology, occupational biomechanics, and ergonomic/work design applications. Of these, the most common practical use is in the ergonomic design of workspaces and tools. Here are some examples:

- The optimal *power zone* for lifting is approximately between standing knuckle height and elbow height, as close to the body as possible. Always use this zone for strategic lifts and releases of loads, as well as for carrying loads.

But minimize the need to carry loads—use carts, conveyors, and workspace redesign.

- Strive to design work that is lower than shoulder height (preferably elbow height), whether standing or sitting. (Special requirements for vision, dexterity, frequency, and weight must also be considered.)
- The upper border of the viewable portion of computer monitors should be placed at or below eye height, whether standing or sitting (Konz and Johnson 2004).
- Computer input devices (keyboard and mouse) should be slightly below elbow height, whether standing or sitting (Konz and Johnson 2004). Use split keyboards to promote neutral wrist posture (Konz and Johnson 2004). Learn keyboard shortcuts to minimize excessive mouse use. Use voice commands—speech recognition software is increasingly effective for many users and applications.
- For seated computer workspace, the lower edge of the desk or table should leave some space for thigh clearance (Konz and Johnson 2004).
- For seating, the height of the chair seat pan should be adjusted so the shoe soles can rest flat on the floor (or on a foot rest), while the thighs are comfortably supported by the length of the seat pan (Konz and Johnson 2004). Use knowledge of the popliteal (rear surface of the knee) height, including the shoe sole allowance from Table 1.
- The chair seat pan should support most of the thigh length (while the lower back is well supported by the seat back), while leaving some popliteal clearance (Konz and Johnson 2004). In other words, the forward portion of the seat pan should not press against the calf muscles or back side of the knees. Refer to the seated buttock-popliteal distance in Table 1.
- For horizontal reach distances, keep controls, tools, and materials within the forward reach (thumbtip) distance. Use the anthropometric principle of designing for the extreme by designing the reach distances for the 5th percentile female, thus accommodating 95 percent of females and virtually 100 percent of males.

Body Systems

In applying work physiology in the evaluation and design of work, it is essential to have fundamental knowledge of several relevant body systems, including the skeletal, skeletal muscular, neuromuscular, respiratory, circulatory, and metabolic systems. A brief introduction to each of these systems is presented to provide an elementary foundation. The practitioner is advised to learn these systems in more detail than is presented in this chapter. Recommendations on authoritative references include *Grant's Atlas of Anatomy* (Dalley and Agur 2004), *The Anatomy Coloring Book* (Kapit and Elson 2002), *The Physiology Coloring Book* (Kapit, Macey, and Meisami 2000), *Engineering Physiology* (Kroemer, Kroemer, and Kroemer-Elbert 1997), *Hollinshead's Functional Anatomy of the Limbs and Back* (Jenkins 2002), and *The Extremities: Muscles and Motor Points* (Warfel 1985).

The Skeletal System and Connective Tissue

A complete discussion of the skeletal system should include all connective tissue. Connective tissue includes bone, tendons, ligaments, fascia, and cartilage. Connective tissue provides support for the body and structural integrity of body parts and transmits forces (Chaffin, Andersson, and Martin 1999).

Ligaments, tendons, and fascia are dense connective tissue. Ligaments connect bone to bone and are quite significant in stabilizing joints. Tendons connect bone to muscle. The most significant tendon in the body is the tendocalcaneus (or Achilles' Tendon). Fascia covers muscle tissue, some internal organs, and holds a significant role in the makeup of the skin layers. Ligaments and tendons consist of dense, parallel fibers—both collagen (inelastic) and elastic—that are capable of powerful axial loads with a slight ability to stretch. The fibers in fascia are irregularly arranged and can resist loading in many directions about a plane, but not parallel to a plane, much like a fish net. There is virtually no vascularization (blood flow) to ligaments, tendons, and fascia, thus its healing ability is limited (Jenkins 2002).

There are two types of cartilage pertinent to our topic: hyaline and fibrocartilage. Hyaline cartilage covers the end of long bones at synovial joints. Synovial joints are lubricated, highly mobile joints throughout the body, including the knuckle, wrist, elbow, shoulder, hip, knee, and ankle joints. (Think of the white cartilage at the end of a chicken leg bone.) Hyaline cartilage is very thin and smooth, protecting bone wear and enhancing smooth joint mobility with the assistance of synovial fluid, while transmitting significant forces between bones.

The major location of fibrocartilage is found in intervertebral discs between each pair of vertebrae in the spinal column. It provides a cushion between the vertebrae and is extremely resistant to compressive forces (up to a point). Fibrocartilage in the intervertebral discs is not well designed to resist tension, shear, and torsion, a fact that provides some insight into some spinal injuries and ideas for proper work design. There is no vascularization (blood flow) in cartilage, but it does receive its nutrition by diffusion. Thus it heals much more slowly or less completely as compared to vascularized tissue (Jenkins 2002).

The final category of connective tissue is bone. Bone consists of collagen fibers in a mineralized (calcium) matrix. Bone is well vascularized (has a good blood supply). Bone functions as a support structure, a site of attachment for skeletal muscle, ligaments, tendons, and joint capsules, a source of calcium, and a significant site of blood cell development for the entire body.

There are five classifications of bones: *long* (clavicle, humerus, radius, ulna, phalanges, femur, tibia, and fibula), *short* (really cube-shaped): carpals (wrist) and tarsals (ankle), *flat* (cranial bones, ribs), *irregular* (scapula, pelvis, vertebrae, sternum), and *sesamoid* (patella) (Jenkins 2002). There are approximately 200 bones in the body. Many of these bones intersect at important joints. Synovial joints were discussed earlier. These joints provide for varying types of mobility, as well as allow for the passage of nerves and blood vessels, and consequently are sites for constriction or pressure.

TABLE 2

Selected Joint Motions or Functions

Joint Name	Degrees of Freedom	Motion or Function
Interphalangeal (finger and toe joints)	1	flexion, extension
Metacarpo-phalangeal, Metatarsal-phalangeal (hand to finger and foot to toe)	2	flexion, extension abduction, adduction
Wrist	2	flexion, extension radial & ulnar deviation
Elbow	2	flexion, extension forearm supination & pronation
Shoulder	3	flexion, extension abduction, adduction internal & external rotation
Hip	3	flexion, extension abduction, adduction internal & external rotation
Knee	2	flexion, extension internal & external rotation
Ankle	2	plantar flexion, dorsiflexion inversion, eversion

A summary of some of the major mobility joints of the body are presented in a simplified form in Table 2. A single degree of freedom consists of a single paired motion (for example, flexion and extension and abduction and adduction each represent one degree of freedom). Adduction means to *bring together*. Abduction means to *move apart*. If we move beyond the simplified presentation of joint movements, we will find that the shoulder, for example, also has movements of elevation, depression, protraction, and retraction because of the nature of the scapula floating on the posterior rib cage (Jenkins 2002).

A significant component of the skeletal system is the *vertebral column* or *spine*. It consists of four regions from superior (top) to inferior (bottom): *cervical*, *thoracic*, *lumbar*, and *sacral*. The cervical, thoracic, and lumbar regions provide varying (but somewhat limited) amounts of motion in three degrees of freedom (flexion/extension, side bending, and twisting). The spine provides a pathway and protection for the spinal cord, with pairs of spinal nerves emanating between intervertebral joints.

In addition to serving as a pathway and protector for the spinal cord, the vertebral column functions as a support structure for most of the body and is a site of attachment for a multitude of muscles and ligaments. The cervical region (neck) consists of seven vertebrae which support the neck and head [weighing approximately 6–8 pounds (2.7–3.6 kilograms)]. They are the most mobile vertebrae and provide the spinal nerves (brachial plexus) serving the upper extremities (the shoulder, upper arm, elbow, lower arm, wrist, hand, and fingers). The *thoracic* region (trunk) consists of twelve vertebrae (progressively larger moving inferiorly) which support the thorax, neck, and head, as well as articulation with twelve sets of ribs and twelve sets of spinal nerves. The thoracic region is much less mobile than the cervical region, largely because of articulation with the ribs. The *lumbar* region (lower back) consists of five vertebrae that are relatively quite massive and provide support for the entire upper body and torso. The lumbar region is capable of more mobility than the thoracic region. In part because of this mobility and considerable support demand, the lumbar region is the site of most clinical attention for injuries and surgical repair of herniated discs. When a disc ruptures (herniates) or bulges, there is great danger that it can compress against a spinal nerve, causing numbness, tingling, and sharp pain in parts of the body effected by that spinal nerve (sensory dermatomes). The *sacrum* is the final region of the spinal column and is actually a fused set of vertebrae, although the coccyx (tail bone) does float at the terminal end. The lateral sides of the sacrum form strong joints with the pelvis in the sacroiliac (SI) joint. The disc that sits atop the sacrum and below the fifth lumbar vertebra (the L5/S1 disc) supports the most weight of all the discs and is an important point of biomechanical and clinical interest (Jenkins 2002).

The Skeletal Muscular System

The human body possesses three types of muscle: skeletal, smooth (found in blood vessels and internal organs), and cardiac (found in the heart). The purpose of skeletal muscle is to move or stabilize body segments. There are 232 distinct skeletal muscles associated with the extremities, with at least another 42 distinct skeletal muscles devoted to the back. Skeletal muscles possess the ability to contract. Muscles are composed primarily of voluntary muscle fibers, but also contain small quantities of connective tissue and considerable blood vessels and nerves. Skeletal muscles are generally long and slender, and traverse a skeletal joint. Each end of a muscle is attached to a bone by one or more tendons. The body of the muscle consists of generally parallel muscle fibers (Jenkins 2002).

When a muscle contracts, we normally think of the muscle as shortening in length, exhibiting strength and providing force for work tasks. However, a contracting muscle may also retain its length (a so-called isometric exertion) or even lengthen (a so-called eccentric contraction). Take the example of holding a bucket with your elbow at a 90-degree angle. If you lift that bucket by flexing your elbow joint, your bicep muscle performs a shortening contraction, while the opposing tricep muscle performs a lengthening contraction. To lower the bucket by extending your elbow joint, the tricep muscle performs a shortening contraction, while the opposing bicep muscle performs a lengthening contraction (Kroemer, Kroemer, and Kroemer-Elbert 1997).

Each muscle consists of hundreds to thousands of muscle fibers, which are controlled in small groups by nerve cells. If you require a mild or controlling exertion, your body has learned to activate only a small group of nerve cells, which recruit a relatively small group of muscle fibers. If you require a strenuous, maximal exertion, your body has learned to activate as many nerve cells as possible, thus recruiting most, if not all, muscle fibers available in that muscle. In either case, these muscle fibers are activated on an *all-or-none principle* (Jenkins 2002). It is not possible to *partially* activate individual muscle fibers. But by the miraculous ability of the body to coordinate motor nerves, it is possible to smoothly control muscles on a continuum from a light, controlling contraction to an all-out maximal contraction. These amazing motor control programs are learned from the time of infancy through adulthood and are practiced and refined thousands of times. Consider that your body flawlessly executes complex motor control programs while climbing stairs or lifting a box.

A stroke may interrupt or erase such motor programs, but fortunately they can in some cases be relearned.

From an occupational safety and health viewpoint, it is important to focus on four points with regards to skeletal muscles: avoiding extreme exertions, avoiding overly excessive repetitive motions, avoiding awkward postures, and avoiding localized muscle fatigue.

Extreme Exertions: Overexertion from extreme use of force can produce an acute type of injury that can traumatically damage muscle, the muscle-tendon interface, the tendon-bone interface, and possibly rupture adjacent fibrocartilage (spinal discs). A good example of this case is forcefully attempting to lift an extremely heavy box whose weight you drastically underestimate. Also, force exertions at less than extreme levels that are repeated can lead to a chronic type of injury that develops over long periods of time.

Excessive Repetition: Overexertion from excessive repetition of joint motion can produce a chronic type of injury in the muscles and tendons. It may take weeks, months, or even years for these types of injuries to develop. In general, a job is considered repetitive if the basic cycle time is less than 30 seconds (Konz and Johnson 2004). The combination of repetition with excessive force may produce a detrimental effect that is worse than the sum of the parts.

Awkward Posture: Overexertion of skeletal muscles in awkward postures should be avoided, primarily because of poor mechanical advantage. In posture extremes, muscles may not be able to produce the forces required by the task, may place extreme stress on tendons, and may put pressure on nerve tissue and blood vessels. Awkward postures are usually at the ends of the range of motion for joints. The combination of awkward posture with excessive repetition and with excessive force may produce a detrimental effect that is worse than the sum of the parts.

Localized Muscle Fatigue: Prolonged isometric muscle exertions should be avoided. In these cases, the muscle motor units are over-used and the circulatory system is unable to provide oxygen and nutrients to the muscle cells, or remove carbon dioxide and lactic acid (Chaffin, Andersson, and Martin 1999). For example, avoid using the hand as a clamp or vise for extended periods of time. Further discussion of fatigue will follow later in the chapter.

The Neuromuscular System

The nervous system is an important control and regulation system in the human body. It gathers input from various sensors throughout the body, both internal and external. It processes information both in the brain and spinal cord to provide regulation of various body functions and control of motor activities. Our interests in work physiology focus primarily on thermal regulation and motor control. Thermal regulation will be addressed later in this chapter. This section will take an introductory look at motor control. Realize there is much more to the nervous system, but is beyond the scope of this chapter.

Anatomically, there are three major subdivisions of the nervous system: the *central nervous system*, the *peripheral nervous system*, and the *autonomic nervous system*. The central nervous system (CNS) includes the brain and spinal cord, and maintains primary controls. There are specific portions of the brain that regulate systems and aspects that are critical to the workplace, including respiration, cardiac function, digestion, attention, thermoregulation, learning, speech, vision, hearing, memory, emotions, and, most pertinent to our discussion, motor control. The CNS receives information from a multitude of sensors in the peripheral nervous system (Kroemer, Kroemer, and Kroemer-Elbert 1997).

The *peripheral nervous system* (PNS) includes the cranial and spinal nerves, transmitting signals to and from the brain along networks of nerve cells, or neurons. The PNS possesses sensors which respond to light, sound, touch, temperature, chemicals, pressure, and pain. Some of the most important sensors for motor control include *proprioceptors*, which provide information about the degree of stretch in muscles, the amount of tension in muscle tendons, the relative location of body joints, and even information about velocity and acceleration of joints. The vestibular system, which regulates equilibrium (or balance), is located in the inner ear and consists of three bony semicircular canals oriented at 90 degrees to one another. The PNS is a two-way system. So just as there are sensors bringing complex information to the CNS, the PNS is also delivering action signals from the CNS for motor control (Kapit and Elson 2002).

The *autonomic nervous system* (ANS) generates the *fright*, *flight*, or *fight response* and regulates involuntary functions such as cardiac muscle, internal organs, blood vessels, and digestion, all of which are critical to the workplace (Kapit and Elson 2002).

So, motor control is controlled from the CNS through the PNS to the muscular system. Some of this was discussed previously in the section title "Skeletal Muscle System." The CNS sends signals to specific motor neurons. Each motor neuron controls a set of muscle fibers and, when called upon, will stimulate those muscle fibers to contract with the help of a chemical neurotransmitter (acetylcholine) following the all-or-none principle discussed previously (Kapit and Elson 2002). This is important to our topic because of our earlier discussion of localized muscle fatigue and the more general discussion of fatigue that follows later in the chapter.

The Respiratory System

The *respiratory system* moves air to and from the lungs from the atmosphere. Within the lungs, part of the oxygen contained in the air is absorbed into the bloodstream. While delivering oxygen to the bloodstream, the air in the lungs simultaneously collects carbon dioxide, water, and heat from the bloodstream and then exhales them to the atmosphere. The respiratory path begins with the mouth and nose, passes through the throat (pharynx), voice box (larynx), and windpipe (trachea) and into the bronchial tree. The bronchial tree divides in 23 steps ending in microscopic spherical-shaped alveoli. There are hundreds of millions of alveoli, which provide as much as 80 square meters of gas exchange surface to the blood circulatory system in an adult (Kroemer, Kroemer, and Kroemer-Elbert 1997). The physiology of the bronchial tree and alveoli are of particular interest in industrial hygiene in the study of airborne contaminants (Nims 1999). Inspiration and expiration of air by the lungs is powered primarily by the contraction and relaxation of the thoracic diaphragm muscle and, to a lesser degree, by the intercostal muscles (between the ribs) (Kapit and Elson 2002).

Our primary interest in the respiratory system with regards to work physiology is both the quantity and quality of air moved in and out of the lungs. The quantity of air processed by the lungs is a function of body size, gender, age, conditioning, and work demand. Highly trained, large males have a lung capacity of 7–8 liters, of which about 6 liters is usable (vital capacity). Women have lung volumes about 10 percent smaller than male peers. Untrained persons have volumes of 60–80 percent of their athletic peers. At rest we breathe 10–20 times per minute, increasing to about 45 times per minute for heavy work or exercise (Kroemer, Kroemer, and Kroemer-Elbert 1997).

The quality of air processed by the lungs begins with the concentration of oxygen in the atmosphere. Normal atmospheric air consists of 20.9 percent oxygen. Concentrations less than 19.5 percent are considered oxygen-deficient and are a concern in confined spaces as well as other industrial environments. Without adequate oxygen, workers can become dizzy, uncoordinated, and pass out. Unless this situation is rectified quickly, brain damage or death can occur. Concentrations more than 23 percent are considered oxygen-enriched and can pose fire or explosion hazards (Nims 1999).

When at rest or during relatively sedentary activity, the body has little demand for oxygen and the exhaled concentration may be 19–20 percent oxygen. During more physically demanding work, the body demands and takes more oxygen. During extremely demanding work, the exhaled concentration may be as low as 14 percent oxygen. Athletes and trained persons also have the ability to process more oxygen than their less-trained peers at the same workload. This points to the importance of conditioning for workers, especially for physically demanding jobs, and for work-hardening when workers return from extended vacations or injury.