CHAPTER 3

Physiological Aspects of Neuromuscular Function

Thomas R. Waters and Amit Bhattacharya

CONTENTS

3.1 INTRODUCTION

The mechanical motions of the body segments necessary to accomplish a task are skillfully controlled by a myriad of neuromuscular components and a series of well-orchestrated neural events encompassing both the central and peripheral nervous systems. Some of these issues are discussed in the following sections of this chapter.

The maintenance of ergonomically efficient posture requires the optimal orientation of various interconnected human body segments to produce minimal biomechanical loadings of the joints. The neural components of movements are the planning and programming units and the performance units. Planning and programming are the functions of the precortical centers (cerebral cortex, bilateral movement), the basal ganglia, the cerebellum, and the thalamus. The premotor and sensory regions provide the input for planning to the basal ganglia and the cerebellum. The performance units include the motor cortex and spinal cord, with the smoothing function performed by the cerebellum. In order for a person to perform a motor act smoothly, all the somatosensory systems have to work in harmony to help provide "accurate" information regarding the position of body segments, muscle tensions, and joint motions to the higher centers. For a detailed discussion of this topic, readers should refer to comprehensive texts of physiology and neuroanatomy [1–5].

3.2 BACKGROUND AND SIGNIFICANCE TO OCCUPATIONAL ERGONOMICS

A worker who performs a simple manual task, such as picking up a box from a table, does so without much difficulty. The underlying physiological chain of events required to perform this seemingly simple task, however, is very complex and involves a number of physiological systems including the muscular, sensory, and central and peripheral nervous systems. Prior to the actual event of reaching for the box, the worker uses his or her visual system and the higher brain centers to make a judgment regarding its weight, size, and location with respect to the orientation and location of his or her body. This information is synthesized by the brain, and a movement plan is developed that will generate a series of complex control commands. These control commands are relayed to the appropriate muscle groups (via motor neurons) to allow for smooth movement of the body segment and load unit.

At the muscle–bone level, when the appropriate commands are received by the muscle, the muscle contracts and applies a pulling force on the tendon attached to the bone segment. If the tensile force generated by the muscle is strong enough to create a moment that will overcome the moment created by the weight of the segment and any external load applied to the segment, then the segment and load will be moved.

To ensure smooth movement, a complex system of sensory elements monitors the condition of the musculoskeletal system. These sensors measure the joint forces, muscle forces, and muscle length and provide continuous feedback to the central nervous system, which then modifies the commands sent to the muscles. The sensors consist of various muscle stretch (change-of-length detector) and tension-monitoring receptors, which balance reciprocally acting pairs of muscles to control the position of a segment at any point in time (e.g., extensor versus flexor muscles around a joint). This positional control system is crucial to coordinated muscle movement. The sensory units are integrated into a highly evolved system of reflexes that provide a short-latency connection between the sensory and motor components of the system that result in stereotypical motor responses to sensory stimulus. This arrangement allows for a rapid response to perturbations in the status of the system (e.g., the knee jerk response to stretching the patella ligament of the knee by striking it with a hammer).

3.3 RELEVANT CONCEPTS AND TERMINOLOGY

3.3.1 Major Components of the Neuromuscular System

Table 3.1 lists the five main elements of the neuromuscular system and their purpose. As shown in Figure 3.1, the five component groups of the neuromuscular system are organized into a highly complex command and control system that integrates physiological and mechanical functions into a single system capable of performing work.

3.3.1.1 Cerebral Cortex, Cerebellum, and Subcortical Centers

In humans, the programming center for a movement is made up of the cerebral cortex of the brain and various components of the subcortical centers (basal ganglia, brainstem nuclei, and brainstem reticular formation). These systems send descending commands (efferent) to the motor neurons and finally to the muscles (Figure 3.2). During contraction of the muscles, various receptors in the muscles (muscle spindles), tendons (Golgi tendon organ), and joints send real-time information (afferent) about the status of the body segment movement to the higher centers for processing. The role of the cerebellum is to smooth the movement of the body segment. It receives information from afferent systems (vestibular, proprioception, and visual) as well as commands from the higher centers. Input signals from the cerebral cortex are conveyed via brainstem nuclei to the cerebellum and tell the brain what the muscles should be doing. Based on its knowledge of the status of various afferent systems (as it relates to motor coordination) and the nature of "expected" controlling commands from the higher centers, the cerebellum is capable of producing smooth movement. It is not clear how the cerebellum processes this information. However,

TABLE 3.1 Major Components of the Neuromuscular System

Component	**Purpose**
Cerebral cortex, cerebellum, and subcortical centers	Central processing unit for coordination of muscular activity
Motor neurons	Neural circuitry
Muscle fibers	Force-generating neuromechanical actuator
Visual, vestibular, and somatic sensory receptors	Feedback sensors for detection of position, stretch, pressure, tension, etc.
Bones, joints, ligaments, and tendons	Mechanical support and linkage connectors

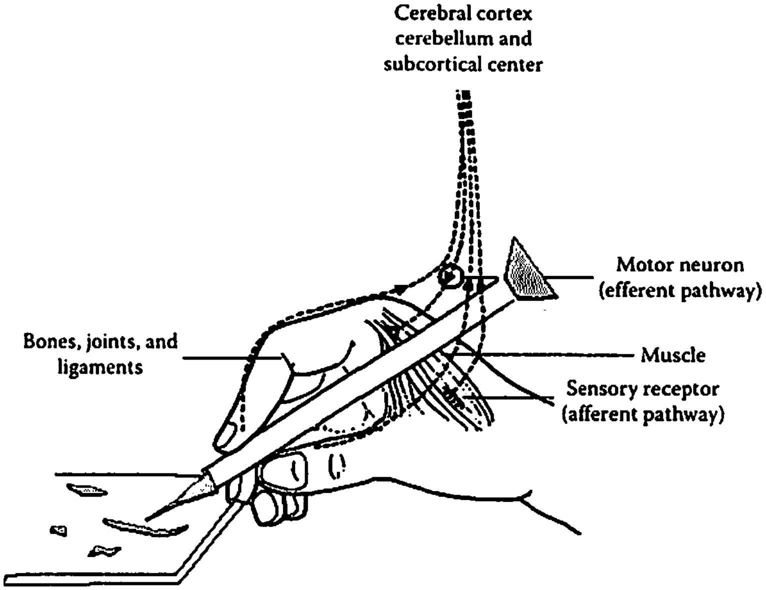


FIGURE 3.1 Components of the neuromuscular system showing the direction of flow of neural signals. A complex system of interneurons (not shown) also provides reflex pathways in which afferent sensory signals can directly affect motor signals without traveling to the higher centers of the brain. The final common pathway for motor function is the motor neuron, which connects directly to the muscle fibers. (Adapted from Astrand, P. and Rodahl, K., *Textbook of Work Physiology*, McGraw-Hill, New York, 1986, pp. 19, 115, 334.)

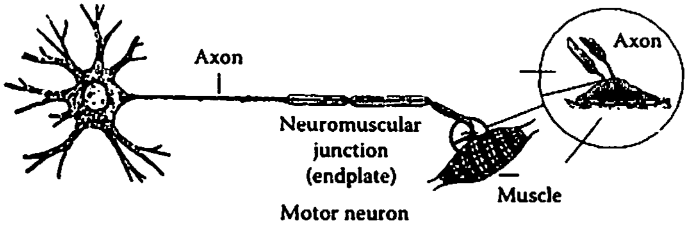


FIGURE 3.2 Illustration of a motor neuron showing the axon and the neuromuscular junction (endplate). When the cell body is stimulated, an action potential is transmitted to the endplate, where a neurotransmitter (acetylcholine) is released into the neuromuscular junction. The neurotransmitter causes the muscle fibers to contract.

although its exact mechanism of action is not clear, it certainly plays an important role in minimizing the error signal between what the muscles are doing and what they "should" be doing. The cerebellum does not initiate muscle contractions directly but controls the activity in the descending motor commands. People with cerebellum damage have jerky uncoordinated movements, poor balance, and unsteady gait [1].

3.3.1.2 Motor Neurons

The motor neuron, illustrated in Figure 3.2, is a nerve cell that links the central nervous system and the appropriate muscle fiber or fibers. The motor neuron consists of a cell body containing the cell nucleus, an elongated segment or axon, and the endplate or neuromuscular junction. When a command signal of sufficient strength is received at the body of the motor neuron, the cell membrane is depolarized (there is a drop in voltage due to a change in cell membrane permeability. This depolarization initiates an action potential along the nerve axon. The action potential is a propagating electric signal that travels toward the endplate. When the action potential reaches the endplate, acetylcholine, a chemical transmitter, is released into the neuromuscular junction. This chemical transmitter then depolarizes the endplate membrane of the muscle fiber to a threshold value (to +30 mV from a resting potential of −70 mV). This action electrically triggers the muscle fiber contraction.

Motor neurons and muscles are organized into motor units that consist of a single motor neuron, its axon, and all the muscle fibers innervated by it. The number of muscle fibers innervated by a single motor unit varies from a few (e.g., muscles that move fingers) to several hundred (e.g., back muscles). The number of muscle fibers innervated by one motor unit is dependent on the function of the muscle rather than its size. Muscles that cause large and strong body motions usually have more muscle fibers under the control of a motor unit than those required to perform fine precision movements.

3.3.1.3 *Muscles*

There are over 600 muscles in the human body accounting for about 45% of the total body weight. Muscles are composed of one of three kinds of fibers, depending upon the function of the muscle. The three types are skeletal, smooth, and cardiac. Skeletal muscle is connected to the bones of the body, and when contracted it causes the body segments to move. Smooth muscle is found in the stomach, intestinal tracts, and walls of blood vessels. Cardiac muscle is the contractile tissue found in the heart that pumps the blood for circulation. In this chapter, we focus our attention on the skeletal muscles.

A single skeletal muscle, as shown in Figure 3.3, consists of hundreds to tens of thousands of muscle fibers, totaling about a quarter of a billion in an average person. Each muscle fiber consists of a single cylindrical muscle cell with a diameter of 10–90 μm and a length of up to 30 cm. Muscle fibers are further divided into individual contractile

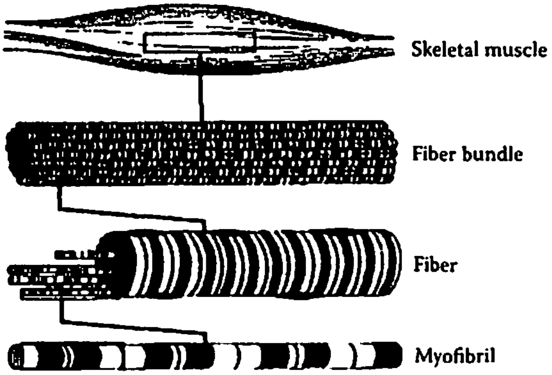


FIGURE 3.3 Illustration of a skeletal muscle showing the fiber composition. Each fiber is innervated by one motor neuron that controls the contraction of the muscle fiber. (Adapted from Dudel, J., in *Fundamentals of Neurophysiology*, Schmidt, R.F., Ed., Springer-Verlag, New York, 1978, Chapter 5, pp. 129–137.)

elements called myofibrils. Myofibrils are the basic contractile element of the muscle, and the forces and movement in a muscle cell are generated by special protein molecules and contractile proteins in the myofibrils. Each muscle fiber contains hundreds of myofibrils that actively contract in the presence of calcium, which is released when a contraction is initiated. Contraction is accomplished by a complex chemical process whereby adjacent filaments of molecular proteins, actin, and myosin, are pulled toward each other in a sliding motion that results in shortening of the muscle cell and the development of tensile force. Generally, muscle fibers are shorter than the muscle they make up, but some fibers run the entire length of the muscle.

The amount of tension or force generated by a contracting muscle is dependent on its precontraction length, the velocity of the contraction, and the direction of muscle movement during the contraction (i.e., whether the muscle is lengthening or shortening). When a muscle is shortening during a contraction, the activity is defined as *concentric*. Conversely, when a muscle is lengthening during a contraction, the activity is defined as *eccentric*. Figure 3.4 graphically illustrates the relationship between muscle force, length, velocity of contraction, and direction of movement.

For a concentric contraction, there is an optimal precontraction muscle length that will produce a maximum tension force when the muscle is stimulated. This length is called the *resting length* of the muscle. If the precontraction muscle length is at or below 60% of the resting length, the muscle will not produce any tension when stimulated. Therefore, the ability of a muscle to produce an optimal force is strongly dependent upon the position of the body segment to which the muscle is attached. For example, optimal biceps muscle tension is generated when the elbow joint angle (subtended between the forearm and the upper arm) is in the region of 90°–100°. Moreover, as the velocity of a concentric contraction increases, the force decreases.

Muscles are usually attached to bones in a paired arrangement, with the *agonist* muscles performing the main movement of the body segment and the *antagonist* muscles acting as the controller. *Fixator* muscles provide support to the proximal joints, and *synergist*

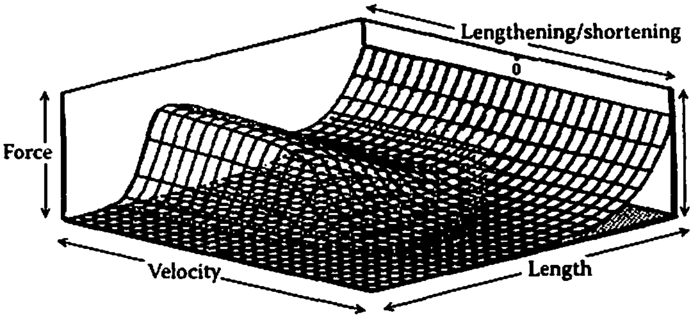


FIGURE 3.4 Graphical illustration of the effects of muscle length, contraction velocity, and direction of muscle movement on muscle force (assuming a fixed excitation level). The surface plot shows the magnitude of force developed as a function of muscle length, velocity, and movement direction. The ridge of the peak corresponds to the resting length of the muscle. (Adapted from Brooks, V.B., *The Neural Basis of Motor Control*, Oxford University Press, New York, 1986.)

muscles help prevent undesirable movements of other joints when the agonist muscle passes over more than one joint.

3.3.1.4 Visual, Vestibular, and Sensory Receptors

In order to move a body segment(s) and/or maintain whole-body upright balance during static and dynamic conditions, the brain must receive feedback information regarding the position and movement of the body. This type of information is provided by a series of biological sensors located in the joints, muscles, and tendons and under the skin, as well as the visual and vestibular systems. The output from these sensory components is transmitted by afferent neurons to the spinal cord and brain, where they are processed and used to alter the motor signals. Feedback from these sensory receptors is essential for smooth, coordinated movement because the sensory input provides the cues necessary to alter the timing of the motor program that controls the motor function. For new, unlearned tasks, the visual and vestibular systems are especially important in generating the coordinated motor patterns for smooth motion. The flowchart shown in Figure 3.5 illustrates how the sensory system provides feedback information to alter the motor signals sent to the muscles.

The visual and vestibular systems provide information about the spatial orientation of the body and the movement of the head. The *visual system* provides information regarding the orientations (horizontal and vertical) of objects in three-dimensional (3-D) space. The *vestibular system*, illustrated in Figure 3.6, provides information regarding the position and movements of the head and their relationship to gravitational forces. The three orthogonally placed semicircular canals provide information regarding acceleration of the head in 3-D space. The utricle and the saccule are position sensors that provide information regarding the position of the head in space.

The actions of the vestibular system are not consciously felt unless one is required to perform a motor task under dim light and/or walk or stand on an uneven surface. The literature indicates that the role of the vestibular system for motor task performance is not as critical when the other afferents from the visual and proprioception systems are intact.

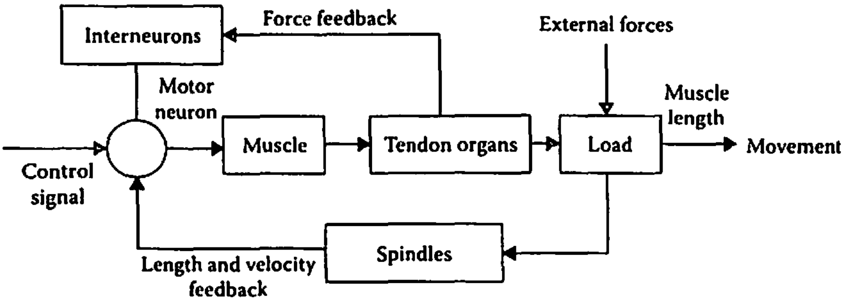


FIGURE 3.5 Flowchart of muscle control system. Feedback loops from tendon organs and muscle spindles provide sensory feedback for control of muscular function. Descending pathways from the brain provide control signals, where they are integrated with the sensory input and sent to the muscles via the motor neurons. (Adapted from Brooks, V.B., *The Neural Basis of Motor Control*, Oxford University Press, New York, 1986.)

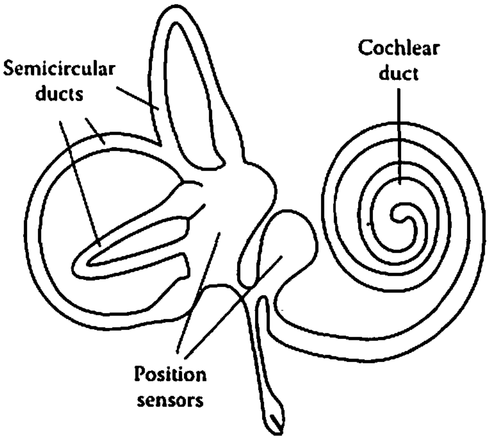


FIGURE 3.6 Vestibular sensory receptors. Semicircular ducts provide sensory input regarding angular acceleration. The position receptors provide information about the orientation of the head. (Adapted from Brooks, V.B., *The Neural Basis of Motor Control*, Oxford University Press, New York, 1986.)

Proprioceptive sensors provide information about the status of the muscles themselves, such as how hard the muscles are pulling and how fast they are being stretched. Muscle stretch receptors (muscle spindle) and the Golgi tendon organs (tension-monitoring receptors) transmit information regarding muscle length and tension to the controlling centers in the cortex and subcortical units as well as to the cerebellum.

Kinesthetic sensors measure joint movements, and somatic sensors in the skin provide information about temperature, pressure, and pain.

3.3.1.5 Bones, Joints, Tendons, and Ligaments

The bones, joints, tendons, and ligaments serve as an integrated support frame for the body and provide an attachment point for the muscles. The bones are connected by a complex arrangement of connective tissue to form a custom-fitted joint that provides a flexible yet stable connection with a wide range of motion. As the muscles contract, they transmit their forces to the bones through the tendons, thereby causing the bones to move around the joints.

There are three classes of joints: fibrous, cartilaginous, and synovial [4]. Most body movements take place around the synovial joints. There are six types of synovial joints: hinge, pivot, ellipsoid, ball-and-socket, plane, and saddle joints. Examples of these joints are found in the elbow, neck, wrist, shoulder, between the bony arches of the vertebrae, and at the base of the thumb. The type of motion and the maximum range of motion of the body segment possible at the synovial joint are dependent upon the shape of the articulating bones, the strength and the orientation of the surrounding ligaments, and the size and strength of the muscles.

The muscles are attached to bones by collagen fibers called tendons. Tendons have strong tensile characteristics but do not possess contracting properties. Tendons are instrumental in transmitting forces generated by the contracting muscles. For example, finger motions

TABLE 3.2 Segment Movements and Muscles Used in Making Those Movements

Body Movement	Agonist	Antagonist
Elbow flexion	Biceps brachii	Triceps brachii
Shoulder abduction	Deltoid	Pectoralis
Spinal extension	Erector spinae	Rectus abdominus
Hip flexion	Psoas, iliacus, rectus femoris, pectineus, tensor fascia	Gluteus maximus and hamstring

are caused by the force transmitted by the long tendons attached to the contracting muscles in the lower arm (between the elbow and the wrist).

Movements of the body segments around the articulating joint surfaces have been given specific names. In general, when the angle between two attached bone segments decreases during a movement, the movement is called *flexion*, and when the angle between the two attached bone segments increases, the movement is called *extension*. When the movement of a limb is away from the midline of the body, the movement is called *abduction*, and when the movement is toward the midline of the body, the movement is called *adduction*. *Pronation* and *supination* movement occur when a body segment undergoes a rotation about its long axis. Pronation or medial rotation is a movement toward the center of the body, whereas supination or lateral rotation defines a movement away from the center of the body. Table 3.2 provides some examples of body movements and the corresponding muscles producing those movements.

3.3.2 Motor Control

3.3.2.1 Motor Programs

Learned tasks, such as touching your nose, standing on one foot, or hitting a baseball, are controlled by overall motor plans that are stored in the central nervous system. These programs provide the proper sequence of motor activity needed to coordinate a specific planned motor function. It is important to note that the motor program must not only provide motor signals to initiate a specific movement but must also provide the motor signals needed to maintain posture. Complex, multijoint movement patterns are difficult to learn, because they are composed of numerous nested subprograms of varying complexity. On the other hand, some neural patterns are repeated so frequently that they may function without external timing cues or sensory input. These programs are sometimes referred to as central pattern generators. Motor activity is monitored by sensory receptors, and the status of the system is relayed to the central nervous system, where the motor program may be altered. Additional neural networks within the spinal cord may modify the motor signals through a feedback system of reflexes.

3.3.2.2 Reflexes

The neuromuscular system has the capability of rapidly adjusting motor function as a result of sensory input through highly developed neural circuits or reflex pathways. These reflex pathways consist of efferent motor neurons, afferent sensory neurons, and interneurons that link and integrate the signals between the sensory and motor neurons. A reflex can be thought of as a negative feedback control system that results in a stereotyped motor response to a sensory stimulus. A number of reflexes have been identified, such as the antigravity reflex for assistance in standing, the stretch reflex for maintaining constant muscle length (demonstrated by the knee tendon jerk test), the flexor and crossed-extensor reflexes that provide a matched response of leg withdrawal to painful stimuli and a resultant extension of the opposite leg, and the reciprocal inhibition reflex that turns the antagonist muscle off during a motor function. It is the network of interneurons in the spinal cord that integrates the control signals from the brain and the afferent signals from the sensory receptors to produce a flow of triggering signals to the muscles. The motor neurons, however, are the final common pathway for muscle activation.

3.3.2.3 Static and Dynamic Contractions

Muscles perform two basic types of tasks: dynamic body segment movement and the holding of body segments in static postures. Concentric contractions involve shortening of the muscles, causing a movement such as lifting a box. Eccentric contractions involve lengthening of an actively contracting muscle, such as the controlled lowering of a weight on a glass surface. In this case, the active muscle is controlling the rate and the motion under the action of the external force of gravity. A static contraction is performed when a posture is maintained without any movement. This type of contraction can cause rapid muscle fatigue due to poor blood circulation and the buildup of metabolites and waste products in the muscle. Most body movements or sustained postures require the use of more than one muscle.

3.3.2.4 Recruitment and Rate Coding

To allow for a wide range of muscle force levels, two physiological mechanisms are used to control the amount of force generated by a muscle: recruitment and rate coding.

Recruitment is defined as the number of motor units involved in the muscle contraction, and *rate coding* is defined as the frequency of discharge of the motor neurons. For slow contractions, such as postural control, the small, slow, fatigue-resistant motor units are recruited first, and the larger, fast, fatiguable motor units are recruited as the desired movement becomes faster or more powerful. Rate coding is used to modulate the force level by increasing the discharge rate as more force is needed. In general, for powerful contractions, all of the motor units are recruited before maximum discharge rates are reached.

3.3.3 Types of Movements

When the decision has been made to move one or more body segments, the neuromuscular system must choose which muscles to turn on, when they should be turned on, and how much force each muscle should develop. Since a wide range of activation sequences, muscle combinations, movement speeds, and motion trajectories could be used to achieve a desired movement, a predictable set of movement strategies must exist in order to optimize the efficiency of the movement. In general, complex movements can be resolved into simpler individual movements that are controlled by the agonist and antagonist muscles, which work together to achieve a specified movement. In a typical movement, for example, the agonist muscle contracts first to initiate the rotation of the segment about the joint at the proper velocity, and a short time later the antagonist muscle contracts to slow or stop the motion of the segment. In broader terms, the accuracy and speed of a movement dictate the selection and sequencing of the muscles, but postural constraints and system equilibrium must also be considered.

A number of goal-directed movement strategies have been proposed. Some of these strategies are based on the method of excitation control. For example, speed-dependent movements are modulated by the excitation amplitude, whereas speed-independent strategies are modulated by the excitation duration [8]. In some movements, coactivation of the agonist and antagonist muscles is needed to increase joint stiffness to stabilize the joint when it is exposed to high inertial loading. Significant coactivation has been shown in the spine for dynamic movements [9]. The stretch–shorten cycle has been proposed as another strategy for controlling movement. The stretch–shorten cycle is a linked eccentric–concentric contraction designed to use the additional force generated by a muscle when it is contracting eccentrically (lengthening), which is helpful in high-performance movements. Also, synergistic muscle action (cooperating agonists) may be used to assist in the development of the proper segment velocities.

3.3.4 Assessing Neuromuscular Function

3.3.4.1 Electromyography

When a muscle is activated, it creates an electric discharge (myoelectric signal) that can be measured directly from the muscle or through an electrode attached to the surface of the skin. Measurement and recording of these signals is called electromyography (EMG). These electric signals provide information about the intensity and duration of the contraction. Although the activity of individual motor units can be measured with needle and fine wire electrodes, surface electrodes are typically used to measure the activity of whole muscle groups. In this case, the measured signal is the summation of all the active motor units within the recording area of the electrodes. Under certain conditions, EMG activity can be used to measure the magnitude of the force being developed in a selected muscle group. Care must be taken, however, in determining muscle force from EMG activity, due to the length–tension and velocity–tension characteristics mentioned previously. For more information about making EMG measurements, the National Institute for Occupational Safety and Health has published a users' manual [10].

3.3.4.2 Evoked Potentials

Evoked potentials are electric signals initiated in a neural pathway by the application of an external stimulus (electric pulse) to a motor or sensory component to determine the functional status of the pathway of interest. Measurement of the amplitude or conduction velocity of an evoked potential along a neural pathway is useful in evaluating the function of the sensory or motor system. For example, visual or auditory evoked potentials can be used to assess the function of the optic or auditory nerve, and somatosensory evoked potentials can be used to assess the function of the various peripheral nerves. Multiple stimulations are required to measure evoked potentials from the skull because the signals must be averaged to remove the random electroencephalographic (EEG) activity of the brain.

3.3.4.3 Postural Stability

When a person is standing upright, the neuromuscular system provides motor control to the musculature of the supporting limbs to maintain a stable posture. These fine motor contractions result in a small natural oscillation or swaying of the body. Techniques for measuring the extent of this natural swaying are discussed in Chapter 4. It has been shown that the natural swaying of the body is modified in clinical and neurological disorders, such as in humans exposed to neurotoxic industrial chemicals and by man-made drugs and physically fatiguing tasks [11–14]. Excessive body sway could very well interfere with the safe performance of tasks and may jeopardize safety in the workplace. Successful application of this method has been illustrated for workers exposed to chemicals that affect the neurological system and may impair their balance, making them sway more than members of an unexposed population [14].

3.3.4.4 Muscular Strength Measurement

Strength is a measure of the maximum force that can be produced by a single muscle or by a series of muscles under prescribed conditions. Owing to the voluntary nature of the test, it is usually thought of as the maximum voluntary contraction level. Standardized tests have been developed for measuring static (isometric) strength as well as dynamic (isokinetic and isoinertial) strength. Recall that muscle force is a function of the resting length of the muscle, the velocity of contraction, and the direction of motion. Thus, muscle strength measures depend upon the position of the body and the type of motion occurring at the time of measurement. Maximum strength values have been published for a wide range of test conditions. For more information on assessment of strength, see the chapter on physical work capacity in this book or refer to studies reported in the literature [15,16].

3.3.4.5 Kinesiology

In its broadest sense, the term *kinesiology* refers to the study of movement. In the context of this chapter, however, kinesiology is the measurement and analysis of human motion and the way in which it relates to the musculoskeletal system that generates those movements. Kinesiological measurements are important to understand musculoskeletal functions such as gait, posture, and static and dynamic muscle action. Kinesiology, which is closely related to biomechanics, is useful for identifying abnormalities in musculoskeletal function (see Chapter 4). For example, movement requirements can be analyzed and used to assess work demands in ergonomics, motion patterns can be compared to normative patterns to assist the clinician in diagnosing neuromuscular dysfunction, and kinematic measurements may be used to improve athletic mechanics.

Measurement techniques are available for either 2- or 3-D analysis. 2-D kinesiological measurements may be made with a simple goniometer (a device designed to measure the relative rotation of a given joint) or with a video camera and markers placed at the joints of interest. The linear translation, velocity, and acceleration of the given joint as well as the relative angle between the segments and the rotation velocity and acceleration of the segments can then be obtained from a frame-by-frame analysis of the videotape. 3-D measurements are usually complex and require sophisticated methods for acquiring and analyzing the kinesiological data. A full description of kinesiology is beyond the scope of this chapter. For more information, refer to studies reported in the literature [15,17,18].

3.3.4.6 Tremor

The muscular contraction needed to move a body part or maintain it in a fixed position is accompanied by small, arrhythmic, involuntary oscillations in the muscle forces that are not visible to the untrained eye. These muscle oscillations are referred to as *physiological tremor*. When muscles become fatigued or damaged, the physiological tremor increases, and large-amplitude monorhythmic oscillations are observed. Musculoskeletal function can thus be assessed by measuring the amplitude and frequency of these oscillations. Findley and Capildeo [19] have edited a book that describes methods of assessing movement disorders from tremor measurements. In addition, Galinsky et al. [20] describe a portable device that can be used to measure tremor in a field environment.

3.3.5 Metabolic Considerations

As mentioned previously, the basis of muscular contraction is the transformation of chemical energy derived from food taken into the body into useful mechanical energy in the form of muscular contractions. To achieve this transformation, high-energy phosphate compounds, such as adenosine triphosphate (ATP) and phosphocreatine (PCr), provide the chemical energy needed for muscular contractions. These high-energy-yielding compounds are crucial in both aerobic metabolism (metabolic processes that use oxygen) and anaerobic metabolism (metabolic processes that occur without oxygen).

3.3.5.1 Functional Fiber Types

Because a whole muscle is required to operate across a wide range of exertion conditions, it is composed of a mixture of different functional types of muscle fibers. Based on the amount of time it takes a muscle fiber to reach its peak tension, two types of muscle fibers have been identified: slow (Type I, or red) and fast (Type II, or white). The slow fibers, which take 80–100 ms to reach peak tension, have more myoglobin and rely on aerobic metabolism. They do not fatigue easily, and therefore a task can be maintained over long periods (e.g., endurance running activities). The fast fibers, which usually take about 40 ms to reach peak tension, have higher concentrations of glycolytic enzymes and glycogen and rely on anaerobic metabolism. The fast fibers fatigue easily, but they are best suited for strong and quick body movements (e.g., weight-lifting activities). The exact reasons behind the nature of the functional behavior of these fibers are still not clear. The literature suggests that the type of nerve fibers that innervate these muscle fibers dictate their functional behavior [2]. The slow muscle fibers are innervated by small-diameter, low-conduction velocity nerve fibers, whereas the fast muscle fibers are innervated by large-diameter, high-conduction velocity nerves. The slow fibers are always active at low levels of contraction, providing a sustained tonic muscle activity such as that required for maintaining posture of the body. The fast fibers are only active during strong movements of the body segments. Most body motions require a combination of slow and fast motor activities. For example, a hand–wrist manipulative task of using a screwdriver above head level may require slow unit activity of the shoulder muscles to stabilize the posture of the arm, but fast units of the hand wrist muscle are needed to turn the screwdriver. A muscle may consist of anywhere between 10% and 90% of any one type, but most muscles have a relatively even distribution (soleus muscle may range as high as 70% Type I).

3.3.5.2 Aerobic Metabolism and Bloodflow

Muscular exertions requiring aerobic metabolism need ample blood flow to carry oxygen to the tissues and to carry away metabolic by-products. Therefore, it is essential that blood flow be maintained to muscles with high workloads. When a muscle is contracted at high tonic levels, such as when a sustained static posture is required, the muscle contractions may inhibit adequate blood flow, thereby reducing the capability for aerobic metabolism. From an ergonomic perspective, it is important to limit static postures so that physiologic function is not compromised.

Maximum aerobic power, which is defined as the highest oxygen uptake an individual can attain during exercise, is a measure of the capability of the cardiovascular system to provide oxygen to the muscles for aerobic metabolism [3]. Maximum aerobic power has been measured as high as 7.4 L/min for a male and 4.5 L/min for a female cross-country skier [3]. The mean for an industrial population would be about 3.0 L/min for men and about 2.0 L/min for women [3,16]. Refer to Chapters 2 and 9 in this book for more information on maximum aerobic power, physical work capacity, and cardiovascular capacity.

3.3.5.3 Anaerobic Metabolism

During activities requiring strong muscular contractions, anaerobic metabolism plays a crucial role in providing energy to the muscles. Energy is provided to the muscles by the anaerobic breakdown of ATP, PCr, and glycogen in a lactic phase. It is difficult to measure an individual's capacity for anaerobic metabolism, but it is known that there is limited capability to sustain high workloads due to the limited supply of energy-yielding substrates. High sustained workloads will result in the buildup of high concentrations of lactate in the muscle, which is removed by the circulatory system. When a muscle has depleted its stores of anaerobic substrate and the workload is higher than about 50% of the maximum voluntary contraction, the muscle may begin to lose strength and become fatigued.

3.3.5.4 Oxygen Debt

During the recovery period following exercise, the amount of oxygen consumed in excess of the resting value is called *oxygen debt*. The higher the exercise level or workload, the higher is the level of oxygen debt incurred. In an exhaustive workload, the energy demand is not met adequately by aerobic metabolism; therefore, anaerobic energy production provides the necessary energy, causing lactic acid to build up. In other words, the more strenuous the workload, the longer it takes to achieve preexercise-level metabolism. Therefore, the concept of oxygen debt is critical in the design of a work (i.e., exercise) and rest regimen so that a task can be performed without experiencing fatigue. The literature provides recommendations of work–rest regimens using the principles of oxygen consumption and oxygen debt [3,16].

3.3.5.5 *Local Muscle Fatigue*

Static as well as dynamic muscular contractions can result in local muscle fatigue. Local muscle fatigue occurs when the endurance time for the muscle is exceeded. The endurance time for a muscle is dependent on the amount of force developed by the muscle as a percentage of the maximum force attainable by the muscle. For example, a muscle can sustain a force of about 15% of its maximum indefinitely without becoming fatigued, but it can sustain 50% of its maximum force for only about 1 min [3]. Similarly, a muscle can sustain a repetitive contraction rate of about 30 contractions/min if the force is about 60% of maximum but can sustain a rate of only about 10 contractions/min if the force is about 80% of maximum [3].

3.3.5.6 *Whole Body Fatigue*

When the metabolic demands of dynamic and sustained activity exceed the energy-producing capacity of a worker, muscle contraction is affected and whole body fatigue is usually experienced. Physiologists generally recommend that energy expenditure not exceed about 50% of maximum aerobic power for 1 h of work, about 40% for 2 h of work, and about 33% for 8 h of continuous work [21]. These values are designed to prevent fatigue, which is believed to increase a worker's risk of musculoskeletal injury. Intervals of heavy, continuous work should be separated by light duty jobs, so that recovery can occur. For more information on whole body fatigue, refer to Astrand and Rodahl [3] and McArdle et al. [22].

REFERENCES

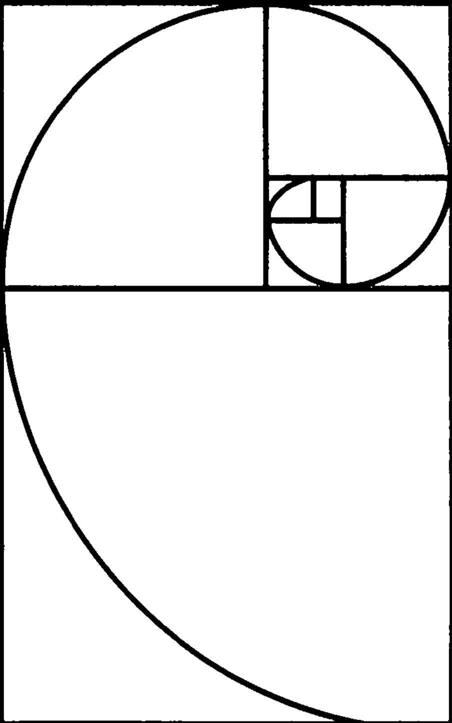
1. A. J. Vander, J. H. Sherman, and D. S. Luciano, *Human Physiology: The Mechanism of Body Function*, McGraw-Hill, New York, 1970.
2. A. C. Guyton, *Function of the Human Body*, Saunders, Philadelphia, PA, 1969.
3. P. Astrand and K. Rodahl, *Textbook of Work Physiology*, McGraw-Hill, New York, 1986, pp. 19, 115, 334.
4. B. Tyldesley and J. I. Grieve, *Muscles, Nerves and Movement: Kinesiology in Daily Living*, Blackwell Scientific, London, U.K., 1989.
5. A. M. Burt, *Textbook of Neuroanatomy*, Saunders, Philadelphia, PA, 1993.
6. J. Dudel, in *Fundamentals of Neurophysiology*, R. F. Schmidt, Ed., Springer-Verlag, New York, 1978, Chapter 5, pp. 129–137.
7. V. B. Brooks, *The Neural Basis of Motor Control*, Oxford University Press, New York, 1986.
8. R. M. Enoka, *Neuromechanical Basis of Kinesiology*, Human Kinetics, Champaign, IL, 1988.
9. W. S. Marras, Toward an understanding of dynamic variables in ergonomics, *Occup. Med.: State Rev.* 7(4):655–677 (1992).
10. DHHS(NIOSH), *Selected Topics in Surface Electromyography for Use in the Occupational Setting: Expert Perspectives*, Department of Health and Human Services, National Institute for Occupational Safety and Health, Cincinnati, OH, 1992.
11. A. Bhattacharya, R. Shukla, K. Dietrich, and R. Bornschein, Effect of early lead exposure on the maturation of children's postural balance: A longitudinal study, *Neurotoxicol. Teratol.* 28:376–385 (2006).
12. R. Seliga, A. Bhattacharya, P. Succop, R. Wickstrom, D. Smith, and K. Willeke, Effect of workload and respirator wear on postural stability, heart rate and perceived exertion, *Am. Ind. Hyg. Assoc. J.* 52(10):417–422 (1991).

13. A. Bhattacharya, R. Shukla, E. Auyang, K. N. Dietrich, and R. L. Bornschein, Effect of succimer chelation therapy on postural balance and gait outcomes in children with early exposure to environmental lead, *Neurotoxicology 28*:686–695 (2007).
14. J. S. Standridge, A. Bhattacharya, P. S. Succop, C. Cox, and E. Haynes, Effect of chronic low level manganese exposure on postural balance: A pilot study of residents in southwest Ohio, *J. Occup. Environ. Med. 50*(12):1421–1429 (December 2008).
15. D. B. Chaffin, G. B. J. Andersson, and B. Martin, *Occupational Biomechanics*, 4th edn., Wiley, New York, 2006.
16. Eastman Kodak, *Kodak's Ergonomic Design for People at Work*, John Wiley & Sons Inc., Hoboken, NJ, 2003.
17. P. Allard, I. A. F. Stokes, and J. P. Blanchi (Eds.), *Three-Dimensional Analysis of Movement*, Human Kinetics, Champaign, IL, 1995.
18. W. J. Vincent, *Statistics in Kinesiology*, Human Kinetics, Champaign, IL, 1995.
19. L. J. Findley and R. Capildeo (Eds.), *Movement Disorders: Tremor*, Oxford Press, New York, 1984.
20. T. L. Galinsky, R. R. Rosa, and D. D. Wheeler, Assessing muscular fatigue with a portable tremor measurement system suitable for field use, *Behav. Res. Methods, Instrum. Comput. 22*(6):507–516 (1990).
21. T. Waters, V. Putz-Anderson, A. Garg, and L. J. Fine, Revised NIOSH equation for the design and evaluation of manual lifting tasks, *Ergonomics 36*(7):749–776 (1993).
22. W. D. McArdle, F. I. Katch, and V. L. Katch, *Exercise Physiology: Energy, Nutrition, and Human Performance*, Lea & Febiger, Philadelphia, PA, 1981.

Occupational Ergonomics

Theory and Applications

Second Edition



edited by

Amit Bhattacharya
James D. McGlothlin

CRC Press
Taylor & Francis Group

Occupational Ergonomics

Theory and Applications

Second Edition

edited by
Amit Bhattacharya
University of Cincinnati Medical College
Cincinnati, Ohio
Co-Founder, OsteoDynamics, Inc.
Cincinnati, Ohio
James D. McGlothlin
Purdue University
West Lafayette, Indiana

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an informa business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

© 2012 by Taylor & Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works

Printed in the United States of America on acid-free paper
Version Date: 20120112

International Standard Book Number: 978-1-4398-1934-0 (Hardback)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (http://www.copyright.com/) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

ERGONOMICS AND HUMAN FACTORS

In the fifteen years since the publication of **Occupational Ergonomics: Theory and Applications**, significant advances have been made in this field. These advances include the impact of aging and obesity on workplace, the role of ergonomics in promoting healthy workplaces and healthy life styles, the role of ergonomic science in the design of consumer products, and much more. The caliber of information and the simple, practical ergonomics solutions in the second edition of this groundbreaking resource, though, haven't changed.

See What's New in the Second Edition:

- Enhanced coverage of ergonomics in the international arena
- Emerging topics such as healthcare ergonomics and economics of ergonomics
- Coverage of disability management and psychosocial rehabilitation aspects of workplace and its ergonomics implication
- Current ergonomics solutions from "research to practice"
- Synergy of healthy workplaces with healthy lifestyles
- Impact of physical agents on worker health/safety and its control
- Additional problems with solutions in the appendix

The book covers the fundamentals of ergonomics and the practical application of those fundamentals in solving ergonomic problems. The scope is such that it can be used as a reference for graduate students in the health sciences, engineering, technology, and business as well as professional practitioners of these disciplines. Also, it can be used as a senior-level undergraduate textbook, with solved problems, case studies, and exercises included in several chapters. The book blends medical and engineering applications to solve musculoskeletal, safety, and health problems in a variety of traditional and emerging industries ranging from the office to the operating room to operations engineering.

CRC Press
Taylor & Francis Group
an informa business
www.taylorandfrancisgroup.com

6000 Broken Sound Parkway, NW
Suite 300, Boca Raton, FL 33487
711 Third Avenue
New York, NY 10017
2 Park Square, Milton Park
Abingdon, Oxon OX14 4RN, UK

K11020
ISBN: 978-1-4398-1934-0
90000
9 781439 819340
www.crcpress.com