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Claude Ghez

The Control of Movement

The sensory systems provide an internal representation of the outside world. A major function of this representation is to extract the information necessary to guide the movements that make up our behavioral repertoire. These movements are controlled by a set of motor systems that allow us to maintain balance and posture, to move our body, limbs, and eyes, and to communicate through speech and gesture. In contrast to the sensory systems, which transform physical energy into neural information, the motor systems transform neural information into physical energy by issuing commands that are transmitted by the brain stem and spinal cord to skeletal muscles. The muscles translate this neural information into a contractile force that produces movements.

As our perceptual skills are a reflection of the capabilities of the sensory systems to detect, analyze, and estimate the significance of physical stimuli, so our agility and dexterity are reflections of the capabilities of the motor systems to plan, coordinate, and execute movements. The beautifully executed pirouette of a ballet dancer, the powered backhand of a tennis player, the fingering technique of a pianist, and the coordinated eye movements of a reader all require a remarkable degree of motor skill that no robot approaches. Yet once trained, the motor systems execute the motor program for each of these skills with ease, almost automatically.

The movements of which our motor systems are capable can be divided into three broad, overlapping classes: voluntary movements, reflex responses, and rhythmic motor patterns. These movements differ in their complexity and degree of voluntary control.

Voluntary movements, reading, manipulating an object, or playing the piano, represent the most complex actions. These movements are characterized by several features. First, they are purposeful. They may be initiated in response to a specific, external stimulus or to the will. Second, voluntary movements are goal directed. Finally, movements are largely learned and their performance improves greatly with practice. As these skilled movements are mastered with practice, they require less or ultimately no conscious participation. Thus, once you have learned to drive a car you do not think through the actions of shifting gears or stepping on the brake before performing them.

Reflex responses, the knee jerk, the withdrawal of a hand from a hot object, or coughing are the simplest motor behaviors and are least affected by voluntary controls. Reflexes are rapid, somewhat stereotyped, and involuntary responses that are usually controlled in a graded way by the eliciting stimulus.

Rhythmic motor patterns, walking, running, chewing, combine features of voluntary and reflex acts. Typically only the initiation and termination of the sequence are voluntary. Once initiated, the sequence of relatively stereotyped, repetitive movements may continue almost automatically in reflex-like fashion.

Muscles relax and contract in each of these classes of movements. Most movements occur at joints, where two or more bones form a lubricated contact point with low friction. Since individual muscles can only pull (they cannot push), separate sets of muscles are required at the opposite side of the joint, and use it as a fulcrum (Figure 36–15). Each movement at a joint thus brings into play two opposing sets of muscles: *Agonists,* the prime movers, are counterbalanced by the *antagonists,* which help to decelerate the moving limb.

Beyond simply contracting and relaxing, the motor systems need to carry out three additional tasks. First, the motor systems must convey accurately timed commands not only to *one* muscle group but to *many* groups, since even a simple movement, such as raising the arm, involves many different joints: the wrist, the elbow, as well as the shoulder. Second, the motor systems must consider the distribution of body mass and make postural adjustments appropriate for the particular movements to be executed. For example, while standing, our leg muscles must contract before we raise an arm, otherwise the arm movement would shift our center of gravity, causing us to fall. Finally, the motor systems must take into account the *motor plant:* the mechanical arrangement of the muscles, bones, and joints. With each movement the motor systems must adjust their commands to compensate for the inertia of the limbs and the mechanical arrangement of the muscles, bones, and joints being moved.

To integrate these three features into voluntary and reflex acts, the motor systems rely on two important and interrelated organizational features. One, the motor systems have available to them a continuous flow of sensory information about events in the environment, the position and orientation of the body and limbs, and the degree of contraction of the muscles. The motor systems use this information to select the response that is appropriate and to make adjustments in ongoing movement. Two, the components of the motor systems are organized as a hierarchy of control levels and each level is provided with that sensory information that is relevant for the functions it controls. Thus, higher levels concerned with strategic issues, such as the selection of a response appropriate to a specific goal, need not monitor the moment-to-moment sensory details of the response. This detailed sensory monitoring goes on at a lower level of the motor hierarchy.

In this chapter we introduce the study of movement by observing how different classes of movement are governed by these two organizational features—the flow of sensory information and the hierarchy of control levels. In later chapters we shall examine in detail the individual components of the motor systems and the pathways through which they act on motor neurons and muscles to produce purposeful motor activity. In addition, we shall also see how the motor systems function cooperatively to control the major classes of movements.

Sensory Information Is Necessary for the Control of Movement

The functioning of the motor systems is intimately related to that of the sensory systems. Experiments conducted in the 1950s by Richard Held and Allan Hein showed that when young kittens were passively moved about and not allowed to actively interact with their environment, they failed to develop the capacity to discriminate important visual cues. The proper moment-to-moment functioning of motor systems depends on a continuous inflow of sensory information. First, vision, hearing, and receptors on the body surface inform us about where objects are in space and our own position relative to them. Second, proprioceptors in the muscle, joints, and the vestibular apparatus inform the motor systems about the length and tension of muscles, the angles of the joints, and the position of the body in space. Both types of information are essential for planning movements and refining those that are in progress.

Sensory Information Is Used to Correct Errors Through Feedback and Feed-forward Mechanisms

When we reach for an object, the arm may initially be off course, but we can correct the end of its trajectory by a feedback process. Many man-made devices, such as thermostats and power steering, use similar feedback processes. How do these feedback mechanisms work? Both natural and man-made systems that use feedback mechanisms have sensors that monitor the outputs. These sensors provide a *feedback signal*, which is compared to a *reference signal* that indicates the desired output value (Figure 35–1A). With *negative feedback*, the feedback signal is subtracted from the reference signal by a device called a *comparator*, and the resultant error signal acts on a device called a *controller* to increase or decrease the output of the controlled system. Thus, in reaching for an object the controlled system is the arm and the difference between the actual position of the hand (feedback signal) and the position we intend for it (reference signal) should be brought to zero. If we do not reach the target, perhaps because an obstacle unexpectedly deflects the hand (disturbance), an error signal is sent to the controller, which issues another command to continue further in the same direction. If we overshoot, a command is emitted to move in the opposite direction.

Feedback can be used either to maintain or to modulate a variable such as position or force. When the variable is to be maintained around a set value, the reference signal remains constant, a process termed *regulation*. An example of regulation is the continued maintenance of a standing posture on a moving boat. Here motion of the support surface (the deck of the boat) is sensed in the feet and ankles and is used by postural mechanisms to maintain the body in a vertical position. In the nervous system feedback is limited to slow movements and to the control of sequential acts because the time taken to process sensory inputs is relatively long. For example, it may take several hundred milliseconds to respond to a visual cue (see Chapter 40) while a quick movement itself may last only 150–200 ms. It is therefore impossible to rely on feedback to catch a ball, or to reach for a rapidly moving object. In addition, when the effect of a feedback loop is very powerful—a condition referred to as a *high gain*—and there are long time delays, the system can readily be driven into an undesirable state of oscillation. This phenomenon is discussed in Chapter 37 in the context of spasticity.

Sensory events can often control motor action more effectively by providing *advance* rather than feedback information. Advance information can then be used to adjust the controlled variables before events occur that would influence them. This *feed-forward control* is essential in a wide variety of movements (Figure 35–1B). Consider the task of catching a ball. To catch the ball it is necessary to predict its trajectory and to place the hand at a point that will intercept its path. As is apparent in the example of catching a ball, the feed-forward control system must interpret visual cues correctly to tense the muscles in anticipation of impact and to set the position feedback correctly. This requires dynamic representations or *internal models* of both the ball's trajectory and the properties of the musculoskeletal system. (See Chapter 30).

These representations are updated by information from additional sensors that monitor changes in the state of the controlled system (labeled as state variables in Figure 35–1B). Proprioceptors in muscles and joints, which sense the length and tension of muscles and the angles of joints, are critical in providing state information to the motor system. However, vision and vestibular inputs are also quite important.

Although the same sensors may provide information for both feedback and feed-forward control, the way in which the information is processed is quite different. With feedback, error signals are computed continuously and control the ongoing response from moment to moment. As a result of the long conduction delay of neural impulses, biological feedback processes generally operate relatively slowly and are therefore used primarily to maintain posture and regulate slow movements. In catching a ball even the most rapid feedback responses would not prevent us from dropping it if we have incorrectly estimated the force of impact. On the other hand, such feedback is crucial for stabilizing the hand once the ball has been caught. In contrast, feed-forward systems, which are not affected by loop delays, operate more quickly. In contrast to feedback control, which operates continuously, feed-forward control is often triggered intermittently, and the resulting state is then reevaluated after the response is completed.

Patients with Impaired Sensation in the Limbs Show Deficits in Both Feedback and Feed-forward Control of Movement

The importance of proprioceptive inputs in the feedback and feed-forward control of posture and movement can be demonstrated dramatically by the motor deficits of patients with impaired proprioception. This occurs in a condition known as *large-fiber sensory neuropathy* in which

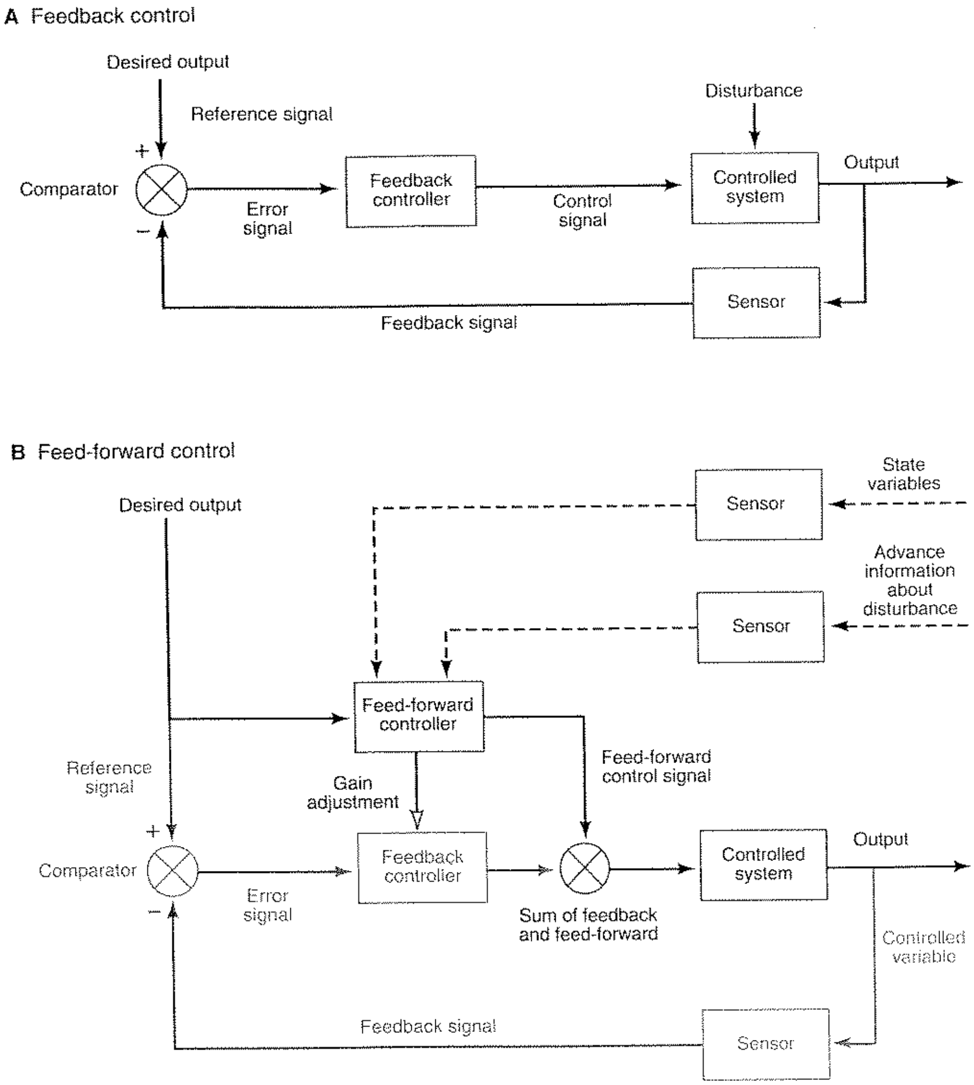

FIGURE 35–1
Feedback and feed-forward control circuits.

A. In a feedback system a feedback signal is compared to a reference signal by a comparator. In reaching slowly for an object, the arm is the controlled system and the intended position of the arm is the reference. The difference between the position of the hand and the reference should be brought to zero to execute the action properly. If the hand is unexpectedly disturbed, an error signal is sent to the controller and a command to continue in the direction of the target is issued. In a feedback system, error signals are monitored continuously to control the action from moment to moment. Feedback control is usually used for slow movements and to maintain posture.

B. Feed-forward control is essential for rapid movements and relies on advance information to adjust controlled variables. In catching a ball, advance information on the ball's trajectory and possible placement of the hand are advance information received by sensors and fed forward by the controller. Feedback control comes into play to position the hand properly after the ball is caught. Feed-forward control also monitors the system to deal with changes that take place over time, such as fatigue, through the mechanism of the adaptive controller.

the large afferent fibers that carry proprioceptive and tactile inputs degenerate. Unless they can see their limbs these patients cannot sense their position nor can they detect motion of their joints, because these sensations are mediated primarily by receptors in muscles and joints supplied by large-diameter fibers. Tendon reflexes are also absent because information from muscle spindles that triggers these reflexes does not reach the spinal cord. Finally, tactile sensation is impaired. Tactile feedback allows one to estimate contact with objects more precisely than does visual monitoring of the hand. When this feedback system does not function, manual dexterity is severely impaired even in such habitually performed tasks as writing or buttoning clothes. On the other hand, pain and temperature sensation are preserved since these modalities are carried by small-diameter afferent fibers.

Without proprioceptive feedback, patients can maintain their limbs in a steady position only when they can see them. When the patient attempts to hold the arm outstretched while closing the eyes, the arm starts to drift randomly after a few seconds (this is termed *pseudo-athetosis*). Similarly, if large axons are affected in the sensory nerves of the legs, the patient is unsteady when walking and falls if the eyes are closed (*Romberg's sign*). Proprioceptive feedback from the ankles is crucial for the control and maintenance of a standing posture (see Chapter 39).

Because loss of proprioceptive inputs provides the state information (including the angle and orientation of the joints) needed for feed-forward control, rapid movements to targets in space are profoundly inaccurate. Whereas normal subjects move their hands straight to a target even if they are prevented from monitoring the movement visually, patients with large-fiber neuropathy make large errors in both the direction and amplitudes of their movements. In addition, at the end of movement their hands do not stop in a stable position; their hands drift away even though the patients believe them to be stationary (Figure 35–2).

Vision can compensate for the loss of proprioceptive sensation through feed-forward as well as through feedback mechanisms. Thus, if the patient is allowed to see the limb *before* making the movement, the errors in direction and extent are much reduced, even when the patient is then prevented from seeing the limb *during* the movement itself. This inaccuracy therefore reflects defective feed-forward control. The errors in direction arise because the motor systems lack a precise representation of the state of the limb (its position in space and the tension of the different muscles) and its current properties. As a result they cannot select the muscles that are appropriate to move the limb in the desired direction.

The defects in feedback and feed-forward regulation also impair the ability to use vision effectively, even to control slow movement of the limbs. While normal subjects can make deliberate movements at a slow speed, stopping precisely at the desired end point, patients with large-fiber sensory neuropathy cannot (Figure 35–2C). These patients are unable to sense the resistance of the surface on which their hand is moving or the tension that is being developed by their muscles, and thus their movements are jerky. Errors in direction are improperly corrected because by the time visual feedback occurs the hand is in a new and unexpected position.

These deficits can be explained by means of the model illustrated in Figure 35–1B. In the deafferented patient the feed-forward controller receives incomplete information about the state of the limb. The nervous system therefore cannot construct an accurate internal model of the limb and cannot set the characteristics of either the feed-forward or the feedback controller. This results in errors in both the feed-forward control of direction, as a result of an incorrect selection of the muscles to be activated, and in the initial acceleration of movement. Once movement is in progress, errors in proprioceptive feedback produce oscillations and irregular movements.

There Are Three Levels in the Hierarchy of Motor Control

The Spinal Cord, the Brain Stem, and Cortical Motor Areas Are Organized Hierarchically and in Parallel

How do the motor systems integrate motor commands with ongoing sensory information so as to control the complicated mechanical machinery of musculoskeletal systems? This is achieved by distributing feedback, feed-forward, and adaptive mechanisms among three levels of motor control: the spinal cord, the descending systems of the brain stem, and the motor areas of the cerebral cortex (Figure 35–3). These different levels of the motor systems are organized both hierarchically and in parallel. The lower levels have the capacity to generate complex spatiotemporal patterns of muscle activation in the form of reflexes and rhythmic motor patterns. The hierarchical organization enables higher centers to give relatively general commands without having to specify the details of the motor action.

By means of their parallel organization, the motor systems can issue commands that can act directly on the lowest level of the chain to adjust the operation of reflex circuits. For example, the corticospinal tract controls pathways descending from the brain stem but, in addition, it also controls spinal interneurons and motor neurons directly. The combination of parallel and hierarchical mechanisms results in an overlap of different functional components of the motor systems, similar to that which we encountered in the sensory systems. This overlap is also important in the recovery of function after local lesions.

The lowest level of the hierarchy, the *spinal cord*, contains neuronal circuits that mediate a variety of automatic and stereotyped reflexes. These reflexes can function even when the cord is disconnected from the rest of the brain. At the beginning of this century Sherrington demonstrated that virtually all reflexes involve the integrated activation and inhibition of activity in different muscle groups. He suggested that many of these actions are coordinated by spinal interneurons. For example, both reflex withdrawal from noxious stimuli and the alternating activity in flexors and extensors during locomotion are organized by networks of spinal interneurons. Even simple descending commands can produce complex effects through these interneurons. It is now known that the same networks of interneurons that organize reflex behavior are also involved in voluntary movements. Ultimately, however, all interneuronal controls converge on the motor neurons that innervate the skeletal muscles. To stress the importance of this convergence, Sherrington called the motor neurons the *final common path*.

The next level of the motor hierarchy, the *brain stem*, contains three neuronal systems (medial, lateral, and

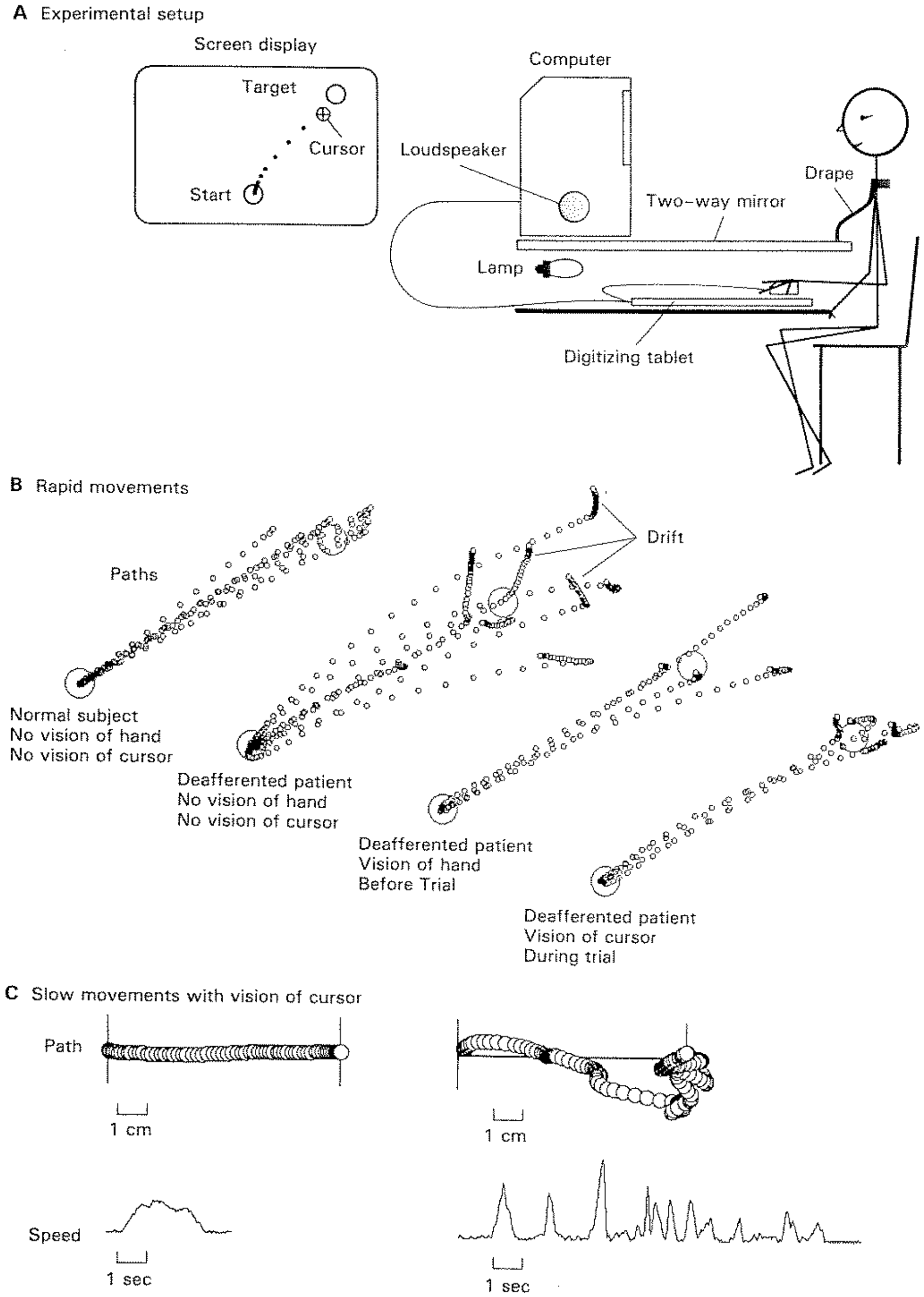

FIGURE 35–2
Patients with large-fiber sensory neuropathy make large errors in aiming and controlling their movements unless they can see their hands.

A. The subject is seated facing a computer screen and moves a hand-held cursor on a digitizing tablet. The position of the cursor on the tablet is displayed on the computer screen as a cross hair. Circular targets or lines to be traced are also displayed on the screen. Vision of the arm is made possible by turning on a lamp under the two-way mirror.

B. Accuracy of rapid arm movement made without visual feedback in a normal subject and deafferented patient. The subject is told to move the cursor rapidly from a start circle to a target, both shown on the screen. The screen cursor is blanked just before the subject's movement and shown again at the end of movement. Although target locations were varied randomly, movements to only one location are illustrated here. The small circles indicate successive positions of the hand every 20 ms. The normal subject correctly aims and carries out each movement without either viewing the screen cursor or his hand and maintains a stable position at the end of movement. The sensory-impaired patient shows marked variation in movement direction and extent and his hand drifts at the end of the movement. The directional errors and drifts are reduced if the patient can see the hand between trials. A similar degree of reduction occurs when the screen cursor remains visible.

C. Slow movements with visual feedback in normal and deafferented patient. The subjects are told to move the cursor slowly and regularly along a straight horizontal line on the screen (between the two parallel lines) while viewing the cross hair on the screen. The subject with intact sensation makes a slow movement and maintains his speed close to a steady value, whereas movements made by the deafferented patient are jerky, indicating multiple adjustments to errors in direction.

aminergic) whose axons project to and regulate the segmental networks of the spinal cord. The brain stem systems integrate visual and vestibular information with somatosensory inputs and play an important role in modulating spinal motor circuits in the control of posture (Chapter 39). In addition, brain stem nuclei control eye and head movements (Chapter 44).

The highest level of motor control consists of three areas of cerebral cortex: the *primary motor cortex*, the *lateral premotor area* (or premotor cortex), and the *supplementary motor area*. Each area projects directly to the spinal cord through the corticospinal tract as well as indirectly through the brain stem motor systems. The premotor and supplementary motor areas also project to the primary motor cortex. The lateral premotor and supplementary motor areas are important for coordinating and planning complex sequences of movement. Both areas receive information from the posterior parietal and prefrontal association cortices. We shall consider these areas in Chapters 40 and 53.

Three organizational features of the motor hierarchy are important. First, each component of the motor system contains somatotopic maps—spatial relations are preserved so that neurons that influence adjacent body parts are adjacent to each other. Moreover, this organization is important in the interconnections between different levels. Thus, regions of primary motor cortex that control the arm receive input from arm-control areas in the premotor cortex and, in turn, influence corresponding arm-control areas of the descending brain stem pathways. Second, each level of control receives information from the periphery, so that sensory input can modify the action of descending commands. Third, higher levels can control the information that reaches them by facilitating or suppressing the transmission of afferent input in sensory relay nuclei.

The Cerebellum and Basal Ganglia Control the Cortical and Brain Stem Motor Systems

In addition to the three hierarchical levels—spinal cord, brain stem, and cortex—two other parts of the brain also regulate motor function—the cerebellum and basal ganglia. The cerebellum improves the accuracy of movement by comparing descending motor commands with information about the resulting motor action. The cerebellum does this by acting on the brain stem and on the cortical motor areas that project directly to the spinal cord, monitoring both their activity and the sensory feedback signals they receive from the periphery. We shall examine this further in Chapter 43.

The basal ganglia receive inputs from all cortical areas and project principally to areas of frontal cortex that are concerned with motor planning. Diseases of the basal ganglia produce a range of motor abnormalities including loss of spontaneous movements, abnormal involuntary movements, and disturbances in posture. We shall discuss the physiology and diseases that affect the basal ganglia in Chapter 42.

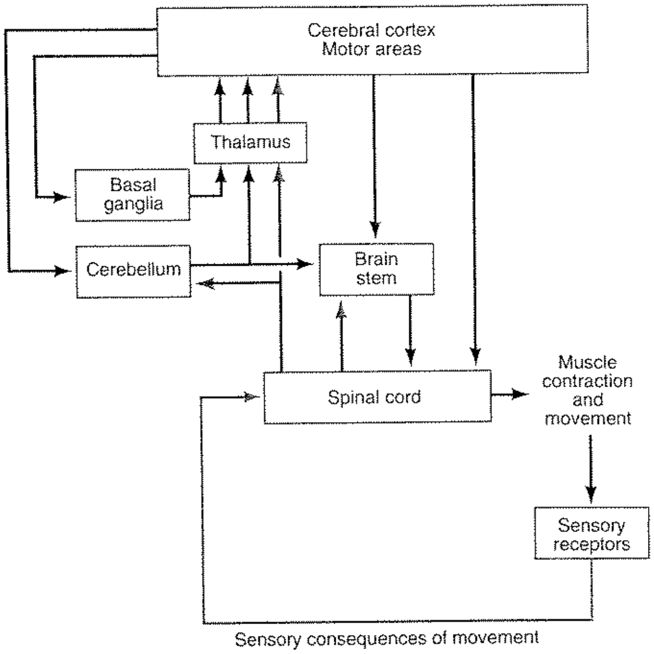

FIGURE 35–3
The motor system consists of three levels of control organized both hierarchically and in parallel. Thus, the motor areas of the cerebral cortex can influence the spinal cord both directly and through the brain stem descending systems. All three levels of the motor systems receive sensory inputs and are also under the influence of two independent subcortical systems: the basal ganglia and the cerebellum. Both the basal ganglia and cerebellum act on the cerebral cortex through relay nuclei in the thalamus.

We now turn to consider each of the three levels of the motor hierarchy.

Motor Neurons in the Spinal Cord Are Subject to Afferent Input and Descending Control

Spinal Motor Neurons Are Topographically Organized into Medial and Lateral Groups That Innervate Proximal and Distal Muscles

The cell bodies of motor neurons that innervate individual muscles are clustered in *motor nuclei*, or *motor neuron pools*, which form longitudinal columns extending over one to four spinal segments. The spatial organization of the different motor nuclei follows two important anatomical and functional rules: a *proximal–distal rule* and a *flexor–extensor rule*.

According to the proximal–distal rule the motor neurons innervating the most proximal muscles are located most medially, while those innervating more distal muscles are located progressively more laterally. The motor nuclei of axial muscles, innervating muscles of the neck and back, form a distinct group in the most medial part of the ventral horn that extends throughout the entire length of the spinal cord. In the lower cervical and lumbosacral spinal cord segments there is also a larger cluster of motor

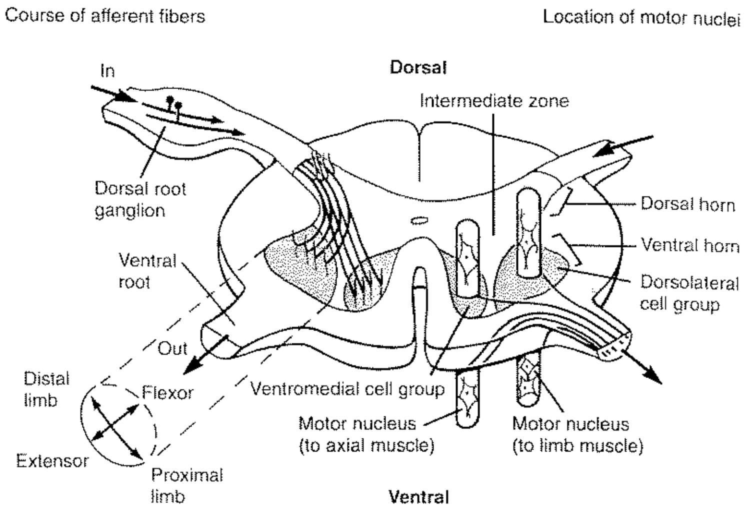

FIGURE 35–4
The motor nuclei of the spinal cord are grouped functionally in distinct medial and lateral positions. The medial group contains the motor neurons innervating axial muscles of the neck and back. Within the lateral group, the most medial motor neurons innervate proximal muscles while the most lateral innervate distal muscles. Ventrally located motor neurons innervate extensors while dorsal ones innervate flexors.

nuclei in the lateral part of the ventral horn. Within these groups, motor neurons innervating the proximal girdle muscles (the shoulder and pelvis) are medial, while those innervating the distal hand and foot muscle are lateral.

According to the flexor–extensor rule, motor neurons that innervate extensor muscles lie ventral to those innervating flexor muscles (Figure 35–4). These anatomical relationships account for an important functional distinction: Proximal muscles (especially the extensor muscles of the legs) are predominantly used to maintain equilibrium and posture, whereas distal muscles (especially those of the upper extremity) are used for fine manipulatory activities. We will now see that the medial and lateral motor neurons are controlled by separate populations of local interneurons, propriospinal neurons, and descending pathways.

The Terminations of Medial and Lateral Interneurons and Propriospinal Neurons Have Different Distributions

The fact that the most medial motor neurons innervate the proximal muscles and the most lateral motor neurons the distal muscles is also reflected in the organization of local interneurons and propriospinal neurons that terminate in more than one segment. The local interneurons in the most medial parts of the intermediate zone project to the medial motor nuclei that control axial muscles on both sides of the body, both ipsilaterally and contralaterally. More laterally located interneurons project only ipsilaterally to the motor neurons innervating girdle muscles, while the most lateral ones synapse on motor neurons that innervate the most distal ipsilateral muscles (Figure 35–5).

The axons of propriospinal neurons run up and down the white matter of the spinal cord and terminate both on interneurons and on motor neurons located several segments away from the cell bodies (Figure 35–5).[1] Axons of medial propriospinal neurons run in the ventral and medial columns, are longer, and may even extend the entire length of the spinal cord; more laterally placed propriospinal neurons interconnect a smaller number of segments and are topographically less diffuse. This pattern of organization allows the axial muscles, which are innervated from many spinal segments, to be coordinated during postural adjustment. In contrast, distal limb muscles, which tend to be used independently, are controlled by the more highly focused lateral propriospinal systems.

The Brain Stem Modulates Motor Neurons and Interneurons in the Spinal Cord Through Three Systems

Many groups of neurons in the brain stem project to the spinal gray matter. Based on their location and distribution in the spinal cord, Hans Kuypers classified these projections into two main pathways (see Figure 35–6). The *medial pathways* terminate in the ventromedial part of the spinal gray matter and thus influence motor neurons that innervate axial and proximal muscles. The *lateral pathways* terminate in the dorsolateral part of the spinal gray matter and influence motor neurons that control distal muscles of the extremities. A third system made up of the *aminergic pathways*, originates in nuclei in the brain stem and branches diffusely throughout the spinal cord.

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[1] The term *interneuron* is used here to indicate a spinal neuron whose main branches are confined to the same or adjacent spinal segment. Propriospinal neurons are spinal neurons whose main axon branches terminate in distant spinal segments. Some propriospinal neurons have branches that ascend outside of the spinal cord like the projection neurons of sensory and spinocerebellar tracts.

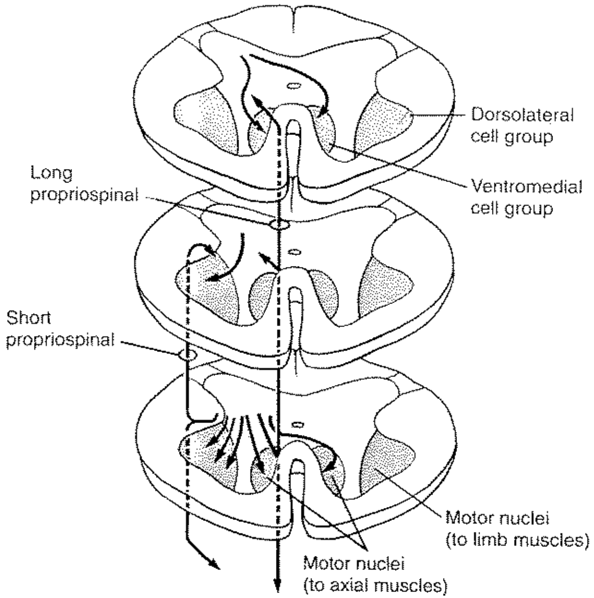


FIGURE 35–5
Medial motor nuclei are interconnected by long propriospinal neurons whereas lateral motor nuclei are interconnected by short propriospinal neurons.

Medial Pathways Control Axial and Proximal Muscles

The medial system has three major components: the vestibulospinal tracts (medial and lateral), the reticulospinal tracts (medial and lateral), and the tectospinal tract. These pathways descend in the ipsilateral ventral columns of the spinal cord and terminate predominantly on interneurons and long propriospinal neurons in the ventromedial part of the intermediate zone. They also terminate directly on some motor neurons, particularly those of the medial cell group, which innervate axial muscles (Figure 35–6A).

The medial and lateral *vestibulospinal tracts* originate in the vestibular nuclei and carry information for the reflex control of balance and posture from the vestibular labyrinth (see Chapter 40).

The medial and lateral *reticulospinal tracts* originate from several nuclei located primarily in the reticular formation of the pons and medulla (see Chapter 40). These systems have both excitatory and inhibitory connections with spinal interneurons and motor neurons. The reticulospinal systems are important for the maintenance of posture. They integrate information from a variety of inputs, notably the vestibular nuclei and cerebral cortex. Axons originating from the primary motor and premotor cortex synapse with reticulospinal neurons to form a *cortico-reticulospinal pathway.* This pathway is particularly important for the suppression of spinal reflexes and activity by motor cortical areas (see Chapter 39).

The *tectospinal tract* originates in the superior colliculus of the midbrain and is the only medial brain stem pathway to project contralaterally. However, it does not project lower than the cervical segments of the spinal cord. This system is important in coordinating head and eye movements and can be controlled from the cerebral cortex by means of a *cortico-tectospinal pathway.*

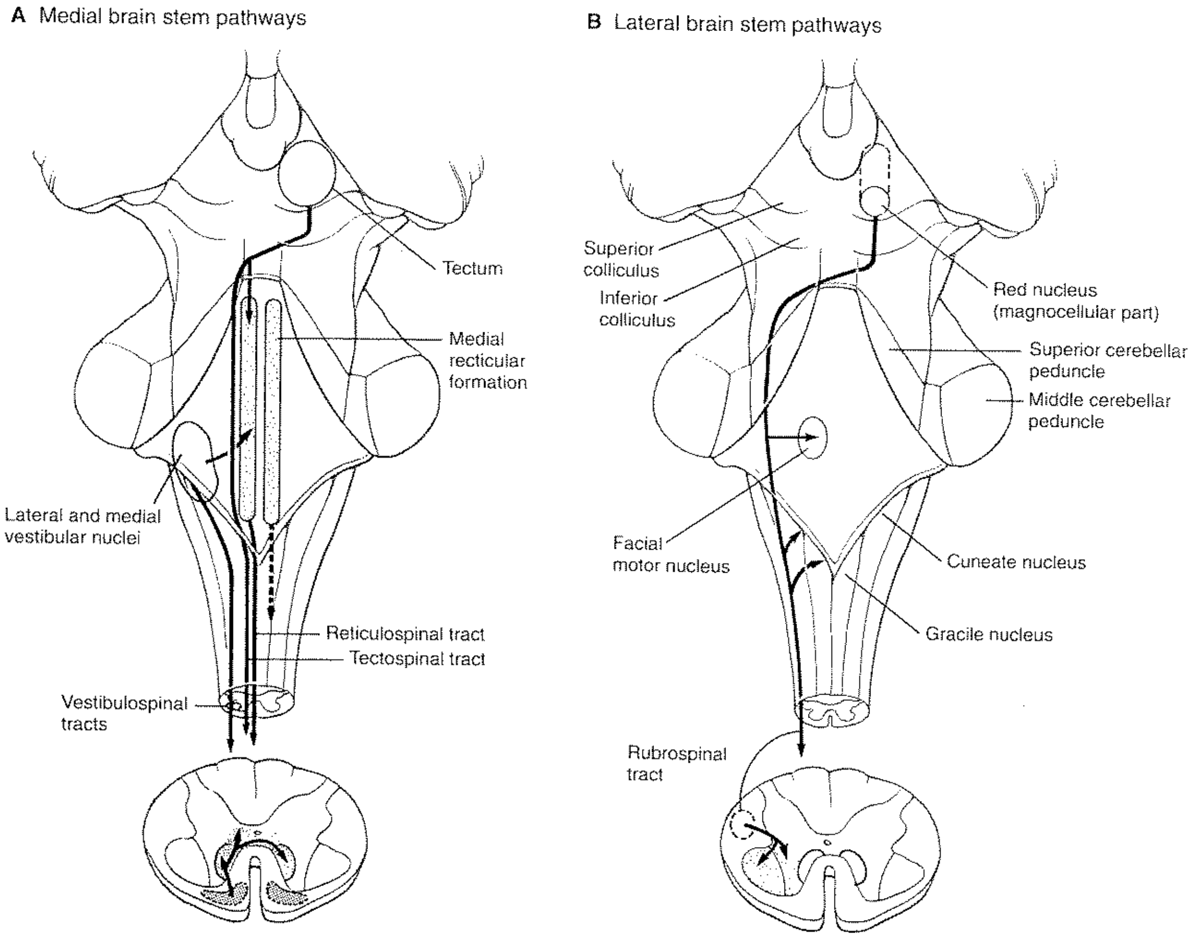
Lateral Pathways Control Distal Muscles

The column of fibers descending in the lateral quadrant of the spinal cord terminates in the lateral portion of the intermediate zone and among the dorsolateral groups of motor neurons innervating more distal limb muscles (Figure 35–6B). The main lateral descending pathway from the brain stem is the *rubrospinal tract,* which originates in the magnocellular portion of the red nucleus in the midbrain. Rubrospinal fibers descend through the medulla to the dorsal part of the lateral column of the spinal cord.

The difference in the distributions of the lateral and medial systems corresponds to their fundamentally different roles in motor function. The medial system is phylogenetically the oldest component of the descending motor systems. It is important in maintaining balance and posture, both of which rely on proximal and axial muscles. The wide area of termination of individual axons is important in distributing control to a variety of different motor nuclei that are functionally related. The medial pathways provide the basic postural control system upon which the cortical motor areas can organize more highly differentiated movements. The lateral pathways function in more varied ways by controlling distal muscles used in a variety of fine movements, such as reaching and manipulating objects with the fingers and hand. In anthropoid apes and humans, where the rubrospinal system is small and vestigial, this function is largely assumed by the corticospinal system.

Aminergic Pathways Modulate the Excitability of Spinal Neurons

Two sets of aminergic pathways send axons to the entire spinal cord. One, the *ceruleospinal system,* is noradrenergic. It originates in the locus ceruleus and from some neurons in the pontomedullary reticular formation and descends in the ventrolateral part of the lateral column. The other, the *raphe–spinal system,* is serotonergic. It originates from nuclei in the raphe of the brain stem and projects through both lateral and ventral columns (Chapter 44). Axons of both systems terminate in the intermediate zone and on motor nuclei throughout the spinal cord. Individual neurons send collaterals to many, and perhaps all, segments. The raphe–spinal system also projects to the outer layers of the dorsal horn, where it modulates the transmission of painful stimuli to projection neurons and spinal interneurons.



	Medial pathways	Lateral pathways
Brain stem	Extraocular motor neurons (III, IV, VI) X, IX (not illustrated)	Cranial nerve nuclei VII, VIII, XII Cuneate and gracile nuclei V
Spinal segments	Medial interneurons Long propriospinal neurons Medial motor neuron pools	Lateral interneurons Short propriospinal neurons Lateral motor neuron pools
Muscles	Proximal ≫ Distal Extensors > Flexors	Distal ≫ Proximal Flexors > Extensors

FIGURE 35–6
Two groups of descending brain stem pathways control different groups of neurons and different groups of muscles.

A. The main components of the medial pathways are the reticulospinal, the medial and lateral vestibulospinal, and the tectospinal tracts that descend in the ventral columns. These terminate in the shaded portions of the gray spinal matter.

B. The main lateral pathway is the rubrospinal tract, which originates in the caudal, magnocellular portion of the red nucleus. The rubrospinal tract descends in the contralateral dorsolateral column terminating in the shaded area of the spinal gray matter.

The Motor Cortex Acts on Motor Neurons Directly Via the Corticospinal Tract and Indirectly Through Brain Stem Pathways

The ability to organize complex motor acts and to execute fine movements with precision depends on control signals transmitted from the motor areas in the cerebral cortex through the corticobulbar and corticospinal tracts. The *corticobulbar fibers* control the cranial motor nerve nuclei, and thus the facial muscles, while the *corticospinal fibers* control the motor neurons innervating the spinal segments. Corticospinal axons act directly on motor neurons and interneurons. They also influence motor activity indirectly through the descending brain stem pathways, notably through cortico-reticulospinal and cortico-rubrospinal projections and other corticobulbar projections.

The Corticospinal Tract Is the Largest Descending Fiber Tract from the Brain

The corticospinal tract is a massive bundle of fibers containing about one million axons. About a third of these originate from the primary motor cortex located in the precentral gyrus of the frontal lobe (Brodmann's area 4). Electrical stimulation of the primary motor cortex evokes movements of different contralateral muscle groups. Another third of the corticospinal fibers originate from the premotor motor areas (area 6), a larger zone that lies rostral to area 4 in the frontal lobe. The remaining third originate in areas 3, 2, and 1 in the somatic sensory cortex and regulate the transmission of afferent input to control structures.

The corticospinal fibers course through the posterior limb of the internal capsule together with corticobulbar fibers to reach the ventral portion of the midbrain. As they descend through the pons the corticospinal fibers separate into small bundles of fibers that course between the pontine nuclei. The fibers regroup in the medulla to form the *medullary pyramid*, a conspicuous landmark on the ventral surface of the medulla. Because of this regrouping, the corticospinal tract is sometimes referred to as the pyramidal tract. This usage is incorrect, however, because some fibers leave the medullary pyramids to terminate in brain stem nuclei, such as the dorsal column nuclei.)

At the junction of the medulla and the spinal cord about three-quarters of the corticospinal fibers cross the midline in the *pyramidal decussation*. The crossed fibers descend in the dorsal part of the lateral columns (dorsolateral column) of the spinal cord, forming the *lateral corticospinal tracts*. The uncrossed fibers descend in the ventral columns as the *ventral corticospinal tracts* (Figure 35–7).

The lateral and ventral corticospinal tracts terminate in approximately the same regions of spinal gray matter as do the lateral and medial descending brain stem systems (Figure 35–7). The lateral corticospinal tract projects primarily to the motor nuclei of the lateral part of the ventral horn and to interneurons in the intermediate zone. The ventral corticospinal tract projects bilaterally to the ventromedial cell column, which contains the motor neurons that innervate the axial muscles and to adjoining portions of the intermediate zones.

The corticobulbar fibers that control muscles of the head and face terminate in both motor and sensory cranial nerve nuclei in the brain stem. In humans there are monosynaptic connections between corticobulbar fibers and motor neurons in the trigeminal, facial, and hypoglossal nuclei. The projections to the trigeminal motor nucleus are bilateral and approximately equal in size. Although the projection to the facial nucleus is also bilateral, the motor neurons innervating muscles of the lower face receive predominantly contralateral fibers. As a result, unilateral damage to corticobulbar fibers on one side produces weakness only of the muscles of the contralateral lower part of the face.

Cortical Control of Movement Is Achieved Only Late in Phylogeny

Phylogenetically, the corticospinal and corticobulbar pathways first appear in mammals. In the most primitive mammals the motor outflow from the cortex first appears as a mechanism that controls and adjusts sensory inflow to spinal interneurons and projection neurons. In the hedgehog the corticospinal tracts are located in the dorsal columns and terminate exclusively in the dorsal horn. Moreover, in hedgehogs and other primitive mammals the somatic sensory representations of the body surface in the cerebral cortex overlap with the motor representation.

Higher mammals have distinct sensory and motor representations of the body in the cortex and have additional corticospinal terminations within the intermediate zone of the spinal cord. With still further phylogenetic development, there is a gradual increase in the number of corticospinal fibers distributed to more ventral regions of the spinal cord, so that corticospinal neurons make direct connections to motor neurons in the lateral motor nuclei that control distal limb muscles and later, phylogenetically, also in medial motor nuclei. Thus, in the phylogeny of primates the number of corticospinal axon terminals ending on spinal motor neurons increases progressively from prosimians to monkeys, anthropoid apes, and finally to humans. In the more primitive primates direct connections are present only in the most dorsolateral cell groups innervating the most distal muscles, but in monkeys the entire lateral group of motor nuclei receives corticospinal input; in higher apes and humans, the medial motor nuclei also receive dense corticospinal terminations. In most carnivores corticospinal fibers terminate exclusively in the dorsal horn and dorsolateral parts of the intermediate zone and do not make any direct connections with motor neurons (Figure 35–8).

Lesions of the Cortical Motor Areas and Their Projections Cause Characteristic Symptoms

Lesions of cortical-motor areas or their projections are especially common in neurological practice. This is easy to understand because of the large size of these areas and because corticospinal axons extend from the cerebral cortex through the brain stem to the spinal cord, and can be damaged by lesions at any of these locations. The most common cause of the lesions is vascular occlusion producing *cerebral infarction*, neuronal cell death. The blood supply of the brain is discussed in Appendix B. Especially common are occlusion of the *middle cerebral artery* (whose branches supply the lateral surface of the cortex and the internal capsule) or of the *vertebrobasilar system*

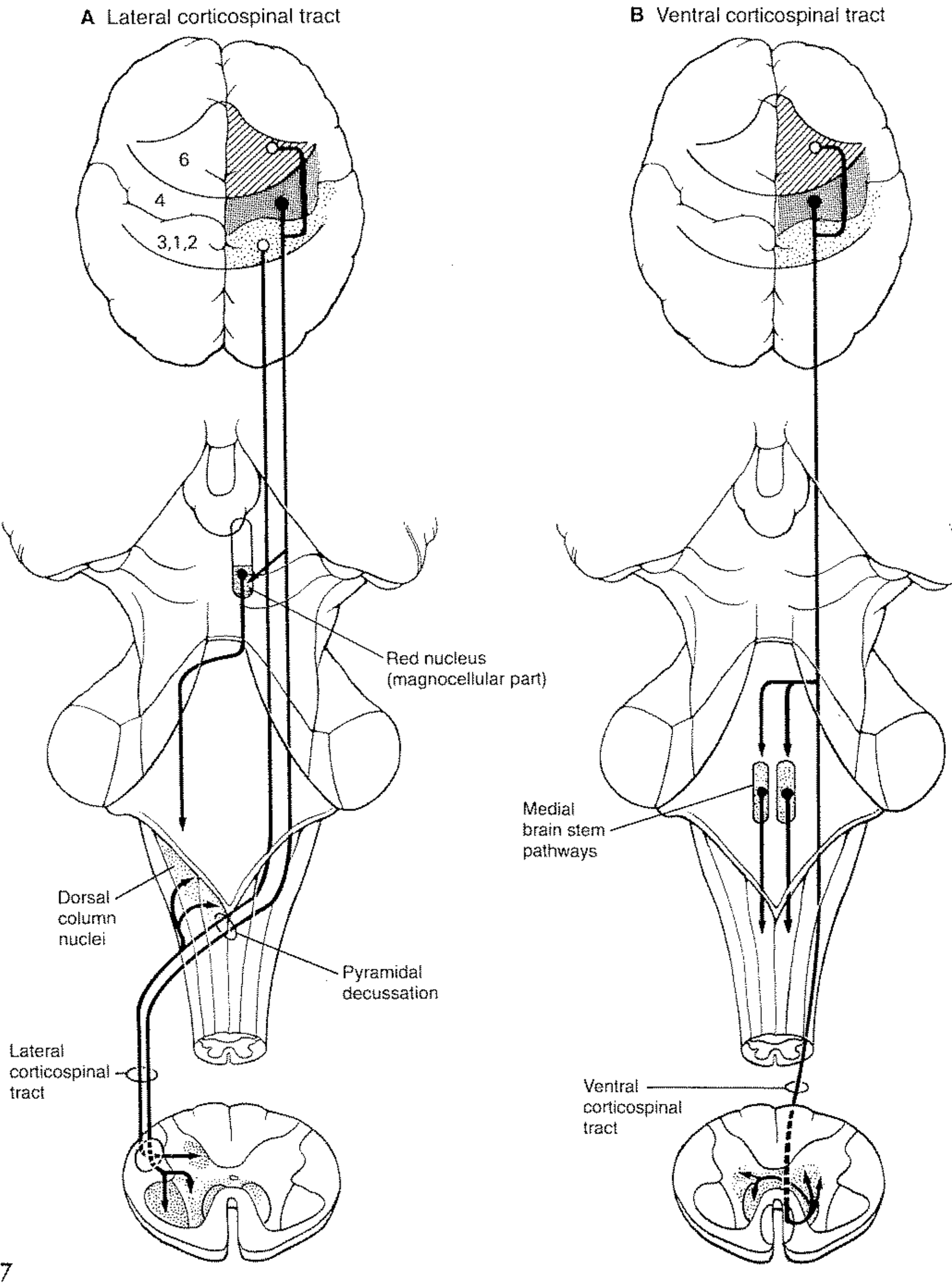


FIGURE 35–7
The descending cortical pathways to the spinal segments.

A. The crossed lateral corticospinal tract originates from Brodmann's areas 4 and 6, and sensory areas 3, 2, and 1. The tract then crosses at the pyramidal decussation, descends in the dorsolateral column, and terminates in the shaded area of spinal gray matter. Corticorubral neurons are mainly located in area 6. The principal area of termination of the corticospinal neurons originating from the sensory cortex is the medial portion of the dorsal horn. Collaterals project to dorsal column nuclei.

B. Uncrossed pathways (ventral corticospinal tract) originate principally in Brodmann's area 6 and in zones controlling the neck and trunk in area 4. Terminations are bilateral and collaterals project to the medial brain stem pathways.

(supplying the brain stem). Tumor, trauma, and demyelinating diseases are other common causes of damage to the corticospinal system.

John Hughlings Jackson first recognized that lesions of the nervous system give rise to two kinds of abnormal function, which he defined as *negative* and *positive*. Negative signs reflect the loss of particular capacities normally controlled by the damaged system, for example, weakness or loss of strength. Positive signs represent stereotyped abnormal responses that may emerge after the lesion. These *release phenomena* are explained by the withdrawal of inhibitory influences on normal interneu-

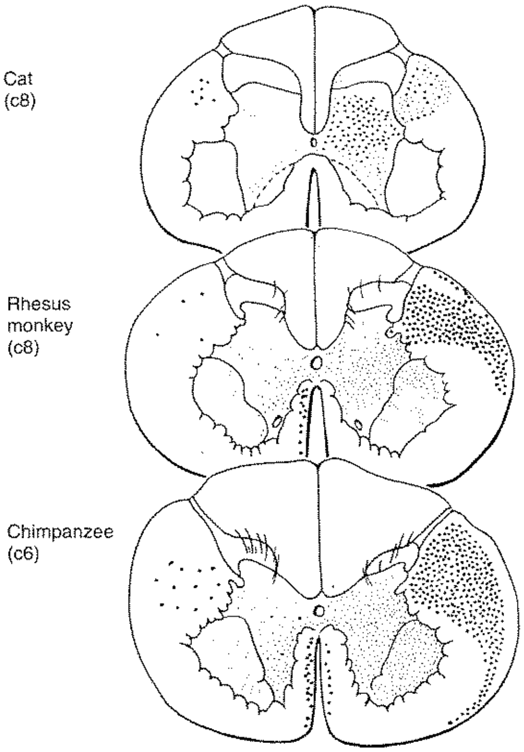


FIGURE 35–8
Cortical motor neurons in different species have different patterns of termination in the spinal cord. In the cat the corticospinal fibers terminate principally on neurons in the ventral parts of the dorsal horn and in the spinal intermediate zone. In lower primates, such as the rhesus monkey, most terminations remain in the intermediate zone but a small number also reach the motor neurons. In the more highly evolved primates, such as the chimpanzee and humans, where lateral brain stem pathways recede, there are extensive terminations throughout the contralateral intermediate zone and both medial and lateral motor neuron groups. A substantial ipsilateral fiber tract is also present and terminates primarily on proximal muscles important for postural control. (Adapted from Kuypers, 1985.)

ronal networks that mediate the responses. Examples of positive signs are the pathological reflexes seen with lesions of descending pathways or the involuntary movements that occur with certain lesions affecting the basal ganglia.

The extensor plantar reflex is an important positive sign of corticospinal damage and is widely used in clinical neurology. The sign was discovered in 1896 by the neurologist Joseph Babinski, then in charge of a ward of syphilitic patients at the Pitié Hospital in Paris. A form of this disease, meningovascular syphilis, produces vascular lesions of the brain that often affect the corticospinal tract. Babinski noted that the reflex response, elicited by stroking the lateral aspect of the foot with a sharp object, was different in patients with lesions of the corticospinal tract than in patients without such lesions. This stimulus normally produces flexion of all the toes, including the large one. In affected patients, however, there is a reflex extension of the big toe, which may be accompanied by fanning of the others (Figure 35–9).

William Landau and others have demonstrated that the extensor plantar response is actually an enhanced withdrawal reflex and is part of a larger family of responses to noxious stimuli that are released by pyramidal lesions. The appearance under pathological conditions of a reflex response that is normally absent illustrates clearly that central lesions can lead to both negative and positive signs: to the loss of some specific functions and to the release of others that are otherwise inhibited.

Muscle Weakness May Result from Disturbances in Descending Motor Pathways or in the Spinal Motor Neurons Themselves

Some pathological processes affecting motor nerves and central motor systems can cause muscle weakness by interfering with the output of spinal motor neurons. When diagnosing the cause of weakness clinicians must first determine whether the disturbance is at the level of the motor neuron or whether it reflects an abnormality in the balance of excitatory and inhibitory inputs to motor neurons, as may arise with lesions of descending pathways. As we have seen in Chapter 17, in clinical literature the motor neurons in the spinal cord and brain stem that innervate skeletal muscles of the body and head are often called *lower motor neurons.* The signs of direct damage to motor neurons (the *lower motor neuron syndrome*) differ from those produced by damage to descending pathways that clinicians call *upper motor neuron* syndrome.

The lower motor neuron syndrome results from dis-

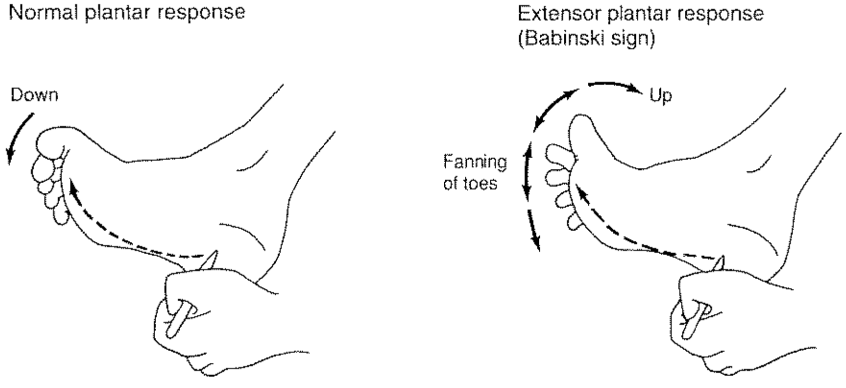


FIGURE 35–9
The Babinski sign is diagnostic of a lesion of the corticospinal tract. When the sole of the foot is stroked firmly along the path indicated, the normal response is flexion of the foot and toes. The Babinski sign is extension of the big toe and fanning of the others.

eases or lesions affecting the motor neuron at the level of the cell body or its axon. An example is poliomyelitis, a viral disease that attacks motor neurons in localized areas of spinal cord, causing weakness of small groups of muscles while nearby muscles may remain normal. Affected muscles often exhibit fasciculation (twitches of muscle fascicles under the skin) and atrophy (loss of muscle volume). The affected muscles always show decreased tone, and tendon reflexes are reduced or absent (see Chapter 18).

In the upper motor neuron syndrome there is damage or interference with the central excitatory drive to the motor neurons. Typically, the disturbance results from dysfunction of descending motor systems other than the corticospinal tract (see Chapter 40). In the upper motor neuron syndrome groups of muscles (synergists) are invariably all affected, atrophy is rare, and there are no fasciculations. In addition there is *spasticity*, a condition in which muscle tone and deep tendon reflexes are both increased (see Chapter 39).

Parallel Control of Motor Neurons Allows Recovery of Function Following Lesions

In primates the corticospinal system provides the only direct descending control over distal limb motor neurons. These connections endow higher primates with the ability to control individual muscles independently, a capacity known as *fractionation of movement*. This ability is completely and irretrievably lost following lesions of the corticospinal fibers in the medullary pyramid. Monkeys whose corticospinal tracts have been interrupted cannot grasp small objects between two fingers (the so-called precision grip) or make isolated movements of the wrist or elbow. When attempting to grasp a small object, the animal uses its hand as a shovel or contracts all the digits simultaneously around the object. These animals are able to maintain balance and can control axial and girdle muscles, however; therefore, they can walk and climb without difficulty.

The fact that several levels of control (segmental interneurons, brain stem, cortex) act on motor neurons contributes to the recovery of function that may occur after lesions of one or another component of the descending motor systems. For example, in monkeys, section of the medullary pyramids is immediately followed by severe weakness. With time, strength recovers; however, the animals are unable to move as rapidly as before. The weakness is much more severe if, in addition to damage of the primary motor area, the outflow from the premotor areas to the brain stem and spinal cord is also damaged.

Younger patients typically recover more muscle strength than do older ones. Several factors contribute to the amount of strength recovered, including the transfer of some of the functions of the corticospinal system to descending brain stem pathways, as well as the sprouting of other axons into the synaptic areas vacated by the degenerating corticospinal axons. If the connections from the primary motor cortex to lateral brain stem pathways are spared, the cerebral cortex can control limb muscles through cortico-rubrospinal and cortico-reticulospinal pathways. This anatomical reorganization is also much greater in neonatal and young animals than in adults. In higher primates the number of axons in the rubrospinal tract decreases substantially relative to that of monkeys and other species, and the degree of functional recovery following cortical lesions is correspondingly smaller.

An Overall View

Behavior involves the contraction of many muscles concurrently and is controlled by motor systems. These systems are hierarchically organized, so that spinal circuits for automatic reflex behaviors are subject to control from the brain stem and motor cortex. These three components—spinal cord, brain stem, and cortex—also function in parallel, so that any one set of controls can to some extent control movement independently of the other two.

Different parts of the motor system carry out distinct but interrelated functions. Thus, while the spinal cord and brain stem mediate reflexive and simple automatized voluntary responses, the cortical motor areas initiate more complex voluntary movements. The prefrontal motor cortex and basal ganglia are thought to be involved in the planning of movement and in large-scale coordination between body parts. The cerebellum is responsible for coordinating precisely timed activity by integrating intended motor output with ongoing sensory feedback.

Sensory information influences motor output in many ways and at all levels of the motor system. Sensory input to the spinal cord directly triggers reflex responses. It is also essential for determining the parameters of programmed voluntary responses. Finally, sensory input, especially proprioceptive information, is integral to both feedback and feed-forward mechanisms, which provide flexibility in the control of motor output.

Three distinct groups of pathways from the brain stem descend in the medial spinal cord to influence the activity of spinal motor circuits: the vestibulospinal, reticulospinal, and tectospinal pathways. The first two originate in the vestibular nuclei and reticular formation, respectively, and are involved in the control of posture and balance, which are mediated by motor neurons of axial muscles. The tectospinal pathway descends only as far as the cervical spinal cord and coordinates head and eye movements.

The corticospinal tract originates primarily in the frontal and parietal cortex. Pathways from the motor and premotor cortex and red nucleus descend in the lateral spinal cord to control the motor neurons that innervate distal muscles that are used in fine independent movements. These fibers pass through the internal capsule and make their way to the medullary decussation, where three-fourths cross the midline and become the lateral corticospinal tracts, while the remaining one-fourth becomes the ipsilateral medial corticospinal tract. The lateral tracts innervate distal motor neurons, while the fewer medial fibers innervate axial motor neurons.

Parallel descending motor pathways offer the advantage that if one pathway is lesioned, the remaining ones can to some extent take over its functions. For example, lesions in the corticospinal tract produce both negative signs (loss of function) and positive signs (release of function). Some of the deficits can, with time, be recovered by the remaining cortico-rubrospinal and cortico-reticulospinal tracts.

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Claude Ghez

Voluntary Movement

Voluntary movements differ from reflex movements in several important ways. First, the motor systems can use different strategies in different circumstances to achieve the same end. For example, when writing on a piece of paper we use primarily the fingers and wrist, but writing on a blackboard we use the arm and shoulder. Donald Hebb called this flexibility of strategy *motor equivalence.* Second, the effectiveness of voluntary movements improves with experience and learning. Thus, the precision of a reach or a throw increases and its variability decreases with practice. The muscle contractions of successive responses become more efficient as co-contraction and movement time decrease. Third, although voluntary movements may be evoked by sensory stimuli as are reflexes, an external stimulus need not precede them. Thus, the trajectory of our hand is the same when we reach for a real target or to its remembered or imagined location. The higher levels of our motor systems can therefore dissociate the information content of a stimulus—which tells us *where* or *how* to move—from its capacity to trigger movement—which tells us *when* to move. Moreover, many movements are initiated by thoughts or emotions as acts of will.

The neural events leading even to a simple voluntary movement, such as reaching for a glass of water, involve three complex processes. First, the glass is identified and its position located in space. Second, a plan of action is selected that will bring the glass to the mouth. To specify which body parts are needed and in what direction they are to be moved, the location of the glass must be assessed in relation to the position of the hand and body. This information allows the motor systems to determine the hand's trajectory. Finally, the response is executed. Commands are conveyed by the cortical and brain stem descending pathways to the final common pathway, the motor neurons. These commands specify the temporal sequence of muscle activation, the forces to be developed, and the changes in joint angles. In addition, while reaching, the hand and fingers are oriented to fit the contours of the glass, coordinating movements of the shoulder and arm with those at the wrist and digits so that the glass will be grasped on contact without delay.

These three phases, target identification, planning of action, and execution are governed by distinct regions of the cerebral cortex: the posterior parietal cortex, the premotor areas of the frontal cortex, and the primary motor cortex. We shall begin by considering the organization of the premotor and primary motor areas. There are distinct somatotopic motor maps within each of these motor areas. Then we examine how the primary motor cortex encodes the features of movements and how the premotor and association areas participate in planning movement and programming its various components.

The Motor Areas of the Cerebral Cortex Are Organized Somatotopically

In 1870 Gustav Fritsch and Eduard Hitzig provided the first direct evidence that distinct areas of the brain control movement on the contralateral side of the body. They discovered that electrical stimulation of different parts of the cortex of dogs produces contractions of different contralateral muscles. These observations were soon extended to monkeys by David Ferrier, who elicited movements of contralateral limbs by stimulating the precentral and postcentral gyri and movements of the eyes by stimulating the posterior parietal cortex. Alfred Leyton and Sherrington next discovered that in primates, motor effects are elicited most readily from the precentral gyrus. This region corresponds to Brodmann's area 4 and is now called the *primary motor cortex.*

The discovery that different areas of cerebral cortex control movements of different parts of the body had immediate clinical relevance. It explained why damage of different areas of the contralateral frontal lobe results in weakness of the face, arm, or leg. It also enabled clinicians to understand the mechanism of focal motor seizures. For example, the Jacksonian seizure, described by Hughlings Jackson, typically begins with a series of tonic and clonic involuntary contractions of muscles on one side, commonly the finger flexors. The contractions then gradually spread proximally to the wrist, then to the elbow, shoulder, trunk, and other muscles. The abrupt, intense muscle jerks that occur during the seizure resemble those elicited by cortical stimulation. Jackson correctly surmised that the sequential activation of different muscle groups during the seizure results from the progressive spread of abnormal neural activity from a site in the cortex controlling distal extremity muscles to ones that control more proximal ones. Frequently, these focal seizures are triggered by tumors, scars, or other abnormalities in nearby areas of the brain. The neurosurgeon Wilder Penfield used cortical stimulation, a technique he learned from Sherrington, in patients undergoing brain surgery to identify functional areas that had to be spared when excising abnormal tissue in the brain.

Penfield's work in patients and similar studies by Clinton Woolsey in monkeys showed that the primary motor cortex contains a *motor map* of the body. The head is represented close to the lateral sulcus; above it are representations of the arms, trunk, and legs (Figure 40–1A). As with the sensory maps, not all body parts are represented equally in the motor map. The parts of the body used in tasks requiring precision and fine control, such as the face and hands, have a disproportionately large representation in the motor map (Figure 40–1B).

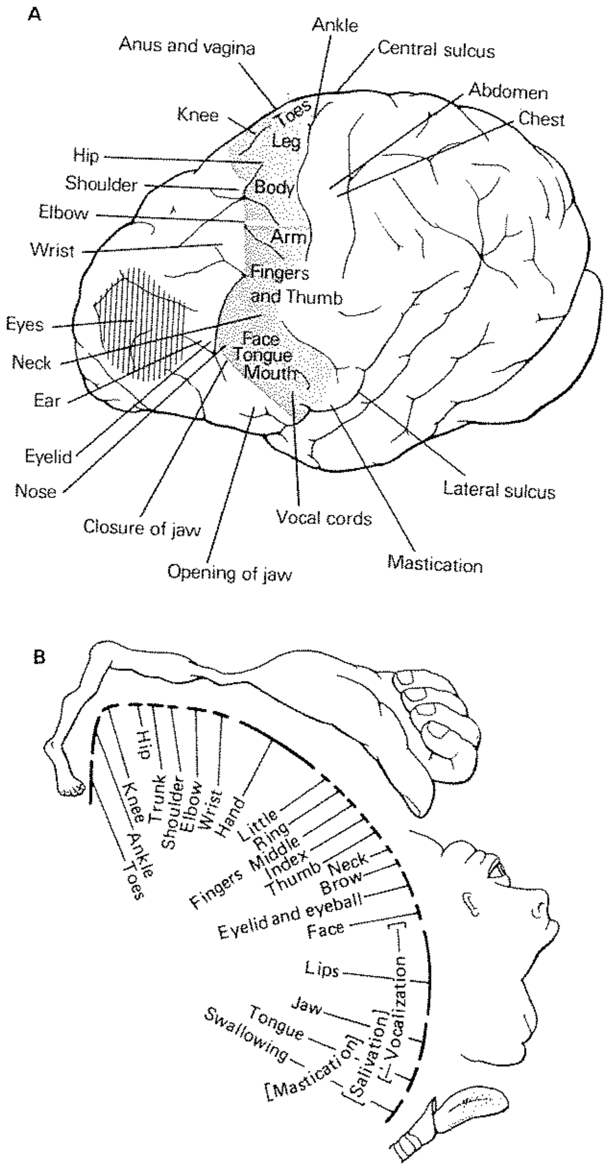


FIGURE 40–1
Comparison of the somatotopic representation in the primary motor cortex in chimpanzees (**A**) and humans (**B**). This sequence of representation is similar, with the ankles being medial, and the face, mouth, and muscles of mastication lateral. But the human motor cortex has a much larger representation of the face and digits. (Part A from Leyton and Sherrington, 1917; part B adapted from Penfield and Rasmussen, 1950.)

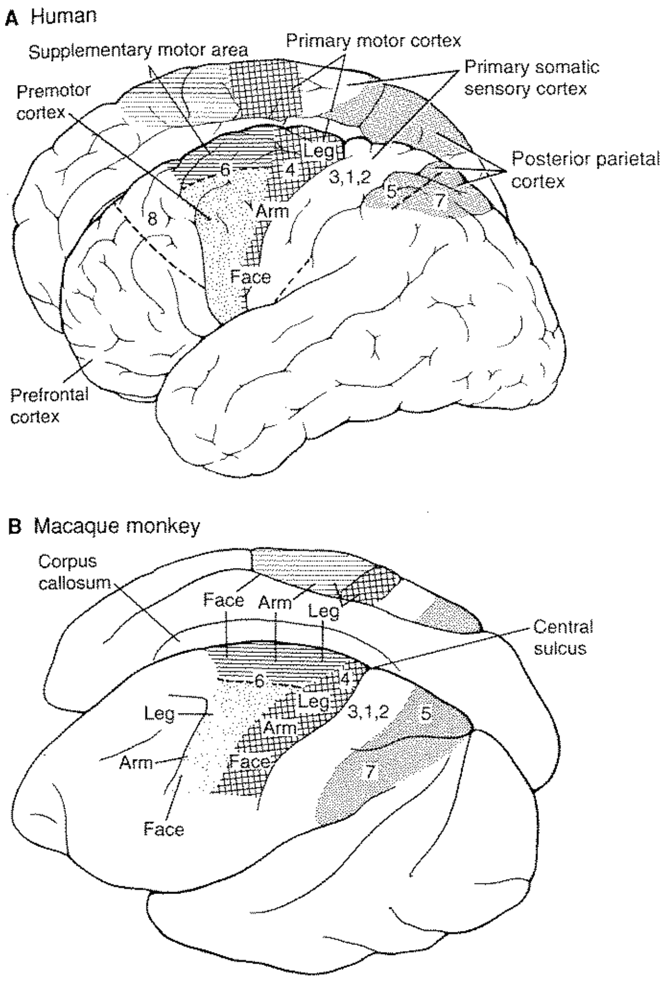


FIGURE 40–2
Locations of the primary and premotor cortical areas in humans (**A**) and the macaque monkey (**B**). Behind the primary motor areas lie the somatic sensory cortex, Brodmann's areas 3, 1, 2, and the posterior parietal cortex, areas 5 and 7.

The studies by Penfield and Woolsey also revealed that stimulation in Brodmann's area 6, anterior to the primary motor cortex, could also produce motor effects. These areas are called the *premotor areas*. The axons of neurons in the premotor areas project to the primary motor cortex, as well as to subcortical structures and to the spinal cord. While the size of the primary motor cortex remains constant across primate phylogeny in proportion to body weight, the premotor areas increase in size sixfold from the macaque monkey to humans. There are two principal premotor areas: the *supplementary motor area* (sometimes referred to as the *secondary motor cortex*, or MII), located on the superior and medial aspects of the hemisphere, and the *premotor cortex*, located on the lateral surface of the hemisphere (Figure 40–2). Movements produced by stimulation of the supplementary motor or premotor areas are more complex and require larger stimulus currents than those produced by stimulation of the primary motor cortex. Stimulation of the premotor areas typically evokes coordinated contractions of muscles at more than one joint and, in the case of the supplementary motor area, on both sides of the body as well. The supplementary motor and premotor areas are also organized somatotopically. Anatomical studies have identified additional premotor areas, notably one located within the cingulate gyrus (area 24), which may be important in allowing motivation to influence motor planning directly.

The Primary Motor, Supplementary Motor, and Premotor Areas Contribute the Majority of Axons in the Corticospinal Tract

The cytoarchitecture of the three cortical motor areas differs from that of the sensory areas behind them and the prefrontal areas in front. Layer 4, the major input layer for sensory cortices, is absent in the motor areas. Since layer 4 is called the *internal granular layer*, these motor areas are referred to as *agranular cortex* (Figure 40–3A). Layer 5 in the primary motor cortex contains a distinctive population of giant (50–80 mm in diameter) pyramidal neurons, the Betz cells, named after their discoverer Vladimir Betz. The axons of these cells run in the corticospinal tract. The 30,000 Betz cells represent only one of several populations of nerve cells contributing to the one million axons that make up the corticospinal tract. The tract originates from neurons of all sizes in layer 5 (Figure 40–3B). About half of the axons in the tract come from the primary motor cortex (Brodmann's area 4). Most of the others come from cells in area 6, mainly from the supplementary motor area; a smaller proportion arises from the lateral premotor area and somatic sensory cortex (areas 3, 2, and 1). As noted in Chapter 35, axons of the corticospinal tract originating from the motor cortex terminate in the intermediate and the ventral zones of the spinal cord, while those from the somatic sensory cortex terminate primarily in the dorsal horn.

Inputs to Motor Areas from the Periphery, Cerebellum, and Basal Ganglia Are Mediated by Other Areas of Cortex and the Thalamus

The motor areas of the cerebral cortex receive input from three sources. First, they receive information from the periphery. This input is transmitted either directly to the primary motor cortex from the thalamus (nucleus VPLo) and the primary somatosensory cortex, or indirectly to the premotor areas from the sensory association areas. Second, the motor areas receive input from the cerebellum. This input is principally distributed to the primary and premotor cortex by way of the thalamus (the oral part of the ventral posterolateral nucleus, VPLo, the caudal part of the ventrolateral nucleus VLc, and a recently identified subdivision of the thalamus referred to as area X). The third source of input is the basal ganglia. This input is also relayed through the thalamus, however, from an area situated more anteriorly (the oral part of the ventrolateral nucleus VLo, and the ventral anterior nucleus VA) than the cerebellar relay (Figure 40–4A).

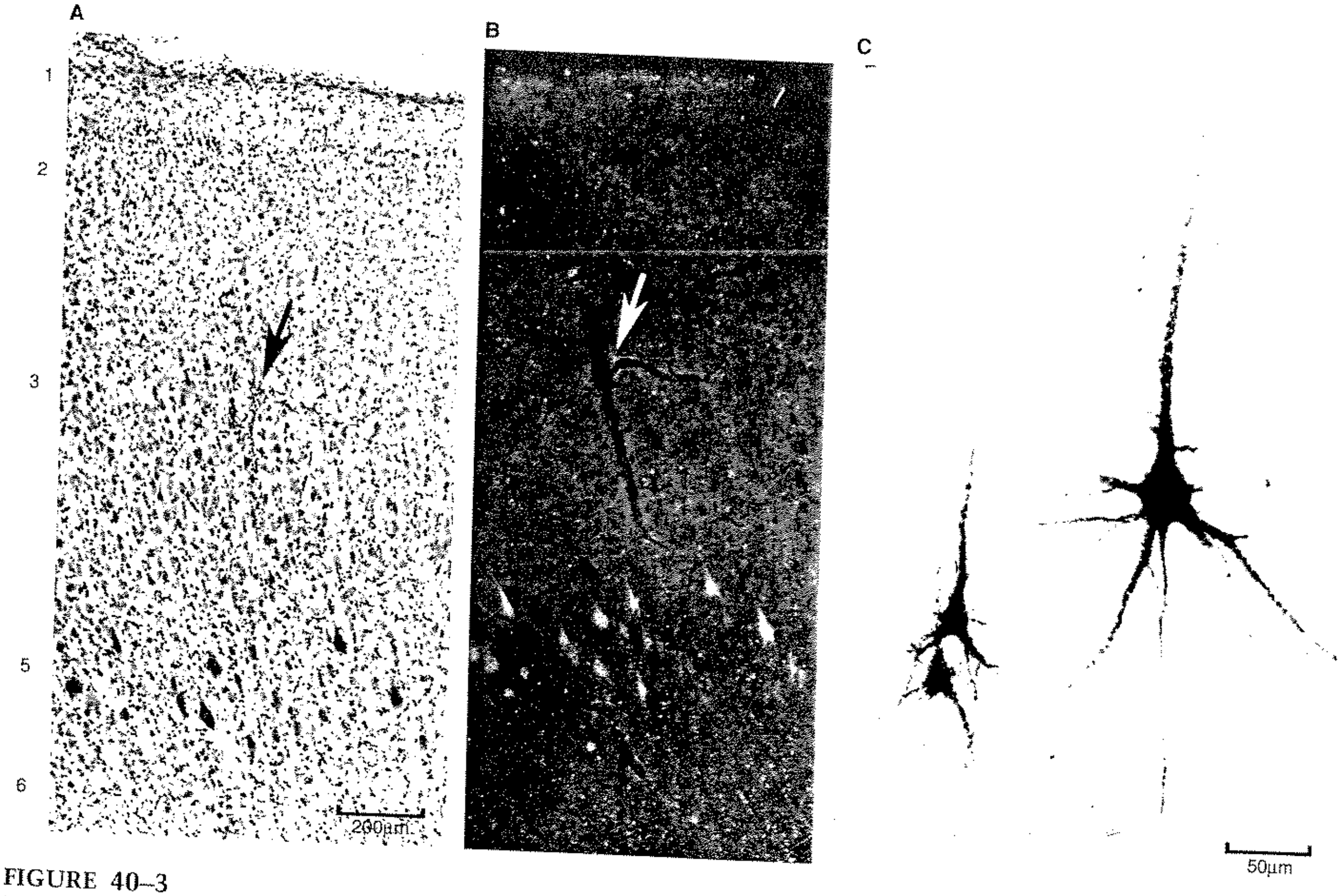


FIGURE 40–3
In the primary motor cortex, layer 4 (also called the *internal granular layer*) is reduced or absent, and layer 5 contains large and small pyramidal neurons. As a result, the motor cortex is called the *agranular cortex*. (From Murray and Coulter, 1981.) Bright-field (**A**) and dark-field (**B**) photomicrographs of Nissl-stained monkey primary motor cortex with corticospinal neurons retrogradely labeled following horseradish peroxidase injection into the contralateral lumbar spinal cord. The labeled neurons are better visualized under dark-field illumination (**B**). In both photographs arrows point to the same branch of the blood vessel. A cluster of three corticospinal neurons of different sizes are located in layer 5 (**C**). These neurons were retrogradely labeled from the contralateral spinal cord.

The motor cortical areas also receive important input from the somatic sensory cortex and sensory association areas. In the monkey there are significant connections to the primary motor cortex from the primary somatic sensory cortices, Brodmann's area 2, and the posterior parietal somatic association area, Brodmann's area 5. These connections are organized in a homotopic fashion (i.e., the same parts of the body map are interconnected). Moreover, areas of motor cortex representing a given body part receive sensory input from the portion of sensory cortex representing the same body part. In addition, intracortical input to the primary motor cortex arises in the lateral, premotor, and supplementary motor areas, which are in turn influenced by primary input from posterior parietal and prefrontal association cortices (Figure 40–4).

Corticospinal Axons Influence Segmental Motor Neurons Through Direct and Indirect Connections

How do corticospinal neurons act on the spinal motor neurons? By stimulating the primary motor cortex and recording synaptic potentials in spinal motor neurons, James Preston and Charles Phillips separately discovered that corticospinal neurons in primates make direct and powerful excitatory connections with alpha motor neurons. Corticospinal axons also excite gamma motor neurons through polysynaptic pathways. As we have seen, this coactivation of alpha and gamma motor neurons allows muscle spindles to sense changes in muscle length, even when limb movement produces muscle shortening (see Chapter 37).

Besides direct connections, corticospinal neurons influence motor neurons indirectly. Anders Lundberg and his co-workers have found that one important indirect pathway to the motor neurons innervating the muscles of the arm involves propriospinal neurons in the upper cervical segments of the spinal cord that project to motor nuclei located two or more segments below. A second indirect path involves the Ia inhibitory interneuron that mediates the disynaptic corticospinal inhibition of motor neurons.

Although the corticospinal tract projects to motor nuclei controlling proximal and distal muscles, the cortico-

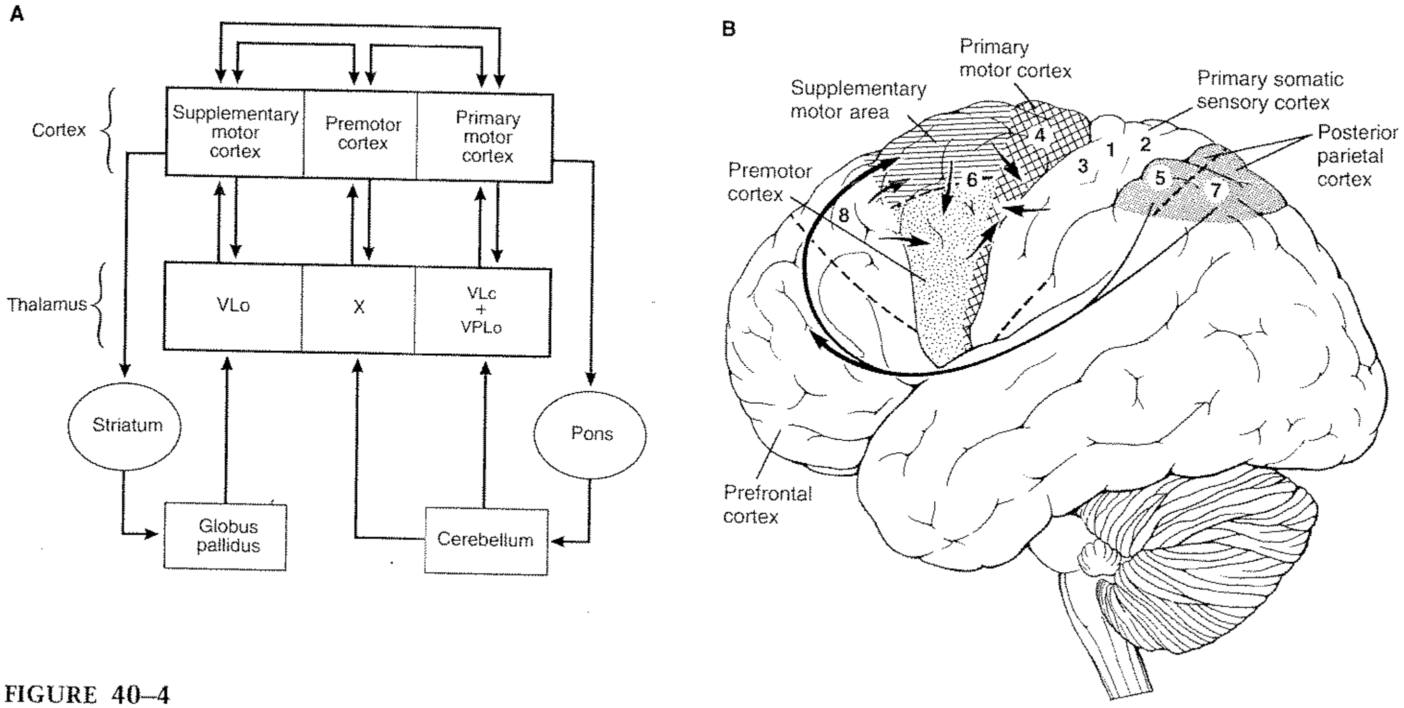


FIGURE 40–4
The motor areas receive both subcortical and corticocortical input.

A. Subcortical input from thalamic nuclei. **VLo** and **VLc** are, respectively, the oral (rostral) and caudal portions of the ventrolateral nucleus and thalamus. **VPLo** is the oral portion of the ventral posterolateral nucleus and **X** represents nucleus X.

B. Corticocortical connections. Although the arrows are unidirectional, the interconnecting pathways are reciprocal.

spinal tract is the only pathway that controls the distal muscles of the fingers. Indeed, the synaptic potentials produced by cortical stimuli are largest in motor neurons innervating distal muscle. Destruction of the primary motor cortex abolishes not only all effects on distal muscles that normally result from stimulation of the motor cortex, but also abolishes the distal effects produced by stimulation of premotor and supplementary motor areas. Thus, both the supplementary motor area and the premotor cortex act on distal muscles principally through their projections to the primary motor cortex.

The motor cortical areas also exert indirect control over spinal motor neurons through parallel projections to brain stem neurons. For example, neurons in the primary motor cortex and premotor and supplementary motor areas terminate on reticulospinal and other brain stem neurons that project to the spinal cord. These various polysynaptic connections allow motor cortical areas to control complex patterns of muscle activation whose details are organized in the brain stem (See Chapter 38).

Neurons of the Primary Motor Cortex Encode the Direction of the Force Exerted

Individual Corticospinal Neurons Control Small Groups of Muscles

The discovery of a somatotopic motor map in the primary motor cortex led Hiroshi Asanuma and his colleagues in the 1960s to ask: How finely detailed is this map? Asanuma inserted microelectrodes into the motor cortex and stimulated small groups of neurons. Using low-current stimuli that activate only about a dozen neurons, he was able to produce the isolated contraction of individual muscles. Asanuma next discovered that the sites where stimulation produces contraction of a given muscle are arranged in radial arrays, similar to the columns of neurons found in the somatic sensory and visual cortices.

Despite this fine localization, detailed mapping studies with microelectrodes have shown that certain muscles, notably distal muscles, are represented at more than one site. Conversely, cortical stimuli that activate a given muscle frequently also influence several other muscles. More importantly, Eberhard Fetz and Paul Cheney discovered that individual corticospinal axons frequently diverge to influence monosynaptically the motor neurons that innervate several muscles. This divergence has now been confirmed anatomically (Figure 40–5). It is, however, smallest for the most distal muscles of the fingers, and greater for the more proximal mucles.

Neurons in the Primary Motor Cortex Encode the Amount of Force to Be Exerted

While ablation and stimulation studies show that specific cortical motor areas control movements of contralateral body parts, they provide no clues as to how these areas

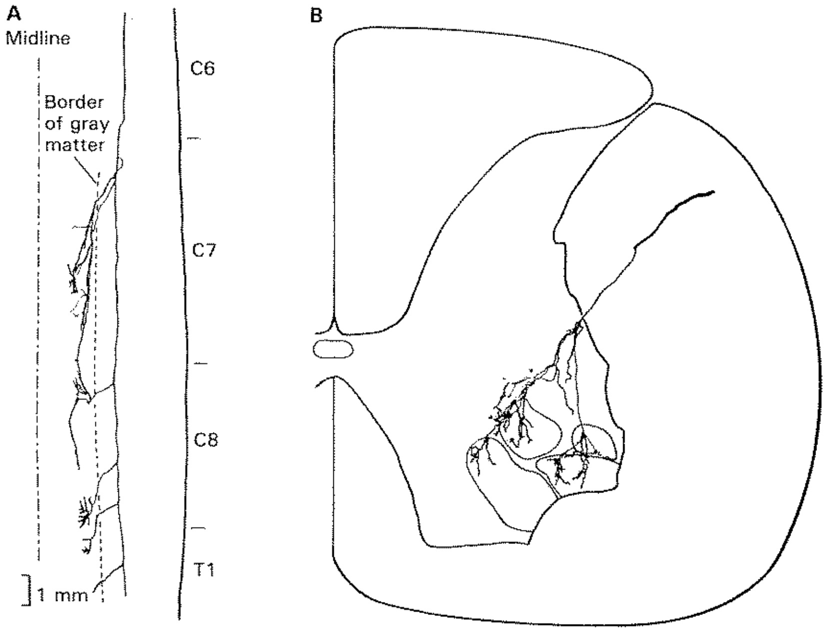


FIGURE 40–5
Corticospinal axons have multiple branches within the spinal cord. A single axon identified physiologically was injected with horseradish peroxidase and its course was reconstructed.

A. Longitudinal view showing branches terminating at several levels.

B. Transverse view showing terminations in four different motor nuclei. (From Shinoda et al., 1981.)

might participate in its initiation or control. In order to address this question we would have to know how neuronal discharge is modulated during the performance of a motor task itself. Edward Evarts was the first to investigate this issue by recording from single neurons in the primary motor cortex of monkeys trained to perform various simple tasks. He studied how cortical neurons in the wrist area of primary motor cortex are modulated during flexion and extension of the wrist (Figure 40–6B). He found that different populations of neurons were active during flexion and during extension and that the modulation in their activity typically occurred *before* the contraction of the relevant muscles. This provided direct evidence that the primary motor cortex actually participates in the initiation or triggering of movement.

What aspect of movement is controlled by the activity of individual corticospinal tract neurons? Is it the extent of the limb movement (that is, a change in position) or the degree of force exerted by the muscles of the limb? If these neurons encode an intended change in position, without regard to force, then their discharge should have the same firing pattern for the same movement against different loads. But, if the cells encode the force exerted, neuronal activity should change with the load and not be affected by the change in position.

Evarts determined that the discharge frequency of corticospinal tract neurons encodes the amount of force used to move the limb rather than the change in the position of the limb. For example, the firing rate of a neuron that becomes active during wrist flexion increases with the flexor load. When the weight is shifted to assist flexion and oppose extension, flexion occurs passively by the relaxation of the antagonist (extensor) muscles and the neuron no longer fires (Figure 40–6B).

In addition to neurons that encode the amount of force exerted, some neurons in the primary motor cortex encode the rate of change of force. These neurons are likely to control the speed of movement. They are assisted by neurons in the rubrospinal system, whose activity is principally related to the dynamics of force and to limb velocity (Figure 40–7).

Movement Direction Is Encoded by Populations of Neurons, Not By Single Cells

The observation that flexion and extension of wrist or elbow are associated with the firing of different populations of cortical neurons fit with the idea of a muscle-like map in primary motor cortex. However, since individual neurons in primary motor cortex can influence multiple muscles, the question arises of how the direction of typical multijoint arm movements might be encoded by cortical neurons. This question was addressed by Apostolos Georgopoulos and his colleagues by studying how neuronal activity varies when monkeys move a handle to one of several targets arranged around a central starting position. They found that activity of individual neurons did indeed vary with the direction of the movement: they fired most briskly for movements in a preferred direction and fell silent during movements in the opposite direction. Moreover, the preferred directions of neurons located within a column of cortex were quite similar. The directional tuning of all recorded neurons was, however, surprisingly broad. Individual neurons contribute predominantly to movements in a preferred direction but also to lesser degrees to movements in other directions (Figure 40–8).

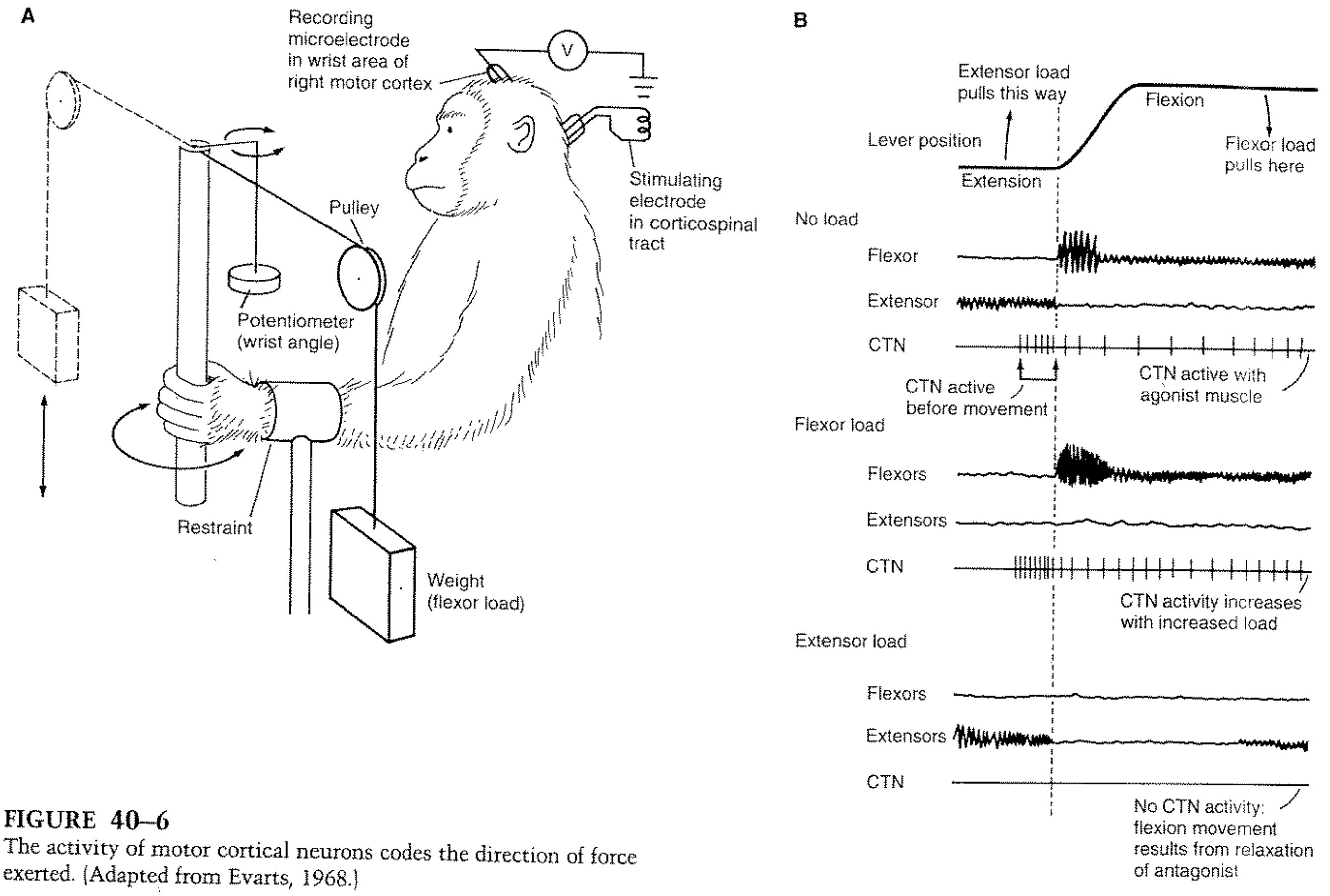


FIGURE 40–6

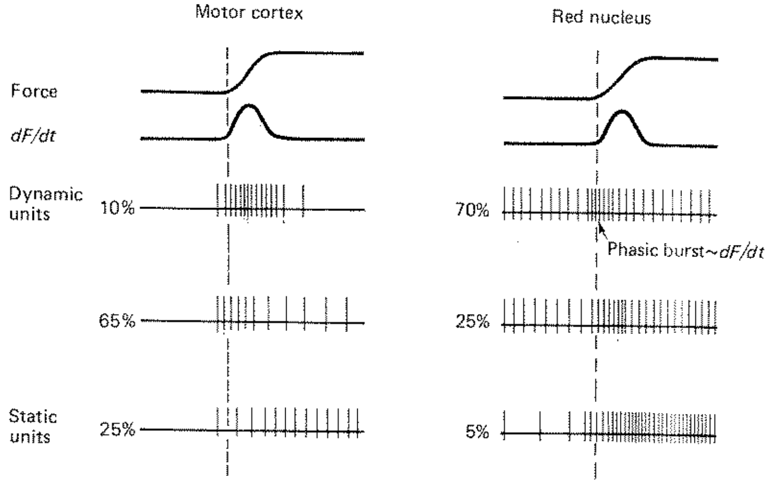
The activity of motor cortical neurons codes the direction of force exerted. (Adapted from Evarts, 1968.)

A. Setup for recording specific corticospinal tract neurons in the motor cortex of an awake monkey. The apparatus permits the animal alternately to flex and extend its wrist. To ascertain that the neuron being recorded projects through the corticospinal tract, corticospinal fibers are stimulated through a separate electrode implanted in the ipsilateral medullary pyramid to produce antidromic action potentials, thus activating output neurons in the motor cortex at a short and consistent latency.

B. Records of a corticospinal tract neuron (**CTN**) that increases its activity with flexion of the wrist. Note that the cell starts firing before movement. Electromyograms of flexor and extensor muscles and discharge records of a corticospinal tract neuron are shown under different load conditions. Absence of neuronal activity with extensor load indicates that the neuron codes for force rather than displacement.

FIGURE 40–7

Dynamic, static, and mixed neurons have distinctive patterns of firing during voluntary isometric contraction in the cat. *dF/dt* = rate of change of force. **Broken line** denotes onset of movement. (Adapted from Ghez and Vicario, 1978; and Vicario, Martin, and Ghez, 1983.)



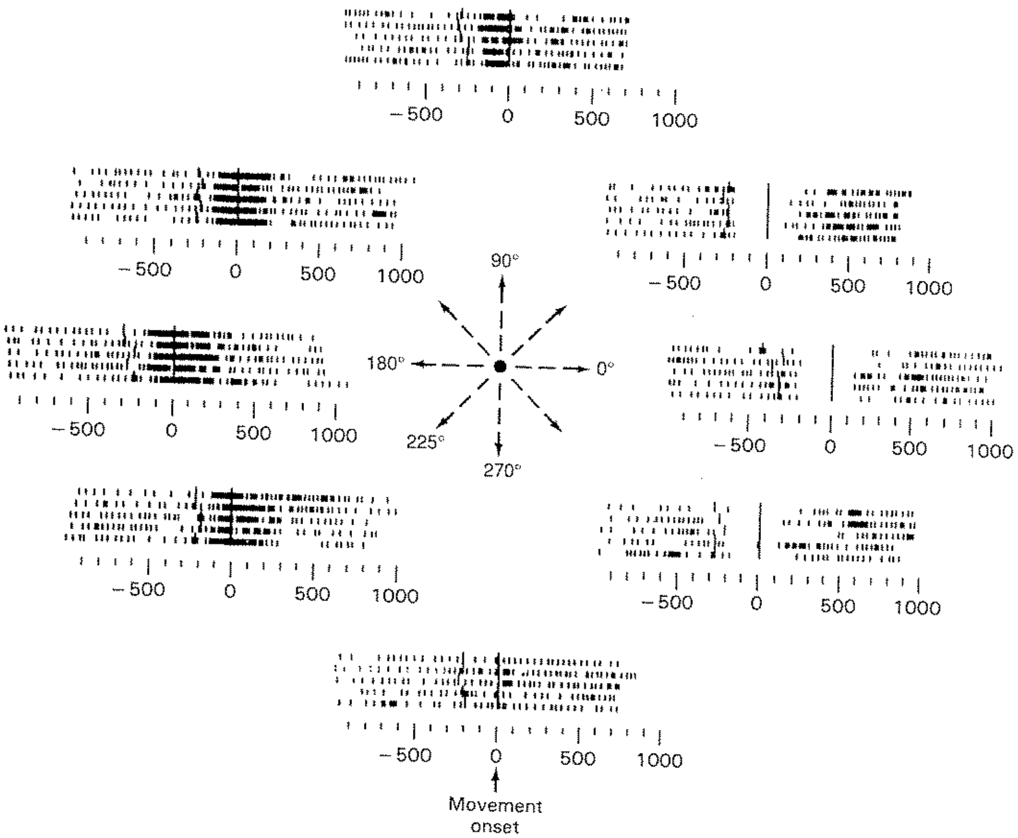


FIGURE 40–8
Individual cortical neurons are broadly tuned to the direction of movement. Raster plots show the firing pattern of a single neuron during movement in eight directions. A monkey was trained to move a handle to eight different locations, represented by light-emitting diodes, arranged radially in one plane around a central starting position. Each row of tics in each raster plot represents activity in a single trial. The rows are aligned at zero time (the onset of movement). The center diagram shows the directions of the eight movements. It can be seen that the cell fires at relatively high rates during movements made in a range of directions from 90° to 225°. (From Georgopoulos et al., 1982.)

How can movement direction be coded precisely by neurons that are so broadly tuned? Georgopoulos proposed that movement in a particular direction is determined not by the action of single neurons but by the net action of a broad population of neurons. Furthermore, he suggested that the contributions of each neuron to movement in a particular direction could be represented as a vector whose length depended on the degree of activity during movements in that particular direction. The contributions of individual cells could then be added vectorally to produce a *population vector*. Georgopoulos has proposed that the direction of the population vector would determine the direction of movement.

To test this idea and to determine the relationship between the direction of the population vector and the ensuing movement, Georgopoulos analyzed the activity of neurons in monkeys reaching toward targets in different directions and found that the directions of the computed population vectors closely match the directions of movement (Figure 40–9). This finding is evidence for the idea that this voluntary behavior is determined by the activity of a rather large population of neurons and cannot be predicted from the discharge patterns of any one neuron. This situation contrasts with that in motion detection where small populations of cells seem to be critically important for perception.

Although neurons in the primary motor cortex encode direction and force exerted during movement, their contribution is not invariant and depends on the nature of the task being performed. For example, Roger Lemon found that neurons that fire when a monkey squeezes a small transducer precisely between the thumb and index finger may remain silent when the monkey exerts the same force by grasping a rod with all fingers together. Similarly, while neurons in the motor cortex may govern an arm movement performed to reach an object, a similar arm movement made during an outburst of anger or an emotional upset may occur without a change in the activity of neurons in the motor cortex. As still another example, cortical neurons in the face area that are active during the jaw movement of a trained biting response have been shown to remain silent when the animal uses the same muscles for chewing, which is a more automatic response.

Neurons in the Motor Cortex Are Informed of the Consequences of Movements

Neurons in the primary motor cortex are kept informed about the position of the limb and the speed of movement

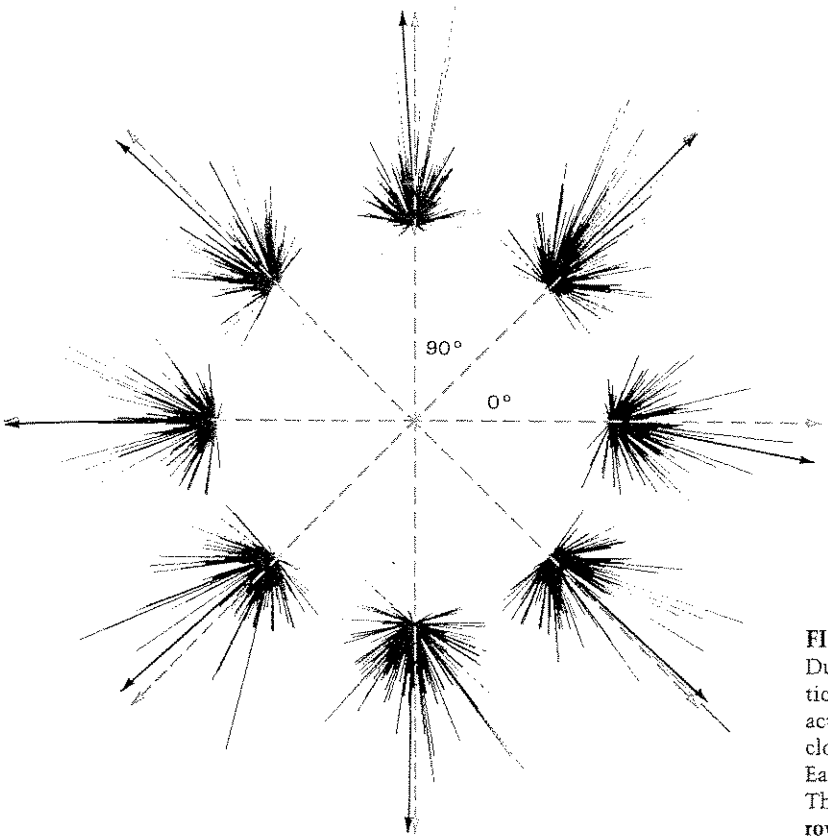


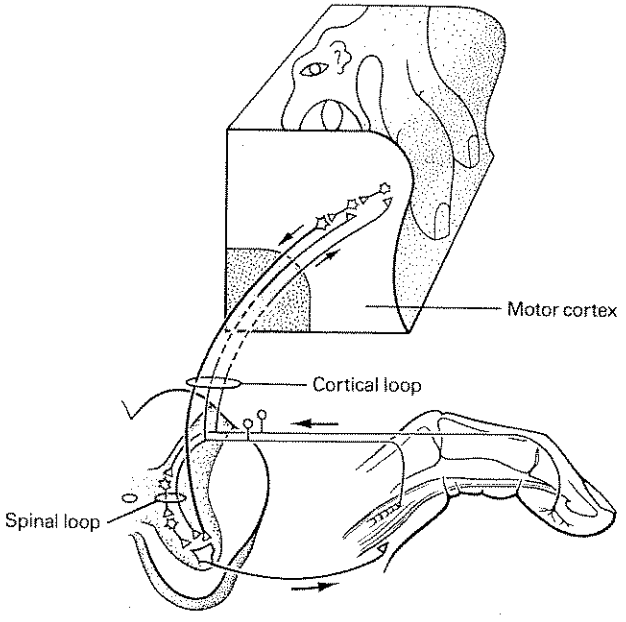
FIGURE 40–9
During movements in any given direction various cortical neurons with different preferred directions are active but the direction of the population vector closely matches that of the direction of movement. Each cluster represents the activity of one population. The directions of the population vectors **(dashed arrows)** closely match the direction of the targets.

through sensory input. Like neurons in the somatic sensory cortex, neurons in the motor cortex have receptive fields in the periphery. Some respond to tactile stimuli, others to movements of the hands, and still others to stretch of individual muscles or rotation of joints.

What is the relationship between the location of these receptive fields on the body and the muscle groups controlled by local sectors of motor cortex? Asanuma and his colleagues found that some neurons in the motor cortex receive proprioceptive input from the muscle to which they project, while others receive input from regions of skin that tend to be contacted during contraction of that same muscle (Figure 40–10). This sensory input is transmitted to the motor cortex by both corticocortical fibers from the somatic sensory cortex, and by direct pathways from the thalamus.

The correspondence between the muscle receptors providing proprioceptive input to cortical neurons and the target muscles of these same neurons is similar to that of muscle afferents and homonymous motor neurons in the spinal cord. Phillips suggested that the motor cortex might therefore function in parallel with the spinal stretch reflex. He envisioned that transcortical circuits convey afferent information from muscles and control contraction of muscles by a long loop pathway through the motor cortex (Figure 40–10). This feedback would provide assistance, supplementing the stretch reflex, when

FIGURE 40–10
Input-output organization of the cortical neurons controlling a flexor of a digit. The neurons are activated by either stretch of the muscle or stimulation of the skin. A parallel mechanism, the spinal loop, is also shown. (Adapted from Asanuma, 1973.)



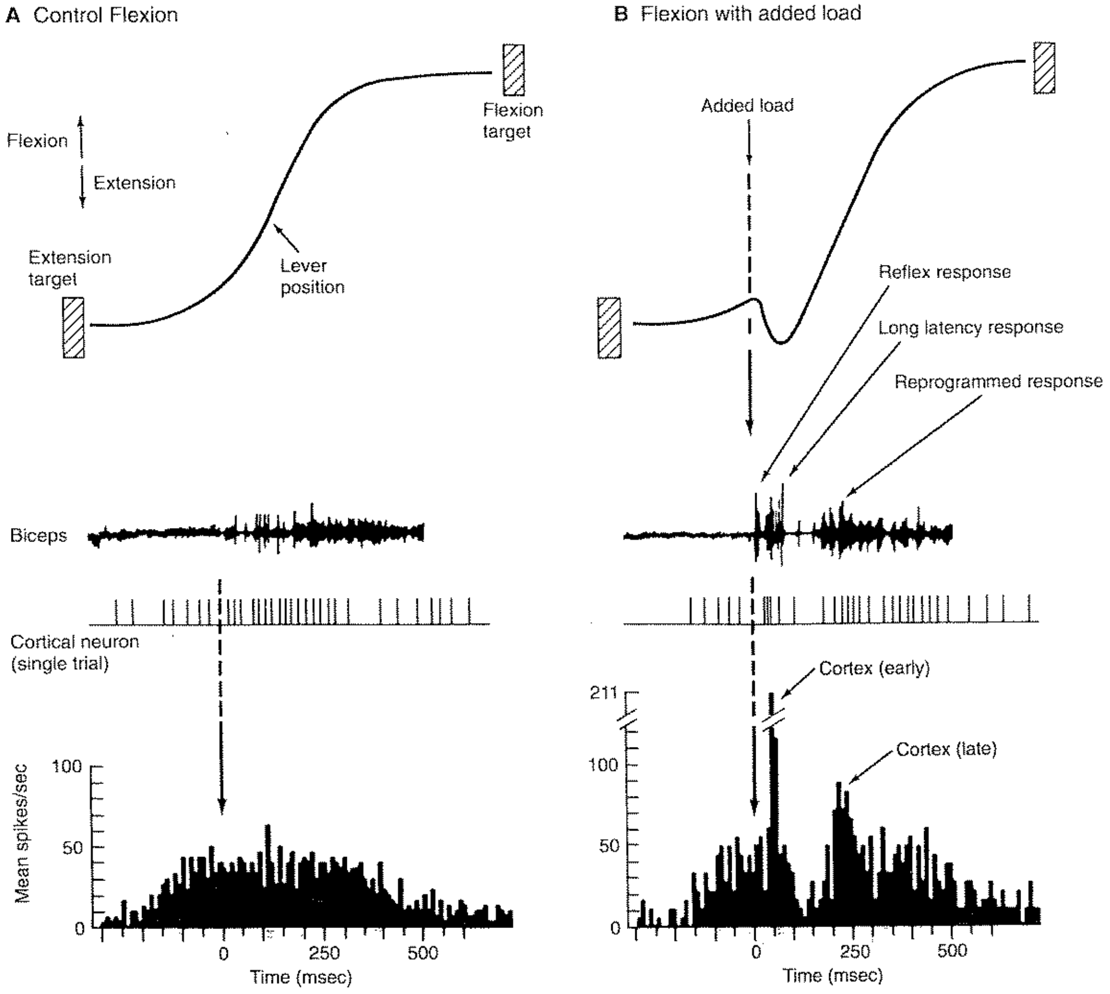
the moving limb encountered an unexpected obstacle: If the movement were appreciably slowed, misalignment would occur between the length of the muscle and its spindles, causing the primary spindle afferents to fire. This input would then boost the cortical output as well as act directly on motor neurons through the stretch reflex arc. A similar process might be set in motion from cutaneous receptors that also influence motor cortical neurons.

Phillips's suggestion that the transcortical pathway mediates kinesthetic inputs is supported by experiments of Vernon Brooks, who trained monkeys to move a handle between two target zones, flexing and extending the forearm. Through a motor attached to the handle, a force opposing the movement could be introduced at any time during the movement, so that the monkey would unexpectedly have to use more force to bring the handle into the target zone. The sudden occurrence of an additional load produced a marked change in the pattern of cortical discharge. First, there was a burst of activity in response to the additional load, and later a more prolonged response during which the monkey repositioned the lever in the target zone (Figure 40–11). The early, short-latency burst of cortical activity indicates that the motor cortex responds to muscle stretch in the same way as the alpha motor neurons in the spinal cord, consistent with Phillips's hypothesis. The effect of the boost in cortical response compensates only for relatively small disturbances. Large disturbances trigger new voluntary responses based

FIGURE 40–11
An unexpected load increases the activity of neurons in the motor cortex. The monkey is trained to move a handle from an extension to a flexion target. On random trials a load is introduced just after movement begins. From **top to bottom**: position of the arm, electromyograms of the triceps and biceps, typical records of neuronal discharge during a single trial, and histograms of neuronal activity over 20 trials. (Adapted from Conrad et al., 1974.)

A. Control movement (flexion) of the arm between two target zones (**hatched rectangles**).

B. Movement opposed by a transient increase in opposing force (at **arrow**). The two periods of increased neuronal activity following the application of the load reflect, first, the activation of the neuron's receptive field and then the execution of a second motor command to overcome the load.



on an updated computation of the new load opposing the movement (Figure 40–11).

Premotor Cortical Areas Prepare the Motor Systems for Movement

Motor Preparation Time Is Longer Than the Response Time to Stimuli

Under optimal conditions of attention, we can respond to a sensory stimulus in 120 to 150 ms (the shortest time is for proprioceptive or auditory stimuli, the longest for visual stimuli, because of extra retinal synapses). In contrast, the time needed to prepare for a spontaneous movement may take several hundred milliseconds (Figure 40–12). This preparation time increases with the anticipated complexity of the response and the degree of precision required for the task. It also depends on the amount of processing needed to decide which response is appropriate to a particular stimulus. The latency is shortest when the subject knows in advance which stimulus will occur and which response to make (*simple reaction time*). Reaction time is longer when the subject must anticipate several different stimuli, each requiring a different response (*choice reaction time*). Choice reaction time increases linearly with the number of alternative responses that are available, a relationship that reflects the added processing needed to select and program the appropriate response.

Lesions of the Premotor Cortex, Supplementary Motor, and Posterior Parietal Areas Impair the Ability to Execute Purposeful Movements

Lesions of the lateral premotor, supplementary motor, and posterior parietal areas cause more complex movement disorders than do lesions of the primary motor cortex. While lesions of the primary motor cortex cause weakness, lesions of premotor areas impair the ability to develop an appropriate strategy for movement. When monkeys with lesions of these areas are presented with food behind a transparent shield with an opening to the side of the food, they do not reach through the opening but instead aim directly for the food, bumping their hands into the shield.

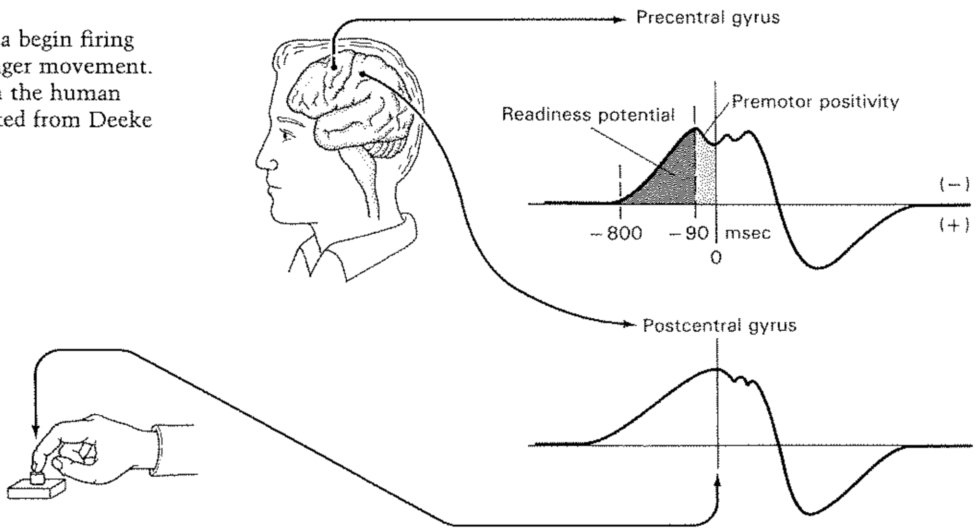
These symptoms in monkeys are similar to *apraxias* that occur in humans with lesions of the frontal association or posterior parietal cortices. Patients with apraxia show neither weakness nor sensory loss and are able to make simple movements accurately, but they are unable to perform complex acts requiring sequences of muscle contractions or a planned strategy such as combing their hair or brushing their teeth (Figure 40–13).

The Supplementary Motor Area Is Important in Programming Motor Sequences and in the Coordination of Bilateral Movements

The supplementary motor area plays an important role in programming complex sequences of movement. Movements elicited by stimulating the supplementary motor area require more intense and longer-lasting trains of pulses than do movements evoked from the primary motor cortex. These include such complex patterns of movement as orienting the body or opening or closing the hand. Many of the movements are bilateral. Movements involving proximal muscles can be mediated through direct projections from the supplementary motor area to the spinal cord. Those involving distal muscles appear to be mediated indirectly through connections to the motor cortex, since they are abolished by lesions of the motor cortex.

The role of the supplementary motor area in programming rather than executing complex movement sequences was discovered by Per Roland and his co-workers while studying local cerebral blood flow in humans performing motor tasks of increasing complexity. During

FIGURE 40–12
Neurons in the lateral premotor area begin firing about 800 ms before a voluntary finger movement. Traces are based on recordings from the human scalp over the frontal cortex. (Adapted from Deeke et al., 1969.)



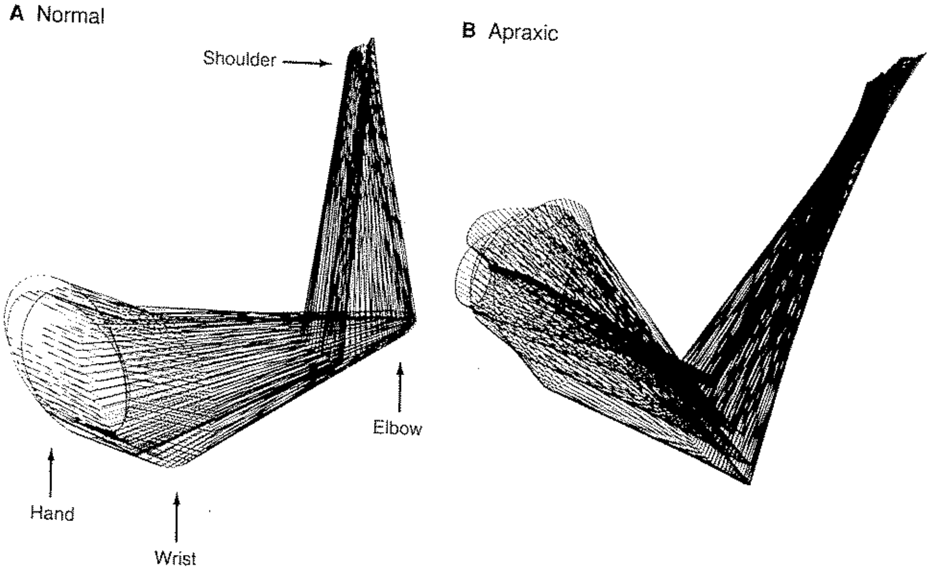


FIGURE 40–13
Three-dimensional reconstruction of the motions of the hand and arm of a normal subject (**A**) and apraxic subject (**B**) performing the gesture of winding a window. The normal subject makes repeated circular motions of the hand, whereas the movements made by the apraxic are tentative and irregular. (From Poizner, 1990.)

simple tasks blood flow increased dramatically within the contralateral hand areas of both the primary motor and somatic sensory cortices but did not increase significantly over lateral premotor areas (Figure 40–14C). During a complex sequence of movements involving all of the digits, the increase in cerebral blood flow extended to the supplementary motor area. When subjects were told to rehearse the sequence of finger movements mentally but not to perform the sequence, blood flow increased *only* in the supplementary motor area (Figure 40–14C).

Cobie Brinkman found two major motor deficits following lesions of the supplementary motor area. These findings also are consistent with the role of this area in programming and coordinating complex movements. First, monkeys are unable to orient their hands and digits appropriately while reaching for a peanut in a small well; rather, the hand assumes awkward positions as it approaches the peanut. Second, monkeys are severely impaired in their ability to use both hands to retrieve a morsel of food stuck into a hole drilled in a transparent plastic plate (Figure 40–15).

The supplementary motor area also plays an important role in coordinating posture and voluntary movement. Jean Massion and his colleagues asked subjects to maintain flexion of the elbow when a weight placed on their wrists was suddenly removed. The ability to perform this task depended on whether the weight was removed actively (by the subject) or passively (by the experimenter). When subjects removed the weight with their free hands, the biceps of the supporting arm relaxed concurrently and without delay as the weight was removed. But if the examiner removed the weight, the subjects could not maintain flexion of the arm, even though they anticipated the removal. Similarly, flexion could not be maintained when the weight was removed passively with an electromechanical device operated by the subject. The biceps relaxed only after a delay, corresponding to a brief simple reaction time following removal of the weight (Figure 40–16).

Patients with unilateral lesions of the supplementary motor area are unable to coordinate muscle contractions of their arms when the weight was placed on the affected (contralateral) arm. Subjects invariably responded with a delay to both active and passive removal of the weight. Task performance was normal, however, if the weight was placed on the unaffected (ipsilateral) limb. This result supports the idea that during the performance of a voluntary movement, two relatively independent but coordinated motor programs operate. One initiates the limb movement; the other program generates a coordinated postural response. This second program requires the integrity of the supplementary motor area.

The Premotor Cortex Controls the Proximal Movements that Project the Arm to Targets

Although the lateral premotor cortex is the most poorly understood of the cortical regions that project to the motor cortex, some preliminary insights into its functions emerge from studies correlating anatomy, single-cell recording, and behavior. The premotor cortex receives its principal input from the posterior parietal cortex. It sends abundant projections to regions of the brain stem that contribute to the medial descending systems (notably the reticulospinal system) and to the region of the spinal cord that controls proximal and axial muscles. These connections led Hans Kuypers to suggest that the premotor cortex plays a primary role in the control of proximal and axial muscles as well as in the initial phases of orienting the body and arm to a target. As first shown by Steven

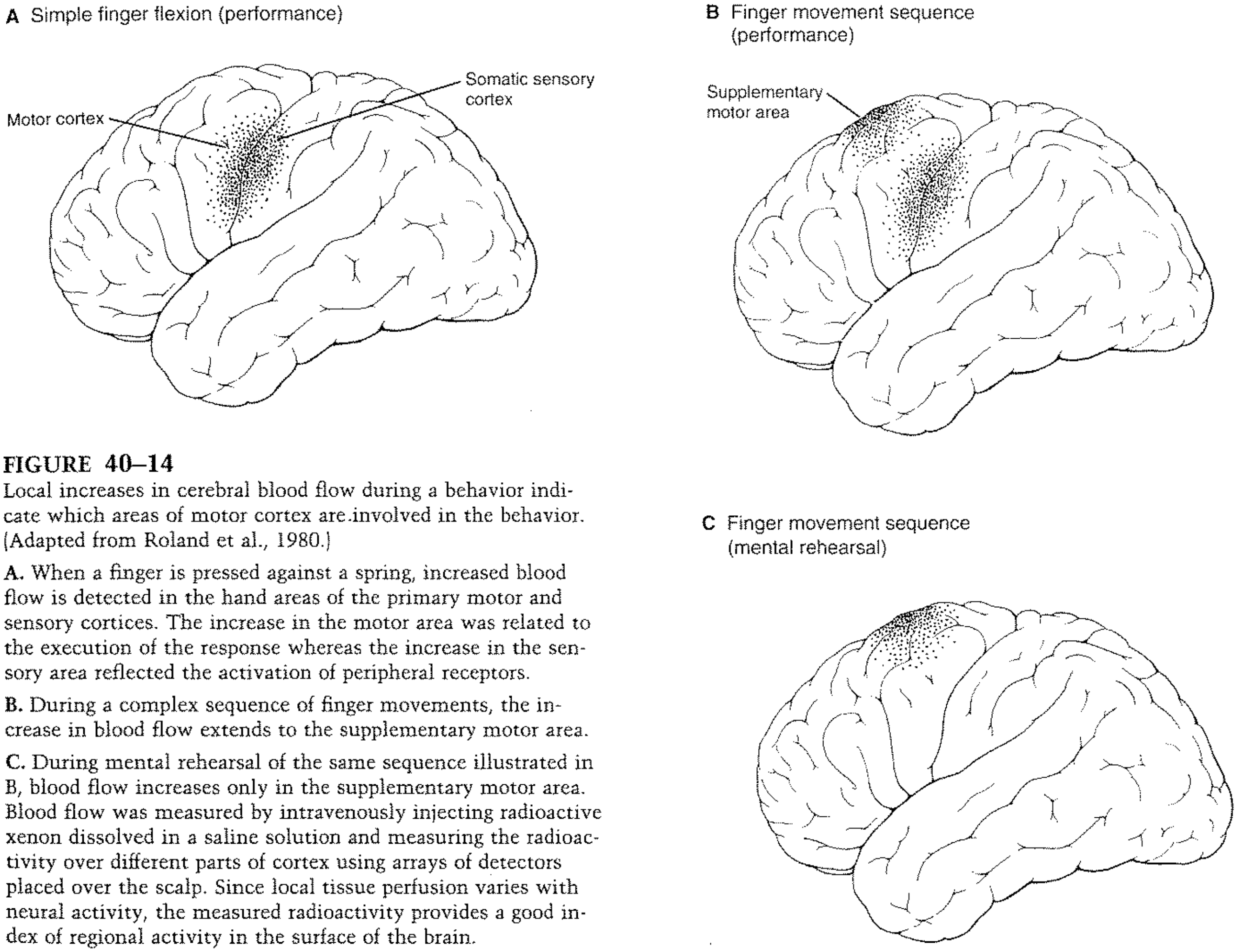


FIGURE 40–14
Local increases in cerebral blood flow during a behavior indicate which areas of motor cortex are involved in the behavior. (Adapted from Roland et al., 1980.)

A. When a finger is pressed against a spring, increased blood flow is detected in the hand areas of the primary motor and sensory cortices. The increase in the motor area was related to the execution of the response whereas the increase in the sensory area reflected the activation of peripheral receptors.

B. During a complex sequence of finger movements, the increase in blood flow extends to the supplementary motor area.

C. During mental rehearsal of the same sequence illustrated in B, blood flow increases only in the supplementary motor area. Blood flow was measured by intravenously injecting radioactive xenon dissolved in a saline solution and measuring the radioactivity over different parts of cortex using arrays of detectors placed over the scalp. Since local tissue perfusion varies with neural activity, the measured radioactivity provides a good index of regional activity in the surface of the brain.

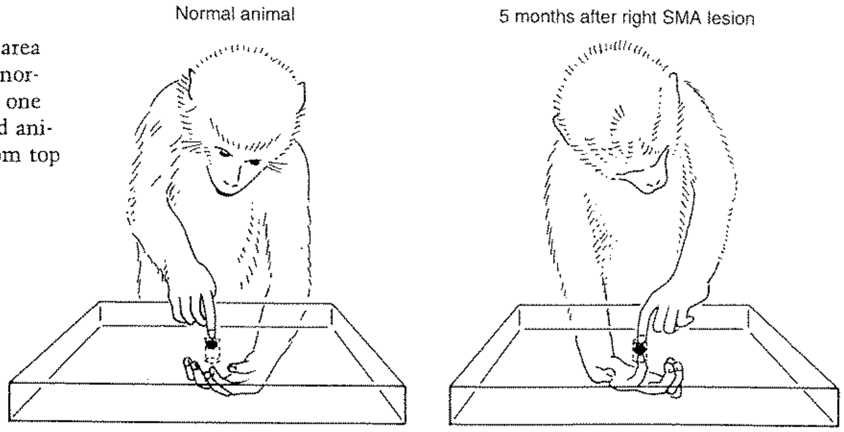


FIGURE 40–15
A unilateral lesion of the supplementary motor area results in a deficit in bimanual coordination. A normal monkey pushes food through the hole with one hand and catches it with the other. The lesioned animal uses both index fingers to push the food from top and bottom. (Adapted from Brinkman, 1984.)

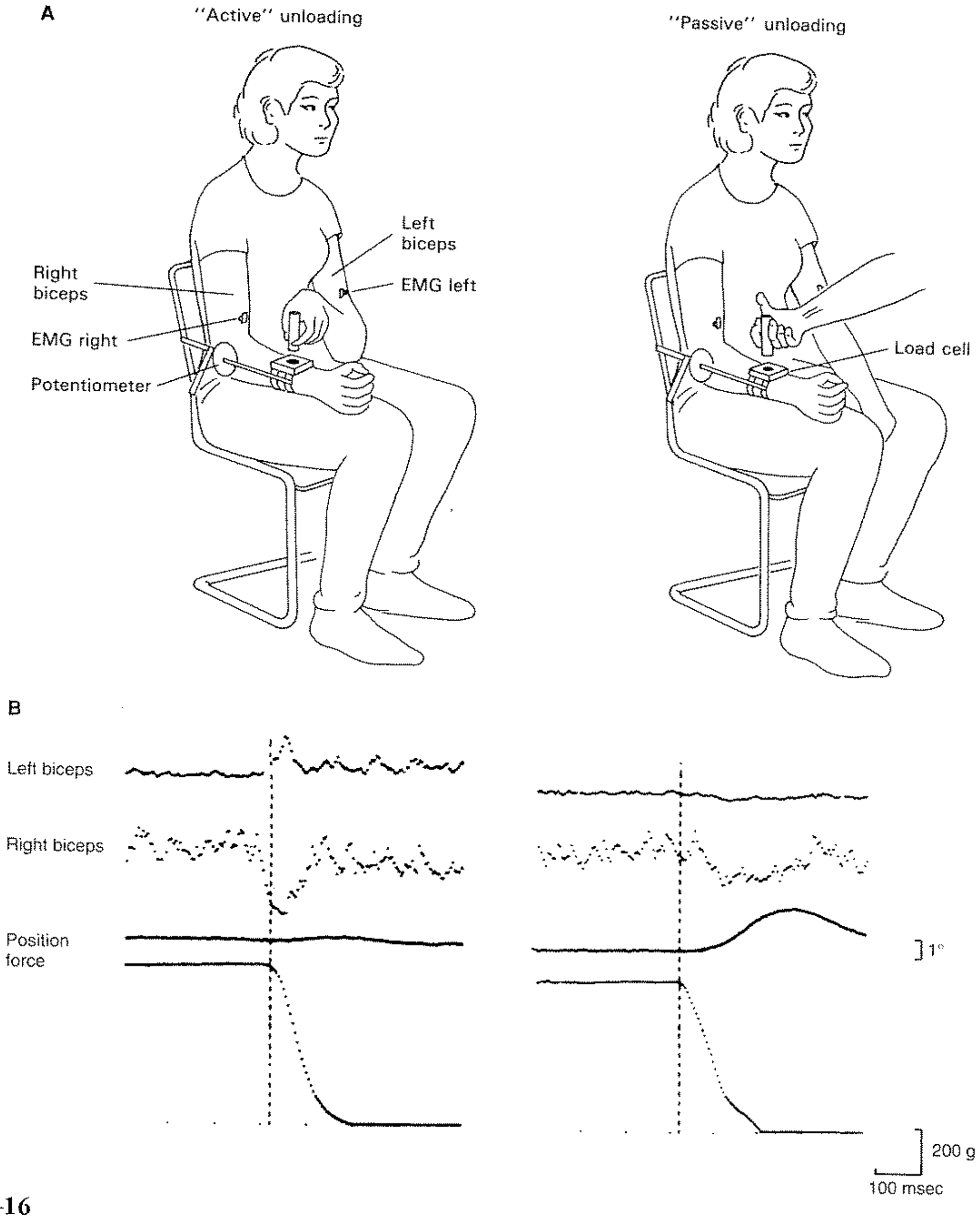


FIGURE 40–16
The dependence of certain postural reflexes on voluntary movement is demonstrated in this experiment. A weight is placed on a force transducer resting on the right arm and a potentiometer measures the elbow angle. The weight is removed by the subject with the left hand (active unloading) or by the experimenter (passive unloading). The records show recordings of force, joint position of the elbow, and rectified and integrated myograms of the left and right biceps. Mean value of 15 trials. Active and passive unloading result in different postural adjustments. At the onset of active unloading the elbow joint does not change position and activity in the biceps is inhibited. In contrast, with passive unloading the supporting biceps is not inhibited and the arm rises. (From Hugon et al., 1982.)

Wise, many neurons in the premotor cortex fire when the animal receives an instruction telling it to move to a particular location in response to a subsequent go-signal (Figure 40–17). Such neurons have been termed *set-related* by Wise to indicate that their activity reflects what the animal is preparing to do and indicate a role for the lateral premotor area in the preparatory process itself.

The Posterior Parietal Lobe Plays a Critical Role in Providing the Visual Information for Targeted Movements

An important step in preparing for movement is the focusing of attention on salient stimuli, such as the spatial relationships among objects. Information about the exter-

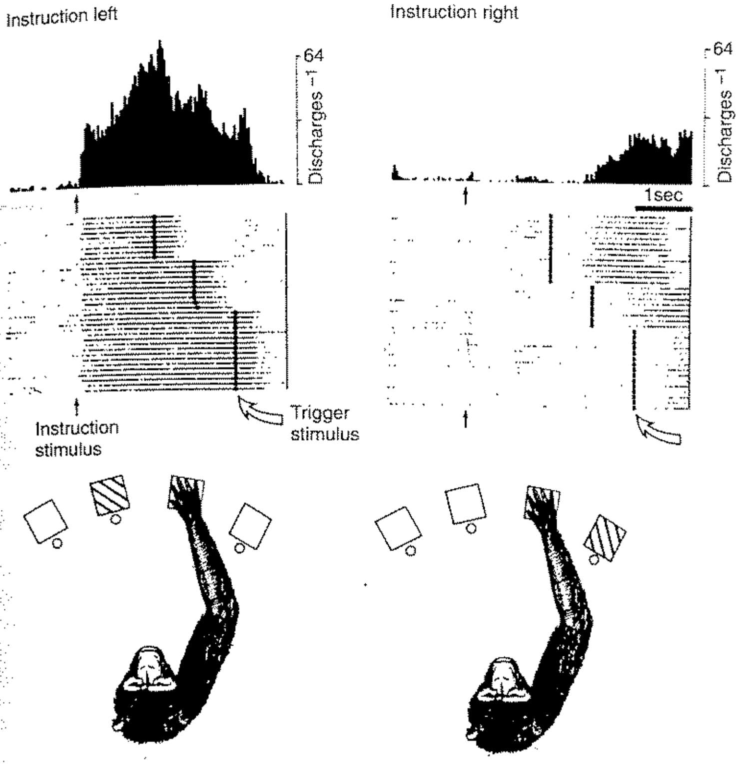


FIGURE 40–17
A set-related neuron in the lateral premotor area becomes active while the animal prepares itself to make a movement to the left. An instruction signal, illumination of one of the four panels, tells the animal which panel it will have to depress when the trigger signal, illumination of the nearby light-emitting diode, is presented. Each dot on each line represents a spike in the recorded neuron. Each line is one trial, and successive trials are aligned on the onset of the instruction signal. The delay between the instruction and trigger signals varied randomly among three values. In the figure the responses made with each delay time are grouped to show that the discharge of the neuron coincides with the instruction signal (**IS**) and lasts until the response is made after the trigger signal (**TS**). (From Wise, 1985.)

nal world conveyed through the various sensory modalities needs to be correlated with information about the position of our body and limbs and our motivational state. There is now clear anatomical and physiological evidence that the posterior parietal cortex plays a role in these processes (see also Chapter 52).

In monkeys the posterior parietal cortex comprises areas 5 and 7 (Figure 40–2). In humans it also includes the supramarginal gyrus (area 39) and the angular gyrus (area 40), which show a strong hemispheric specialization: The left posterior parietal cortex is specialized for processing linguistic information and the right posterior parietal cortex is specialized for processing spatial information. Patients with lesions in these areas have severe attentional disturbances, referred to as neglect, of tactile or visual stimuli on one side of their body. They also make peculiar errors in locating objects in space, and their ability to recognize or perform complex gestures is defective (see Chapter 53). Somatic sensation may be almost normal, although these patients are unable to recognize complex objects placed in the hand without vision. However, these patients typically do not use information from either the contralateral side of the body or the contralateral visual field. They synthesize the spatial coordinates of surrounding objects incorrectly. For example, when drawing a clock, a patient with a posterior parietal lesion puts all the numbers on one side and does not notice that the drawing is inaccurate.

Area 5 receives its main input from the somatic sensory cortex, Brodmann's areas 3, 1, and 2 and relates this somatosensory input to limb position. Area 5 is also informed by the vestibular system about the orientation of the head in space, by the premotor areas about motor plans, and by inputs from limbic cingulate cortices about motivational state. Area 5 in turn projects both posteriorly to area 7 and anteriorly to the premotor areas. Area 7 is involved primarily in the processing of visual information that relates to the location of objects in space (as opposed to information about the features of the visual scene. In area 7 visual information is integrated with somatosensory inputs from area 5 and auditory inputs from area 22. Area 7 directs movement by its projections to the premotor areas and to the lateral cerebellum (see Chapter 41).

Major insights into the roles of posterior parietal association areas in motor control have been obtained by Vernon Mountcastle and his colleagues studying neuronal activity in these regions during natural behaviors. They found that the discharge of neurons in these areas is modulated by states of attention. Two classes of neurons in area 5 are of further interest for their possible role in the initiation of movement. The first, called *arm projection neurons*, fire only when a monkey reaches for a desired object (food or reward-related stimuli) within its immediate surroundings. These neurons were otherwise unresponsive to sensory stimulation and do not fire when the animal moves its limb to the same region of space as when the object of interest was absent. The second class of neurons, in area 5, called *hand manipulation neurons*, became active only when the animal manually explored objects of interest. Neurons with similar movement-dependent properties are found in area 7.

Thus, neurons in the posterior parietal cortex can be driven by sensory stimuli, but only in the context of specific behavioral responses. By integrating information about the state of the animal with that of potential targets, the posterior parietal areas are thought to create a context or frame of reference for directing movement.

An Overall View

The discovery that the motor areas of the cerebral cortex are electrically excitable and organized somatotopically has had important implications for understanding neurological diseases. However, these motor areas are not simple distribution centers as was long believed. Rather, three advances have given us new insight into the cortical mechanisms subserving voluntary movement. First, the motor areas have a modular organization. In the primary motor cortex, local modules in the form of columnar arrays of neurons control the direction of limb movements. For the most distal movements such as those of the digits, individual cortical neurons control direction by acting on single muscles. For movements of more proximal body parts, the directional signal is distributed both through axon collaterals and spinal interneurons to produce facilitation and inhibition in multiple motor neurons. It seems likely that this branching provides the elements of a fundamental motor vocabulary.

Second, the firing of individual cortical neurons encodes movement parameters such as the amount of force or the rate of change of force that needs to be developed. This intensity coding is nevertheless continuously modulated by feedback from the periphery. Thus, the distinction between sensory and motor processes is somewhat blurred by the tight interactions that continuously take place between these processes.

Finally, studies of premotor and parietal association areas provide new and deep insights into how intention is translated into action. In premotor and parietal association areas, neuronal activity does not simply result from external stimulation, but also reflects the subject's intentions. Neurons in these areas do not encode the fine detail of actions to be executed; instead they are concerned with more global aspects of motor tasks—the coordination of posture and movements, particularly complex movements or sequences of movements involving both the contralateral and ipsilateral limbs.

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