MOVEMENT

FROM THE STANDS, WE MARVEL at the perfectly placed serves of professional tennis players and the lightning-fast double plays executed by big league baseball infielders. But in fact, each of us in our daily activities performs a host of complex, skilled movements — such as walking upright, speaking, and writing — that are just as remarkable. This is made possible by a finely tuned and highly complex central nervous system, which controls the actions of hundreds of muscles. Through learning, the nervous system can adapt to changing movement requirements to accomplish these everyday marvels and to perform them more skillfully with practice.

To understand how the nervous system performs such tricks, we have to start with the muscles, for these are the body parts that produce movement under the control of the brain and spinal cord.

Most muscles attach to points on the skeleton and cross one or more joints, so they are called *skeletal muscles*. Activation of a given muscle can open or close the joints that it spans, depending upon whether it is a joint *flexor* (closer) or *extensor* (opener).

In addition, if flexors and extensors at the same joint are activated together, they can "stiffen" a joint, thus maintaining limb position in the face of unpredictable external forces that would otherwise displace the limb. Muscles that move a joint in an intended direction are called *agonists*, and those that oppose this direction of movement are antagonists. Skilled movements at high speed are started by agonists and stopped by *antagonists*, thus placing the joint or limb at a desired position.

Some muscles act on soft tissue, such as the muscles that move the eyes and tongue and those that control facial expression. These muscles also are under control of the central nervous system, and their principles of operation are similar to those that attach to bone.

Each skeletal muscle is made up of thousands of individual muscle fibers, and each muscle fiber is controlled by one *alpha motor neuron* in either the brain or the spinal cord. On the other hand, each single alpha motor neuron controls many muscle fibers (ranging from a few to 100 or more); an alpha motor neuron and all the muscle fibers it contains form a functional unit referred to as a *motor unit*. These motor units are the critical link between the brain and muscles. If the motor neurons die, which can happen in certain diseases, a person is no longer able to move, either voluntarily or through reflexes.

Perhaps the simplest and most fundamental movements are reflexes. These are relatively fixed, automatic muscle responses to particular stimuli, such as the sudden withdrawal of the foot when you step on a sharp object or the slight extension of the leg when a physician taps your knee with a small rubber hammer. All reflexes involve the activation of small sensory receptors in the skin, the joints, or even in the muscles themselves. For example, the knee movement referred to above is produced by a slight stretch of the knee extensor muscles when the physician taps the muscle tendon at the knee. This slight muscle stretch is "sensed" by receptors in the muscle called *muscle spindles*. Innervated by sensory fibers, the spindles send information to the spinal cord and brain about the length and speed of the shortening or lengthening of a muscle. This information is used in reflex control of the joint at which the muscle acts and also for control of voluntary movements.

A sudden muscle stretch sends a barrage of impulses into the spinal cord along the muscle spindle sensory fibers. In turn, these fibers activate motor neurons in the stretched muscle, causing a contraction called the *stretch reflex*. The same sensory stimulus causes inactivation, or inhibition, of the motor neurons of the antagonist muscles through connecting neurons, called *inhibitory interneurons*, within the spinal cord. Thus, even the simplest of reflexes involves a coordination of activity across motor neurons that control agonist and antagonist muscles.

The brain can control not only the actions of motor neurons and muscles but, even more amazing, the nature of the feedback that it receives from sensory receptors in the muscles as movements occur. For example, the sensitivity of the muscle spindle organs is controlled by the brain through a separate set of *gamma motor neurons* that control the specialized muscle fibers and allow the brain to fine-tune the system for different movement tasks.

In addition to such exquisite sensing and control of muscle length by muscle spindles, other specialized sense organs in muscle tendons — the *golgi tendon organs* — detect the force applied by a contracting muscle, allowing the brain to sense and control the muscular force exerted during movement.

We now know that these complex systems are coordinated and organized to respond differently for tasks that require precise control of position, such as holding a full teacup, than for those requiring rapid, strong movement, such as throwing a ball. You can experience such changes in motor strategy when you compare walking down an illuminated staircase with the same task done in the dark.

Another useful reflex is the *flexion withdrawal* that occurs if your bare foot encounters a sharp object. Your leg is immediately lifted from the source of potential injury (flexion), but the opposite leg responds with increased extension in order to maintain your balance. The latter event is called the *crossed extension reflex*.

These responses occur very rapidly and without your attention because they are built into systems of neurons that are located within the spinal cord itself. It seems likely that the same systems of spinal neurons also participate in controlling the alternating action of the legs during normal walking. In fact, the basic patterns of muscle activation that produce coordinated walking can be generated in four-footed animals within the spinal cord itself. These spinal mechanisms, which evolved in primitive vertebrates, are likely still present in the human spinal cord.

The most complex movements that we perform, including voluntary ones that require conscious planning, involve control of these basic spinal mechanisms by the brain. Scientists are only beginning to understand the complex interactions that take place among different brain regions during voluntary movements, mostly through careful experiments on animals.

One important brain area in the control of voluntary movement is the *motor cortex*, which exerts powerful control over the spinal cord, in part through direct control of its alpha motor neurons. Some neurons in the motor cortex appear to specify the coordinated action of many muscles to produce the organized movement of a limb to a particular place in space. Others appear to control only two or three functionally related muscles, such as those of the hand or arm, that are important for finely tuned, skilled movement.

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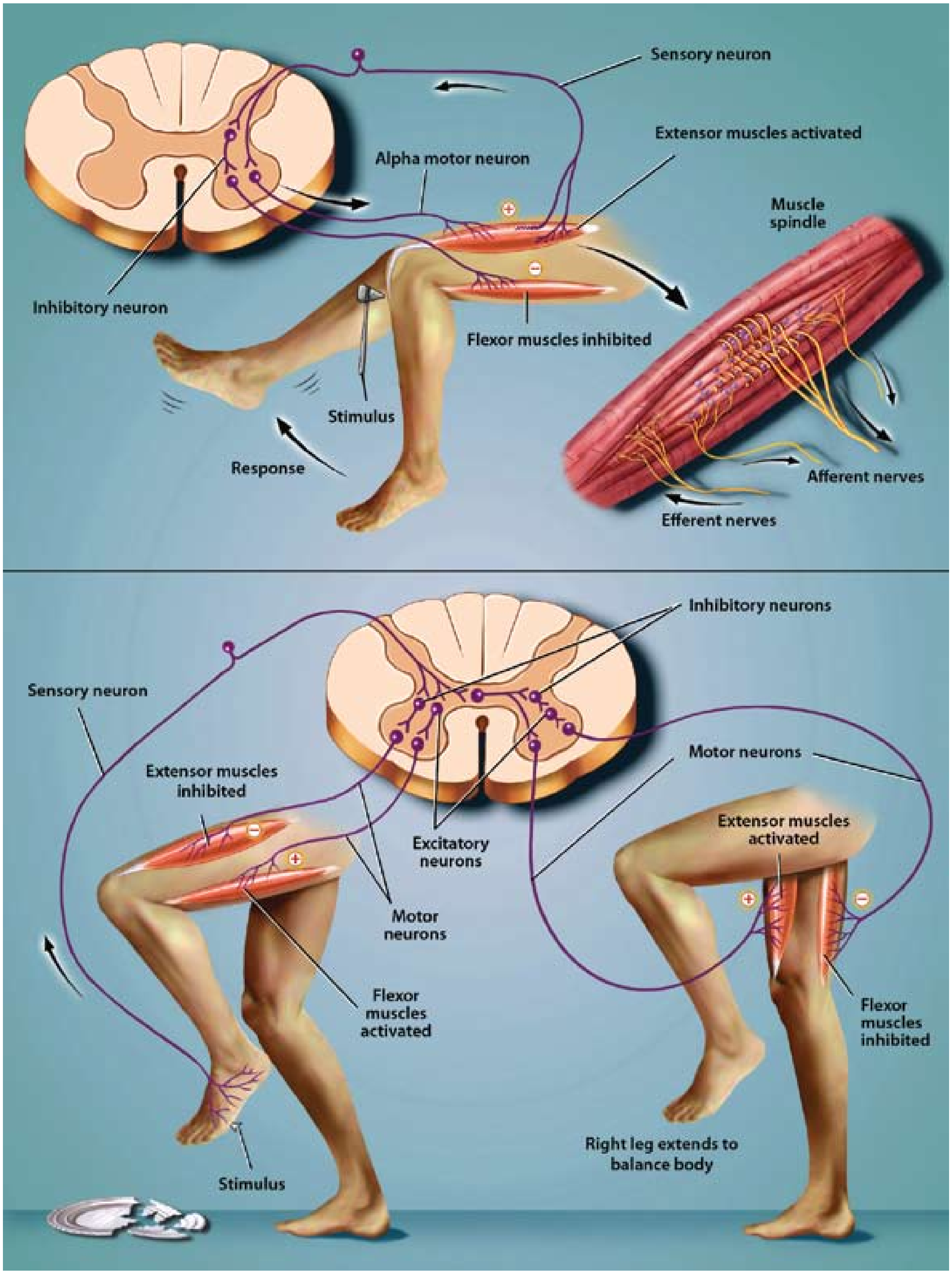
In addition to the motor cortex, movement control involves the interaction of many other brain regions, including the *basal ganglia*, thalamus, *cerebellum*, and a large number of neuron groups located within the midbrain and brainstem — regions that send axons to the spinal cord. Scientists know that the basal ganglia and thalamus have widespread connections with motor and sensory areas of the cerebral cortex.

Dysfunction of the basal ganglia can lead to serious movement disorders. For example, the depletion of the neurotransmitter dopamine from specific portions of the basal ganglia results in the tremor, rigidity, and akinesia of Parkinson's disease. Dopamine is supplied to the basal ganglia by the axons of neurons located in the *substantia nigra*, a midbrain cell group. Dopamine is depleted during Parkinson's disease because of the degeneration of the nigral neurons.

Another brain region that is crucial for coordinating and adjusting skilled movement is the cerebellum. A disturbance of cerebellar function leads to poor coordination of muscle control, disorders of balance and reaching, and even difficulties in speech, one of the most intricate forms of movement control.

The cerebellum receives direct and powerful information from all the sensory receptors in the head and the limbs and from most areas of the cerebral cortex. The cerebellum apparently acts to integrate all this information to ensure smooth coordination of muscle action, enabling us to perform skilled movements more or less automatically. Considerable evidence indicates that the cerebellum helps us adjust motor output to deal with changing conditions, such as growth, disability, changes in weight, and aging. It tunes motor output to be appropriate to the specific requirements of each new task: Our ability to adjust when picking up a cup of coffee that is empty or full depends on the cerebellum. Evidence suggests that as we learn to walk, speak, or play a musical instrument, the necessary, detailed control information is stored within the cerebellum, where it can be called upon by commands from the cerebral cortex.



MOVEMENT. The stretch reflex (top) occurs when a doctor taps a muscle tendon to test your reflexes. This sends a barrage of impulses into the spinal cord along muscle spindle sensory fibers and activates motor neurons to the stretched muscle to cause contraction (stretch reflex). The same sensory stimulus causes inactivation, or inhibition, of the motor neurons to the antagonist muscles through connection neurons, called inhibitory neurons, within the spinal cord. Afferent nerves carry messages from sense organs to the spinal cord; efferent nerves carry motor commands from the spinal cord to muscles. Flexion withdrawal (bottom) can occur when your bare foot encounters a sharp object. Your leg is immediately lifted (flexion) from the source of potential injury, but the opposite leg responds with increased extension in order to maintain your balance. The latter event is called the crossed extension reflex. These responses occur very rapidly and without your attention because they are built into systems of neurons located within the spinal cord itself.