32

Sensory-Motor Integration in the Spinal Cord

DURING PURPOSEFUL MOVEMENTS the central nervous system uses information from a vast array of sensory receptors to ensure that the pattern of muscle activity suits the purpose. Without this sensory information, movements tend to be imprecise, and tasks requiring fine coordination in the hands, such as buttoning one's shirt, are difficult. The sensory-motor integration that makes the ongoing regulation of movement possible takes place at many levels of the nervous system, but the spinal cord has a special role because of the close coupling in the cord between sensory input and the motor output to the muscles.

Charles Sherrington was among the first to recognize the importance of sensory information in regulating movements. In 1906, he proposed that simple

reflexes—stereotyped movements elicited by activation of receptors in skin or muscle—are the basic units for movement. He also emphasized that all parts of the nervous system are connected and that no part is ever capable of activation without affecting or being affected by other parts. In his words, the simple reflex is a convenient if not a probable fiction.

Laboratory studies of reflexes in animals from the 1950s and onward demonstrated that descending motor pathways and afferent sensory pathways converge on common interneurons in the spinal cord. Later research in intact animals and in humans engaged in normal behavior confirmed that the neural circuitries in the spinal cord take part in conveying and shaping the motor command to the muscles by integrating descending motor commands and sensory feedback signals. Nevertheless, the idea of simple reflexes is convenient for understanding the principles of organization of sensory-motor integration in the spinal cord and of how sensory input to different spinal circuits contributes to movement control.

In this chapter, we explain the principles underlying sensory-motor integration in the spinal cord and describe how this integration regulates movement. For this purpose, we must first have a thorough knowledge of how reflex pathways in the spinal cord are organized.

Reflex Pathways in the Spinal Cord Produce Coordinated Patterns of Muscle Contraction

The sensory stimuli that activate spinal reflex pathways act outside the spinal cord, on receptors in muscles, joints, and skin. By contrast, the neural circuitry responsible for the motor response is entirely contained within the spinal cord. The interneurons in the reflex pathways and the resulting reflexes have traditionally been classified based on the sensory modality and type of sensory fiber that activates the interneurons. As we shall see, this classification is inconsistent with the significant convergence of multiple modalities on common interneurons, but as a starting point, it is still useful to distinguish reflex pathways based on whether the principal sensory input originates from muscle or skin.

The Stretch Reflex Acts to Resist the Lengthening of a Muscle

The simplest and certainly the most studied spinal reflex is the *stretch reflex,* a reflex muscle contraction elicited by lengthening of the muscle. Stretch reflexes were originally thought to be an intrinsic property of muscles. Early in the 20th century, however, Liddell and Sherrington showed that the stretch reflex could be abolished by cutting either the dorsal or ventral root, thus establishing that these reflexes require sensory input from muscle to spinal cord and a return path to muscle (Figure 32–1A).

We now know that the receptor that senses the change of length is the muscle spindle (Box 32–1) and that the type Ia sensory axon from this receptor makes direct excitatory connections with motor neurons. (The classification of sensory fibers from muscle is discussed in Box 32–2.) The afferent axon also connects to interneurons that inhibit the motor neurons innervating antagonist muscles, an arrangement called reciprocal innervation. This inhibition prevents muscle contractions that might otherwise resist the movements produced by the stretch reflexes.

Sherrington developed an experimental model for investigating spinal circuitry that is especially valuable in the study of stretch reflexes. He conducted his experiments on cats whose brain stems had been surgically transected at the level of the midbrain, between the superior and inferior colliculi. This is referred to as a *decerebrate preparation.* The effect of this procedure is to disconnect the rest of the brain from the spinal cord, thus blocking sensations of pain as well as interrupting normal modulation of reflexes by higher brain centers. A decerebrate animal has stereotyped and usually heightened stretch reflexes, making it easier to examine the factors controlling their expression.

Without control by higher brain centers, descending pathways from the brain stem powerfully facilitate the neuronal circuits involved in the stretch reflexes of extensor muscles. This results in a dramatic increase in tone of the extensor muscle that sometimes can suffice to support the animal in a standing position. In normal animals and humans, owing to the balance between facilitation and inhibition, stretch reflexes are weaker and considerably more variable in strength than those in decerebrate animals.

Neuronal Networks in the Spinal Cord Contribute to the Coordination of Reflex Responses

The Stretch Reflex Involves a Monosynaptic Pathway

The neural circuit responsible for the stretch reflex was one of the first reflex pathways to be examined in detail. The physiological basis of this reflex was examined by measuring the latency of the response in

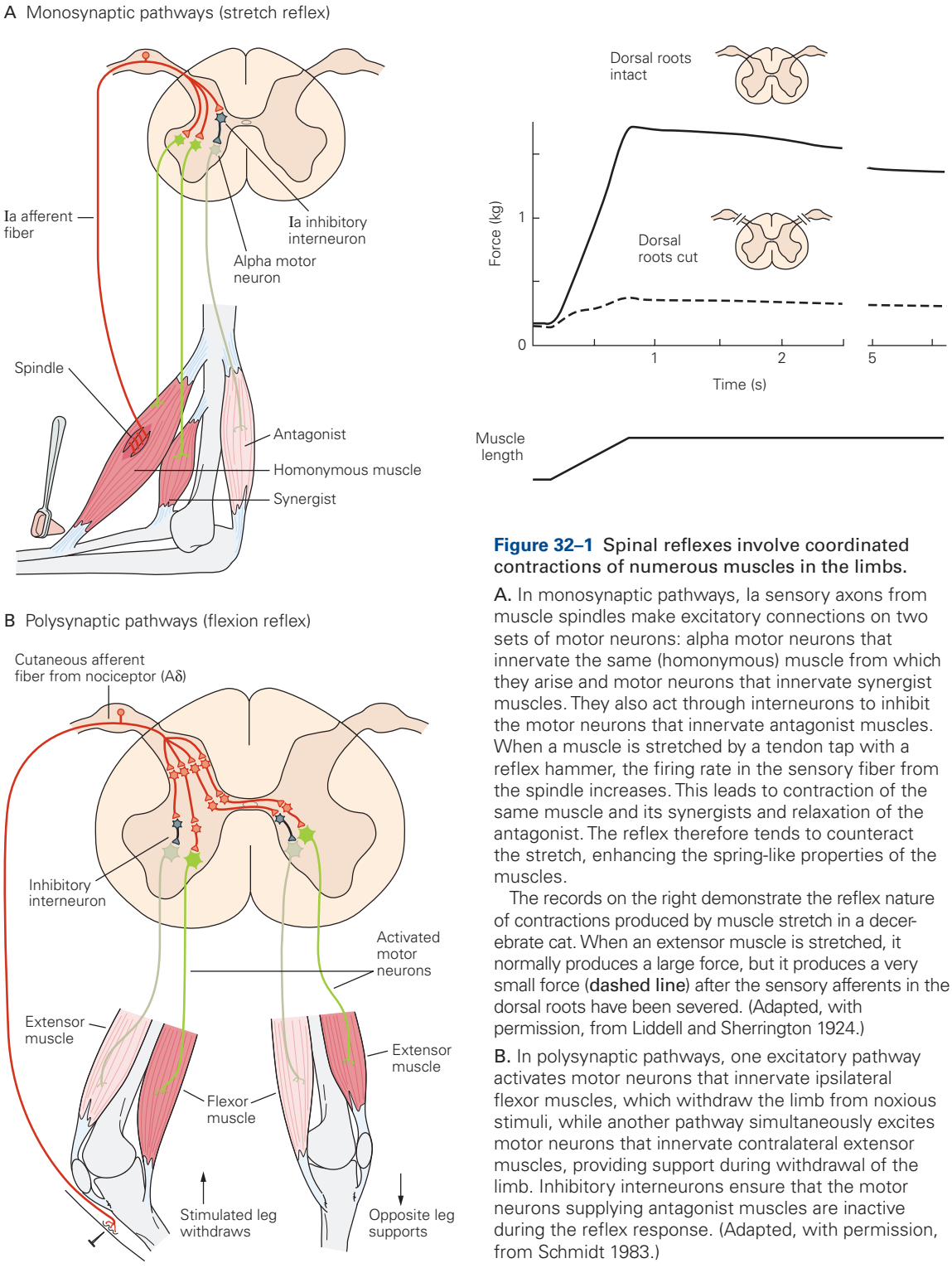

Figure 32–1 Spinal reflexes involve coordinated contractions of numerous muscles in the limbs.

A. In monosynaptic pathways, Ia sensory axons from muscle spindles make excitatory connections on two sets of motor neurons: alpha motor neurons that innervate the same (homonymous) muscle from which they arise and motor neurons that innervate synergist muscles. They also act through interneurons to inhibit the motor neurons that innervate antagonist muscles. When a muscle is stretched by a tendon tap with a reflex hammer, the firing rate in the sensory fiber from the spindle increases. This leads to contraction of the same muscle and its synergists and relaxation of the antagonist. The reflex therefore tends to counteract the stretch, enhancing the spring-like properties of the muscles.

The records on the right demonstrate the reflex nature of contractions produced by muscle stretch in a decerebrate cat. When an extensor muscle is stretched, it normally produces a large force, but it produces a very small force (**dashed line**) after the sensory afferents in the dorsal roots have been severed. (Adapted, with permission, from Liddell and Sherrington 1924.)

B. In polysynaptic pathways, one excitatory pathway activates motor neurons that innervate ipsilateral flexor muscles, which withdraw the limb from noxious stimuli, while another pathway simultaneously excites motor neurons that innervate contralateral extensor muscles, providing support during withdrawal of the limb. Inhibitory interneurons ensure that the motor neurons supplying antagonist muscles are inactive during the reflex response. (Adapted, with permission, from Schmidt 1983.)

Box 32–1 Muscle Spindles

Muscle spindles are small encapsulated sensory receptors that have a spindle-like or fusiform shape and are located within the fleshy part of a muscle. Their main function is to signal changes in the length of the muscle within which they reside. Changes in length of muscles are closely associated with changes in the angles of the joints that the muscles cross. Thus, muscle spindles are used by the central nervous system to sense relative positions of the body segments.

Each spindle has three main components: (1) a group of specialized *intrafusal* muscle fibers with noncontractile central regions; (2) sensory fibers that terminate on the central regions of the intrafusal fibers; and (3) motor axons that terminate on the contractile polar regions of the intrafusal fibers (Figure 32–2A,B).

When the intrafusal fibers are stretched, often referred to as "loading the spindle," the sensory axon endings are also stretched and increase their firing rate. Because muscle spindles are arranged in parallel with the *extrafusal* muscle fibers that make up the main body of the muscle, the intrafusal fibers change in length as the whole muscle changes. Thus, when a muscle is stretched, activity in the sensory axons of muscle spindles increases. When a muscle shortens, the spindle is unloaded and the activity decreases.

The intrafusal muscle fibers are innervated by *gamma* motor neurons, which have small-diameter myelinated axons, whereas the extrafusal muscle fibers are innervated by *alpha* motor neurons, with large-diameter myelinated axons. Activation of gamma motor neurons causes shortening of the polar regions of the intrafusal fibers. This in turn stretches the central region from both ends, leading to an increase in firing rate of the sensory axons or to a greater likelihood that the axons will fire in response to stretch of the muscle. Thus, the gamma motor neurons adjust the sensitivity of the muscle spindles. Contraction of the intrafusal muscle fibers does not contribute significantly to the force of muscle contraction.

The structure and functional behavior of muscle spindles is considerably more complex than this simple description depicts. As a muscle is stretched, the change in length has two phases: a dynamic phase, the period during which length is changing, and a static or steady-state phase, when the muscle has stabilized at a new length. Structural specializations within each component of the muscle spindle enable the sensory axons to signal aspects of each phase separately.

The intrafusal muscle fibers include nuclear bag fibers and nuclear chain fibers. The bag fibers can be classified as dynamic or static. A typical spindle has two or three bag fibers and a variable number of chain fibers, usually about five. Furthermore, the intrafusal fibers receive two types of sensory endings. A single Ia (large diameter) axon spirals around the central region of all intrafusal muscle fibers and serves as the *primary sensory ending* (Figure 32–2B). A variable number of type II (medium diameter) axons spiral around the static bag and chain fibers near their central regions and serve as *secondary sensory endings*.

The gamma motor neurons can also be divided into two classes: Dynamic gamma motor neurons innervate the dynamic bag fibers, whereas the static gamma motor neurons innervate the static bag fibers and the chain fibers.

This duality of structure is reflected in a duality of function. The tonic discharge of both primary and secondary sensory endings signals the steady-state length of the muscle. The primary sensory endings are, in addition, highly sensitive to the velocity of stretch, allowing them to provide information about the speed of movements. Because they are highly sensitive to small changes, the primary endings rapidly provide information about sudden unexpected changes in length, which can be used to generate quick corrective reactions.

Increases in the firing rate of dynamic gamma motor neurons increase the dynamic sensitivity of primary sensory endings but have no influence on secondary sensory endings. Increases in the firing rate of static gamma motor neurons increase the tonic level of activity in both primary and secondary sensory endings, decrease the dynamic sensitivity of primary endings (Figure 32–2C), and can prevent the silencing of primary endings when a muscle is released from stretch. Thus, the central nervous system can independently adjust the dynamic and static sensitivity of the different sensory endings in muscle spindles.

ventral roots to electrical stimulation of dorsal roots. When the Ia sensory axons innervating the muscle spindles were selectively activated, the reflex latency through the spinal cord was less than 1 ms. This demonstrated that the Ia fibers make direct connections on the alpha motor neurons because the delay at a single synapse is typically 0.5 ms to 0.9 ms (Figure 32–3B). In humans, an analog of the monosynaptic stretch reflex, the Hoffmann reflex, may be elicited by electrical stimulation of peripheral nerves (Box 32–3).

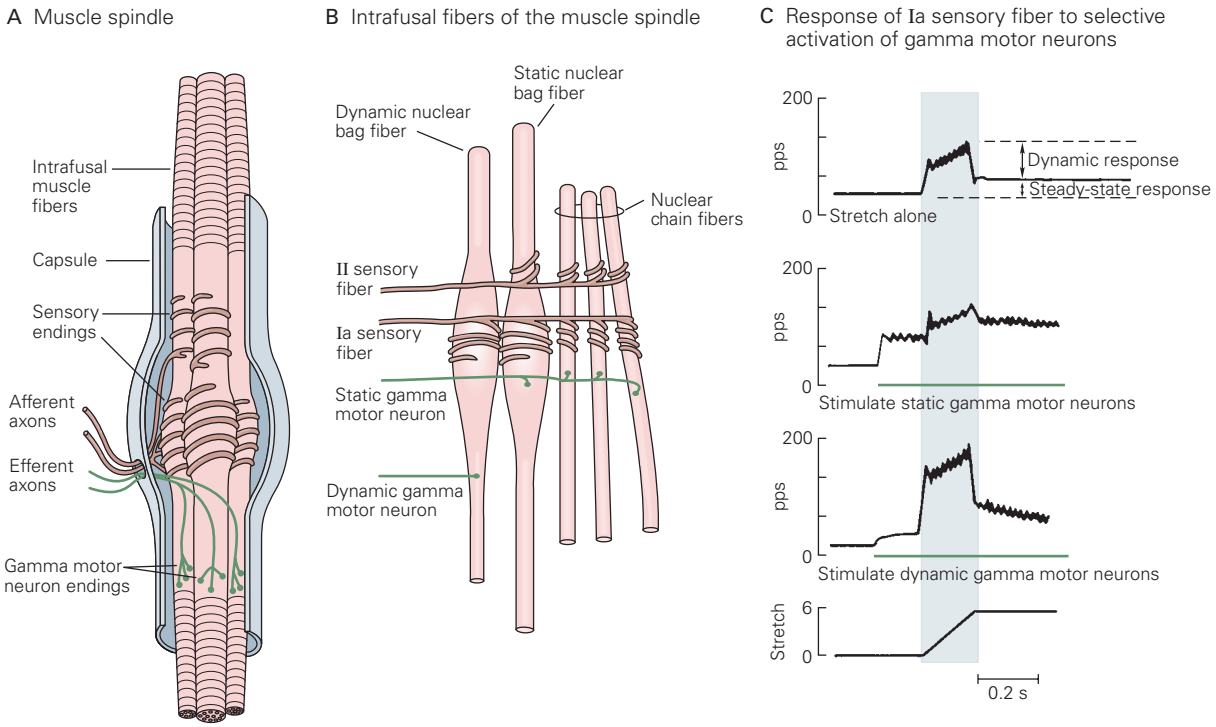

Figure 32–2 The muscle spindle detects changes in muscle length.

A. The main components of the muscle spindle are intrafusal muscle fibers, sensory axon endings, and motor axon endings. The intrafusal fibers are specialized muscle fibers with central regions that are not contractile. Gamma motor neurons innervate the contractile polar regions of the intrafusal fibers. Contraction of the polar regions pulls on the central regions of the intrafusal fiber from both ends. The sensory endings spiral around the central regions of the intrafusal fibers and are responsive to stretch of these fibers. (Adapted, with permission, from Hulliger 1984. Copyright © Springer-Verlag 1984.)

B. The muscle spindle contains three types of intrafusal fibers: dynamic nuclear bag, static nuclear bag, and nuclear chain fibers. A single Ia sensory axon innervates all three types of fibers, forming a primary sensory ending. Type II sensory axons innervate the nuclear chain fibers and static bag fibers, forming a secondary sensory ending. Two types of motor neurons innervate different intrafusal fibers. Dynamic gamma motor neurons innervate only dynamic bag fibers; static gamma motor neurons innervate various combinations of chain and static bag fibers. (Adapted, with permission, from Boyd 1980. Copyright © 1980. Published by Elsevier Ltd.)

C. Selective stimulation of the two types of gamma motor neurons has different effects on the firing of the Ia sensory fibers from the spindle. Without gamma stimulation, the Ia fiber shows a small dynamic response to muscle stretch and a modest increase in steady-state firing. When a static gamma motor neuron is stimulated, the steady-state response of the Ia fiber increases but the dynamic response decreases. When a dynamic gamma motor neuron is stimulated, the dynamic response of the Ia fiber is markedly enhanced, but the steady-state response gradually returns to its original level. (Adapted, with permission, from Brown and Matthews 1966.)

The pattern of connections of Ia fibers to motor neurons can be shown directly by intracellular recording. Ia fibers from a given muscle excite not only the motor neurons innervating that same (*homonymous*) muscle but also the motor neurons innervating other (*heteronymous*) muscles with a similar mechanical action.

Lorne Mendell and Elwood Henneman used a computer enhancement technique called *spike-triggered averaging* to determine the extent to which the action

Box 32–2 Classification of Sensory Fibers From Muscle

Sensory fibers are classified according to their diameter. Axons with larger diameters conduct action potentials more rapidly than those with smaller diameters (Chapters 9 and 18). Because each class of sensory receptors is innervated by fibers with diameters within a restricted range, this method of classification distinguishes to some extent the fibers that arise from different types of receptor organs. The main groups of sensory fibers from muscle are listed in Table 32–1.

The organization of reflex pathways in the spinal cord has been established primarily by electrically stimulating the sensory fibers and recording evoked responses in different classes of neurons in the spinal cord. This method of activation has three advantages over natural stimulation. The timing of afferent input can be precisely established; the responses evoked in motor neurons and other neurons by different classes of sensory fibers can be assessed by grading the strength of the electrical stimulus; and certain classes of receptors can be selectively activated.

The strength of the electrical stimulus required to activate a sensory fiber is measured relative to the strength required to activate the fibers with the largest diameter because these fibers have the lowest threshold for electrical activation. The thresholds of most type I fibers usually range from one to two times that of the largest fibers (with Ia fibers having, on average, a slightly lower threshold than Ib fibers). For most type II fibers, the threshold is 2 to 5 times higher, whereas types III and IV have thresholds in the range of 10 to 50 times that of the largest sensory fibers.

Table 32–1 Classification of Sensory Fibers From Muscle

Type	Axon	Receptor	Sensitivity to
Ia	12–20 μm myelinated	Primary spindle ending	Muscle length and rate of change of length
Ib	12–20 μm myelinated	Golgi tendon organ	Muscle tension
II	6–12 μm myelinated	Secondary spindle ending	Muscle length (little rate sensitivity)
II	6–12 μm myelinated	Nonspindle endings	Deep pressure
III	2–6 μm myelinated	Free nerve endings	Pain, chemical stimuli, and temperature (important for physiological responses to exercise)
IV	0.5–2 μm nonmyelinated	Free nerve endings	Pain, chemical stimuli, and temperature

potentials in single Ia fibers are transmitted to a population of spinal motor neurons. They found that individual Ia axons make excitatory synapses with all homonymous motor neurons innervating the medial gastrocnemius of the cat. This widespread divergence effectively amplifies the signals of individual Ia fibers, leading to a strong excitatory drive to the muscle from which they originate (*autogenic excitation*).

The Ia axons in reflex pathways also provide excitatory inputs to many of the motor neurons innervating synergist muscles (up to 60% of the motor neurons of some synergists) (Figure 32–1A). Although widespread, these connections are not as strong as the connections to homonymous motor neurons.

The Ia fibers also send inhibitory signals via the *Ia inhibitory interneurons* to the alpha motor neurons innervating antagonistic muscles. This disynaptic inhibitory pathway is the basis for reciprocal innervation: When a muscle is stretched, its antagonists relax.

Gamma Motor Neurons Adjust the Sensitivity of Muscle Spindles

Activity of muscle spindles may be modulated by changing the level of activity in the gamma motor neurons, which innervate the intrafusal muscle fibers of muscle spindles (Box 32–1). This function of gamma motor neurons, often referred to as the fusimotor

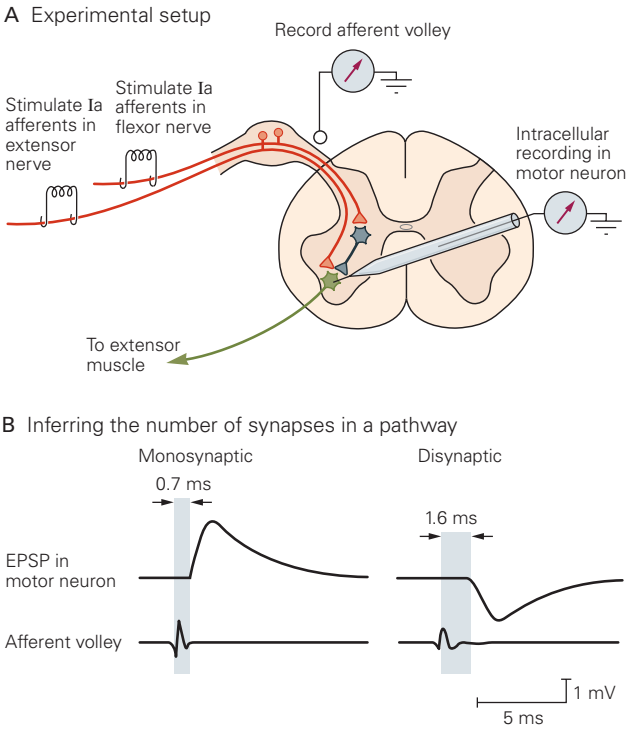

Figure 32–3 The number of synapses in a reflex pathway can be inferred from intracellular recordings.

A. An intracellular recording electrode is inserted into the cell body of a spinal motor neuron that innervates an extensor muscle. Stimulation of Ia sensory fibers from flexor or extensor muscles produces a volley of action potentials at the dorsal root.

B. *Left:* When Ia fibers from an extensor muscle are stimulated, the latency between the recording of the afferent volley and the excitatory postsynaptic potential (EPSP) in the motor neuron is only 0.7 ms, approximately equal to the duration of signal transmission across a single synapse. Thus, it can be inferred that the excitatory action of the stretch reflex pathway is monosynaptic. *Right:* When Ia fibers from an antagonist flexor muscle are stimulated, the latency between the recording of the afferent volley and the inhibitory postsynaptic potential in the motor neuron is 1.6 ms, approximately twice the duration of signal transmission across a single synapse. Thus, it can be inferred that the inhibitory action of the stretch reflex pathway is disynaptic.

system, can be demonstrated by selectively stimulating the alpha and gamma motor neurons under experimental conditions.

When only alpha motor neurons are stimulated, the firing of the Ia fiber from the muscle spindle pauses during contraction of the muscle because the muscle is shortening and therefore unloading (slackening) the spindle. However, if gamma motor neurons are activated at the same time as alpha motor neurons, the pause is eliminated. The contraction of the intrafusal fibers by the gamma motor neurons keeps the spindle under tension, thus maintaining the firing rate of the Ia fibers within an optimal range for signaling changes in length, whatever the actual length of the muscle (Figure 32–5). This *alpha-gamma co-activation* is recruited for many voluntary movements because it stabilizes the sensitivity of the muscle spindles.

In addition to the axons of gamma motor neurons, collaterals of alpha motor neuron axons sometimes innervate the intrafusal fibers. Axons that innervate both intrafusal and extrafusal muscle fibers are referred to as *beta* axons. Beta axon collaterals provide the equivalent of alpha-gamma coactivation. Beta innervation in spindles exists in both cats and humans, although it is unquantified for most muscles.

The forced linkage of extrafusal and intrafusal contraction by the beta fusimotor system highlights the importance of the independent fusimotor system (the gamma motor neurons). Indeed, in lower vertebrates, such as amphibians, beta efferents are the only source of intrafusal innervation. Mammals have evolved a mechanism that frees muscle spindles from complete dependence on the behavior of their parent muscles. In principle, this uncoupling allows greater flexibility in controlling spindle sensitivity for different types of motor tasks.

This conclusion is supported by recordings in spindle sensory axons during a variety of natural movements in cats. The amount and type of activity in gamma motor neurons are set at steady levels, which vary according to the specific task or context. In general, activity levels in both static and dynamic gamma motor neurons (Figure 32–2B) are set at progressively higher levels as the speed and difficulty of the movement increase. Unpredictable conditions, such as when the cat is picked up or handled, lead to marked increases in activity in dynamic gamma motor neurons and thus increased spindle responsiveness when muscles are stretched. When an animal is performing a difficult task, such as walking across a narrow beam, both static and dynamic gamma activation are at high levels (Figure 32–6).

Thus, the nervous system uses the fusimotor system to fine-tune muscle spindles so that the ensemble output of the spindles provides information most appropriate for a task. The task conditions under which independent control of alpha and gamma motor neurons occurs in humans have not yet been clearly established.

The Stretch Reflex Also Involves Polysynaptic Pathways

The monosynaptic Ia pathway is not the only spinal reflex pathway activated when a muscle is stretched. Type II sensory fibers from muscle spindles are also activated. These discharge tonically depending on

Box 32–3 The Hoffmann Reflex

The characteristics of the monosynaptic connections from Ia sensory fibers to spinal motor neurons in humans can be studied using an important technique introduced in the 1950s and based on early work by Paul Hoffmann. This technique involves electrically stimulating the Ia sensory fibers in a peripheral nerve and recording the reflex electromyogram (EMG) response in the homonymous muscle. The response is known as the *Hoffmann reflex*, or H-reflex.

The H-reflex is readily measured in the soleus muscle, an ankle extensor. The Ia fibers from the soleus and its synergists are excited by an electrode placed above the tibial nerve behind the knee (Figure 32–4A). The response recorded from the soleus muscle depends on stimulus strength. At low stimulus strengths, a pure H-reflex is evoked, for the threshold for activation of the Ia fibers is lower than the threshold for motor axons. Increasing the stimulus strength excites the motor axons innervating the soleus, producing two successive responses.

The first results from direct activation of the motor axons, and the second is the H-reflex evoked by stimulation of the Ia fibers (Figure 32–4B). These two components of the evoked EMG are called the M-wave and H-wave. The H-wave occurs later because it results from signals that travel to the spinal cord, across a synapse, and back again to the muscle. The M-wave, in contrast, results from direct stimulation of the motor axon innervating the muscle.

As the stimulus strength is increased still further, the M-wave continues to become larger and the H-wave progressively declines (Figure 32–4C). The decline in the H-wave amplitude occurs because action potentials in the motor axons propagate toward the cell body (antidromic conduction) and cancel reflexively evoked action potentials in the same motor axons. At very high stimulus strengths, only the M-wave persists.

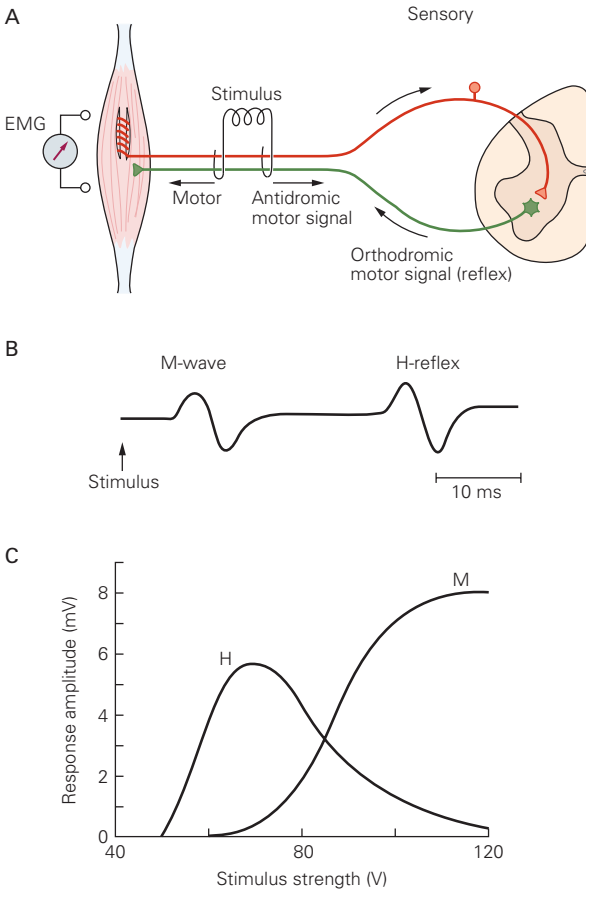

Figure 32–4 The Hoffmann reflex.

A. The Hoffmann reflex (H-reflex) is evoked by electrically stimulating Ia sensory fibers from muscle spindles. The sensory fibers excite alpha motor neurons, which in turn activate the muscle. When a mixed nerve is used, the motor neurons axons may also be activated directly.

B. At intermediate stimulus strengths, an M-wave precedes the H-wave (H-reflex) in the electromyogram (EMG).

C. As the stimulus strength increases, the orthodromic motor neuron spikes generated reflexively by the spindle sensory fibers are obliterated by antidromic spikes initiated by the electrical stimulus in the same motor axons. (Adapted, with permission, from Schieppati 1987. Copyright © 1987. Published by Elsevier Ltd.)

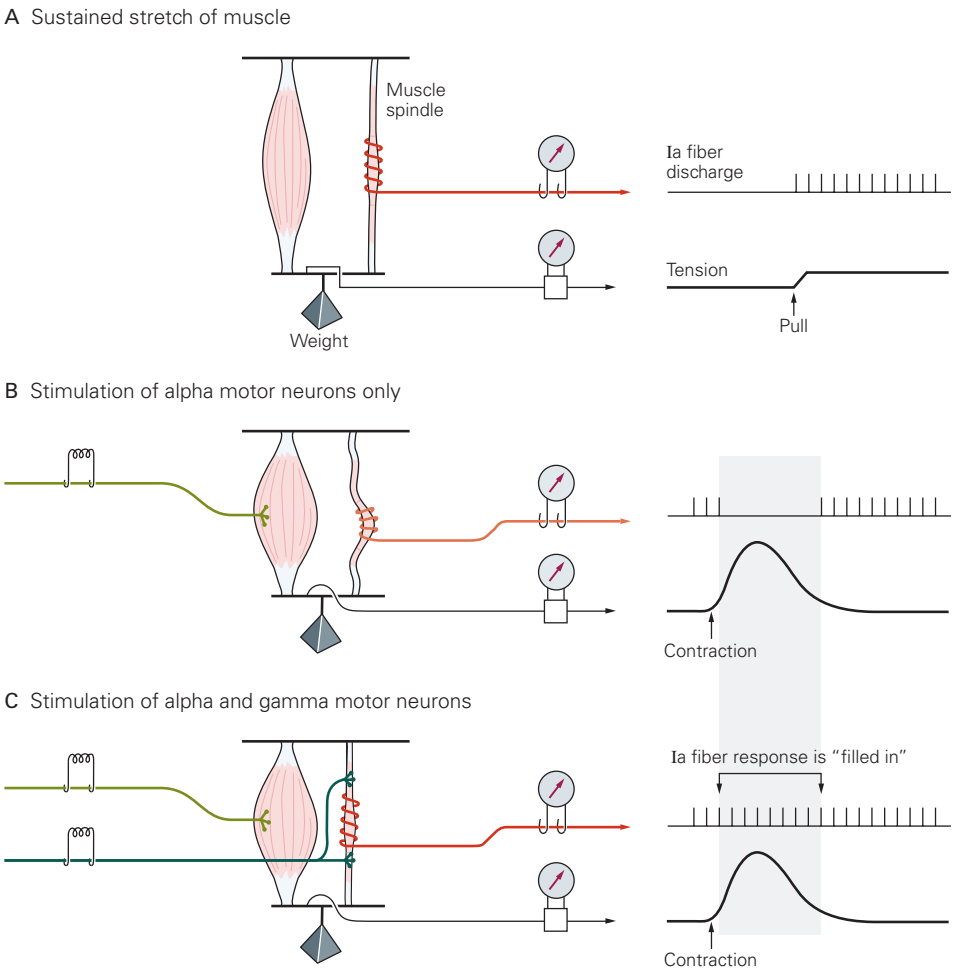

Figure 32–5 Activation of gamma motor neurons during active muscle contraction maintains muscle spindle sensitivity to muscle length. (Adapted, with permission, from Hunt and Kuffler 1951.)

A. Sustained tension elicits steady firing in the Ia sensory fiber from the muscle spindle (the two muscle fibers are shown separately for illustration only).

B. A characteristic pause occurs in the discharge of the Ia fiber when the alpha motor neuron is stimulated, causing a brief contraction of the muscle. The Ia fiber stops firing because the spindle is unloaded by the contraction.

C. Gamma motor neurons innervate the contractile polar regions of the intrafusal fibers of muscle spindles (see Figure 32–2A). If a gamma motor neuron is stimulated at the same time as the alpha motor neuron, the spindle is not unloaded during the contraction. As a result, the pause in discharge of the Ia sensory fiber that occurs when only the alpha motor neuron is stimulated is "filled in" by the response of the fiber to stimulation of the gamma motor neuron.

muscle length and gamma motor neuron activity (Box 32–1) and connect to different populations of excitatory and inhibitory interneurons in the spinal cord.

Some of the interneurons project directly to the spinal motor neurons, whereas others have more indirect connections. Because of the slower conduction velocity of type II sensory fibers and the signal relay through interneurons, the muscular responses elicited by group II fibers are smaller, more variable, and delayed compared to the monosynaptic stretch reflex. Some of the interneurons activated by group II fibers send axons across the midline of the spinal cord and give rise to crossed reflexes. Such connections that cross the midline are important for coordination of bilateral muscle activity in functional motor tasks.

Golgi Tendon Organs Provide Force-Sensitive Feedback to the Spinal Cord

Stimulation of Golgi tendon organs or their Ib sensory fibers in passive animals produces disynaptic inhibition of homonymous motor neurons (*autogenic*

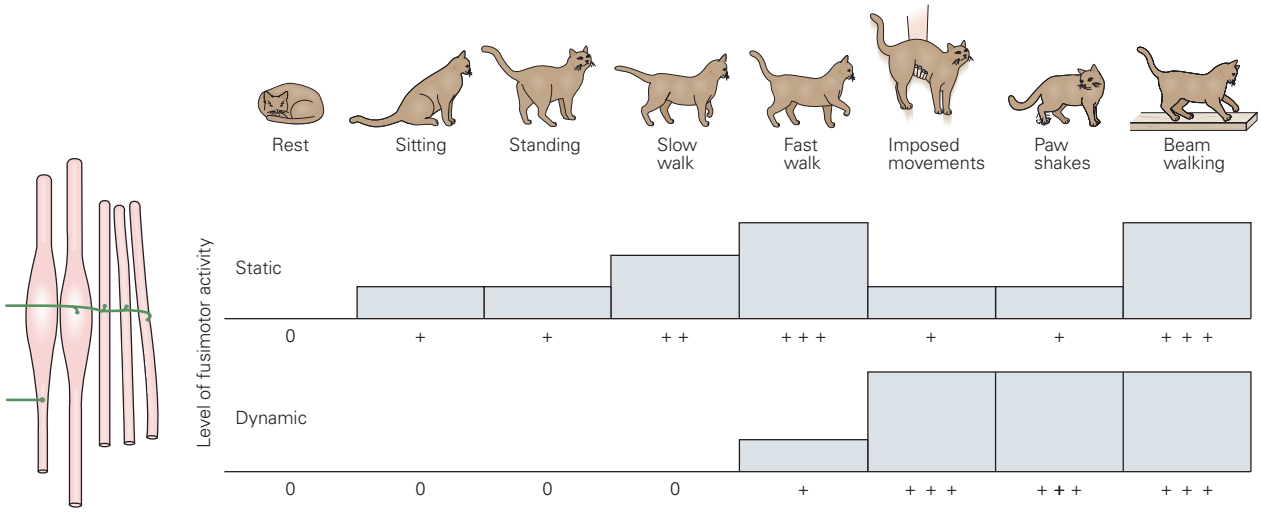

Figure 32–6 The level of activity in the fusimotor system varies with the type of behavior. Only static gamma motor neurons are active during activities in which muscle length changes slowly and predictably. Dynamic gamma motor neurons are activated during behaviors in which muscle length may change rapidly and unpredictably. (Adapted, with permission, from Prochazka et al. 1988.)

inhibition) and excitation of antagonist motor neurons (reciprocal excitation). Thus, these effects are the exact opposite of the responses evoked by muscle stretch or stimulation of Ia sensory axons.

This autogenic inhibition is mediated by *Ib inhibitory interneurons.* These inhibiting interneurons receive their principal input from Golgi tendon organs, sensory receptors that signal the tension in a muscle (Box 32–4), and they make inhibitory connections with homonymous motor neurons. However, stimulation of the Ib sensory fibers from tendon organs in active animals does not always inhibit homonymous motor neurons. Indeed, as we shall see later, stimulation of tendon organs may in certain conditions excite homonymous motor neurons.

One reason that the reflex actions of the sensory axons from tendon organs are complex in natural situations is that the Ib inhibitory interneurons also receive input from the muscle spindles, cutaneous receptors, and joint receptors (Figure 32–8A). In addition, they receive both excitatory and inhibitory input from various descending pathways.

Golgi tendon organs were first thought to have a protective function, preventing damage to muscle. It was assumed that they always inhibited homonymous motor neurons and that they fired only when tension in the muscle was high. We now know that these receptors signal minute changes in muscle tension, thus providing the nervous system with precise information about the state of a muscle's contraction.

The convergent sensory input from tendon organs, cutaneous receptors, and joint receptors to the Ib inhibitory interneurons (Figure 32–8A) may allow for precise spinal control of muscle force in activities such as grasping a delicate object. Additional input from cutaneous receptors may facilitate activity in the Ib inhibitory interneurons when the hand reaches an object, thus reducing the level of muscle contraction and permitting a soft grasp.

As is the case with the Ia fibers from muscle spindles, the Ib fibers from tendon organs form widespread connections with motor neurons that innervate muscles acting at different joints. Therefore, the connections of the sensory fibers from tendon organs with the Ib inhibitory interneurons are part of spinal networks that regulate movements of whole limbs.

Cutaneous Reflexes Produce Complex Movements That Serve Protective and Postural Functions

Most reflex pathways involve interneurons. One such reflex pathway is that of the flexion-withdrawal reflex, in which a limb is quickly withdrawn from a painful stimulus. Flexion-withdrawal is a protective reflex in which a discrete stimulus causes all the flexor muscles in that limb to contract coordinately. We know that this is a spinal reflex because it persists after complete transection of the spinal cord.

The sensory signal of the flexion-withdrawal reflex activates divergent polysynaptic reflex pathways. One

Box 32–4 Golgi Tendon Organs

Golgi tendon organs are slender encapsulated structures approximately 1 mm long and 0.1 mm in diameter located at the junction between skeletal muscle fibers and tendon. Each capsule encloses several braided collagen fibers connected in series to a group of muscle fibers.

Each tendon organ is innervated by a single Ib axon that branches into many fine endings inside the capsule; these endings become intertwined with the collagen fascicles (Figure 32–7A).

Stretching of the tendon organ straightens the collagen fibers, thus compressing the Ib nerve endings and causing them to fire. Because the nerve endings are so closely associated with the collagen fibers, even very small stretches of the tendons can compress the nerve endings.

Whereas muscle spindles are most sensitive to changes in length of a muscle, tendon organs are most sensitive to changes in muscle tension. Contraction of the muscle fibers connected to the collagen fiber bundle containing the receptor is a particularly potent stimulus to a tendon organ. The tendon organs are thus readily activated during normal movements. This has been demonstrated by recordings from single Ib axons in humans making voluntary finger movements and in cats walking normally.

Studies in anesthetized animal preparations have shown that the average level of activity in the population of tendon organs in a muscle is a good index of the total force in a contracting muscle (Figure 32–7B). This close agreement between firing frequency, and force is consistent with the view that the tendon organs continuously measure the force in a contracting muscle.

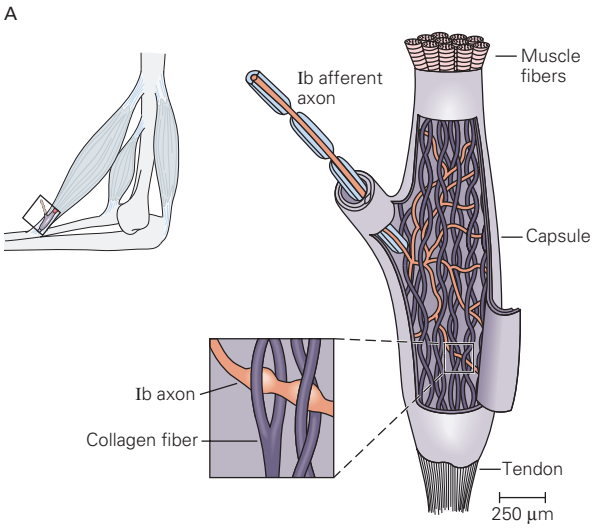

Figure 32–7A When the Golgi tendon organ is stretched (usually because of contraction of the muscle), the Ib afferent axon is compressed by collagen fibers (see enlargement) and its rate of firing increases. (Adapted, with permission, from Schmidt 1983; inset adapted, with permission, from Swett and Schoultz 1975.)

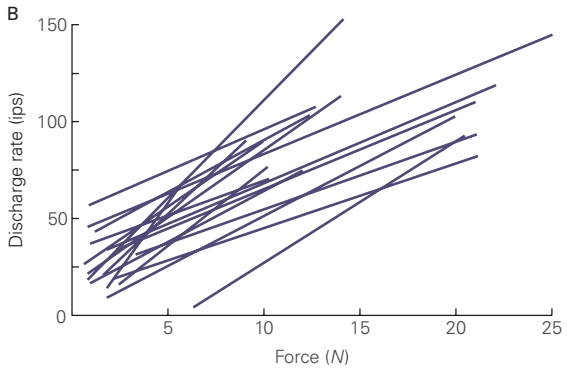

Figure 32–7B The discharge rate of a population of Golgi tendon organs signals the force in a muscle. Linear regression lines show the relationship between discharge rate and force for Golgi tendon organs of the soleus muscle of the cat. (Adapted, with permission, from Crago, Houk, and Rymer 1982.)

excites motor neurons that innervate flexor muscles of the stimulated limb, whereas another inhibits motor neurons that innervate the limb's extensor muscles (Figure 32–1B). This reflex can produce an opposite effect in the contralateral limb, that is, excitation of extensor motor neurons and inhibition of flexor motor neurons. This *crossed-extension reflex* serves to enhance postural support during withdrawal of a foot from a painful stimulus. Activation of the extensor muscles in the opposite leg counteracts the increased load caused by lifting the stimulated limb. Thus, flexion-withdrawal is a complete, albeit simple, motor act.

Although flexion reflexes are relatively stereotyped, both the spatial extent and the force of muscle contraction depend on stimulus intensity. Touching a stove that is slightly hot may produce moderately

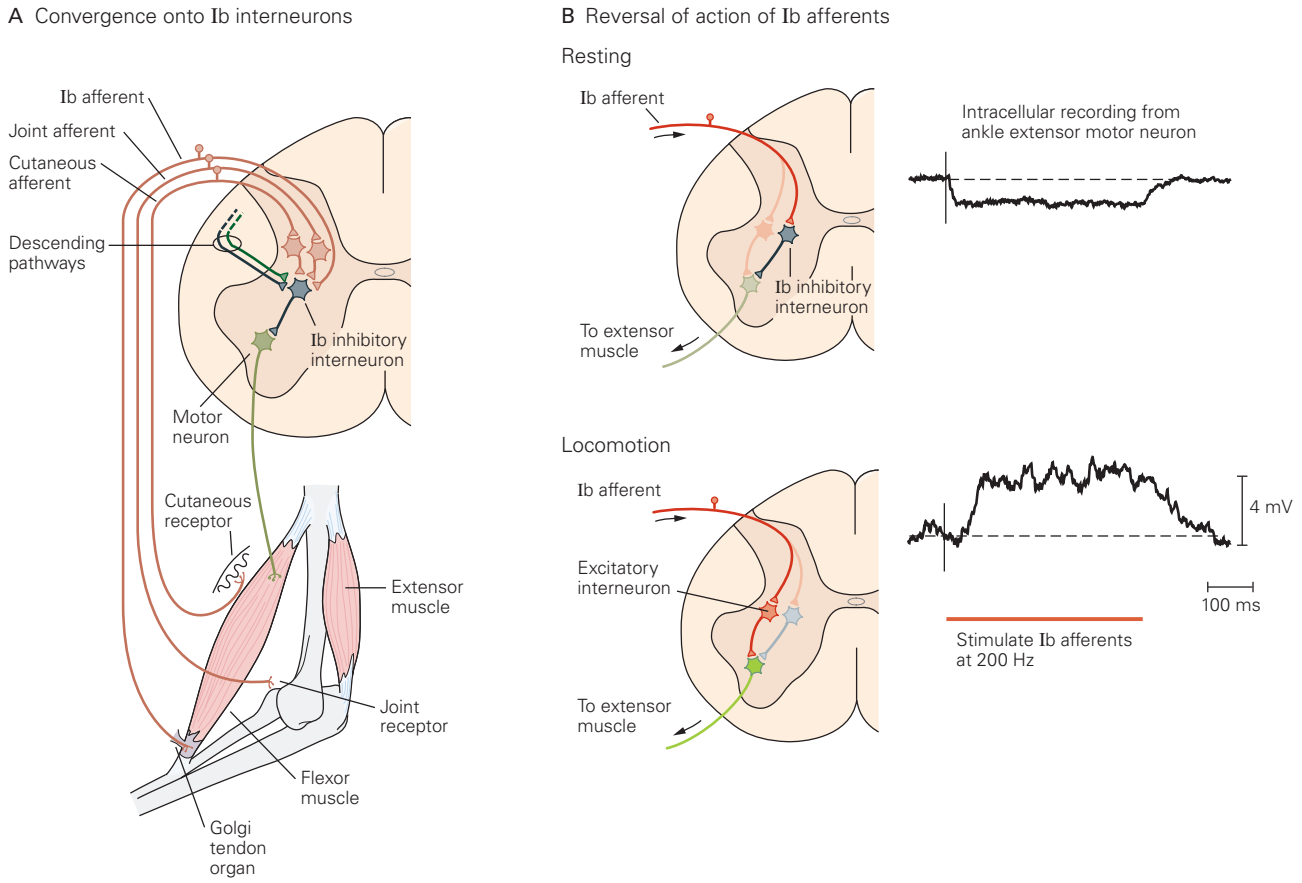

Figure 32–8 The reflex actions of Ib sensory fibers from Golgi tendon organs are modulated during locomotion.

A. The Ib inhibitory interneuron receives input from tendon organs, muscle spindles (not shown), joint and cutaneous receptors, and descending pathways.

B. The action of Ib sensory fibers on extensor motor neurons is reversed from inhibition to excitation when walking is initiated. When the animal is resting, stimulation of Ib fibers from the ankle extensor muscle inhibits ankle extensor motor neurons through Ib inhibitory interneurons, as shown by the hyperpolarization in the record. During walking, the Ib inhibitory interneurons are inhibited while excitatory interneurons that receive input from Ib sensory fibers are facilitated by the command system for walking, thus opening a Ib excitatory pathway from the Golgi tendon organs to motor neurons.

fast withdrawal only at the wrist and elbow, whereas touching a very hot stove invariably leads to a forceful contraction at all joints, leading to rapid withdrawal of the entire limb. The duration of the reflex usually increases with stimulus intensity, and the contractions produced in a flexion reflex always outlast the stimulus.

Because of the similarity of the flexion-withdrawal reflex to stepping, it was once thought that the flexion reflex is important in producing contractions of flexor muscles during walking. We now know, however, that a major component of the neural control system for walking is a set of intrinsic spinal circuits that do not require sensory stimuli (Chapter 33). Nevertheless, in mammals, the intrinsic spinal circuits that control walking share many of the interneurons involved in flexion reflexes.

Convergence of Sensory Inputs on Interneurons Increases the Flexibility of Reflex Contributions to Movement

The Ib inhibitory interneuron is not the only interneuron that receives convergent input from many different sensory modalities. An enormous diversity of sensory information converges on interneurons in the spinal cord, enabling them to integrate information from muscle, joints, and skin.

Interneurons activated by groups I and II sensory fibers have received special attention. It was thought

for some time that excitatory and inhibitory interneurons activated by group II fibers could be distinguished from those activated by group Ib afferents, but it is now believed that this distinction has to be abandoned and that groups I and II fibers converge on common populations of interneurons that integrate force and length information from the active muscle and thereby help coordinate muscle activity according to the length of the muscle, its activity level, and the external load.

Sensory Feedback and Descending Motor Commands Interact at Common Spinal Neurons to Produce Voluntary Movements

As pointed out by Michael Foster in his 1879 physiology textbook, it must be an "economy to the body" that the will should make use of the networks in the spinal cord to generate coordinated movements "rather than it should have recourse to an apparatus of its own of a similar kind." Research in the subsequent 140 years has confirmed this conjecture.

The first evidence came from intracellular recordings of synaptic potentials elicited in cat spinal motor neurons by combined and separate stimulation of sensory fibers and descending pathways. When separate stimuli are reduced in intensity to just below threshold for evoking a synaptic potential, combining the stimulations at appropriate intervals makes the synaptic potential reappear. This provides evidence of convergence of the sensory fibers and the descending pathways onto common interneurons in the reflex pathway (see Figure 13–14). Direct recordings from spinal interneurons have confirmed this, as have noninvasive Hoffmann reflex tests in human subjects (Figure 32–9).

Direct evidence that sensory feedback helps to shape voluntary motor commands through spinal reflex networks in humans comes from experiments in which sensory activity in length- and force-sensitive afferents has suddenly been reduced or abolished. This can be done by suddenly unloading or shortening a muscle during a voluntary contraction. The short latency of the consequent reduction in muscle activity can only be explained by sensory activity through a reflex pathway that directly contributes to the muscle activity.

Muscle Spindle Sensory Afferent Activity Reinforces Central Commands for Movements Through the Ia Monosynaptic Reflex Pathway

Stretch reflex pathways can contribute to the regulation of motor neurons during voluntary movements and during maintenance of posture because they form closed feedback loops. For example, stretching a muscle increases activity in spindle sensory afferents, leading to muscle contraction and consequent shortening of the muscle. Muscle shortening in turn leads to decreased activity in spindle afferents, reduction of muscle contraction, and lengthening of the muscle.

The stretch reflex loop thus acts continuously—the output of the system, a change in muscle length, becomes the input—tending to keep the muscle close to a desired or reference length. The stretch reflex pathway is a negative feedback system, or *servomechanism*, because it tends to counteract or reduce deviations from the reference value of the regulated variable.

In 1963, Ragnar Granit proposed that the reference value in voluntary movements is set by descending signals that act on both alpha and gamma motor neurons. The rate of firing of alpha motor neurons is set to produce the desired shortening of the muscle, and the rate of firing of gamma motor neurons is set to produce an equivalent shortening of the intrafusal fibers of the muscle spindle. If the shortening of the whole muscle is less than what is required by a task, as when the load is greater than anticipated, the sensory fibers increase their firing rate because the contracting intrafusal fibers are stretched (loaded) by the relatively greater length of the whole muscle. If shortening is greater than necessary, the sensory fibers decrease their firing rate because the intrafusal fibers are relatively slackened (unloaded) (Figure 32–10A).

In theory, this mechanism could permit the nervous system to produce movements of a given distance without having to know in advance the actual load or weight being moved. In practice, however, the stretch reflex pathways do not have sufficient control over motor neurons to overcome large unexpected loads. This is immediately obvious if we consider what happens when we attempt to lift a heavy suitcase that we believe to be empty. Automatic compensation for the greater-than-anticipated load does not occur. Instead, we have to pause briefly to plan a new movement with much greater muscle activation.

Strong evidence that alpha and gamma motor neurons are co-activated during voluntary human movement comes from direct measurements of the activity of the sensory fibers from muscle spindles. In the late 1960s, Åke Vallbo and Karl-Erik Hagbarth developed microneurography, a technique for recording from the largest afferent fibers in peripheral nerves. Vallbo later found that during slow movements of the fingers the large-diameter Ia fibers from spindles in the contracting muscles increase their rate of firing even when the muscle shortens as it contracts (Figure 32–10B). This occurs because the gamma motor neurons, which have

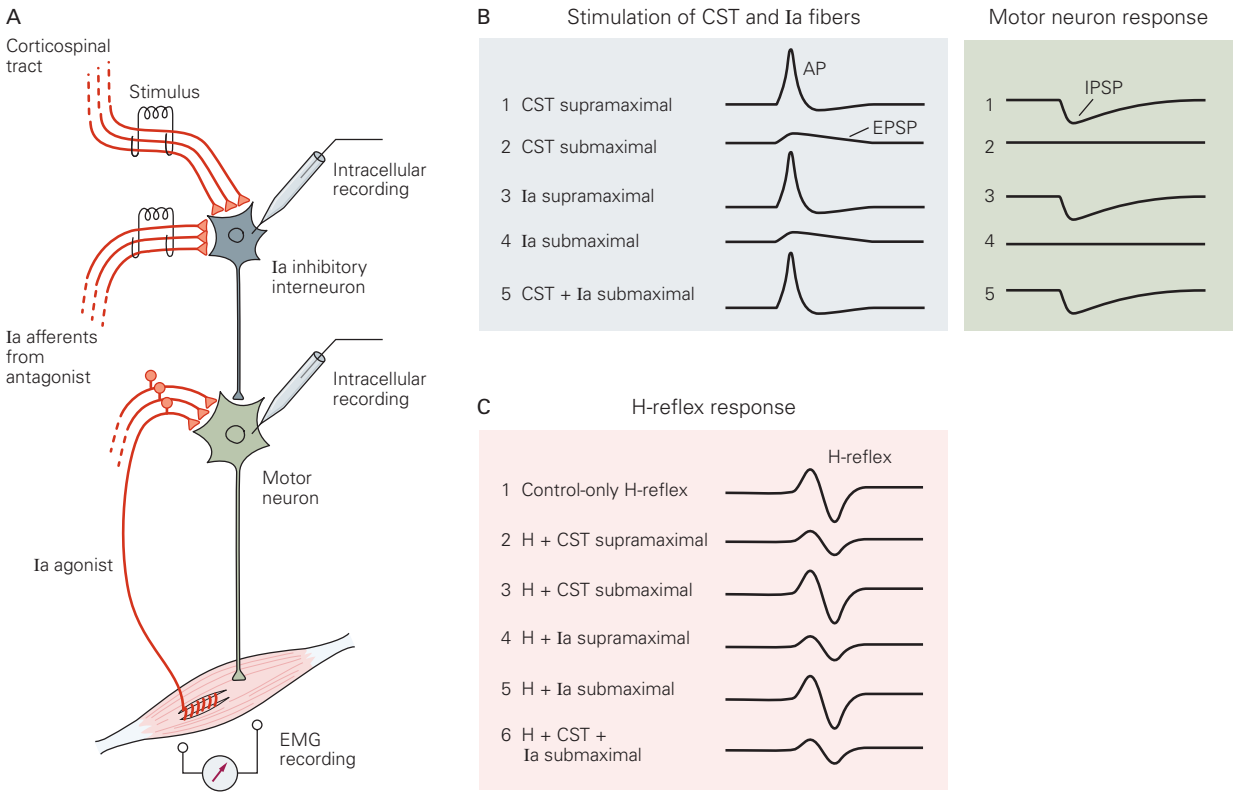

Figure 32–9 The spatial summation technique demonstrates how signals from descending inputs and spinal networks are integrated. This technique was introduced originally for investigation of spinal circuits in the cat in the 1950s, but it is also the basis of later investigations of the human spinal mechanisms of motor control. It relies on the spatial summation of synaptic inputs (see Figure 13–14), as illustrated here using the reciprocal Ia inhibitory pathway and corticospinal tract (**CST**).

A. The diagram shows the experimental setups for testing for convergence of excitatory reciprocal Ia and corticospinal pathways onto Ia inhibitory interneurons in the spinal cord.

B. In acute experiments on the cat spinal cord, supramaximal stimuli were applied separately to corticospinal fiber tracts (**1**) and Ia axons (**3**); each stimulus elicited an inhibitory postsynaptic potential (**IPSP**) in the motor neuron. Next, the intensities of the two stimuli were reduced to just submaximal levels, at which point each pathway failed to elicit an IPSP in the motor neuron (**2**, **4**). Then, when the two sets of submaximal stimuli were paired, they elicited an IPSP in the motor neuron (**5**), leading to the conclusion that the two input pathways converge on the same interneurons. This was confirmed by direct recording from a Ia inhibitory interneuron. (**AP**, action potential).

C. In humans, direct intracellular recording from interneurons and motor neurons is not possible, but recording of H-reflexes (Box 32–4, Figure 32–4) and transcutaneous stimulation of the corticospinal tract have provided indirect evidence for convergence similar to that demonstrated in cats (see part **B**). The electromyogram (**EMG**) record of the H-reflex provides a measure of the excitability of the spinal motor neurons (**1**). When the CST and antagonist Ia fibers were stimulated separately at supramaximal levels, the H-reflex amplitude was diminished due to the compound IPSPs elicited in the motor neurons (**2**, **4**). Next, the stimuli to these two excitatory pathways to the inhibitory interneurons were reduced until neither stimulus alone elicited a reduction in amplitude of the H-reflex (**3**, **5**). Then, the two submaximal stimuli were timed to produce synchronous subthreshold excitatory postsynaptic potentials (**EPSPs**) in the inhibitory interneurons (**6**). Because this protocol caused suppression of the H-reflex, one may conclude that the CST and Ia afferents converge on the same Ia inhibitory interneurons.

direct excitatory connections with spindles, are coactivated with alpha motor neurons.

Furthermore, when subjects attempt to make slow movements at a constant velocity, the firing of the Ia fibers mirrors the small deviations in velocity in the trajectory of the movements (sometimes the muscle shortens quickly and at other times more slowly). When the velocity of flexion increases transiently, the rate of firing in the fibers decreases because the muscle is shortening more rapidly and therefore exerts less tension on the intrafusal fibers. When the velocity decreases, firing increases because the muscle is

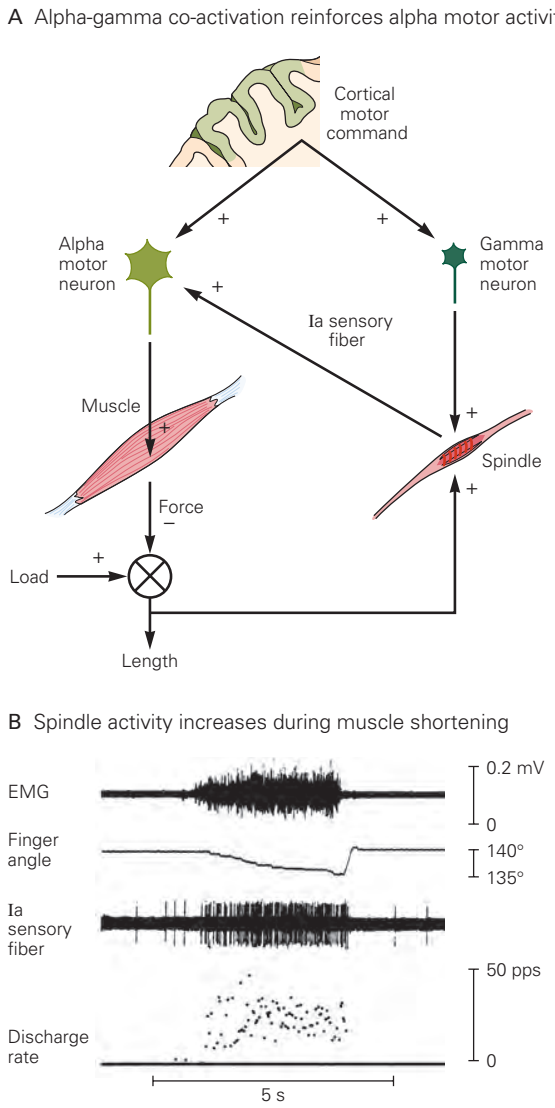

Figure 32–10 Co-activation of alpha and gamma motor neurons.

A. Co-activation of alpha and gamma motor neurons by a cortical motor command allows feedback from muscle spindles to reinforce activation in the alpha motor neurons. Any disturbance during a movement alters the length of the muscle and thus changes the activity in the sensory fibers from the spindles. The changed spindle input to the alpha motor neuron compensates for the disturbance.

B. The discharge rate in the Ia sensory fiber from a spindle increases during slow flexion of a finger. This increase depends on alpha-gamma co-activation. If the gamma motor neurons were not active, the spindle would slacken, and its discharge rate would decrease as the muscle shortened. (EMG, electromyogram; PPS, pulses/s) (Adapted, with permission, from Vallbo 1981.)

shortening more slowly, and therefore, the relative tension on the intrafusal fibers increases. This information can be used by the nervous system to compensate for irregularities in the movement trajectory by exciting the alpha motor neurons.

Modulation of Ia inhibitory Interneurons and Renshaw Cells by Descending Inputs Coordinate Muscle Activity at Joints

Reciprocal innervation is useful not only in stretch reflexes but also in voluntary movements. Relaxation of the antagonist muscle during a movement enhances speed and efficiency because the muscles that act as prime movers are not working against the contraction of opposing muscles.

The Ia inhibitory interneurons receive inputs from collaterals of the axons of neurons in the motor cortex that make direct excitatory connections with spinal motor neurons. This organizational feature simplifies the control of voluntary movements, because higher centers do not have to send separate commands to the opposing muscles.

It is sometimes advantageous to contract both the prime mover and the antagonist at the same time. Such *co-contraction* has the effect of stiffening the joint and is most useful when precision and joint stabilization are critical. An example of this phenomenon is the co-contraction of flexor and extensor muscles of the elbow immediately before catching a ball. The Ia inhibitory interneurons receive both excitatory and inhibitory signals from all of the major descending pathways (Figure 32–11A). By changing the balance of excitatory and inhibitory inputs onto these interneurons, supraspinal centers can modulate reciprocal inhibition of muscles and enable co-contraction, thus controlling the relative amount of joint stiffness to meet the requirements of the motor act.

The activity of spinal motor neurons is also regulated by another important class of inhibitory interneurons, the *Renshaw cells.* Excited by collaterals of the axons of motor neurons and receiving significant synaptic input from descending pathways, Renshaw cells make inhibitory synaptic connections with several populations of motor neurons, including the motor neurons that excite them, as well as Ia inhibitory interneurons (Figure 32–11B). The connections with motor neurons form a negative feedback system that regulates the firing rate of the motor neurons, whereas the connections with the Ia inhibitory interneurons regulate the strength of inhibition of antagonistic motor neurons, for instance in relation to co-contraction of antagonists. The distribution of projections from Renshaw

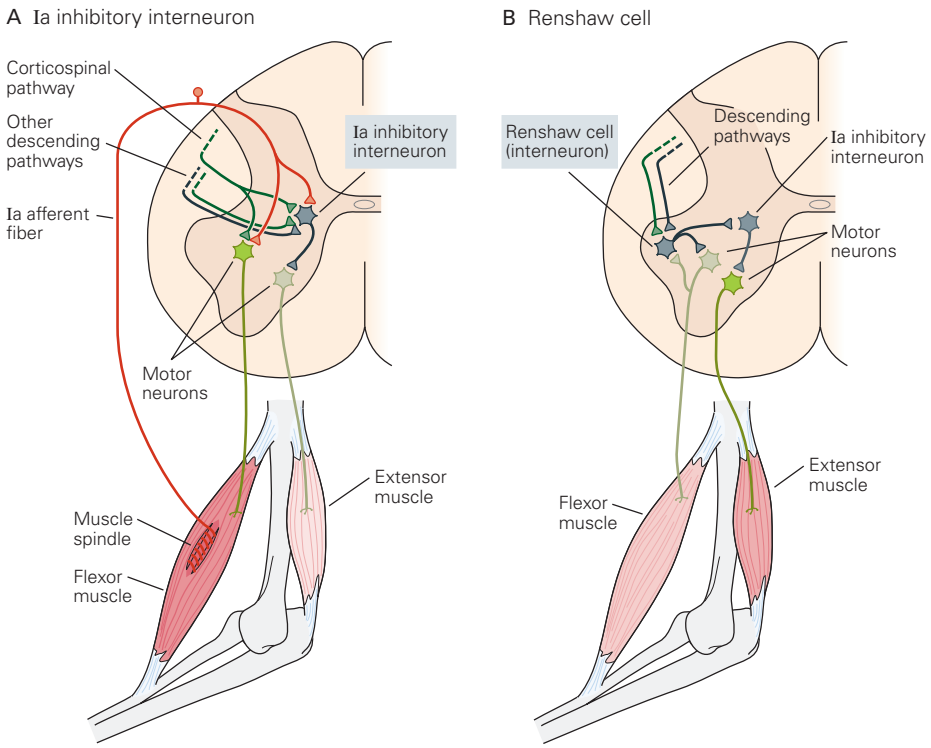

Figure 32–11 Inhibitory spinal interneurons coordinate reflex actions.

A. The Ia inhibitory interneuron regulates contraction in antagonist muscles in stretch reflex circuits through its divergent contacts with motor neurons. In addition, the interneuron receives excitatory and inhibitory inputs from corticospinal and other descending pathways. A change in the balance of these supraspinal signals allows the interneuron to coordinate co-contractions in antagonist muscles at a joint.

B. The Renshaw cell produces recurrent inhibition of motor neurons. These interneurons are excited by collaterals from motor neurons and inhibit those same motor neurons. This negative feedback system regulates motor neuron excitability and stabilizes firing rates. Renshaw cells also send collaterals to synergist motor neurons (not shown) and Ia inhibitory interneurons that synapse on antagonist motor neurons. Thus, descending inputs that modulate the excitability of the Renshaw cells adjust the excitability of all the motor neurons that control movement around a joint.

cells to different motor nuclei also facilitate that muscle activity is coordinated in functional synergies during movement.

Transmission in Reflex Pathways May Be Facilitated or Inhibited by Descending Motor Commands

As we have seen, in an animal at rest, the Ib sensory fibers from extensor muscles have an inhibitory effect on homonymous motor neurons. During locomotion, they produce an excitatory effect on those same motor neurons because transmission in the disynaptic inhibitory pathway is depressed (Figure 32–8B), while at the same time transmission through excitatory interneurons is facilitated.

This phenomenon, called *state-dependent reflex reversal*, illustrates how transmission in spinal circuit is regulated by descending motor commands to meet the changing requirements during movement. By favoring transmission through excitatory pathways from the load-sensitive Golgi tendon organs, the descending motor commands ensure that feedback from the active muscles automatically facilitates the activation of the muscles, thereby greatly simplifying the task for supraspinal centers.

State-dependent reflex reversal has also been demonstrated in humans. Stimulation of skin and muscle afferents from the foot produces facilitation of muscles that lift the foot early in the swing phase, but suppresses activity of the same muscles late in the swing phase. Both effects make good functional sense. Early in the swing phase, positive feedback from the foot will help to lift the foot over an obstacle, whereas suppression of the same muscles in late swing will help to lower the foot quickly to the ground so that the obstacle may be passed using the opposite leg first.

Descending Inputs Modulate Sensory Input to the Spinal Cord by Changing the Synaptic Efficiency of Primary Sensory Fibers

In the 1950s and early 1960s, John C. Eccles and his collaborators demonstrated that monosynaptic excitatory postsynaptic potentials (EPSPs) elicited in cat spinal motor neurons by stimulation of Ia sensory fibers become smaller when other Ia fibers are stimulated. This led to the discovery in the spinal cord of several groups of GABAergic inhibitory interneurons that exert presynaptic inhibition of primary sensory neurons (Figure 32–12). Some interneurons inhibit mainly Ia sensory axons, whereas others inhibit mainly Ib axons or sensory fibers from skin.

The principal mechanism responsible for sensory inhibition is a depolarization of the primary terminal caused by an inward Cl^- current when GABAergic receptors on the terminal are activated. This depolarization inactivates some of the Na^+ channels in the terminal, so the action potentials that reach the synapse are reduced in size. The effect of this is that release of neurotransmitter from the sensory afferent is diminished.

When tested by stimulation of peripheral afferents, presynaptic inhibition is widespread in the spinal cord and affects primary afferents from all muscles in a limb. However, similar to other interneurons, the neurons responsible for presynaptic inhibition are also controlled by descending pathways, making possible a much more focused modulation of presynaptic inhibition in relation to movement. Presynaptic inhibition at the synapse of Ia axons with motor neurons of the muscles that are activated as part of a movement is reduced at the onset of movement. In contrast, presynaptic inhibition of Ia axons on motor neurons connected to inactive muscles is increased. One example of this selective modulation is increased presynaptic inhibition of Ia axons at their synapse with antagonist motor neurons, which explains part of the reduction of stretch reflexes in antagonist muscles at the onset of agonist contraction. In this way, the nervous system takes advantage of the widespread connectivity of Ia axons, using presynaptic inhibition to shape activity in the Ia afferent network to facilitate activation of specific muscles.

Presynaptic inhibition provides a mechanism by which the nervous system can reduce sensory feedback predicted by the motor command, while allowing unexpected feedback access to the spinal motor circuit and the rest of the nervous system. In line with this function, presynaptic inhibition of Ia sensory axons from muscle spindles generally increases during

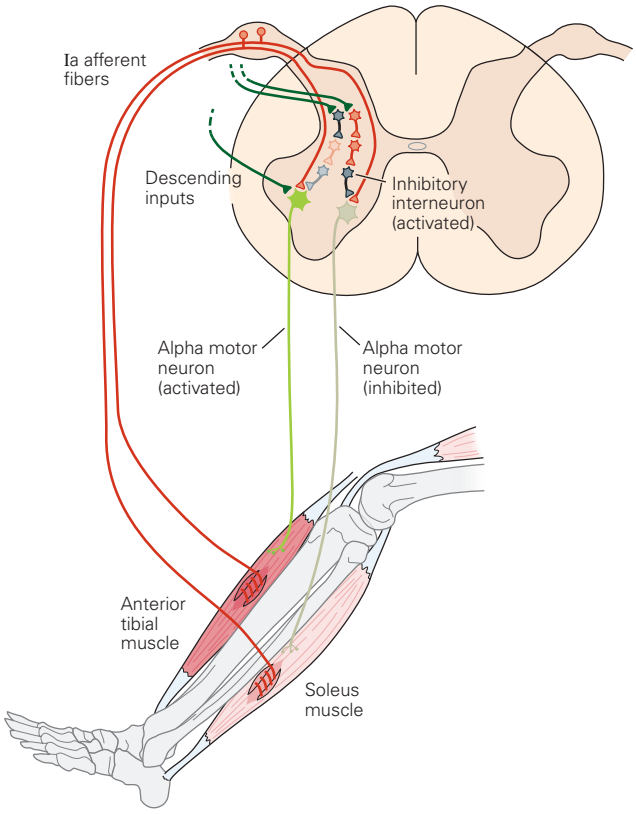

Figure 32–12 **Selective modulation of primary sensory axon terminals by descending presynaptic inhibitory inputs contributes to generation of coordinated limb movements.** Inhibitory interneurons (**blue**) activated by descending inputs can have either pre- or postsynaptic effects. Some interneurons releasing the inhibitory neurotransmitter γ-aminobutyric acid (GABA) form axo-axonic synapses with the primary sensory fibers. The principal inhibitory mechanism involves activation of GABAergic receptors on the terminals of the presynaptic Ia sensory axons, resulting in depolarization of the terminals and reduced transmitter release. Such presynaptic inhibition is widely distributed in the spinal cord. Stimulation of Ia sensory fibers from one flexor muscle may elicit presynaptic inhibition of both flexor and extensor Ia axon terminals on motor neurons innervating muscles throughout the limb. However, several different populations of interneurons mediating presynaptic inhibition exist, which allows a very specific regulation of presynaptic inhibition in relation to voluntary movements. Interaction of sensory inputs with descending motor commands in the corticospinal tract may thus *decrease* presynaptic inhibition of Ia axon terminals on agonist motor neurons (eg, anterior tibial motor neurons) and at the same time *increase* presynaptic inhibition of Ia terminals on antagonist motor neurons (eg, soleus motor neurons). Regulation of presynaptic inhibition may thus simultaneously facilitate the sensory feedback to the activation of agonist motor neurons and at the same time diminish the risk that stretch of the antagonist muscles will elicit a stretch reflex that would counteract the movement.

movements that are highly predictable, such as walking and running.

Finally, presynaptic inhibition may help stabilize the execution of movements by preventing excessive sensory feedback and associated self-reinforcing oscillatory activity.

Part of the Descending Command for Voluntary Movements Is Conveyed Through Spinal Interneurons

In cats as well as most other vertebrates, the corticospinal tract has no direct connections to spinal motor neurons; all the descending commands have to be channeled through spinal interneurons that are also part of reflex pathways. Humans and Old World monkeys are the only species in which corticospinal neurons make direct connections with the spinal motor neurons in the ventral horn of the spinal cord. Even in these species, a considerable fraction of the corticospinal tract fibers terminate in the intermediate nucleus on spinal interneurons, and the corticospinal fibers that terminate on motor neurons also have collaterals that synapse on interneurons. A considerable part of each descending command for movement in the corticospinal tract therefore has to be conveyed through spinal interneurons—and integrated with sensory activity—before reaching the motor neurons.

Propriospinal Neurons in the C3–C4 Segments Mediate Part of the Corticospinal Command for Movement of the Upper Limb

In the 1970s, Anders Lundberg and his collaborators demonstrated that a group of neurons in the C3–C4 spinal segments of the cat spinal cord send their axons to motor neurons located in more caudal cervical segments (Figure 32–13). Since the neurons in the C3–C4 segments project to motor neurons that innervate a range of forelimb muscles controlling different joints, and receive input from both skin and muscles throughout the forelimb, they are named *propriospinal neurons*. In addition to sensory input from skin and muscle afferents, the C3–C4 propriospinal neurons are activated by collaterals from the corticospinal tract and thereby relay disynaptic excitation from the motor cortex to the spinal motor neurons.

Subsequent experiments by Bror Alstermark in Sweden and Tadashi Isa in Japan have confirmed that similar propriospinal neurons also exist in the C3–C4 segments of the monkey spinal cord and are involved in mediating at least part of the motor command for reaching. Noninvasive experiments have also provided indirect evidence of the existence of C3–C4 propriospinal neurons in the human spinal cord. With the evolution of direct monosynaptic corticomotor connections in monkeys and humans, the corticospinal transmission through this disynaptic pathway may have become less important.

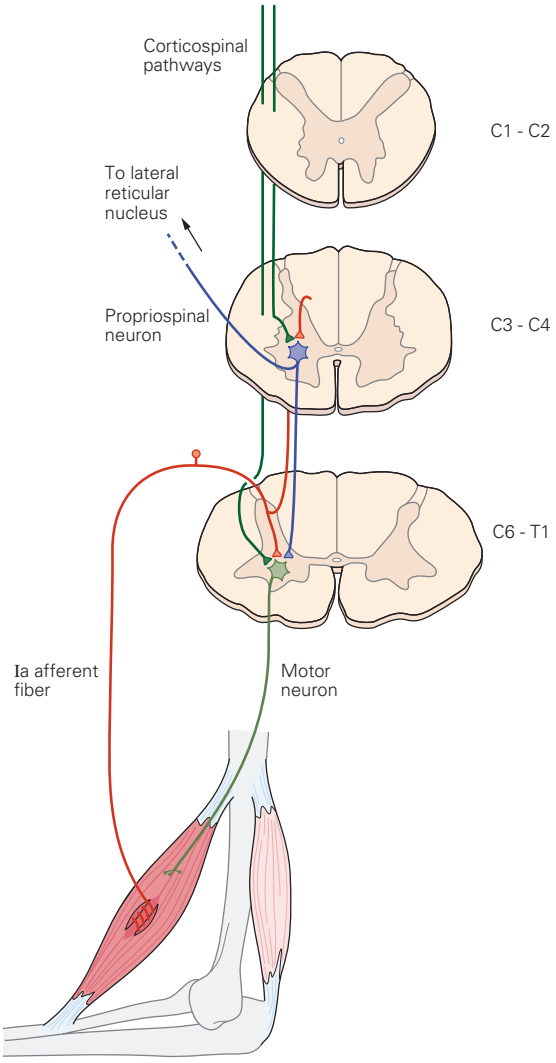

Figure 32–13 **Propriospinal neurons in spinal segments C3–C4 mediate part of the descending motor command to cervical motor neurons.** Some corticospinal fibers (**green**) send collaterals to propriospinal neurons in the C3–C4 segments (**blue**). These C3–C4 propriospinal neurons project to motor neurons located in more caudal cervical segments. They also receive excitatory input from muscle afferents and send collaterals to the lateral reticular nucleus.

Lumbar interneurons that receive input from groups I and II sensory axons from muscle also receive significant input from descending motor tracts and provide excitatory projections to spinal motor neurons. These interneurons thus convey part of the indirect motor command for voluntary movements to the spinal motor neurons that control leg muscles and may be a lumbar equivalent of the C3–C4 propriospinal neurons in the cervical spinal cord.

Neurons in Spinal Reflex Pathways Are Activated Prior to Movement

Synaptic transmission in spinal reflex pathways may change in response to the intention to move, independent of movement. Intracellular recordings from active monkeys have demonstrated that the intention to make a movement modifies activity in interneurons in the spinal cord and alters transmission in spinal reflex pathways. Similarly, in human subjects who have been prevented from contracting a muscle (by injection of lidocaine into the peripheral nerve supplying the muscle), the voluntary effort to contract the muscle still changes transmission in reflex pathways as if the movement had actually taken place.

In both humans and monkeys, spinal interneurons also change their activity well in advance of the actual movement. For example, in human subjects, Hoffmann reflexes elicited in a muscle that is about to be activated are facilitated fully 50 ms prior to the onset of contraction and remain facilitated throughout the movement. Conversely, reflexes in the antagonist muscles are suppressed. The suppression of stretch reflexes in the antagonist muscle prior to the onset of movement is an efficient way of preventing the antagonist from being reflexively activated when it is stretched at the onset of the agonist contraction.

Transmission in spinal reflex pathways can also be modified in connection with higher cognitive functions. Two examples are (1) an increase in the tendon jerk reflex in the soleus muscle of a human subject imagining pressing a foot pedal and (2) modulation of the Hoffmann reflex in arm and leg muscles while a subject observes grasping and walking movements, respectively.

Proprioceptive Reflexes Play an Important Role in Regulating Both Voluntary and Automatic Movements

All movements activate receptors in muscles, joints, and skin. Sensory signals generated by the body's own movements were termed *proprioceptive* by Sherrington, who proposed that they control important aspects of normal movements. A good example is the Hering-Breuer reflex, which regulates the amplitude of inspiration. Stretch receptors in the lungs are activated during inspiration, and the Hering-Breuer reflex eventually triggers the transition from inspiration to expiration when the lungs are expanded.

A similar situation exists in the walking systems of many animals; sensory signals generated near the end of the stance phase initiate the onset of the swing phase (Chapter 33). Proprioceptive signals can also contribute to the regulation of motor activity during voluntary movements, as shown in studies of individuals with sensory neuropathy of the arms. These patients display abnormal reaching movements and have difficulty in positioning the limb accurately because the lack of proprioception results in a failure to compensate for the complex inertial properties of the human arm.

Therefore, a primary function of proprioceptive reflexes in regulating voluntary movements is to adjust the motor output according to the changing biomechanical state of the body and limbs. This adjustment ensures a coordinated pattern of motor activity during an evolving movement and compensates for the intrinsic variability of motor output.

Spinal Reflex Pathways Undergo Long-Term Changes

Transmission in spinal reflex pathways is modulated not only to suit the immediate requirements of the movement but also to adapt the motor command to the motor experience of the individual. For example, transmission in the reciprocal Ia inhibitory pathway shows a gradual change when subjects improve their ability in coordinating agonist and antagonist contraction. Inactivity following long periods of bedrest or immobilization also results in changes in stretch reflexes and H-reflexes. Conversely, the soleus stretch reflex is low in highly trained ballet dancers and varies among different kinds of athletes.

Extensive studies of humans, monkeys, and rats by Jonathan Wolpaw and his colleagues have found that stretch reflexes can be operantly conditioned to either increase or decrease. The mechanisms underlying these changes are complex and involve alterations at multiple sites including changes in the properties of motor neurons. A general prerequisite for these changes is that corticospinal control of the spinal motor circuits must be intact.

Damage to the Central Nervous System Produces Characteristic Alterations in Reflex Responses

Stretch reflexes are routinely used in clinical examinations of patients with neurological disorders. They are typically elicited by sharply tapping the tendon of a muscle with a reflex hammer. Although the responses are often called tendon reflexes or tendon jerks, the receptor that is stimulated, the muscle spindle, actually lies in the muscle rather than the tendon. Only the primary sensory fibers in the spindle participate in the tendon reflex, for these are selectively activated by a rapid stretch of the muscle produced by the tendon tap.

Measuring alterations in the strength of the stretch reflex can assist in the diagnosis of certain conditions and in localizing injury or disease in the central nervous system. Absent or hypoactive stretch reflexes often indicate a disorder of one or more of the components of the peripheral reflex pathway: sensory or motor axons, the cell bodies of motor neurons, or the muscle itself (Chapter 57). Nevertheless, because the excitability of motor neurons is dependent on descending excitatory and inhibitory signals, absent or hypoactive stretch reflexes can also result from lesions of the central nervous system. Hyperactive stretch reflexes, conversely, always indicate that the lesion is in the central nervous system.

Interruption of Descending Pathways to the Spinal Cord Frequently Produces Spasticity

The force with which a muscle resists being lengthened depends on the muscle's intrinsic elasticity, or stiffness. Because a muscle has elastic elements in series and parallel that resist lengthening, it behaves like a spring (Chapter 31). In addition, connective tissue in and around the muscle may also contribute to its stiffness. These elastic elements may be pathologically altered following brain and spinal cord injury and thereby cause contractures and abnormal joint positions. However, there is also a neural contribution to the resistance of a muscle to stretch; the feedback loop inherent in the stretch reflex pathway acts to resist lengthening of the muscle.

Spasticity is characterized by hyperactive tendon jerks and an increase in resistance to rapid stretching of the muscle. Slow movement of a joint elicits only passive resistance, which is caused by the elastic properties of the joint, tendon, muscle, and connective tissues. As the speed of the stretch is increased, resistance to the stretch rises progressively. This phasic relation is what characterizes spasticity; an active reflex contraction occurs only during a rapid stretch, and when the muscle is held in a lengthened position, the reflex contraction subsides.

Spasticity is seen following lesion of descending motor pathways caused by stroke, injuries of the brain or spinal cord, and degenerative diseases such as multiple sclerosis. It is also seen in individuals with brain damage that occurs before, during, or shortly after birth, resulting in *cerebral palsy*.

Spasticity is not seen immediately following lesions of descending pathways, but develops over days, weeks, and even months. This parallels plastic changes at multiple sites in the stretch reflex circuitry. Sensory group Ia axons release more transmitter substance when active, and the alpha motor neurons change their intrinsic properties and their morphology (dendritic sprouting and denervation hypersensitivity) so that they become more excitable. Changes in excitatory and inhibitory interneurons that project to the motor neurons also take place and probably contribute to the increased excitability.

Whatever the precise mechanisms that produce spasticity, the effect is a strong facilitation of transmission in the monosynaptic reflex pathway. It is not the only reflex pathway affected by lesions of descending motor pathways. Pathways involving group I/II interneurons and sensory fibers from skin are also affected and exhibit the symptomatology observed in patients with central motor lesions. In the clinic, spasticity is therefore used in a broader sense and does not only relate to stretch reflex hyperexcitability. It is still debated whether reflex hyperexcitability contributes to the movement disorder following lesion of descending pathways or whether it may be a pertinent adaptation that helps to activate the muscles when descending input is diminished.

Lesion of the Spinal Cord in Humans Leads to a Period of Spinal Shock Followed by Hyperreflexia

Damage to the spinal cord can cause large changes in the strength of spinal reflexes. Each year, approximately 11,000 Americans sustain spinal cord injuries, and many more suffer from strokes. More than half of these injuries produce permanent disability, including impairment of motor and sensory functions and loss of voluntary bowel and bladder control. Approximately 250,000 people in the United States today have some permanent disability from spinal cord injury.

When the spinal cord is completely transected, there is usually a period immediately after the injury when all spinal reflexes below the level of the

transection are reduced or completely suppressed, a condition known as *spinal shock*. During the course of weeks and months, spinal reflexes gradually return, often greatly exaggerated. For example, a light touch to the skin of the foot may elicit strong flexion withdrawal of the leg.

Highlights

1. Reflexes are coordinated, involuntary motor responses initiated by a stimulus applied to peripheral receptors.
2. Many groups of interneurons in spinal reflex pathways are also involved in producing complex movements such as walking and transmitting voluntary commands from the brain.
3. Some components of reflex responses, particularly those involving the limbs, are mediated by supraspinal centers, such as brain stem nuclei, the cerebellum, and the motor cortex.
4. Reflexes are smoothly integrated into centrally generated motor commands because of the convergence of sensory signals onto spinal and supraspinal interneuronal systems involved in initiating movements. Establishing the details of these integrative events is one of the major challenges of contemporary research on sensory-motor integration in the spinal cord.
5. Because of the role of supraspinal centers in spinal reflex pathways, injury to or disease of the central nervous system often results in significant alterations in the strength of spinal reflexes. The pattern of changes provides an important aid to diagnosis of patients with neurological disorders.

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