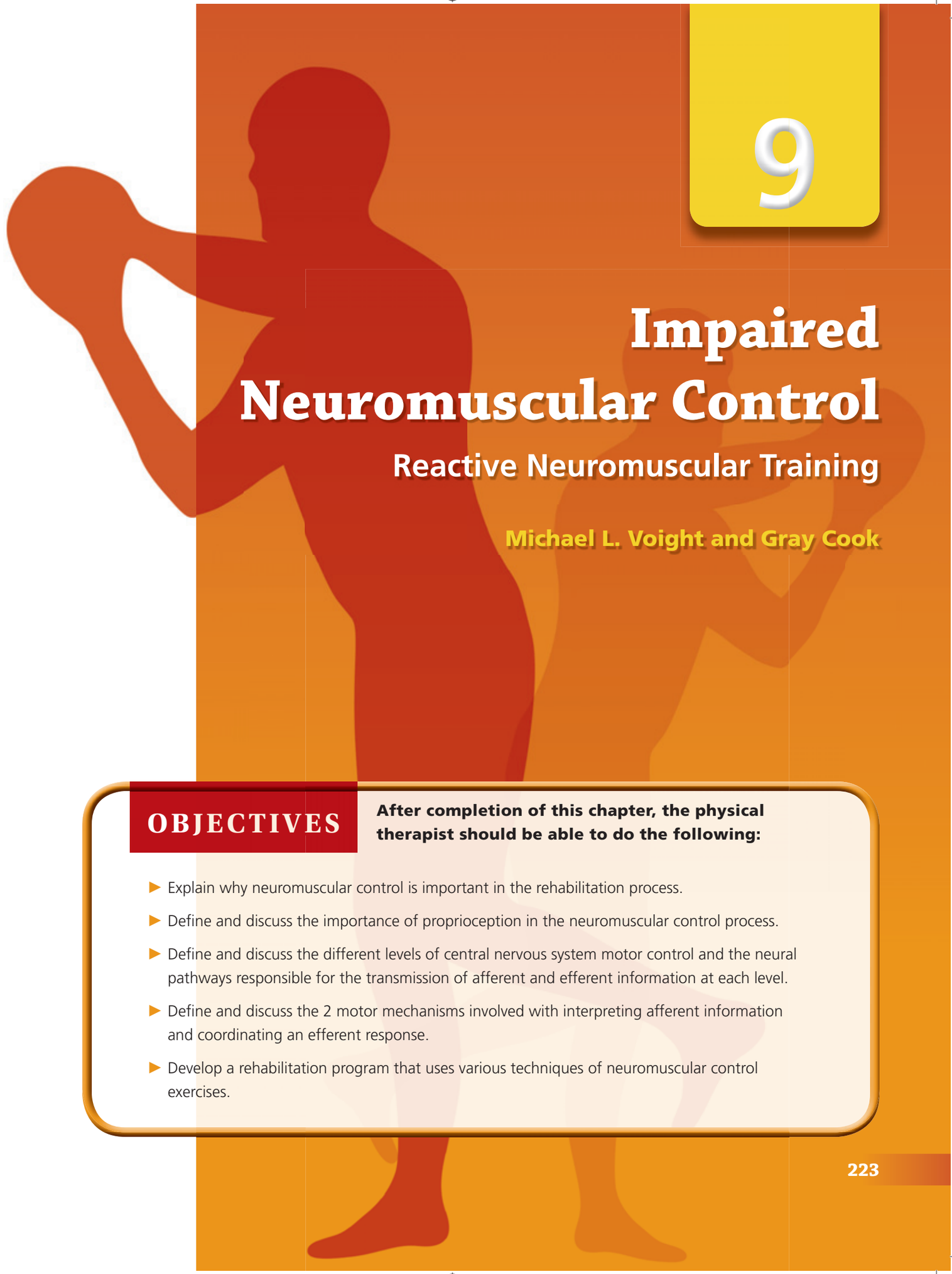


9

Impaired Neuromuscular Control

Reactive Neuromuscular Training

Michael L. Voight and Gray Cook

OBJECTIVES

After completion of this chapter, the physical therapist should be able to do the following:

- Explain why neuromuscular control is important in the rehabilitation process.
- Define and discuss the importance of proprioception in the neuromuscular control process.
- Define and discuss the different levels of central nervous system motor control and the neural pathways responsible for the transmission of afferent and efferent information at each level.
- Define and discuss the 2 motor mechanisms involved with interpreting afferent information and coordinating an efferent response.
- Develop a rehabilitation program that uses various techniques of neuromuscular control exercises.

What Is Neuromuscular Control and Why Is It Important?

The basic goal in rehabilitation is to enhance one's ability to function within the environment and to perform the specific activities of daily living (ADL). The entire rehabilitation process should be focused on improving the functional status of the patient. The concept of functional training is not new. In fact, functional training has been around for many years. It is widely accepted that to get better at a specific activity, or to get stronger for an activity, one must practice that specific activity. Therefore, the functional progression for return to ADL can be defined as breaking the specific activities down into a hierarchy and then performing them in a sequence that allows for the acquisition or reacquisition of that skill.

From a historical perspective, the rehabilitation process following injury has focused upon the restoration of muscular strength, endurance, and joint flexibility without any consideration of the role of the neuromuscular mechanism. This is a common error in the rehabilitation process. We cannot assume that clinical programs alone using traditional methods will lead to a safe return to function. Limiting the rehabilitation program to these traditional programs alone often results in an incomplete restoration of ability and quite possibly leads to an increased risk of reinjury.

The overall objective of the functional exercise program is to return the patient to the preinjury level as quickly and as safely as possible. Specific training activities should be designed to restore both dynamic stability about the joint and specific ADL skills. To accomplish this objective, a basic tenet of exercise physiology is employed. The SAID (specific adaptations to imposed demands) principle states that the body will adapt to the stress and strain placed upon it.[130] Patients cannot succeed in ADL if they have not been prepared to meet all of the demands of their specific activity.[130] Reactive neuromuscular training (RNT) is not intended to replace traditional rehabilitation, but rather to help bridge the gap left by traditional rehabilitation in a complementary fashion via proprioceptive and balance training in order to promote a more functional return to activity.[130] The main objective of the RNT program is to facilitate the unconscious process of interpreting and integrating the peripheral sensations received by the central nervous system (CNS) into appropriate motor responses.

Terminology: What Do We Really Need to Know?

Success in skilled performance depends upon how effectively the individual detects, perceives, and uses relevant sensory information. Knowing exactly where our limbs are in space and how much muscular effort is required to perform a particular action is critical for the successful performance in all activities requiring intricate coordination of the various body parts. Fortunately, information about the position and movement of various body parts is available from the peripheral receptors located in and around the articular structures.

About the normal healthy joint, both static and dynamic stabilizers serve to provide support. The role of the capsule-ligamentous tissues in the dynamic restraint of the joint has been well established in the literature.[2,3,19,33,45-50,110] Although the primary role of these structures is mechanical in nature by providing structural support and stabilization to the joint, the capsuloligamentous tissues also play an important sensory role by detecting joint position and motion.[33,34,105] Sensory afferent feedback from the receptors in the capsuloligamentous structures projects directly to the reflex and cortical pathways, thereby mediating reactive muscle activity for dynamic restraint.[2,3,33,34,67] The efferent motor response that

ensues from the sensory information is called neuromuscular control. Sensory information is sent to the CNS to be processed, and appropriate motor activities are executed.

Physiology of Proprioception

Although there has been no definitive definition of proprioception, Beard et al described proprioception as consisting of 3 similar components: (a) a static awareness of joint position, (b) kinesthetic awareness, and (c) a closed-loop efferent reflex response required for the regulation of muscle tone and activity.[7] From a physiologic perspective, proprioception is a specialized variation of the sensory modality of touch. Specifically defined, proprioception is the cumulative neural input to the CNS from mechanoreceptors in the joint capsules, ligaments, muscles, tendons, and skin.

A rehabilitation program that addresses the need for restoring normal joint stability and proprioception cannot be constructed until one has a total appreciation of both the mechanical and sensory functions of the articular structures.[12] Knowledge of the basic physiology of how these muscular and joint mechanoreceptors work together in the production of smooth controlled coordinated motion is critical in developing a rehabilitation training program. This is because the role of the joint musculature extends beyond absolute strength and the capacity to resist fatigue. Simply restoring mechanical restraints or strengthening the associated muscles neglects the smooth coordinated neuromuscular controlling mechanisms required for joint stability.[12] The complexity of joint motion necessitates synergy and synchrony of muscle firing patterns, thereby permitting proper joint stabilization, especially during sudden changes in joint position, which is common in functional activities. Understanding these relationships and functional implications will allow the clinician greater variability and success in returning patients safely back to their playing environment.

Sherrington first described the term proprioception in the early 1900s when he noted the presence of receptors in the joint capsular structures that were primarily reflexive in nature.[77,105] Since that time, mechanoreceptors have been morphohistologically identified about the articular structures in both animal and human models. Mechanoreceptors are specialized end organs that function as biologic transducers that can convert the mechanical energy of physical deformation (elongation, compression, and pressure) into action nerve potentials yielding proprioceptive information.[45] Although receptor discharge varies according to the intensity of the distortion, mechanoreceptors can also be based upon their discharge rates. Quickly adapting receptors cease discharging shortly after the onset of a stimulus, while slowly adapting receptors continue to discharge while the stimulus is present.[21,33,45] About the healthy joint, quickly adapting receptors are responsible for providing conscious and unconscious kinesthetic sensations in response to joint movement or acceleration, while slowly adapting mechanoreceptors provide continuous feedback and thus proprioceptive information relative to joint position.[21,45,71]

Once stimulated, mechanoreceptors are able to adapt. With constant stimulation, the frequency of the neural impulses decreases. The functional implication is that mechanoreceptors detect change and rates of change, as opposed to steady-state conditions.[104] This input is then analyzed in the CNS for joint position and movement.[139] The status of the articular structures is sent to the CNS so that information regarding static versus dynamic conditions, equilibrium versus disequilibrium, or biomechanical stress and strain relations can be evaluated.[129,130] Once processed and evaluated, this proprioceptive information becomes capable of influencing muscle tone, motor execution programs, and cognitive somatic perceptions or kinesthetic awareness.[92] Proprioceptive information also protects the joint from damage caused by movement exceeding the normal physiologic range of motion and helps to determine the appropriate balance of synergistic and antagonistic forces. All of this

information helps to generate a somatosensory image within the CNS. Therefore, the soft tissues surrounding a joint serve a double purpose: they provide biomechanical support to the bony partners making up the joint, keeping them in relative anatomic alignment, and through an extensive afferent neurologic network, they provide valuable proprioceptive information.

Before the 1970s, articular receptors in the joint capsule were held primarily responsible for joint proprioception.[104] Since then there has been considerable debate as to whether muscular and articular mechanoreceptors interact. As originally described, the articular mechanoreceptors were located primarily on the parts of the joint capsule that are stretched the most when the joint is moved. This led investigators to believe that these receptors were primarily responsible for perception of joint motion. Skoglund found individual receptors that were active at very specific locations in the range of limb movement (eg, from 150 to 180 degrees of joint angle for a particular cell).[113] Another cell would fire at a different set of joint angles. By integrating the information, the CNS could "know" where the limb was in space by detecting which receptors were active. The problem with this theory is that several studies have shown that the majority of the capsular receptors only respond at the extremes of the range of motion or during other situations when a strong stimulus is imparted onto the structures such as distraction or compression.[21,43,48,49] Furthermore, other studies found that the nature of the firing pattern is dependent on whether the movement is active or passive.[14] In addition, the mechanoreceptor firing is dependent on the direction of motion from the joint.[115] The fact that the firing pattern of the joint receptors is dependent on factors other than simple position sense has seriously challenged the thought that the articular mechanoreceptors alone are the means by which the system determines joint position.

A more contemporary viewpoint is that muscle receptors play a more important role in signaling joint position.[25,42] There are 2 main types of muscle receptors that provide complementary information about the state of the muscles. The muscle spindle is located within the muscle fibers and is most active when the muscle is stretched. The Golgi tendon organ (GTO) is located in the junction between the muscle and the tendon, and is most active when the muscle contracts.

Muscle Spindle

The muscle spindle consists of 3 main components: small muscle fibers called *intrafusal fibers* that are innervated by the gamma efferent motor neurons, and types Ia and II afferent neurons (Figure 9-1). The intrafusal fibers are made up of 2 types—bag and chain fibers—the polar ends of which provide a tension on the central region of the spindle, called the *equatorial region*. The sensory receptors located here are sensitive to the length of the equatorial region when the spindle is stretched. The major neurologic connection to this sensory region is the Ia afferent fiber, whose output is related to the length of the equatorial region (position information) as well as to the rate of change in length of this region (velocity information). The spindle connects to the alpha motor neurons for the same muscle, providing excitation to the muscle when it is stretched.

There has been a great deal of controversy about what the spindle actually signals to the CNS.[36] A major conceptual problem in the past was that the output of the Ia afferent that presumably signals stretch or velocity is related to 2 separate factors.[102] First, Ia output is increased by the elongation of the overall muscle via elongation of the spindle as a whole. However, the Ia output is also related to the stretch placed on the equatorial region by the intrafusal fibers by the gamma motor neurons. Therefore, the CNS would have difficulty in interpreting changes in the Ia output as being caused by changes in the overall muscle length with a constant gamma motor neuron activity, changes in gamma motor neuron activity with a constant muscle length, or perhaps changes in both.[102] Another problem was

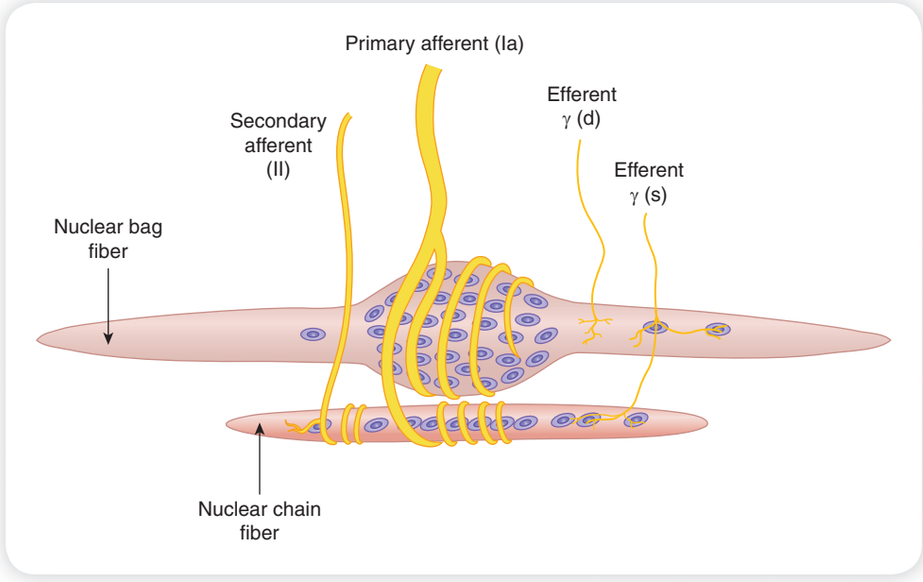


Figure 9-1 **The anatomy of muscle receptors**

Muscle spindle and GTO. (Reproduced, with permission, from Shumway-Cook A, Woollacott M. Physiology of motor control. In: Shumway-Cook A, Woollacott M, eds. *Motor Control: Theory and Practical Applications*. Baltimore, MD: Williams & Wilkins; 1995:53.)

presented by Gelfan and Carter, who suggested that there was no strong evidence that the Ia afferent fibers actually sent their information to the primary sensory cortex.[39] Because of these factors, it was widely held that the muscle spindle was not important for the conscious perception of movement or position.

Goodwin et al were the first to refute this viewpoint.[43] They found as much as 40 degrees of misalignment of arm that had vibration applied to the biceps tendon.[43] The vibration of the tendon produces a small, rapid, alternating stretch and release of the tendon, which affects the muscle spindle and distorts the output of the Ia afferents from the spindles located in the vibrated muscle. The interpretation was that the vibration distorted the Ia information coming from the same muscle, which led to a misperception of the limb's position. Others have found the same results when applying vibration to a muscle tendon.[97,108,109] This information supports the idea that the muscle spindle is important in providing information to the CNS about limb position and velocity of movement.

Golgi Tendon Organ

The GTOs are tiny receptors located in the junction where the muscle "blends into" the tendon. They are ideally located to provide information about the tension within the muscles because they lie in series with the muscle force-producing contractile elements. The GTO has been shown to produce an inhibition of the muscle in which it is located when a stretch to the active muscle is produced. The fact that a stretch force near the physiologic limit of the muscle was required to induce the tendon organ to fire led to the speculation that this receptor was primarily a protective receptor that would prevent the muscle from contracting so forcibly that it would rupture the tendon. Houk and Henneman[62] and Stuart et al[119] have provided a more precise understanding of the sensitivity of the GTOs. Anatomic evidence reveals that each organ is connected to only a small group (3 to 25) of

muscle fibers, not to the entire muscle as had been previously suspected. Therefore, the GTO appears to be in a good position to sense the tensions produced in a limited number of individual motor units, not in the whole muscle. Houk and Henneman determined that the tendon organs could respond to forces of less than 0.1 G.[62] Therefore, the GTOs are very sensitive detectors for active tension in localized portions of a muscle, in addition to having a protective function.

It is most likely that the muscle and joint receptors work complementarily to one another in this complex afferent system, with each modifying the function of the other.[15,46,52,61] An important concept is that any one of the receptors in isolation from the others is generally ineffective in signaling information about the movements of the body. The reason for this is that the various receptors are often sensitive to a variety of aspects of body motion at the same time. For example, the GTOs probably cannot signal information about movement, because they cannot differentiate between the forces produced in a static contraction and the same forces produced when the limb is moving.[102] Although the spindle is sensitive to muscle length, it is also sensitive to the rate of change in length (velocity) and to the activity in the intrafusal fibers that are known to be active during contractions. Therefore, the spindle confounds information about the position of the limb and the level of contraction of the muscle. The joint receptors are sensitive to joint position, but their output can be affected by the tensions applied and by the direction of movement.

Because both the articular and muscle receptors have well-described cortical connections to substantiate a central role in proprioception, some have suggested that the CNS combines and integrates the information in some way to resolve the ambiguity in the signals produced by any one of the receptors.[102,138] Producing an ensemble of information by combining the various separate sources could enable the generation of less ambiguous information about movement.[36] Therefore, the sensory mechanoreceptors may represent a continuum rather than separate distinct classes of receptor.[105] This concept is further illustrated by research that demonstrated a relationship between the muscle spindle sensory afferent and joint mechanoreceptors.[18] McCloskey has also demonstrated a relationship between the cutaneous afferent and joint mechanoreceptors.[78] These studies suggest a complex role for the joint mechanoreceptors in smooth, coordinated, and controlled movement.

Neural Pathways

Information generated and encoded by the mechanoreceptors in the muscle tendon units is projected upward via specialized pathways toward the cortex, where it is further analyzed and integrated with other sensory inputs.[99] Proprioceptive information is relayed to the cerebral cortex via 1 of 2 major ascending systems: the dorsal column and the spinothalamic tract. Both of these pathways involve 3 orders of neurons and 3 synapses in transmitting sensory input from the periphery to the cortex. The primary afferent, which is connected to the peripheral receptor, synapses with a second neuron in the spinal cord or lower brain, depending upon the type of sensation. Before reaching the cerebral cortex, all sensory information passes through an important group of nuclei located in the area of the brain called the *diencephalon*. It is within this group of more than 30 nuclei, collectively called the *thalamus*, that neurophysiologists consider the initial stages of sensory integration and perceptual awareness to begin. Therefore, the second neuron then conveys the information to the thalamus where it synapses with the third and final neuron in the area of the thalamus called the *ventroposterolateral* area. The thalamus achieves these functions by "gating out" irrelevant sensory inputs and directing those that are relevant to an impending or ongoing action toward primary sensory areas within the cortex. The sensory pathways finally terminate in the primary sensory areas located in different regions of the cortex. It is at this point that we become consciously aware of the sensations.

The final perception of what is occurring in the environment around us is achieved after all of these sensations are integrated and then interpreted by the association areas that lie adjacent to the various primary sensory areas associated with the different types of sensory input. With the assistance of memory, objects seen or felt can be interpreted in a meaningful way. The dorsal column plays an important role in motor control because of its speed in transmission. For proprioception to play a protective role through reflex muscle splinting, the information must be transmitted and processed rapidly. The heavily myelinated and wide-diameter axons within this system transmit at speeds of 80 to 100 m/s. This characteristic facilitates rapid sampling of the environment, which enhances the accuracy of motor actions about to be executed and of those already in progress. By comparison, nociceptor transmission occurs at a rate of approximately 1 m/s. Thus proprioceptive information may play a more significant role than pain in the prevention of injuries.

In contrast to the transmission properties associated with the dorsal column system, neurons that make up the spinothalamic tract are small in diameter (some of which are unmyelinated) and conduct slowly (1 to 40 m/s). The 4 spinocerebellar tracts also convey important proprioceptive information from the neuromuscular receptors to the cerebellum. Unlike the dorsal column, these pathways do not synapse in either the thalamus or cerebral cortex. As a result, the proprioceptive information conveyed by the spinocerebellar tracts does not lead to conscious perceptions of limb position. The afferent sources are believed to contribute to kinesthesia.

Assessment of Joint Proprioception

Assessment of proprioception is valuable for identifying proprioceptive deficits. If deficiencies in proprioception can be clinically diagnosed in a reliable manner, a clinician would know when and if a problem exists and when the problem has been corrected.[130] There are several ways to measure or assess proprioception about a joint. From an anatomic perspective, histologic studies can be conducted to identify mechanoreceptors within the specific joint structures. Neurophysiologic testing can assess sensory thresholds and nerve conduction velocities.[6,20,31] From a clinical perspective, proprioception can be assessed by measuring the components that make up the proprioceptive mechanism: kinesthesia (perception of motion) and joint position sensibility (perception of joint position).[17]

Measuring either the angle or time threshold to detection of passive motion can assess kinesthetic sensibility.[112] With the subject seated, the patient's limb is mechanically rotated at a slow constant angular velocity (2 degrees per second). With passive motion, the capsuloligamentous structures come under tension and deform the mechanoreceptors located within. The mechanoreceptor deformation is converted into an electrical impulse, which is then processed within the CNS. Patients are instructed to stop the lever arm movement as soon as they perceive motion. Depending on which measurement is used, either the time to detection or degrees of angular displacement is recorded.

Joint position sense is assessed through the reproduction of both active and passive joint repositioning. The examiner places the limb at a preset target angle and holds it there for a minimum of 10 seconds to allow the patient to mentally process the target angle. Following this, the limb is returned to the starting position. The patient is asked to either actively reproduce or stop the device when passive repositioning of the angle has been achieved (Figure 9-2). The examiner measures the ability of an individual to accurately reproduce the preset target angle position. The angular displacement is recorded as the error in degrees from the preset target angle. Active angle reproduction measures the ability of both the muscle and capsular receptors while passive repositioning primarily measures the capsular receptors. With both tests of proprioception, the patient is blindfolded during

Figure 9-2 Open-chain proprioceptive testing using the Biodex dynamometer

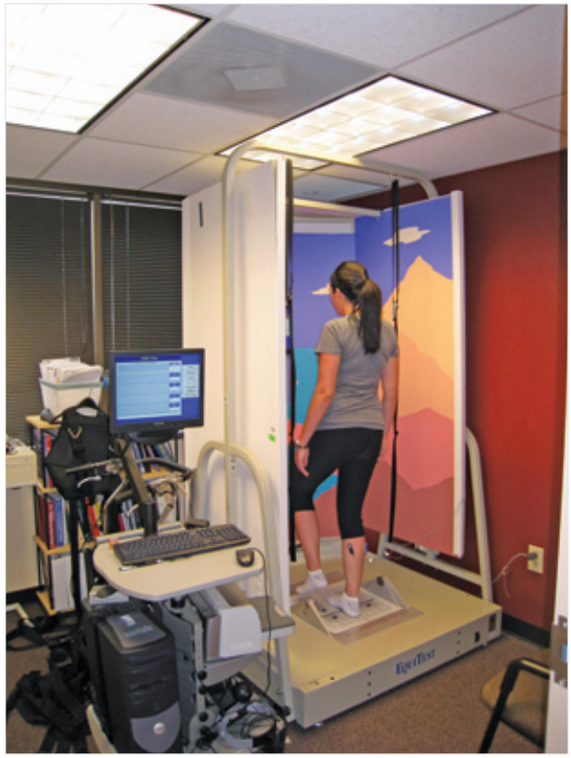


Figure 9-3 EMG assessment of reflex muscle firing as a result of perturbation on the NeuroCom EquiTest

testing to eliminate all visual cueing. In patients with unilateral involvement, the contralateral uninjured limb can serve as an external control for comparison.

The main limitation to current proprioceptive testing is that neither time/angle threshold to detection of passive motion provides an assessment of the unconscious reflex arc believed to provide dynamic joint stability. The assessment of reflex capabilities is usually performed by measuring the latency of muscular activation to involuntary perturbation through electromyogram (EMG) interpretation of firing patterns of those muscles crossing the respective joint (Figure 9-3).[132] The ability to quantify the sequence of muscle firing can provide a valuable tool for the assessment of asynchronous neuromuscular activation patterns following injury.[74,140] A delay or lag in the firing time of the dynamic stabilizers about the joint can result in recurrent joint subluxation and joint deterioration.

Proprioception and Motor Control

The efferent response that is produced as the result of the proprioceptive afferent input is termed *neuromuscular control*. In general, there are 2 motor control mechanisms involved in the interpretation of afferent information and coordinating an efferent response.[54] One of the ways in which motor control is achieved relies heavily on the concept that sensory feedback information is used to regulate our movements. This is a more traditional viewpoint of motor control. The closed-loop system of motor control emphasizes the essential role

of the reactive or sensory feedback in the planning, execution, and modification of action. The closed-loop systems involve the processing of feedback against a reference of correctness, the determination of error, and a subsequent correction.[102] The feedback mechanism of motor control relies on the numerous reflex pathways in an attempt to continuously adjust ongoing muscle activation.[29,102] The receptors for the feedback supplied to closed-loop systems are the eyes, vestibular apparatus, joint receptors, and muscle receptors. One important point to note about the closed-loop system of feedback motor control is that this loop requires a great deal of time for a stimulus to be processed and yield a response. Rapid actions do not provide sufficient time for the system to (a) generate an error, (b) detect the error, (c) determine the correction, (d) initiate the correction, and (e) correct the movement before a rapid movement is completed.[102] The best example of this concept is demonstrated by the left jab of former boxing champion Muhammad Ali. The movement itself was approximately 40 milliseconds, yet visually detecting an aiming error and correcting it during the same movement should require approximately 200 milliseconds.[102] The movement is finished before any correction can begin. Therefore, closed-loop feedback control models seem to have their greatest strength in explaining movements that are very slow in time or that have very high movement accuracy requirements.[102]

In contrast, a more contemporary theory emphasizes the open-loop system, which focuses upon the a priori generation of action plans in anticipation of movement produced by a central executor somewhere in the cerebral cortex.[102] The ability to prepare the muscles prior to movement is called *pretuning* or *feed-forward motor control*. The springlike qualities of a muscle can be exploited (through preactivation) by the CNS in anticipation of movements and joint loads. This concept has been termed feed-forward motor control, in which prior sensory feedback (experience) concerning a task is fed forward to preprogram muscle activation patterns.[62] Vision serves an important feed-forward function by preparing the motor system in advance of the actual movement. Preactivated muscles can provide quick compensation for external loads and are critical for dynamic joint stability. Researchers have shown that corrections for rapid changes in body position can occur far more rapidly (30 to 80 milliseconds) than the closed-loop latencies of 200 milliseconds that were previously reported.[27,63,69] Therefore, the motor control system operates with a feed-forward mode in order to send some signals "ahead of" the movement that (a) readies the system for the upcoming motor command and/or (b) readies the system for the receipt of some particular kind of feedback information.

Anticipatory muscle activity contributes to the dynamic restraint system in several capacities. By increasing muscle activation levels in anticipation of an external load, the stiffness properties of the entire muscular unit can be increased.[84] Stiffness is one of the measures used to describe the characteristics of elastic materials. It is defined in terms of the amount of tension increase required to increase the length of the object by a certain amount. From a mechanical perspective, muscle stiffness can be defined as the ratio of the change of force to the change in length. If a spring is very stiff, a great deal of tension is needed to increase its length by a given amount; for a less-stiff spring, much less tension is required. When a muscle is stretched, the change in tension is instantaneous, just as the change in length of a spring. An increase in tension would offset the perturbation or deforming force and bring the system back to its original position. Research demonstrates that the muscle spindle is responsible for the maintenance of the muscle stiffness when the muscle is stretched, so that it can still act as a spring in the control of an unexpected perturbation.[60,63,86] Therefore, stiff muscles can resist stretching episodes more effectively, have greater tone, and provide a more effective dynamic restraint to joint displacement. Increased muscle stiffness can improve the stretch sensitivity of the muscle spindle system while at the same time reduce the electromechanical delay required to develop muscle tension.[28,60,80,84] Heightening the stretch sensitivity can improve the reactive capabilities of the muscle by providing additional sensory feedback.[28]

Central Nervous System Motor Control Integration

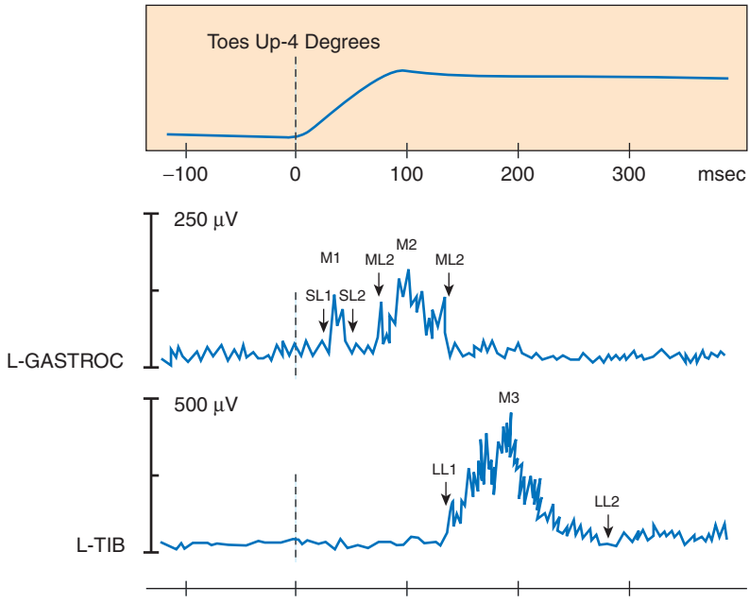
It has already been established that the CNS input provided by the peripheral mechanoreceptors and the visual and vestibular receptors is integrated by the CNS to generate a motor response.[26] In addition to the many conscious modifications that can be made while movement is in progress, certain neural connections within the CNS contribute to the modification of movements in progress by providing sensory information at a subconscious level. The influence of some of these reflexive loops is limited to local control of muscle force, but others are capable of influencing force levels in muscle groups quite distant from those originally stimulated. These longer reflex loops are therefore capable of modifying movements to a much larger extent than the shorter reflex loops that are confined to single segments within the spinal cord.

In general, the CNS response falls under 3 categories or levels of motor control: spinal reflexes, brainstem processing, and cognitive cerebral cortex program planning. The goal of the rehabilitation process is to retrain the altered afferent pathways so as to enhance the neuromuscular control system. To accomplish this goal, the objective of the rehabilitation program should be to hyperstimulate the joint and muscle receptors so as to encourage maximal afferent discharge to the respective CNS levels.[12,71,122,126,127]

First Level of Integration: The M1 Reflex

When faced with an unexpected load, the first reflexive muscle response is a burst of EMG activity that occurs after between 30 and 50 milliseconds. The afferent fibers of the mechanoreceptors synapse with the spinal interneurons and produce a reflexive facilitation or inhibition of the motor neurons.[122,126,131] The monosynaptic stretch reflex or M1 reflex is one of the most rapid reflexes underlying limb control (Figure 9-4). The latency or time of this response is very short because it involves only 1 synapse and the information has a relatively short distance to travel. Unfortunately, the muscle response is brief, which does not result in much added contraction of the muscle. The M1 short reflex loop is most often called into play when minute adjustments in muscle length are needed. The stimulus of small muscular stretches occurs during postural sways or when our limbs are subjected to unanticipated loads. Therefore, this mechanism is responsible for regulating motor control of the antagonistic and synergistic patterns of muscle contraction.[99] These adjustments are necessary when misalignment exists between intended muscle length and actual muscle length. This misalignment is most likely to occur in situations where unexpected forces are applied to the limb or the muscle begins to fatigue. In the situation of involuntary and undesirable lengthening of muscles about a joint during conditions of abnormal stress, the short M1 loop must provide for reflex muscle splinting in order to prevent injury from occurring. The M1 reflex occurs at an unconscious level and is not affected by outside factors. These responses can occur simultaneously to control limb position and posture. Because they can occur at the same time, are in parallel, are subconscious, and are without cortical interference, they do not require attention and are thus automatic.

There are 2 important short reflex loops acting in the body: the stretch reflex and the gamma reflex loop. The stretch reflex (Figure 9-5) is triggered when the length of an extrafusal muscle fiber is altered, causing the sensory endings within the muscle spindle to be mechanically deformed. Once deformed, these sensory endings fire, sending nerve impulses into the spinal cord via an afferent sensory neuron located just outside the spinal cord. The information from the Ia afferent is sent essentially to 2 places: to the alpha motor



	SL1	SL2	ML1	ML2
ms	32	50	79	138
μV	21	14	48	21
peak	148		163	
μVs	1.3		4.9	

	LL1	LL2
ms	138	273
μV	67	21
peak	470	
μVs	23.2	

Figure 9-4 **CNS levels of integration: short- and long-loop postural reflexes**

The components of the evoked postural assessment: (M1) myotatic reflex (SL1, SL2), (M2) segmental (polysynaptic) response (ML1, ML2), and (M3) long-loop response (LL1, LL2) involving the brainstem, cortex, and ascending and descending spinal pathways (LL, long loop; ML, mediam loop; SL, short loop). (Reproduced, with permission, from NeuroCom International, Clackamas, OR.)

neurons in the same muscle and upward to the various sensory regions in the cerebral cortex. As soon as these impulses reach the spinal cord, they are transferred to alpha motor neurons that innervate the very same muscle that houses the activated muscle spindles. The loop time, or the time from the initial stretch until the extrafusal fibers are increased in their innervation, is approximately 30 to 40 milliseconds in humans.[102] Stimulation of the muscle spindle ceases when the muscle contracts, because the spindle fibers, which lie parallel to the extrafusal fibers, return to their original length. It is through the operation of this reflex that we are able to continuously alter muscle tone and/or make subtle adjustments in muscle length during movement. These latter adjustments may be in response to external factors producing unexpected loads or forces on the moving limbs.

Consider, for example, what happens when an additional load is applied to an already loaded limb being held in a given position in space.[27] The muscles of the limb are set at a given length, and alpha motor neurons are firing so as to maintain the desired limb position in spite of the load and gravity. Now an additional load is added to the end of the limb, causing the muscles to lengthen as the limb drops. This stretching of the extrafusal muscle fibers results in almost simultaneous stretching of the muscle spindle, which then fires and sends signals to the spinal cord and alpha motor neurons that serve the same muscle. The firing rate of these alpha motor neurons is subsequently increased, causing the muscles in the dropping limb to be further contracted, and the limb is restored to its previous position. Visual information to the stimulus of loading would also lead to increased contraction in the falling limb, but initiating the corrective response consciously would involve considerably longer delays because of additional processing at the cortical level.[27] The short-loop M1 stretch reflex response times

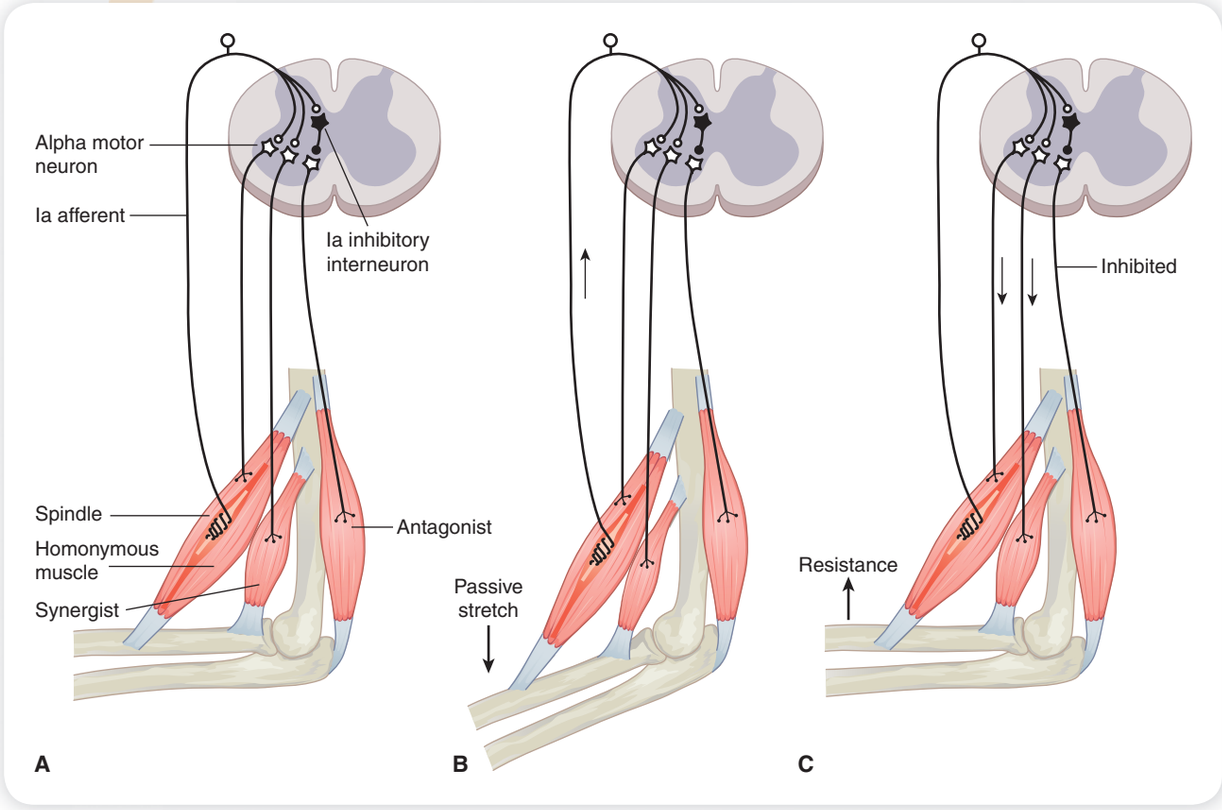


Figure 9-5 **Excitation of the muscle spindle is responsible for the stretch reflex**

A. Ia afferent fibers making monosynaptic excitatory connections to alpha motor neurons innervating the same muscle from which they arise and motor neurons innervating synergist muscles. They also inhibit motor neurons to antagonist muscles through an inhibitory interneuron. **B.** When a muscle is stretched, the Ia afferents increase their firing rate. **C.** 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 springlike properties of the muscle. (Reproduced, with permission, from Gordon J, Ghez C. Muscle receptors and stretch reflexes. In: Kandel E, et al, eds. *Principles of Neural Science*. 3rd ed. East Norwalk, CT, Appleton & Lange; 1991:576.)

are possible within 30 to 50 milliseconds.[58] Visual-based corrections involved corrective delays on the order of 150 to 200 milliseconds.[58] Given that the rapid correction is required for injury prevention, it is important that these short-loop reflex pathways are available for use.

Muscle spindles also play an important role in the ongoing control and modification of movement by virtue of their involvement in a spinal reflex loop known as the gamma reflex loop. The afferent information from the muscle spindle synapses with both the alpha and gamma motor neurons. The alpha motor neuron sends the information it receives to the muscles involved in the movements. The gamma motor neuron sends the same information back to the muscle spindle, which can be stimulated to begin firing at its polar ends. The independent innervation of the muscle spindle by the gamma motor neuron is thought to be important during muscle contractions when the intrafusal fibers of the spindle would normally be slack. Gamma activation of the spindle results in stretching of the intrafusal fibers even though the extrafusal fibers are contracting. In essence, the gamma system takes up the slack in the spindle caused by muscle contraction, thereby making corrections in minute changes in length of the muscle more quickly.

In the short-loop system of spinal control, the activity of the Ia afferent fibers is determined by 2 things: (a) the length and the rate of the stretch of the extrafusal muscle fibers, and (b) the amount of tension in the intrafusal fibers, which is determined by the firing of the gamma efferent fibers. Both alpha and gamma motor neurons can be controlled by higher motor centers, and are thought to be "coordinated" in their action by a process termed *alpha–gamma coactivation*.[44,98] Therefore, the output to the main body of the muscle is determined by (a) the level of innervation provided directly from higher centers and (b) the amount of added innervation provided indirectly from the Ia afferent.[102] This helps to explain how an individual can respond quickly to an unexpected event without conscious involvement of the CNS. When an unexpected event or perturbation causes a muscle to stretch, the spindle's sensory receptors are stimulated. The resulting Ia afferent firing causes a stretch reflex that will increase the activity in the main muscle, all within 40 milliseconds. All of this activity occurs at the same level of the spinal cord as did the innervation of the muscle in the first place. Consequently, no high centers are involved in this 40-millisecond loop.

At this level of motor control, activities to encourage short-loop reflex joint stabilization should dominate.[12,71,110,126] These activities are characterized by sudden alterations in joint position that require reflex muscle stabilization. With sudden alterations or perturbations, both the articular and muscular mechanoreceptors are stimulated for the production of reflex stabilization. Rhythmic stabilization exercises encourage monosynaptic cocontraction of the musculature, thereby producing a dynamic neuromuscular stabilization.[114] These exercises serve to build a foundation for dynamic stability.

Second Level of Integration: The M2 Reflex

For larger adjustments in limb and overall body position, it is necessary to involve the longer reflex loops that extend beyond single segments within the spinal cord. When the muscle spindle is stretched and the Ia afferent fibers are activated, the information is relayed to the spinal cord, where it synapses with the alpha motor neuron. Additionally, information is sent to higher levels of control, where the Ia information is integrated with other information in the sensory and motor centers in the cerebral cortex to produce a more complete response to the imposed stretch. Approximately 50 to 80 milliseconds after an unexpected stimulus, there is a second burst of EMG activity (see Figure 9-4). Because the pathways involved in these neural circuits travel to the more distant subcortical and cortical levels of the CNS to connect with structures such as the motor cortex and cerebellum within the larger projection system, the reflex requires more time or has a longer latency.[51] Therefore, the 80-millisecond loop time for this activity corresponds not only to the additional distance that the impulses have to travel, but also to the multiple synapses that must take place to close the circuit. Both the M1 and M2 responses are responsible for the reflex response that occurs when a tendon is tapped. An example of this occurs when the patellar tendon is tapped with a reflex hammer. The quadriceps muscle is stretched, initiating a reflex response that contracts the quadriceps and produces an involuntary extension of the lower leg.

Even though there is a time lapse for the longer-loop reflexes to take place, there are 2 important advantages for these reflexes. First, the EMG activity from the long-loop reflex is far stronger than that involved in the monosynaptic stretch reflex. The early short-loop monosynaptic reflex system does not result in much actual increase in force. The long-loop reflex can, however, produce enough force to move the limb/joint back into a more neutral position. Second, because the long-loop reflexes are organized in a higher center, they are more flexible than the monosynaptic reflex. By allowing for the involvement of a few other sources of sensory information during the response, an individual can voluntarily adjust the size or amplitude of the M2 response for a given input

to generate a powerful response when the goal is to hold the joint as firmly as possible, or to produce no response if the goal is to release under the increasing load. The ability to regulate this response allows an individual to prepare the limb to conform to different environmental demands.

The second level of motor control interaction is at the level of the brainstem.[11,122,130] At this level, afferent mechanoreceptors interact with the vestibular system and visual input from the eyes to control or facilitate postural stability and equilibrium of the body.[12,71,122,127,130] Afferent mechanoreceptor input also works in concert with the muscle spindle complex by inhibiting antagonistic muscle activity under conditions of rapid lengthening and periarticular distortion, both of which accompany postural disruption.[92,126] In conditions of disequilibrium where simultaneous neural input exists, a neural pattern is generated that affects the muscular stabilizers, thereby returning equilibrium to the body's center of gravity.[122] Therefore, balance is influenced by the same peripheral afferent mechanism that mediates joint proprioception and is at least partially dependent upon the individual's inherent ability to integrate joint position sense with neuromuscular control.[120]

Integration of Balance Training: The Second Level of Motor Control

Both proprioception and balance training have been advocated to restore motor control to the lower extremity. In the clinic, the term "balance" is often used without a clear definition.[30] It is important to remember that proprioception and balance are not the same. Proprioception is a precursor of good balance and adequate function. Balance is the process by which we control the body's center of mass with respect to the base of support, whether it is stationary or moving.

Berg attempted to define balance in 3 ways: the ability to maintain a position, the ability to voluntarily move, and the ability to react to a perturbation.[9] All 3 of these components of balance are important in the maintenance of upright posture. Static balance refers to an individual's ability to maintain a stable antigravity position while at rest by maintaining the center of mass within the available base of support. Dynamic balance involves automatic postural responses to the disruption of the center of mass position. Reactive postural responses are activated to recapture stability when an unexpected force displaces the center of mass.[85]

Postural sway is a commonly used indicator of the integrity of the postural control system. Horak defined postural control as the ability to maintain equilibrium and orientation in the presence of gravity.[57,142] Researchers measure postural sway as either the maximum or the total excursion of center of pressure while standing on a forceplate. Little change is noted in healthy adults in quiet standing, but the frequency, amplitude, and total area of sway increase with advancing age or when vision or proprioceptive inputs are altered.[32,59,89,91]

To maintain balance, the body must make continual adjustments. Most of what is currently known about postural control is based upon stereotypical postural strategies activated in response to anteroposterior perturbation.[57,58,85] Horak and Nashner described several different strategies used to maintain balance.[58] These strategies include the ankle, hip, and stepping strategies. These strategies adjust the body's center of gravity so that the body is maintained within the base of support to prevent the loss of balance or falling. There are several factors that determine which strategy would be the most effective response to postural challenge: speed and intensity of the displacing forces, characteristics of the support surface, and magnitude of the displacement of the center of mass. The automatic postural responses can be categorized as a class of functionally organized long-loop responses that produce muscle activation that brings the body's center of mass into a state of equilibrium.[85] Each of the strategies has reflex, automatic, and volitional components that interact to match the response to the challenge.

Small disturbances in the center of gravity can be compensated by motion at the ankle. The ankle strategy repositions the center of mass after small displacements caused by slow-speed perturbations, which usually occur on a large, firm, supporting surface. The oscillations around the ankle joint with normal postural sway are an example of the ankle strategy. Anterior sway of the body is counteracted by gastrocnemius activity, which pulls the body posterior. Conversely, posterior sway of the body is counteracted by contraction of the anterior tibial muscles. If the disturbance in the center of gravity is too great to be counteracted by motion at the ankle, the patient will use a hip or stepping strategy to maintain the center of gravity within the base of support.[82] The hip strategy uses rapid compensatory hip flexion or extension to redistribute the body weight within the available base of support when the center of mass is near the edge of the sway envelope. The hip strategy is usually in response to a moderate or large postural disturbance, especially on an uneven, narrow, or moving surface. The hip strategy is often employed while standing on a bus that is rapidly accelerating. When sudden, large-amplitude forces displace the center of mass beyond the limits of control, a step is used to enlarge the base of support and redefine a new sway envelope. New postural control can then be reestablished. An example of the stepping strategy is the uncoordinated step that often follows a stumble on an unexpected or uneven sidewalk.

The maintenance of balance requires the integration of sensory information from a number of different systems: vision, vestibular, and proprioception. For most healthy adults, the preferred sense for postural control comes from proprioceptive information. Therefore, if proprioception is altered or diminished, balance will also be altered. The functional assessment of the combined peripheral, visual, and vestibular contributions to neuromuscular control can be measured with computerized balance measures of postural stability.[23] The sensory organization test protocol is used to evaluate the relative contribution of vision, vestibular, and proprioceptive input to the control of postural stability when conflicting sensory input occurs.[85] Postural sway is assessed (NeuroCom Smart System) under 6 increasingly challenging conditions (Figure 9-6). Baseline sway is recorded in quiet standing with the eyes open. The reliance on vision is evaluated by asking the patient to close the eyes. A significant increase in sway or loss of balance suggests an overreliance on visual input.[85,107,143] Sensory integration is evaluated when the visual surround moves in concert with sway (sway-referenced vision), creating inaccurate visual input.[103] The patient is then retested on a support surface that moves with sway (sway-referenced support), thereby reducing the quality and availability of proprioceptive input for sensory integration. With the eyes open, vision and vestibular input contribute to the postural responses. With the eyes closed, vestibular input is the primary source of information, because proprioceptive input is altered. The most challenging condition includes sway-referenced vision and sway-referenced support surface.[57,85,107]

Balance activities, both with and without visual input, will enhance motor function at the brainstem level.[11,122] It is important that these activities remain specific to the types of activities or skills that will be required of the athlete upon return to sport.[96] Static balance activities should be used as a precursor to more dynamic skill activity.[96] Static balance skills can be initiated once the individual is able to bear weight on the lower extremity. The general progression of static balance activities is to progress from bilateral to unilateral and from eyes open to eyes closed.[71,96,122,133,134] With balance training, it is important to remember that sensory systems respond to environmental manipulation. To stimulate or facilitate the proprioceptive system, vision must be disadvantaged. This can be accomplished in several ways: remove vision with either the eyes closed or blindfolded, destabilize vision by demanding hand and eye movements (ball toss) or moving the visual surround, or confuse vision with unstable visual cues that disagree with the proprioceptive and vestibular inputs (sway referencing).

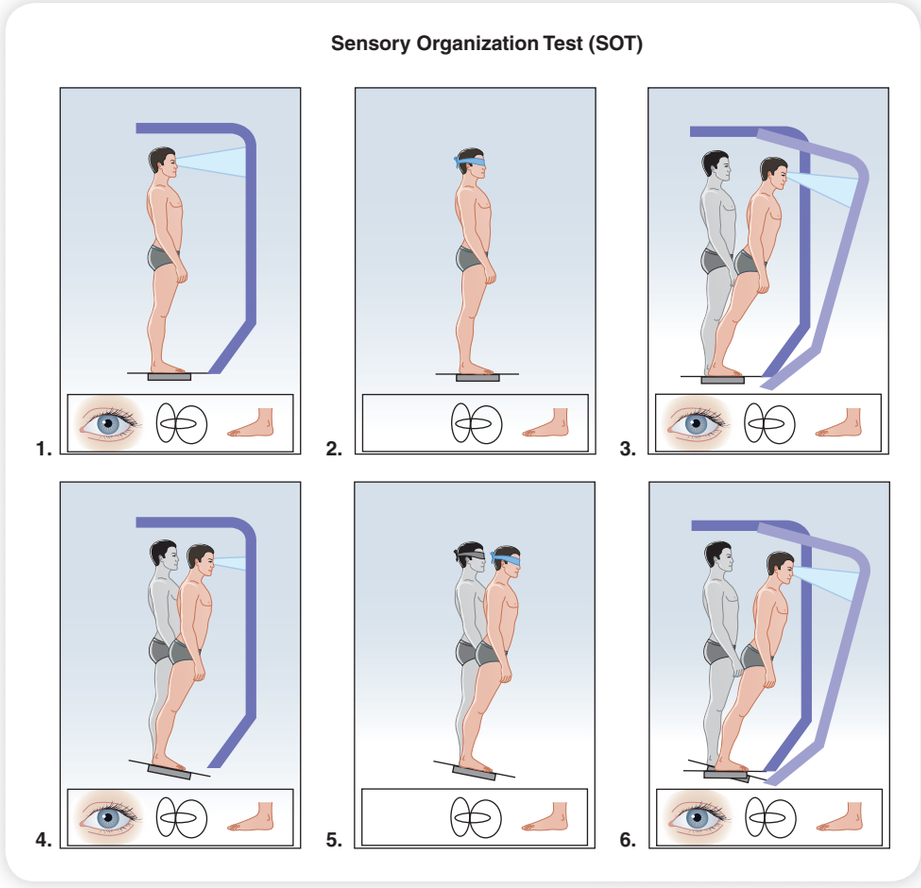


Figure 9-6

The sensory organization conditions integrating vestibular, visual, and somatosensory contributions to balance. (Reproduced, with permission, from NeuroCom International, Clackamas, OR.)

To stimulate vision, proprioception must be either destabilized or confused. The logical progression to destabilize proprioception is to progress the balance training from a stable surface to an unstable surface such as a minitramp, balance board, or dynamic stabilization trainer.[71,122,130] As joint position changes, dynamic stabilization must occur for the patient to control the unstable surface (Figure 9-7). Vision can be confused during balance training by having the patient stand on a compliant surface such as a foam mat or using a sway-referenced moving forceplate. Disadvantaging both vision and proprioceptive information can stimulate the vestibular system. This can be accomplished by several different methods. Absent vision with an unstable or compliant surface is achieved with eyes-closed training on an unstable surface. Demanding hand and eye movements while on a floor mat or foam pad will destabilize both vision and proprioception. A moving surround with a moving forceplate will confuse both vision and proprioceptive input.

The patients should initially perform the static balance activities while concentrating on the specific task (position sense and neuromuscular control) to facilitate and maximize sensory output. As the task becomes easier, activities to distract the athlete's concentration (catching a ball or performing mental exercises) should be incorporated into the training program. This will help to facilitate the conversion of conscious to unconscious motor programming.[122,130] Balance training exercises should induce joint perturbations in order to facilitate reflex muscle activation.

Figure 9-7

Unstable surface training on the Biodex Stability Trainer.

Several studies have assessed the effect of lower-quarter injury on standing balance. Usually the balance characteristics of the injured extremity are compared to those of the uninjured extremity. Mizuta et al measured postural sway in 2 groups: a functionally stable group and a functionally unstable group, both of which had unilateral anterior cruciate ligament (ACL)-deficient knees.[83] An additional group of individuals was also studied to serve as a control group. When compared to the control group, impairment in standing balance was found in the functionally unstable group, but not in the functionally stable group. These results suggest that stabiliometry was a useful tool in the assessment of functional knee stability. Both Friden et al and Gauffin et al demonstrated impaired standing balance during unilateral stance in individuals with chronic ACL-deficient knees.[35,38] Following injury to the lower quarter, impaired standing balance may be caused by the loss of muscular coordination, which could have resulted from the loss of normal proprioceptive feedback.[4,67]

Third Level of Integration: The Voluntary Reaction—Time Response (M3)

The final response that occurs when an unexpected load is applied to the limb is the voluntary long-loop reaction or M3 response (see Figure 9-4). Seen as the third burst of EMG activity, it is a powerful and sustained response that brings the limb back into the desired position. The latency of the M3 response is approximately 120 to 180 milliseconds,

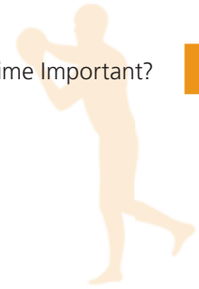
depending upon the task and the circumstances. Information is processed at the cerebral cortex, where the mechanoreceptors interact and influence cognitive awareness of body position and movement in which motor commands are initiated for voluntary movements.[12,92,99,122] It is in this region of the primary sensory cortex that there is a high degree of spatial orientation.

The M3 response is very flexible and can be modified by a host of factors such as verbal instructions or anticipation of the incoming sensory information. The delay in the M3 response makes it sensitive to a number of stimulus alternatives. Therefore, the individual's ability to respond will require some conscious attention. Training at this level of the cerebral cortex stimulates the conversion of conscious programming to unconscious programming. These responses have often been referred to as *triggered reactions*. Triggered reactions are prestructured, coordinated reactions in the same or closely related musculature that are "triggered" into action by the mechanoreceptors. The triggered reaction may bypass the information-processing centers because the reaction is stereotyped, predictable, and well practiced. These reactions have latencies from 80 to 180 milliseconds and are far more variable than the latencies of the faster reflexes.[102] The triggered reactions can be learned and can become a more or less automatic response. The individual does not have to spend time processing a response reaction and programming; the reaction is just "triggered off" almost as if it were automatic.[101] Thus, with training, the speed of the M3 response could be increased so as to produce a more automatic reflex response.

The appreciation of joint position at the highest or cognitive level needs to be included in the RNT program. These types of activities are initiated on the cognitive level and include programming motor commands for voluntary movement. The repetitions of these movements will maximally stimulate the conversion of conscious programming to unconscious programming.[12,71,122,126,127,130] The term for this type of training is the *forced-use paradigm*. By making a task significantly more difficult or asking for multiple tasks, we bombard the CNS with input. The CNS attempts to sort and process this overload information by opening additional neural pathways. When the individual goes back to a basic task of ADL, the task becomes easier. This information can then be stored as a central command and ultimately performed without continuous reference to the conscious mind as a "triggered response."[12,71,122,126,127] As with all training, the single greatest obstacle to motor learning is the conscious mind. We must get the conscious mind out of the act!

Coordinating the Muscle Response with Unexpected Loads

The relative roles of these 3 muscle responses depend upon the duration of the movement. As previously discussed, the quickest action occurring in the body has a movement time of approximately 40 milliseconds. When this type or action occurs, the M2 response is incapable of completing or modifying the activity once it is initiated. Even the M1 response has only enough time to begin influencing the muscles near the end of the movement. As the movement time increases, there is a greater potential for the M1 and M2 responses to contribute to the intended action. Movements that take a longer time to be completed (>100 milliseconds) allow both the M1 and M2 responses sufficient time to contribute to all levels of the action. Only when the duration of the movement is 300 milliseconds or longer is there potential for the M3 long-loop response to be involved in amending the movement. Therefore, for movements that take longer than 300 milliseconds for individuals to complete, closed-loop control is possible at several levels of integration at the same time.



Why Is Response Time Important?

When an unexpected load is placed upon a joint, ligamentous damage occurs after the passing of between 70 and 90 milliseconds unless an appropriate response ensues.[7,94,140] Therefore, reactive muscle activity must occur with sufficient magnitude in the 40- to 80-millisecond time frame after loading begins, in order to protect the capsuloligamentous structures. The closed-loop system of CNS integration may not be fast enough to produce a response to increase muscle stiffness. Simply, there is no time for the system to process the information and process the feedback about the condition. Failure of the dynamic restraint system to control these abnormal forces will expose the static structures to excessive forces. In this case, the open-loop system of anticipation becomes more important in producing the desired response. Preparatory muscle activity in anticipation of joint loading can influence the reactive muscle activation patterns. Anticipatory activation increases the sensitivity of the muscle spindles, thereby allowing the unexpected perturbations to be detected more quickly.[29]

Very quick movements are completed before feedback can be used to produce an action to alter the course of movement.[61] Therefore, if the movement is fast enough, a mechanism like a motor program would have to be used to control the entire action, with the movement being carried out without any feedback. Fortunately, the open-loop control system allows the motor control system to organize an entire action ahead of time. For this to occur, previous knowledge of the following needs to be preprogrammed into the primary sensory cortex:

- The particular muscles that are needed to produce an action.
- The order in which these muscles need to be activated.
- The relative forces of the various muscle contractions.
- The relative timing and sequencing of these actions.
- The duration of the respective contractions.

In the open-loop system, movement is organized in advance by a program that sets up some kind of neural mechanism or network that is preprogrammed. A classic example of this occurs in the body as postural adjustments are made before the intended movement. When an individual raises the arm up into forward flexion, the first muscle groups to fire are not even in the shoulder girdle region. The first muscles to contract are those in the lower back and legs (approximately 80 milliseconds before noticeable activity in the shoulder).[8] Because the shoulder muscles are linked to the rest of the body, their contraction affects posture. If no preparatory compensations in posture were made, raising the arm would shift the center of gravity forward, causing a slight loss of balance. The feed-forward motor control system takes care of this potential problem by preprogramming the appropriate postural modification first, rather than requiring the body to make adjustments after the arm begins to move.

Lee has demonstrated that these preparatory postural adjustments are not independent of the arm movement, but rather a part of the total motor pattern.[70] When the arm movements are organized, the motor instructions are preprogrammed to adjust posture first and then move the arm. Therefore, arm movement and postural control are not separate events, but rather different parts of an integrated action that raises the arm while maintaining balance. Lee showed that these EMG preparatory postural adjustments disappear when the individual leans against some type of support prior to raising the arm. The motor control system recognizes that advance preparation of postural control is not needed when the body is supported against the wall.

It is important to remember that most motor tasks are a complex blend of both open- and closed-loop operations. Therefore, both types of control are often at work simultaneously. Both feed-forward and feedback neuromuscular control can enhance dynamic stability if the sensory and motor pathways are frequently stimulated.[71] Each time a signal passes through a sequence of synapses, the synapses become more capable of transmitting the same signal.[50,56] When these pathways are "facilitated" regularly, memory of that signal is created and can be recalled to program future movements.[50,102]

Reestablishing Proprioception and Neuromuscular Control

Although the concept and value of proprioceptive mechanoreceptors have been documented in the literature, treatment techniques directed at improving their function generally have not been incorporated into the overall rehabilitation program. The neurosensory function of the capsuloligamentous structures has taken a backseat to the mechanical structural role. This is mainly a result of the lack of information about how mechanoreceptors contribute to the specific functional activities and how they can be specifically activated.[37,42] Following injury to the capsuloligamentous structures, it is thought that a partial deafferentation of the joint occurs as the mechanoreceptors become disrupted. This partial deafferentation, which is secondary to injury, may be related to either direct or indirect injury. Direct trauma effects include disruption of the joint capsule or ligaments, whereas posttraumatic joint effusion or hemarthrosis[67] can illustrate indirect effects.

Whether a direct or indirect cause, the resultant partial deafferentation alters the afferent information into the CNS and, therefore, the resulting reflex pathways to the dynamic stabilizing structures. These pathways are required by both the feed-forward and feedback motor control systems to dynamically stabilize the joint. A disruption in the proprioceptive pathway will result in an alteration of position and kinesthesia.[4,111] Barrack et al showed an increase in the threshold to detect passive motion in a majority of patients with ACL rupture and functional instability.[4] Corrigan et al, who also found diminished proprioception after ACL rupture, confirmed this finding.[24] Diminished proprioceptive sensitivity also has been shown to cause giving way or episodes of instability in the ACL-deficient knee.[13] Injury to the capsuloligamentous structures not only reduces the joint's mechanical stability but also diminishes the capability of the dynamic neuromuscular restraint system. Consequently, any aberration in joint motion and position sense will impact both the feed-forward and feedback neuromuscular control systems. Without adequate anticipatory muscle activity, the static structures may be exposed to insult unless the reactive muscle activity can be initiated to contribute to dynamic restraint.

Deficits in the neuromuscular reflex pathways may have a detrimental effect on the motor control system as a protective mechanism. Diminished sensory feedback can alter the reflex stabilization pathways, thereby causing a latent motor response when faced with unexpected forces or trauma. Beard et al demonstrated disruption of the protective reflex arc in subjects with ACL deficiency.[7] A significant deficit in reflex activation of the hamstring muscles after a 100-newton anterior shear force in a single-legged closed-chain position was identified, as compared to the contralateral uninjured limb.[7] Beard demonstrated that the latency was directly related to the degree of knee instability; the greater the instability, the greater the latency. Other researchers found similar alterations in the muscle-firing patterns in the ACL-deficient patient.[65,116,140] Solomonow et al found that a direct stress applied to the ACL resulted in reflex hamstring activity, thereby contributing to the maintenance of joint stability.[116] Although this response was also present in ACL-deficient knees, the reflex was significantly slower.

Although it has been demonstrated that a proprioceptive deficit occurs following knee injury, both kinesthetic awareness and reposition sense can be at least partially restored with surgery and rehabilitation. A number of studies have examined proprioception following ACL reconstruction. Barrett measured proprioception after autogenous graft repair and found that the proprioception was better than that of the average ACL-deficient patient, but still significantly worse than the proprioception in the normal knee.[5] Barrett further noted that the patient's satisfaction was more closely correlated with the patient's proprioception than with the patient's clinical score.[5] Harter et al could not demonstrate a significant difference in the reproduction of passive positioning between the operative and nonoperative knee at an average of 3 years after ACL reconstruction.[53] Kinesthesia has been reported to be restored after surgery as detected by the threshold to the detection of passive motion in the midrange of motion.[4] A longer threshold to the detection of passive motion was observed in the ACL-reconstructed knee compared with the contralateral uninvolved knee when tested at the end range of motion.[4] Lephart et al found similar results in patients after either arthroscopically assisted patellar tendon autograft or allograft ACL reconstruction.[74] The importance of incorporating a proprioceptive element in any comprehensive rehabilitation program is justified based upon the results of these studies.

The effects of how surgical and nonsurgical interventions may facilitate the restoration of the neurosensory roles is unclear; however, it has been shown that ligamentous retensioning coupled with rehabilitation can restore proprioceptive sensitivity.[72] As afferent input is altered after joint injury, proprioceptive rehabilitation must focus on restoring proprioceptive sensitivity to retrain these altered afferent pathways and enhance the sensation of joint movement. Restoration may be facilitated by (a) enhancing mechanoreceptor sensitivity, (b) increasing the number of mechanoreceptors stimulated, and (c) enhancing the compensatory sensation from the secondary receptor sites. Research should be directed toward developing new techniques to improve proprioceptive sensitivity.

Methods to improve proprioception after injury or surgery could improve function and decrease the risk for reinjury. Ihara and Nakayama demonstrated a reduction in the neuromuscular lag time with dynamic joint control following a 3-week training period on an unstable board.[65] The maintenance of equilibrium and improvement in reaction to sudden perturbations on the unstable board served to improve the neuromuscular coordination. This phenomenon was first reported by Freeman and Wyke in 1967, when they found that proprioceptive deficits could be reduced with training on an unstable surface.[33] They found that proprioceptive training through stabiliometry, or training on an unstable surface, significantly reduced the episodes of giving way following ankle sprains. Tropp et al confirmed the work of Freeman by demonstrating that the results of stabiliometry could be improved with coordination training on an unstable board.[124] Hocherman et al also showed an improvement in the movement amplitude on an unstable board and the weight distribution on the feet found in hemiplegic patients who received training on an unstable board.[55]

Barrett[5] has demonstrated the relationship between proprioception and function. Barrett's study suggests that limb function relies more on proprioceptive input than on strength during activity. Borsa et al also found a high correlation between diminished kinesthesia with the single-leg hop test.[12] The single-leg hop test was chosen for its integrative measure of neuromuscular control, because a high degree of proprioceptive sensibility and functional ability is required to successfully propel the body forward and land safely on the limb. Giove et al reported a higher success rate in returning athletes to competitive sports through adequate hamstring rehabilitation.[40] Tibone et al and Ihara and Nakayama found that simple hamstring strengthening alone was not adequate; it was necessary to obtain voluntary or reflex-level control on knee instability in order to return to functional

activities.[65,121] Walla et al found that 95% of patients were able to successfully avoid surgery after ACL injury when they were able to achieve "reflex-level" hamstring control.[136] Ihara and Nakayama found that the reflex arc between stressing the ACL and hamstring contraction could be shortened with training.[65] With the use of unstable boards, the researchers were able to successfully decrease the reaction time. Because afferent input is altered after joint injury, proprioceptive sensitivity to retrain these altered afferent pathways is critical to shorten the time lag of muscular reaction so as to counteract the excessive strain on the passive structures and to guard against injury.

What About Muscle Fatigue?

It has been well established in the literature that muscle fatigue can play a major role in destabilizing a joint.[100,111,117,129] With fatigue, an increase in knee joint laxity has been noted in both males and females.[100,117,118] More importantly, the body's ability to receive and accurately process proprioceptive information is affected by muscular fatigue. There is evidence that exercise to the point of clinical fatigue does have an effect on proprioception.[111,129] Research demonstrates that the ability to learn or make improvement in joint position sense is severely impaired with muscle fatigue.[75,100] Likewise, muscle fatigue alters both kinesthesia and joint position sense.[2,111,129] Skinner et al showed that the reproduction of passive positioning was significantly diminished following a fatigue protocol.[111] Voight et al also demonstrated a significant proprioceptive deficit following a fatigue protocol.[129] This suggests that patients who are fatigued may have a change in their proprioceptive abilities and are more prone to injury. Following a lower-quarter isokinetic fatigue protocol, postural sway as measured with EMG and forceplates is also increased following muscular fatigue.[66,129] This suggests that muscular fatigue results in a possible motor control deficit. In addition to disruption balance or postural sway, Nyland et al also demonstrated on EMG that muscular fatigue affects muscle activity by extending the latency of the muscle firing.[87]

Modifying Afferent/Efferent Characteristics: How Do We Do It?

The mechanoreceptors in and around the respective joints offer information about the change of position, motion, and loading of the joint to the CNS, which, in turn, stimulates the muscles around the joint to function.[65] If a time lag exists in the neuromuscular reaction, injury may occur. The shorter the time lag, the less stress to the ligaments and other soft-tissue structures about the joint. Therefore, the foundation of neuromuscular control is to facilitate the integration of peripheral sensations relative to joint position and then process this information into an effective efferent motor response. The main objective of the rehabilitation program for neuromuscular control is to develop or reestablish the afferent and efferent characteristics about the joint that are essential for dynamic restraint.[71]

There are several different afferent and efferent characteristics that contribute to the efficient regulation of motor control. As discussed previously, these characteristics include the sensitivity of the mechanoreceptors and facilitation of the afferent neural pathways, enhancing muscle stiffness, and the production of reflex muscle activation. The specific rehabilitation techniques must also take into consideration the levels of CNS integration. For the rehabilitation program to be complete, each of the 3 levels must be addressed in order to produce dynamic stability. The plasticity of the neuromuscular system permits rapid adaptations during the rehabilitation program that enhance preparatory and reactive activity.[7,56,65,71,74,141] Specific rehabilitation techniques that produce adaptations that

enhance the efficiency of these neuromuscular techniques include balance training, biofeedback training, reflex facilitation through reactive training, and eccentric and high-repetition/low-load exercises.[41,71]

Objectives of Neuromuscular Control: Reactive Neuromuscular Training

RNT activities are designed to restore functional stability about the joint and to enhance motor control skills. The RNT program centers around the stimulation of both the peripheral and central reflex pathways to the skeletal muscles. The first objective that should be addressed in the RNT program is the restoration of dynamic stability. Reliable kinesthetic and proprioceptive information provides the foundation on which dynamic stability and motor control are based. It has already been established that altered afferent information into the CNS can alter the feed-forward and feedback motor control systems. Therefore, the first objective of the RNT program is to restore the neurosensory properties of the damaged structures while at the same time enhancing the sensitivity of the secondary peripheral afferents.[74] The restoration of dynamic stability allows for the control of abnormal joint translation during functional activities. For this to occur, the reestablishment of dynamic stability is dependent upon the CNS receiving appropriate information from the peripheral receptors. If the information into the system is altered or inappropriate for the stimulus, a bad motor response will ensue.

To facilitate appropriate kinesthetic and proprioceptive information to the CNS, joint reposition exercises should be used to provide a maximal stimulation of the peripheral mechanoreceptors.[135] The use of closed kinetic chain activities creates axial loads that maximally stimulate the articular mechanoreceptors via the increase in compressive forces.[22,45] The use of closed-chain exercises not only enhances joint congruency and neurosensory feedback but also minimizes the shearing stresses about the joint.[128] At the same time, the muscle receptors are facilitated by both the change in length and tension.[22,45] The objective is to induce unanticipated perturbations, thereby stimulating reflex stabilization. The persistent use of these pathways will decrease the response time when faced with an unanticipated joint load.[88] In addition to weightbearing exercises, joint repositioning exercises can be used to enhance the conscious appreciation of proprioception. Rhythmic stabilization exercises can be included early in the RNT program to enhance neuromuscular coordination in response to unexpected joint translation. The intensity of the exercises can be manipulated by increasing either the weight loaded across the joint or the size of the perturbation. The addition of a compressive sleeve, wrap, or taping about the joint can also provide additional proprioceptive information by stimulating the cutaneous mechanoreceptors.[5,71,76,90] Following the restoration of range of motion and strength, dynamic stability can be enhanced with reflex stabilization and basic motor learning exercises.

The second objective of the RNT program is to encourage preparatory agonist–antagonist cocontraction. Efficient coactivation of the musculature restores the normal force couples that are necessary to balance joint forces and increase joint congruency, thereby reducing the loads imparted onto the static structures.[71] The cornerstone of rehabilitation during this phase is postural stability training. Environmental conditions are manipulated to produce a sensory response. Specifically, the 3 variables of balance that are manipulated include bilateral to unilateral stance, eyes open to eyes closed, and stable to unstable surfaces. The use of unstable surfaces allows the clinician to use positions of compromise in order to produce maximal afferent input into the spinal cord, thereby producing a reflex response. Dynamic coactivation of the muscles about the joint to produce a stabilizing force requires both the feed-forward and feedback motor control systems. In order to

facilitate these pathways, the joint must be placed into positions of compromise in order for the patient to develop reactive stabilizing strategies. Although it was once believed that the speed of the stretch reflexes could not be directly enhanced, efforts to do so have been successful in human and animal studies. This has significant implications for reestablishing the reactive capability of the dynamic restraint system. Reducing the electromechanical delay between joint loading and the protective muscle activation can increase dynamic stability. In the controlled clinical environment, positions of vulnerability can be used safely.

Proprioceptive training for functionally unstable joints following injury has been documented in the literature.[65,106,123,125,135] Tropp et al[124] and Wester et al[137] reported that ankle disk training significantly reduced the incidence of ankle sprain. Concerning the mechanism of effects, Tropp et al suggested that unstable surface training reduced the proprioceptive deficit.[124] Sheth et al demonstrated changes with healthy adults in the patterns of contractions on the inversion and eversion musculature before and after training on an unstable surface.[106] They concluded that the changes would be supported by the concept of reciprocal Ia inhibition via the mechanoreceptors in the muscles. Konradsen and Ravin also suggested that the afferent input from the calf musculature was responsible for dynamic protection against sudden ankle inversion stress.[68] Pinstaar et al reported that postural sway was restored after 8 weeks of ankle disk training when carried out 3 to 5 times a week.[93] Tropp and Odenrick also showed that postural control improved after 6 weeks of training when performed 15 minutes per day.[125] Bernier and Perrin, whose program consisted of balance exercises progressing from simple to complex sessions (3 times a week for 10 minutes), also found that postural sway was improved after 6 weeks of training.[10] Although there were some differences in each of these training programs, the postural control improved after 6 to 8 weeks of proprioceptive training for participants with functional instability of the ankle.

Once dynamic stability has been achieved, the focus of the RNT program is to restore ADL and sport-specific skills. Exercise and training drills should be incorporated into the program that will refine the physiologic parameters that are required for the return to preinjury levels of function. Emphasis in the RNT program must be placed upon a progression from simple to complex neuromotor patterns that are specific to the demands placed upon the patient during function. The training program should begin with simple activities, such as walking/running, and then progress to highly complex motor skills requiring refined neuromuscular mechanisms including proprioceptive and kinesthetic awareness that provide reflex joint stabilization.

Exercise Program/Progression

Dynamic reactive neuromuscular control activities should be initiated into the overall rehabilitation program once adequate healing has occurred. The progression to these activities is predicated on the athlete satisfactorily completing the activities that are considered prerequisites for the activity being considered. Keeping this in mind, the progression of activities must be goal-oriented and specific to the tasks that will be expected of the athlete.

The general progression for activities to develop dynamic reactive neuromuscular control is from slow-speed to fast-speed activities, from low-force to high-force activities, and from controlled to uncontrolled activities. Initially, these exercises should evoke a balance reaction or weight shift in the lower extremities and ultimately progress to a movement pattern. These reactions can be as simple as a static control with little or no visible movement or as complex as a dynamic plyometric response requiring explosive acceleration, deceleration, or change in direction. The exercises will allow the clinician to challenge the patient using visual and/or proprioceptive input via tubing and other devices (medicine balls, foam rolls, visual obstacles). Although these exercises will improve physiologic parameters, they are specifically designed to facilitate neuromuscular reactions. Therefore, the clinician must

be concerned with the kinesthetic input and quality of the movement patterns rather than the particular number of sets and repetitions. Once fatigue occurs, motor control becomes poor and all training effects are lost. Therefore, during the exercise progression, all aspects of normal motor control/movement should be observed. These should include isometric, concentric, and eccentric muscle control; articular loading and unloading; balance control during weight shifting and direction changes; controlled acceleration and deceleration; and demonstration of both conscious and unconscious control.

Phase I: Static Stabilization (Closed-Chain Loading/Unloading)

Phase I involves minimal joint motion and should always follow a complete open-chain exercise program that restores near-full active range of motion. The patient should stand bearing full weight with equal distribution on the affected and unaffected lower extremity. The feet should be positioned approximately shoulder-width apart. Greater emphasis can be placed on the affected lower extremity by having the patient put the unaffected lower extremity on a 6- to 8-inch stool or step bench. This flexes the hip and knee and forces a greater weight shift to the affected side, yet allows the unaffected extremity to assist with balance reactions (Figure 9-8). The weightbearing status then progresses to having the unaffected extremity suspended in front or behind the body, forcing a single-leg stance on the affected side (Figure 9-9). The patient is then asked to continue the single-leg stance while shifting weight to the forefoot and toes by lifting the heel and plantarflexing the ankle. This places the complete responsibility for weightbearing and balance reactions on the affected lower extremity. This position will also require slight flexion of the hip and knee. Support devices are often helpful and can minimize confusion. When the patient is first

Figure 9-8 Static stabilization

Weight shifting technique to enhance transfer onto the left leg.

Figure 9-9

Static stabilization: Uniplanar anterior weight shift.

Figure 9-10

Static stabilization: Single-leg stance/unstable surface.

asked to progress weight bearing to the forefoot and toes, a heel lift device can be used. A support device can also be used to place the ankle in dorsiflexion, inversion, or eversion to increase kinesthetic input or decrease biomechanical stresses on the hip, knee, and ankle.

At each progression, the clinician may ask that the patient train with eyes closed to decrease the visual input and increase kinesthetic awareness. The clinician may also use an unstable surface with training in this phase to increase the demands on the mechanoreceptor system. The unstable surface will facilitate the reflex pathways mediated by the peripheral efferent receptors. Single or multidirectional rocker devices will assist the progression to the next phase (Figure 9-10).

The physiologic rationale for this phase of RNT is the use of static compression of the articular structures to produce maximal output of the mechanoreceptors, thereby facilitating isometric contractions of the musculature and providing a dynamic reflex stabilization. The self-generated oscillations will help increase the interplay between visual, mechanoreceptor, and equilibrium reaction. Changes in the isometric muscle tension will assist in the sensitization of the muscle spindle (gamma bias).

The exercise tubing technique used in this phase is called *oscillating technique for isometric stabilization* (OTIS). The technique can be used to stimulate muscle spindle and mechanoreceptor activity. The exercises involve continuously loaded short-arc movements of 1 body part, which, in turn, causes an isometric stabilization reaction of the involved body part. This is accomplished by pulling 2 pieces of tubing toward the body and returning the tubing to a start position in a smooth rhythmical fashion with increasing speeds. Resistance builds as the tubing is stretched. This forces a transfer of weight in the direction of the tubing. Because the involved body part is only required to react or respond to a simple stimulus, the oscillating stimulus will produce an isometric contraction in the lower extremity that must produce a stabilizing force in the direction opposite to the tubing pull. The purpose of this technique is to quickly involve the proprioceptive system with minimal verbal and visual cueing. Ognibene et al demonstrated a significant improvement in both single-leg postural stability and reaction time with a 4-week training program using OTIS techniques.[88]

Change in direction—according to anterior, posterior, medial, and lateral weight shifting—will create specific planar demands. Each technique is given a name, which is related to the weight shift produced by the applied tension. The body will then react with an equal and opposite stabilization response. Consequently, the exercise is named for the cause and not the effect. The goal during this phase is static stabilization. Numerous successful repetitions demonstrating stability are required to achieve motor learning and control.

Uniplanar Exercise

Anterior Weight Shift The patient faces the tubing and pulls the tubing toward the body using a smooth, comfortable motion. This causes forward weight shift that is stabilized with an isometric counterforce consisting of hip extension, knee extension, and ankle plantarflexion. There should be little or no movement noted in the lower extremity. If movement is noted, resistance should be decreased to achieve the desired stability (see Figure 9-9).

Lateral Weight Shift The patient stands with the affected side facing the tubing. The tubing is pulled by 1 hand in front of the body and by the other hand behind the body to

equalize the force and minimize the rotation. This causes a lateral weight shift (LWS), which is stabilized with an isometric counterforce consisting of hip abduction, knee cocontraction, and ankle eversion.

Medial Weight Shift The patient stands with the unaffected side facing the tubing. The tubing is pulled in the same fashion as above. This causes a medial weight shift (MWS), which is stabilized with an isometric counterforce consisting of hip adduction, knee cocontraction, and ankle inversion.

Posterior Weight Shift The patient stands with his/her back to the tubing in the frontal plane. The tubing is pulled to the body from behind, causing a posterior weight shift (PWS), which is stabilized by an isometric counterforce consisting of hip flexion, knee flexion, and ankle dorsiflexion.

Multiplanar Exercise

The basic exercise program can be progressed to multiplanar activity by combining the proprioceptive neuromuscular facilitation chop and lift patterns of the upper extremities. The chop patterns from the affected and unaffected side will cause a multiplanar stress requiring isometric stabilization. The patient will now be forced to automatically integrate the isometric responses that were developed in the previous uniplanar exercises. The force will be representative of the proprioceptive neuromuscular facilitation diagonals of the lower extremities (Figure 9-11). The lift patterns from the affected to the unaffected side will add multiplanar stress in the opposite direction (Figure 9-12). Changing the resistance, speed of movement, or spatial orientation relative to the resistance can make modifications to the multiplanar exercise. If resistance is increased, the movement speed should be decreased to allow for a strong stabilizing counterforce. If the speed of movement is increased, then

Figure 9-11

Static stabilization: Multiplanar PNF chop technique to provide rotational stress.

Figure 9-12

Static stabilization: Multiplanar PNF lift technique to provide rotation stress.

Figure 9-13 Static stabilization

ITIS technique in unilateral stance using a Plyoball and plyoback for an impulse stimulus.

resistance should be decreased to allow for a quick counterforce response. By altering the angle of the body in relation to the resistance, the quality of the movement is changed. A greater emphasis can be placed on one component while reducing the emphasis on another component.

Technique Modification

These techniques can also be used with medicine ball exercises. The posture and position are nearly the same, but the medicine ball does not allow for the oscillations provided by the tubing. The medicine ball provides impulse activity and a more complex gradient of loading and unloading (Figure 9-13). This is referred to as impulse technique for isometric stabilization (ITIS). As described, the patient is positioned to achieve the desired stress. The medicine ball is then used with a rebounding device or thrown by the clinician. Progression to ball toss while stabilizing on an unstable surface will disrupt concentration, thereby facilitating the conversion to unconscious reflex adaptation.

The elastic tubing and medicine ball techniques are similar in position but differ somewhat in physiologic demands. Therefore, they should be used to complement each other and not replace or substitute the other at random. When performing an ITIS activity with a medicine ball, the force exerted by the exercise device names the weight shift. The tubing will exert a pull and the ball will exert a push; therefore, they will be performed from the opposite sides to achieve the same weight shift.

Phase II: Transitional Stabilization (Conscious Controlled Motion Without Impact)

Phase II replaces isometric activity with controlled concentric and eccentric activity progressing through a full range of functional motion. The forces of gravity are coupled with tubing to simulate stress in both the vertical and horizontal planes. In phase I, gravitational forces statically load the neuromuscular system. Varying degrees of imposed lateral stress via the tubing are used to stimulate isometric stabilization. Phase II requires that the movement occur in the presence of varying degrees of imposed lateral stress. The movement stimulates the mechanoreceptors in 2 ways: (a) articular movement causes capsular stretch in a given direction at a given speed and (b) the changes in the body position cause loading and unloading of the articular structures and pressure changes in the intracapsular fluid. The exercises in this phase use simple movements such as the squat and lunge. The addition of tubing adds a horizontal stress. Other simple movements such as walking, sidestepping, and the lateral slide board can also be emphasized to stimulate a more efficient and controlled movement.

The physiologic rationales for activities in this phase are the stimulation of dynamic postural responses and facilitation of concentric and eccentric contractions via the compression and translation of the articular structures. This, in turn, helps to increase muscle stiffness, which has a significant role in producing dynamic stabilization about the joint by resisting and absorbing joint loads.[80,81] Research has established that eccentric loading increases both muscle stiffness and tone.[16,95] Chronic overloading of the

musculotendinous unit via eccentric contractions will result in not only connective tissue proliferation but also a desensitization of the GTO and increased muscle spindle activity.[64]

The self-generated movements require dynamic control in the midrange and static control at the end range of motion. Because a change in direction is required at the end ranges of motion, the interplay between visual, mechanoreceptor, and equilibrium reactions continues to increase. The "gamma bias" now responds to changes in both length and tension of the involved musculature.

Assisted techniques can also be used in this phase to progress patients who may find phase II exercise fatiguing or difficult. Assisted exercise is used to reduce the effect of gravity on the body or an extremity to allow for an increase in the quality or quantity of a desired movement. The assisted technique will offset the weight of the body or extremity by a percentage of the total weight. This will allow improved range of motion, a reduction in substitution, minimal eccentric stress, and a reduction in fatigue. The closed-chain tubing program can also benefit from assisted techniques, which allow for a reduction in vertical forces by decreasing relative body weight on one or both lower extremities.

The need for assisted exercise is only transitional in nature. The goal is to progress from unweighted to weight with overloading. The tubing, if used effectively, can also provide an overloading effect by causing exaggerated weight shifting. This overloading will be referred to as resisted techniques for all closed-chain applications. The 2 basic exercises used are the squat and the lunge.

Squat

The squat is used first because it employs symmetrical movement of the lower extremities. This allows the affected lower extremity to benefit from the visual and proprioceptive feedback from the unaffected lower extremity. The clinician should observe the patient's posture and look for weight shifting, which almost always occurs away from the affected limb. Each joint can be compared to its unaffected counterpart. In performing the squat, a weight shift may be provided in 1 of 4 different directions. The tubing is used to assist, resist, and modify movement patterns. The PWS works to identify closed-chain ankle dorsiflexion. A chair or bench can be used as a range-of-motion block (range-limiting device) when necessary. This minimizes fear and increases safety. The anterior weight shift (AWS) provides an anterior pull that helps facilitate the hip flexion mobility during the descent. Medial and lateral changes may be provided with resistance in order to promote weight bearing on the involved side or decrease weight bearing on the involved side as progression is made (Figure 9-14). The varying weight shifts may be used to intentionally increase the load or resistance on a particular side for means of strengthening or to facilitate a neuromuscular response on the opposite side. For example, an individual who is reluctant to weight bear on the involved side may be helped in doing so by causing increased weight shift to the uninvolved side. This will create the need to shift weight to the involved side, thus encouraging a joint response to the required stimulus.

Figure 9-14 **Transitional stabilization**

Resisted squat with an LWS in the home health setting.

Assisted Technique The patient faces the tubing, which is placed at a descending angle and is attached to a belt. The belt is placed under the buttocks to simulate a swing. A bench is used to allow a proper stopping point. The elastic tension of the tubing

is at its greatest when the patient is in the seated position and decreases as the mechanical advantage increases. Therefore, the tension curve of the tubing complements the needs of the patient. The next 4 exercises follow the assisted squat in difficulty. The tubing is now used to cause weight shifting and demands a small amount of dynamic stability.

Anterior Weight Shift The patient faces the tubing, which comes from a level halfway between the hips and the knees and attaches to a belt. The belt is worn around the waist and causes an AWS. During the squat movement, the ankles plantarflex as the knees extend.

Posterior Weight Shift The patient faces away from the tubing at the same level as above and attaches to a belt. The belt is worn around the waist and causes a PWS. This places a greater emphasis on the hip extensors and less emphasis on the knee extensors and plantar flexors.

Medial Weight Shift The patient stands with the unaffected side toward the tubing at the same level as above. The belt is around the waist and causes an MWS. This places less stress on the affected lower extremity and allows the patient to lean onto the affected lower extremity without incurring excessive stress or loading.

Lateral Weight Shift The patient stands with the affected side toward the tubing that is at the same level as above. The belt is worn around the waist, which causes a weight shift onto the affected lower extremity. This exercise will place a greater stress on the affected lower extremity, thereby demanding increased balance and control. The exercise simulates a single-leg squat but adds balance and safety by allowing the unaffected extremity to remain on the ground.

Lunge

The lunge is more specific in that it simulates sports and normal activity. The exercise decreases the base while at the same time producing the need for independent disassociation. The range of motion can be stressed to a slightly higher degree. If the patient is asked to alternate the lunge from the right to the left leg, the clinician can easily compare the quality of the movement between the limbs. When performing the lunge, the patient may often use exaggerated extension movements of the lumbar region to assist weak or uncoordinated hip extension. This substitution is not produced during the squat exercise. Therefore, the lunge must be used not only as an exercise but also as a part of the functional assessment. The substitution must be addressed by asking the patient to maintain a vertical torso (note that the assisted technique will assist the clinician in minimizing this substitution).

Assisted Technique—Forward Lunge The patient faces away from the tubing, which descends at a sharp angle (approximately 60 degrees). This angle parallels the patient's center of gravity, which moves forward and down (Figure 9-15). This places a stretch on the tubing and assists the patient up from the low point of the lunge position. The ability to perform a lunge with correct technique is often negated as a result of the inability to support one's body weight. The assisted lunge corrects this by modifying the load required of the patient, thus improving the quality of the movement. The assistance also minimizes eccentric demands for deceleration when lowering and provides balance assistance by helping the patient focus on the center of gravity (anatomically located within the hip and pelvic region). The patient is asked to first alternate the activity to provide kinesthetic feedback. The clinician can then use variations of full and partial motion to stimulate the appropriate control before moving on to the next exercise.

Figure 9-15

Transitional stabilization: Assisted lunge technique.

Figure 9-16 **Transitional stabilization**

Resisted forward lunge to facilitate deceleration stress.

Resisted Technique—Forward Lunge The patient faces the tubing, which is at an ascending angle from the floor to the level of the waist (Figure 9-16). The tubing will now increase the eccentric loading on the quadriceps with the deceleration or the downward movement. For the upward movement, the patient is asked to focus on hip extension and not knee extension. The patient must learn to initiate movement from the hip and not from lumbar hyperextension or excessive knee extension. Initiation of hip extension should automatically stimulate isometric lumbar stabilization along with the appropriate amounts of knee extension and ankle plantarflexion. A foam block is often used to protect the rear knee from flexing beyond 90 degrees and touching the floor. The block can also be made larger to limit range of motion at any point in the lunge.

Resisted Technique—Lateral and Medial Weight Shift Forward lunges can be performed to stimulate static lateral and medial stabilization during dynamic flexion and extension movements of the lower extremities. The LWS lunge is performed by positioning the patient with the affected lower extremity toward the direction of resistance. The tubing is placed at a level halfway between the waist and the ankle. The patient is then asked to perform a lunge with minimal lateral movement. This movement stimulates static lateral stabilization of the hip, knee, ankle, and foot during dynamic flexion (unloading) and extension (loading). The MWS lunge is performed by positioning the patient with the affected extremity opposite to the resistance. The tubing is attached as described in the LWS. The movement stimulates static medial stabilization of the affected lower extremity in the presence of dynamic flexion and extension.

The lunge techniques teach weight shifting onto the affected lower extremity during lateral body movements. The assisted technique lateral lunge complements the assisted technique forward lunge, because it also reduces relative body weight while allowing

closed-chain function. The prime mover is the unaffected lower extremity that moves the center of gravity over the affected lower extremity for the sole purpose of visual and proprioceptive input prior to excessive loading. The resisted technique lateral lunge complements the resisted technique forward lunge, because it also provides an overloading effect on the affected lower extremity. In this exercise, the affected lower extremity is the prime mover, as well as the primary weightbearing extremity. The affected lower extremity must not only produce the weight shift but also react, respond, and repeat the movement. Sets, repetitions, and resistance for all of the exercises described are selected by the clinician to produce the appropriate reaction without pain or fatigue.

Technique Modification

As in phase I, the medicine ball can be used to add variety and increase stimulation. However, it is used to stimulate control in the beginning, middle, and end ranges of the squat and lunges. The tubing can also be used to create ITIS and OTIS applications to reinforce stability throughout the range of motion.

Functional Testing

Functional testing provides objective criteria and can help the clinician to justify a progression to phase III or an indication that the patient should continue working in phase II. A single-leg body weight squat or lunge can be performed. The quality and quantity of the repetitions are compared to the unaffected lower extremity and a deficit can be calculated. An isotonic leg press machine can also be used in this manner by setting the weight at the patient's body weight and comparing the repetitions. Open-chain isotonic and isokinetic testing can also be helpful in identifying problem areas when specificity is needed. Regardless of the mode of testing, it is recommended that the affected lower extremity display 70% to 80% of the capacity demonstrated by the unaffected lower extremity, or no more than a 20% to 30% strength deficit. When the patient has met these criteria, the patient can move safely into phase III.

Phase III: Dynamic Stabilization (Unconscious Control/Loading)

Phase III introduces impact and ballistic exercise to the patient. This movement will produce a stretch-shortening cycle that has been described in plyometric exercises. Plyometric function is not a result of the magnitude of the prestretch, but rather relies on the rate of stretch to produce a more forceful contraction. This is done in 2 ways.

1. The stretch reflex is a neuromuscular response to tension produced in the muscle passively. The muscle responds with an immediate contraction to reorient itself to the new position, protect it, and maintain posture. If a voluntary contraction is added in conjunction with this reflex, a more forceful contraction can be produced.
2. The elastic properties of the tendon allow it to temporarily store energy and release it. When a quick prestretch is followed by a voluntary contraction, the tendon will add to the strength of the contraction by providing force in the direction opposite to the prestretch.

Dynamic training at this level can increase the descending cortical drive to the large motor nerves of the skeletal muscles as well as the small efferent nerves of the muscle spindle.[79] If both the muscle tension and efferent output to the muscle spindles are increased, the stretch sensitivity of the muscle spindle will also be increased, thereby reducing the reflex latency.[64] Both feed-forward and feedback loops are used concurrently to superimpose stretch reflexes on preprogrammed motor activity.

As has been previously discussed, there have been previous studies that were directed toward reducing muscle reaction times.[7,65,141] Ihara and Nakayama significantly reduced the latency of muscle reaction times with a 3-week training period of unanticipated perturbations via the use of unstable wobble boards.[65] Both Beard et al and Wojtys et al found similar results when comparing agility training with traditional strength training.[7,141] Reducing the muscle reaction time in order to produce a protective response following an abnormal joint load will enhance dynamic stability about the joint.

Before the patient is asked to learn any new techniques, the patient is instructed to demonstrate unconscious control by performing various phase II activities while throwing and catching the medicine ball. The squat and lunge exercises are performed with various applications of tubing at the waist level. This activity removes the attention from the lower extremity exercise, thereby stimulating unconscious control. The forces added by throwing and catching the medicine ball stimulate balance reactions needed for the progression to plyometric activities. Simple rope jumping is another transitional exercise that can be used to provide early plyometric information. The double-leg rope jumping is done first. The patient is then asked to perform alternating leg jumping. Rope jumping is effective in building confidence and restoring a plyometric rhythm to movement. Four-way resisted stationary running is an exercise technique used to orient the patient to light plyometric activity.

Resisted Walking

Resisted walking uses the same primary components as in gait training. The applied resistance of the tubing, however, allows for a reactive response unavailable in nonresisted activities. For example, a patient may present with a slight Trendelenburg gait associated with a weak gluteus medius. By initiating a program that would incorporate a progression such as that used with the squat, the patient should be able to progress to resisted walking. The addition of resistance permits for increased loading and also brings about the need for improved balance and weight shift.

Resisted Hopping

Bilateral hopping should be introduced following adequate training with the jump rope, then followed by increased unilateral training. The use of resistance in the hopping technique is to promote increased resistance in 1 of 4 directions. This increased resistance is used to simulate those forces normally seen on the field or court in the return to activity. Introduction of the program should begin with bilateral training and then progress to a unilateral format, which may be accommodated with box drills or diagonal training. At higher levels, implementing cones, hurdles, and/or foam rolls may be used in order to increase the plyometric demands during the hopping drills.

Resisted Running

Resisted running simply involves jogging or running in place with tubing attached to a belt around the waist. The clinician can analyze the jogging or running activity because it is a stationary drill. The tubing resistance is applied in 4 different directions, providing simulation of the different forces that the patient will experience as the patient returns to full activity.

1. The PWS run causes a balance reaction that results in an AWS (opposite direction) and simulates the acceleration phase of jogging or running (Figure 9-17). The patient faces opposite the direction of the tubing resistance and should be encouraged to stay on the toes (for all running exercises). The initial light stepping activity can be progressed to jogging and then running. The most advanced form of the PWS run involves the exaggeration of the hip flexion called “high knees.” Exaggeration of hip

Figure 9-17

Dynamic stabilization—stationary run with a posterior weight shift.

flexion helps to stimulate a plyometric action in the hip extensors, thus facilitating acceleration. This form of exercise lends itself to slow, controlled endurance conditioning (greater than 3 minutes), or interval training, which depends greatly on the intensity of the resistance, cadence, and rest periods. The interval-training program is most effective and shows the greatest short-term gains. Intervals can be 10 seconds to 1 minute; however, the most common drills are 15 to 30 seconds in length. The patient is usually allowed a 1- to 2-minute rest and is required to perform 3 to 5 sets. To make sure that the patient is delivering maximum intensity, the clinician should count the number of foot touches (repetitions) that occur during the interval. The clinician needs to only count the touches of the affected lower extremity. The patient is then asked to equal or exceed the amount of foot touches on the next interval (set). This is also extremely effective as a functional test for acceleration. The interval time/repetitions can be recorded and compared to future tests. The clinician should note that the PWS places particular emphasis on the hip flexors and extensors, as well as the plantar flexors of the ankle.

2. The MWS run follows the same progression as the PWS run (from light jogging to high knees) with the resistance now applied medial to the affected lower extremity (which causes an automatic weight shift laterally). Endurance training, interval training, and testing should also be performed for this technique. This technique simulates the forces that the patient will experience when cutting or turning quickly away from the affected side. This drill is the same as in phase I MWS. Although the phase I MWS is static, the same muscles are responsible for dynamic stability. This exercise represents the forces that the patient will encounter when sprinting into a turn on the affected side.
3. The LWS run should follow the same progression as above except that the resistance is now lateral to the affected lower extremity (which causes an automatic MWS). This technique simulates the forces that the patient will experience when cutting or turning quickly toward the affected side.

   When performing the MWS and LWS runs, high knees should be used when working on acceleration. Instructing the patient to perform exaggerated knee flexion or "butt kicks" can emphasize deceleration. The exaggeration of knee flexion places greater plyometric stress on the knee, which has a large amount of eccentric responsibility during deceleration. This exercise represents the forces that the patient will encounter when sprinting into a turn on the unaffected side.
4. The AWS run is probably the most difficult technique to perform correctly and is therefore taught last. The tubing that is set to pull the patient forward stimulates a PWS. This technique simulates deceleration and eccentric loading of the knee extensors. The patient should start with light jogging on the toes and progress to butt kicks. This is a plyometric exercise that incorporates exaggerated knee flexion and extension. This exercise serves to assist the patient in developing the

eccentric/concentric reactions that are required in function. The clinician should note that injuries occur more frequently during deceleration and direction changes than on acceleration or straightforward running. Therefore, AWS training is extremely important to the athlete returning to the court or field.

Resisted Bounding

The bounding exercise is a progression taken from both the hopping and running exercise to increase demands placed on the horizontal component. Therefore, bounding is an exercise technique that places greater emphasis on the lateral movements. The progression of the bounding exercises follows the same weight-shifting sequence as the previous running exercise. Side-to-side bounding in a lateral resisted exercise promotes symmetrical balance and endurance required for progression to higher-level strength and power applications. Distraction activities also may be included in the bounding and/or running exercises in order to promote increased upper extremity demands and to detract from visual and/or verbal reference needed on the lower extremity.

It is suggested that the patient be taught how to perform the bounding exercise without the tubing first. A foam roll, cone, or other obstacle can be used to simulate jump height and/or distance. The tubing can then be added to provide the secondary forces to cause anterior, lateral, medial, or posterior weight shifting. Bounding should be taught as a jump from one foot to another. A single lateral bound can be used as a supplementary functional test. Measurements can be taken for a left and right lateral bound. Bounding is only considered valid if the patient can maintain his or her balance when landing. To standardize the bounding exercise, the body height is used for the bound stride and markers can be placed for the left and right foot landings.

1. The AWS lateral combines lateral motion with an automatic PWS or deceleration reaction. It is slightly more demanding than the stationary running exercises because the body weight is driven to a greater distance.
2. The LWS bound causes an excessive lateral plyometric force and will help to develop lateral acceleration and deceleration in the affected lower extremity. This is the most strenuous of the lateral bounding activities because it actually accelerates the body weight onto the affected lower extremity. This is, however, necessary so that the clinician can observe the ability of the affected limb to perform a quick direction change and controlled acceleration/deceleration.
3. The MWS bound is used as an assisted plyometric exercise. The patient works with the total body weight but impact is greatly lowered by reducing both acceleration and deceleration forces. This exercise is an excellent transitional exercise at the end of phase II as well as at the beginning of phase III. It also serves as a warm-up drill providing submaximal stimulation of the proprioceptive system prior to a phase III exercise session.
4. The PWS bound facilitates an anterior lateral push-off of each leg and stimulates an AWS. This exercise assists in teaching acceleration and lateral cutting movements.

Multidirectional Drills

Multidirectional drills include jumping (2-foot takeoff followed by a 2-foot landing), hopping (1-foot takeoff followed by a landing on the same foot), and bounding (1-foot takeoff followed by an opposite-foot landing). A series of floor markers can be placed in various patterns to simulate functional movements. A weight shift can be produced in any direction by the orientation of the tubing. Obstacles can also be used to make the exercise more complicated.

The jumping exercise can be developed to simulate downhill skiing, while the hopping exercise can be designed to stress single-leg push-off for vertical jumping sports such as basketball and volleyball.

SUMMARY

1. There has been increased attention to the development of balance and proprioception in the rehabilitation and reconditioning of athletes following injury. It is believed that injury results in altered somatosensory input that influences neuromuscular control.
2. If static and dynamic balance and neuromuscular control are not reestablished following injury, then the patient will be susceptible to recurrent injury and the patient's performance may decline.
3. The following rules should be employed when designing the RNT program:
   - Make sure that the exercise program is specific to the patient's needs. The most important thing to consider during the rehabilitation of patients is that they should be performing functional activities that simulate their ADL requirements. This rule applies to not only the specific joints involved but also the speed and amplitude of movement required in ADL.
   - Practice does appear to be task specific in both athletes and people who have motor-control deficits.[73] As retraining of balance continues, it is best to practice complex skills in their entirety rather than in isolation, because the skills will transfer more effectively.[1]
   - Make sure to include a significant amount of "controlled chaos" in the program. Unexpected activities with the ADL are by nature unstable. The more the patient rehearses in this type of environment, the better the patient will react under unrehearsed conditions.
   - Progress from straight-plane to multiplane movement patterns. In ADL, movement does not occur along a single joint or plane of movement. Therefore, exercise for the kinetic chain must involve all 3 planes simultaneously.
   - Begin your loading from the inside out. Load the system first with body weight and then progress to external resistance. The core of the body must be developed before the extremities.
   - Have causative cures as a part of the rehabilitation process. The cause of the injury must eventually become a part of the cure. If rotation and deceleration were the cause of the injury, then use this as a part of the rehabilitation program in preparation for return to activity.
   - Be progressive in nature. Remember to progress from simple to complex. The function progression breaks an activity down into its component parts and then performs them in a sequence that allows for the acquisition or reacquisition of the activity. Basic conditioning and skill acquisition must be acquired before advanced conditioning and skill acquisition.
   - Always ask: Does the program make sense? If it does not make sense, chances are that it is not functional and therefore not optimally effective.
   - Make the rehabilitation program fun. The first 3 letters of functional are FUN. If it is not fun, then compliance will suffer and so will the results.
   - An organized progression is the key to success. Failing to plan is planning to fail.

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