

The Role of the Sensorimotor System in the Athletic Shoulder

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Objective: To discuss the role of the sensorimotor system as it relates to functional stability, joint injury, and muscle fatigue of the athletic shoulder and to provide clinicians with the necessary tools for restoring functional stability to the athletic shoulder after injury.

Data Sources: We searched MEDLINE, SPORT Discus, and CINAHL from 1965 through 1999 using the key words "proprioception," "neuromuscular control," "shoulder rehabilitation," and "shoulder stability."

Data Synthesis: Shoulder functional stability results from an interaction between static and dynamic stabilizers at the shoulder. This interaction is mediated by the sensorimotor system. After joint injury or fatigue, proprioceptive deficits have been demonstrated, and neuromuscular control has been altered. To restore stability after injury, deficits in both mechanical stability and proprioception and neuromuscular control must be ad-

ressed. A functional rehabilitation program addressing awareness of proprioception, restoration of dynamic stability, facilitation of preparatory and reactive muscle activation, and implementation of functional activities is vital for returning an athlete to competition.

Conclusions/Recommendations: After capsuloligamentous injury to the shoulder joint, decreased proprioceptive input to the central nervous system results in decreased neuromuscular control. The compounding effects of mechanical instability and neuromuscular deficits create an unstable shoulder joint. Clinicians should not only address the mechanical instability that results from joint injury but also implement both traditional and functional rehabilitation to return an athlete to competition.

Key Words: proprioception, neuromuscular control, functional stability

The primary role of the shoulder is to place the upper extremity in a position that allows for function of the hand.¹ In order to accommodate this role, the osseous geometry of the glenohumeral joint allows for a high level of mobility.² As a result of this increased mobility, stability at the shoulder joint is compromised.³

The lack of osseous stability requires the shoulder to rely on an interaction between static and dynamic structures to provide joint stability.⁴ Statically, capsuloligamentous structures, including the glenoid labrum, glenohumeral joint capsule, and glenohumeral ligaments, and intra-articular pressure provide static joint stability. Dynamically, the rotator cuff, deltoid, biceps brachii, teres major, latissimus dorsi, and pectoralis major muscles provide vital stabilizing support. Functional stability is defined as possessing adequate stability to perform functional activity and results from the interaction between these static and dynamic components.⁵ This interaction between the static and dynamic components of functional stability is mediated by the sensorimotor system.⁵ The sensorimotor system encompasses all of the sensory, motor, and central integration and processing components of the central nervous system (CNS) involved in maintaining functional joint stability.⁶

Our purpose is to discuss the role of the sensorimotor system as it relates to functional stability, joint injury, and muscle fatigue of the athletic shoulder. In addition, we will provide

clinicians with the necessary tools for restoring functional stability in the athletic shoulder after injury.

ROLE OF THE SENSORIMOTOR SYSTEM IN GLENOHUMERAL STABILITY

As previously stated, the sensorimotor system encompasses the sensory, motor, and central integration and processing components involved in maintaining functional joint stability.⁶ Sensory information (proprioception) travels through afferent pathways to the CNS, where it is integrated with input from other levels of the nervous system, eliciting efferent motor responses (neuromuscular control) vital to coordinated movement patterns and functional stability.

Originally, Sherrington⁷ defined proprioception as the afferent information arising from the "proprioceptive field" and specifically "proprioceptors."⁵ A contemporary interpretation suggests that proprioception is defined as the afferent information concerning the 3 submodalities of joint position sense, kinesthesia, and sensation of resistance.⁵ We define joint position sense as the ability to consciously recognize where one's joint is oriented in space, while kinesthesia describes one's ability to consciously appreciate joint motion. We define sensation of resistance as one's ability to appreciate force generated within a joint. All 3 submodalities can be appreciated both consciously and unconsciously, mediating neuromuscular control.

Proprioceptive information originates at the level of the mechanoreceptor or "proprioceptor," as termed by Sherrington.⁷ Mechanoreceptors are sensory neurons or peripheral

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afferents present within the muscle, tendon, fascia, joint capsule, ligament, and skin about a joint.⁸⁻¹⁰ Mechanoreceptors are mechanically sensitive and transduce mechanical tissue deformation as frequency-modulated neural signals to the CNS through afferent sensory pathways.⁸ Deformation to the tissues in which the mechanoreceptors lie causes a mechanically gated release of stored sodium, eliciting an action potential.¹¹ An increase in tissue deformation causes an increase in action potentials, thereby increasing neural input to the CNS.^{8,11}

Specifically, at the shoulder joint, Vangness et al¹⁰ reported that neural endings exist in ligamentous structures. Low-threshold, slow-adapting Ruffini afferents were most abundant overall, except in the glenohumeral ligaments, where low-threshold, rapid-adapting, Pacinian-type afferents outnumber Ruffini afferents.¹⁰ Ruffini afferents are believed to be stimulated only with extremes of motion through tensile force, acting as limit detectors.⁸ Like Ruffini receptors, Pacinian corpuscles respond to extremes of motion but through both compressive and tensile mechanisms rather than stretching alone.⁸ No mechanoreceptors were present in the subacromial bursa or glenoid labrum.¹⁰ Because the capsuloligamentous structures of the shoulder are reported lax in mid ranges of motion,^{12,13} mechanoreceptors present within the joint capsule and ligaments are believed to contribute proprioception information when maximal deformation occurs at end ranges of motion.^{8,14} The spiral tightening of the capsule that occurs with abduction and external rotation sequentially tightens the capsuloligamentous structures, stimulating the mechanoreceptors.¹⁵

In addition to the capsuloligamentous mechanoreceptors, the musculotendinous mechanoreceptors play a significant role in providing proprioceptive input. Both Golgi tendon organs and muscle spindles are present in the musculature about the shoulder joint.^{8,9} At the tendinous region of muscle, the tension-sensitive Golgi tendon organs are recruited when muscle contraction pulls on the tendon, relaying afferent feedback concerning joint position and musculotendinous tension.^{16,17} As a protective mechanism, stimulation of the Golgi tendon organ facilitates relaxation of the agonist muscle under tension while eliciting contraction of the antagonist muscle group.¹⁷

The intrafusal muscle spindle lies parallel to the extrafusal contractile elements of muscle.¹⁷ Because the intrafusal muscle spindles are innervated by gamma motoneurons, while the extrafusal contractile elements are innervated by alpha motoneurons, muscle spindle sensitivity is adjusted during the entire range of motion, continuously signaling alterations in both muscle length and rate-of-length changes.^{5,17} Afferent proprioceptive information originating from musculotendinous, capsuloligamentous, and cutaneous receptors is integrated with messages descending from higher levels of the CNS at fusimotor neurons within the muscle spindle.^{18,19} All incoming input is adjusted so that a single composite signal is passed from the muscle spindle to the CNS and directly to the alpha motoneurons of the muscle.^{18,19} This resulting proprioceptive input to the CNS results in joint movement and position sense, reflexive muscle contraction, and regulation of muscle tone and stiffness.^{5,18,20} Because the capsuloligamentous and cutaneous afferents influence the muscle spindle, it appears that musculotendinous, capsuloligamentous, and cutaneous mechanoreceptors play a complementary role in movement and joint position sense.¹⁸

The proprioceptive information provided by the mechanoreceptors present within the musculotendinous, capsuloligamentous, and cutaneous structures is appreciated at 3 distinct levels of motor control in the CNS. Those levels of motor control include the spinal level, the brain stem, and higher levels of the central nervous system such as the cerebral cortex and cerebellum.^{5,21-23} Each level elicits unique motor responses vital to coordinated movement and functional joint stability. At the spinal level, direct motor responses in the form of reflexes and elementary patterns of motor control result.⁵ (The role of reflexes in glenohumeral joint stabilization is addressed later within this section.) At the brain stem, information from the periphery is integrated with both visual and vestibular input to control automatic and stereotypical movement patterns, as well as modulate balance and posture.^{5,21,24} In addition, the brain stem may play an influential role at the muscle spindle by maintaining and modulating muscle tone.⁵ The third level of motor control is the higher regions of the central nervous system such as the cerebral cortex and cerebellum. Tibone et al²⁵ demonstrated an afferent pathway from the mechanoreceptors present in the joint capsule to the cerebral cortex using cortical evoked potentials. Evidence of this pathway indicates that conscious awareness of proprioception may occur at the cortical level, where proprioceptive information is appreciated and plays a role in voluntary movements that are stored as central commands.²⁶ Tyldesley and Grievess²¹ reported that awareness of body position at this level allows for various skills to be performed without conscious reference. The cortical level initiates and modulates both complex and discrete movements and organizes and prepares motor commands.⁵ In addition, the cerebellum plays a significant role by acting as a "comparator."²⁷ Subconsciously, the cerebellum takes information from the periphery and compares outcome movements with expected movements, playing a vital role in motor control.²⁷

The unconscious activation of dynamic restraints occurring in preparation and in response to joint motion and loading for the purpose of maintaining functional joint stability is termed neuromuscular control.⁵ Several neuromuscular control mechanisms contributing to functional joint stability will be discussed in this section, including coactivation of glenohumeral and scapulothoracic musculature, reflex stabilization, preparatory activation, and muscle stiffness.

Coactivation of the dynamic stabilizers at the shoulder joint is vital to dynamic stabilization. Inman et al²⁸ first described force couples resulting from coactivation of the dynamic stabilizers around the shoulder, providing joint stability. Two force couples are commonly described. Contraction of the subscapularis muscle counteracts contraction of the infraspinatus and teres minor muscles in the frontal plane, while contraction of the deltoid muscle counteracts contraction of the lower rotator cuff muscles (infraspinatus, teres minor, and subscapularis) in the transverse plane.²⁸ Force couples are believed to produce joint compression, which in turn provides maximum joint congruency of the articulating surfaces.²² The rotator cuff musculature is essential for dynamic stability by centralizing the humeral head within the glenoid fossa, preventing excessive humeral translation.²⁹ Wilk et al³⁰ referred to the resulting vector forces that stabilize the humeral head within the glenoid as a "balance of forces." This muscle balance describes the coordinated synergistic action of all glenohumeral musculature providing joint stability. When those forces are not properly balanced or equalized, abnormal

glenohumeral mechanics and glenohumeral instability may result.³⁰

In addition to the synergistic action of glenohumeral musculature, the common insertion of the rotator cuff tendons within the joint capsule provides an element of dynamic capsular tension. As the cuff muscles contract simultaneously, the forces generated in their tendinous insertions apply tension to the joint capsule.^{31,32} This increased capsular tension aids in drawing the humeral head into the glenoid fossa, supplementing joint stability.

In addition to glenohumeral coactivation, a force couple also exists at the scapulothoracic articulation. The upward scapular rotation necessary for full glenohumeral abduction results from combined action by the trapezius (upper and lower portions) and serratus anterior muscles.^{33,34} In addition to the trapezius-serratus anterior force couple, synergistic contraction of all scapular-stabilization musculature provides a firm base of support for movement of the humerus at the glenoid by drawing the scapula to the thorax. As the head of the humerus moves on the glenoid fossa, the scapula simultaneously rotates, keeping the glenoid fossa and humeral head in proper alignment. Proper alignment is believed to provide an optimal length-tension relationship for the rotator cuff, which is important for glenohumeral dynamic stability.³⁵

Reflex stabilization is an efferent neuromuscular response elicited at the spinal cord level. Several investigators demonstrated that a spinal reflex exists between fibrous joint capsule and musculature about the feline glenohumeral joint.³⁶⁻³⁸ Jerosch et al³⁹ followed up by arthroscopically demonstrating a similar reflex arc between the shoulder capsule and the deltoid, trapezius, pectoralis major, and rotator cuff musculature in a human model. Initially, these reflex arcs were believed to play a primary role in joint stabilization.^{40,41} The stabilizing structures are deformed on application of a traumatic force to the joint, eliciting a feedback, reflexive muscle contraction.⁴² The problem is that the time lapse between tissue deformation (mechanoreceptor excitation) and the resulting reflexive response may not be quick enough or the response strong enough to counter a traumatic event.^{39,42,43} Jerosch et al³⁹ demonstrated a latency of 100 to 516 milliseconds in humans. While these latencies appear to be fast, they simply might not be sufficient to protect the joint. Speer and Garrett⁴³ speculated that even though the reflex activity may not be quick enough for joint stabilization, reflex activity may play a role in modifying preprogrammed responses effective in altering joint motion. Reflex activity arising from the muscle spindle assists with programmed motor patterns through a dampening function. The reflexive activity regulates both extrafusal and intrafusal length, preventing jerky, oscillation-type movements.¹⁷

A final mechanism responsible for functional joint stability is the role of preparatory muscle contraction and the resulting muscle stiffness.⁴⁴ Preparatory activation and muscle stiffness are often addressed at the knee and ankle joint,⁴⁵⁻⁴⁸ with minimal literature applying these concepts to the upper extremity.⁴⁹ The roles of preparatory activation and muscle stiffness at the shoulder joint are much-needed areas of exploration. As a result of preactivation, muscle stiffness is believed to increase. McNair et al⁴⁵ defined muscle stiffness as the ratio of change in force per change in length. This increased muscle stiffness resists stretching episodes, heightens muscle spindle sensitivity, and reduces the electromechanical delay involved in reflexive stabilization.^{19,45} Peripheral sensory information

(proprioception) from previous experiences is learned, stored, and used for planning and executing motor patterns.⁵⁰ This planning and execution of muscle activation results in preparatory muscle activity, which in turn braces the joint before some external load is placed on the shoulder. Preparatory muscle contraction offers quick compensatory responses for external loads, providing joint stability.^{19,49} In essence, a stiffer muscle produces a stiffer, more functionally stable joint.⁵ Dietz et al⁴⁹ demonstrated that both preparatory and reactive muscle activity of the triceps brachii muscle occurs during forward falls. This preparatory activation and reactive contraction are believed to provide joint stability.

SENSORIMOTOR SYSTEM ASSESSMENT

Proprioception Assessment

Measurement of the sensorimotor system encompasses evaluation of the integrity and function of the sensory and motor components along afferent or efferent, or both, neural pathways, as well as the resulting muscle activation patterns.⁵¹ We discuss common assessments of both proprioception and neuromuscular control as they relate to the shoulder.

We previously stated that proprioception is defined as the afferent information concerning the 3 submodalities of kinesthesia, joint position sense, and sensation of resistance.⁵ As such, measurement techniques attempt to quantify these submodalities through clinical assessment. Kinesthesia assessment is addressed through threshold to detection of passive motion (TTDPM). TTDPM quantifies one's ability to consciously detect shoulder movement and is often performed on some type of proprioception testing device (Figure 1).⁵²⁻⁵⁶ Subjects are fitted with a blindfold, headphones, and a pneumatic sleeve to eliminate visual, auditory, and tactile cues, causing them to

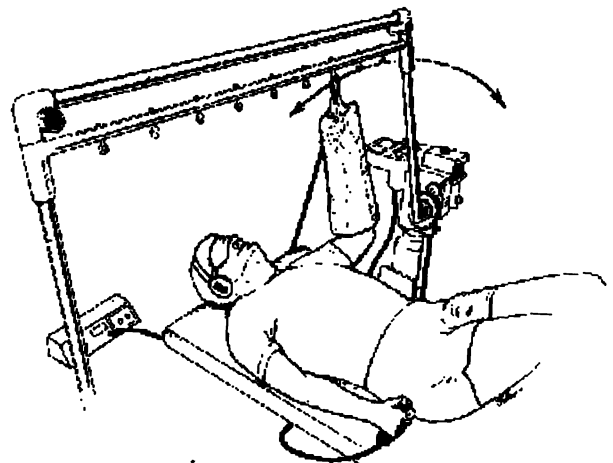


Figure 1. An individual performing either joint position sense or threshold to detection of passive motion on a proprioception testing device. The subject lies supine with the upper extremity supported at 90° of abduction and in elbow flexion. The subject is fitted with a blindfold, pneumatic air splint, and headphones to eliminate visual, tactile, and auditory cues. Using a handheld switch, the subject signals when either the joint position is passively reproduced or motion is detected. (Reprinted by permission from Lephart SM, Kocher MS: The role of exercise in the prevention of shoulder disorders, in Matsen FA, Fu FH, Hawkins RJ (eds): *The Shoulder: A Balance of Mobility and Stability*. Rosemont, IL, American Academy of Orthopaedic Surgeons, 1993.²⁹)

rely strictly on sensation from peripheral afferents to detect motion. The limb is passively rotated at a velocity from $0.5^{\circ}\cdot\text{s}^{-1}$ to $2^{\circ}\cdot\text{s}^{-1}$, depending on the literature.^{53,55,56} Extensive reliability work in our laboratory^{52,53} has shown that slower speeds are necessary to reduce variability, creating a more reliable test. The subject signals as soon as the motion is detected; therefore, the amount of rotation occurring before detection is recorded. Testing often incorporates internal and external rotation movements and occurs at both mid and end ranges of rotation. End-range external rotation is more sensitive to motion detection.^{52,53}

Joint position sense is measured in the laboratory setting with a number of assessment tools, including isokinetics,^{57,58} standard goniometry and electrogoniometry,⁵⁹ proprioception testing devices (Figure 1),^{52,55,60} and electromagnetic motion analysis systems (Figure 2).^{61,62} Joint

position sense assessment measures the ability to appreciate where one's extremity is oriented in space. Testing protocols usually begin by placing the upper limb in some standardized position and allowing the subject to appreciate its spatial orientation. The subject reproduces the presented joint position. Variations in testing include both active and passive reproduction of joint positions. As in kinesthesia testing, visual and tactile cues are often negated.

In addition to traditional assessments of proprioception (joint position sense and kinesthesia), our laboratory is currently using a 6 degrees-of-freedom electromagnetic motion analysis system as part of our proprioception testing battery. Because proprioceptive input influences motor performance, replication of a path of motion is being implemented. Figure 2 demonstrates an athlete reproducing a presented motor pattern. Using the motion analysis software, the clinician quantifies the

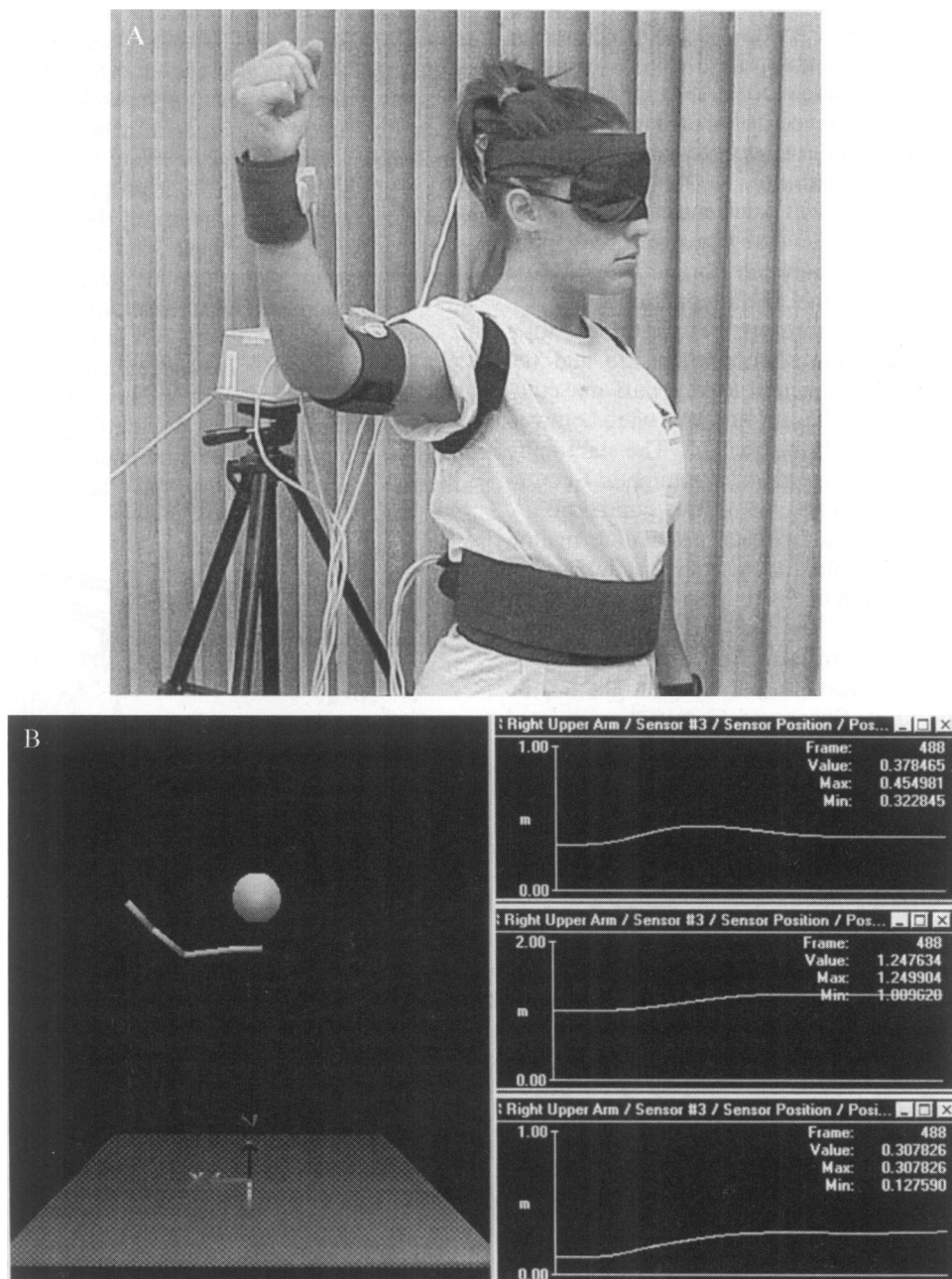


Figure 2. A, An individual performing path replication with electromagnetic motion analysis system's 6 degrees of freedom, B, with the clinician using a computer-generated image to quantify path variability during rehabilitation and assessment.

degree of 3-dimensional variation between the presented and reproduced path of motion. The motion analysis system allows for a more effective assessment of proprioception by testing in more functional positions, with less input from the testing device.

Neuromuscular Control Assessment

Resulting efferent responses to proprioceptive input are measured through neuromuscular control assessments. These assessments can include muscle activation patterns through electromyography (EMG), muscle performance characteristics with isokinetics, and functional performance tests.

Muscle activation patterns are assessed with EMG. EMG records muscle activity by measuring the accompanying electrical potential.⁶³ Uhl et al⁶⁴ used EMG to measure motor responses at the shoulder resulting from isokinetic dynamometer joint perturbations. Trying to establish the relationship between proprioception (passive joint position sense) and motor responses to joint perturbation, the authors reported no correlation between joint position sense and motor latencies.⁶⁴ At the shoulder joint specifically, fine-wire EMG and surface-electrode EMG were used to investigate athletic activity,⁶⁵⁻⁶⁹ neuromuscular alterations after injury,^{70,71} and shoulder rehabilitation.⁷²⁻⁷⁵

Isokinetic dynamometry can be a valuable tool in assessing muscle performance. Through variations of common muscle performance characteristics such as torque, work, and power, adaptations in muscle performance resulting from rehabilitation, injury, and fatigue can be assessed. Whitley and Terrio⁷⁶ demonstrated decreased peak torque with shoulder adduction and internal rotation in baseball pitchers during 1 baseball season. These findings may be associated with injuries to the pitching arm.⁷⁶ Wooden et al⁷⁷ showed increased external rotation torque and increased throwing velocity in teenage baseball players after 5 weeks of variable isotonic resistance training. These results indicated the efficacy of resistive training for improving shoulder muscle function and throwing performance.⁷⁷

Finally, neuromuscular control can indirectly be assessed through the use of functional performance tests. Davies and Dickoff-Hoffman⁷⁸ described a Functional Throwing Performance Index to assess functional performance after injury or surgery. Individuals toss a rubber playground ball at a 0.30-m × 0.30-m (1-ft × 1-ft) square target on a wall as many times as possible during a 30-second trial. The performance index is calculated by dividing the total number of throws by the number of throws that strike the target.⁷⁸ Myers et al⁵⁷ and Padua et al⁷⁹ described a single-arm dynamic stability test. Individuals maintain a single-arm tripod position as still as possible with the involved limb on a force plate and the feet on an unstable surface. Both the amount of sway that occurs over one's center of gravity and the number of compensatory touchdowns were calculated. Because the upper extremity was the only fixed segment on the body, subjects relied on shoulder dynamic stabilization to maintain the tripod position.⁵⁷

Assessments of the sensorimotor characteristics, whether proprioception measures such as joint position sense, kinesthesia, and path replication or neuromuscular control measures including EMG, muscle performance characteristics, and functional performance tests, are valuable tools for both the researcher in the laboratory and the therapist in the clinical setting. Such instruments provide means of assessing sensori-

motor characteristics, including deficits after injury and fatigue, and provide a measure of efficacy for improving proprioception and neuromuscular control through surgical intervention and rehabilitation.

PROPRIOCEPTION AND NEUROMUSCULAR CONTROL AFTER INJURY

Lephart and Henry²² presented a shoulder functional stability paradigm illustrating the cyclic role of joint injury on functional stability (Figure 3). Disruption of the stabilizing structures (capsuloligamentous and musculotendinous), whether caused by a traumatic or atraumatic mechanism, results in mechanical instability of the shoulder joint.^{80,81} Accompanying the disruption of the mechanical stabilizing structures is decreased capsuloligamentous mechanoreceptor stimulation resulting from tissue deafferentation or the increased tissue laxity limiting mechanoreceptor stimulation, or both, thus decreasing proprioception.^{22,25} This combination of capsuloligamentous disruption resulting in mechanical instability and the subsequent proprioceptive deficits contributes to functional instability.

The presence of proprioceptive deficits in unstable shoulders has been repeatedly demonstrated in the literature. Smith and Brunolli⁵⁶ were the first to demonstrate decreased proprioception after shoulder joint injury. They reported kinesthetic deficits in subjects who sustained unilateral anterior glenohumeral dislocations. A similar study by Lephart et al⁵⁵ compared the subjects' ability to both detect passive motion and passively reproduce joint positions in normal, unstable, and surgically repaired shoulders. A significant decrease in kinesthesia and joint position sense was seen in subjects with instability when compared with normal individuals and those with surgical reconstructions. Zuckerman et al⁸² similarly demonstrated a significant decrease in joint position sense and kinesthesia when moving into shoulder flexion, abduction, and external rotation in subjects with unilateral glenohumeral instability of traumatic origin. Interestingly, using cortical evoked potentials, Tibone et al²⁵ reported no significant differences between normal subjects and subjects with instability. Given that joint capsule mechanoreceptors were stimulated with electrical potentials rather than tissue deformation, these results suggest that capsular laxity alone rather than mechanoreceptor trauma resulting in deafferentation is responsible for proprioception

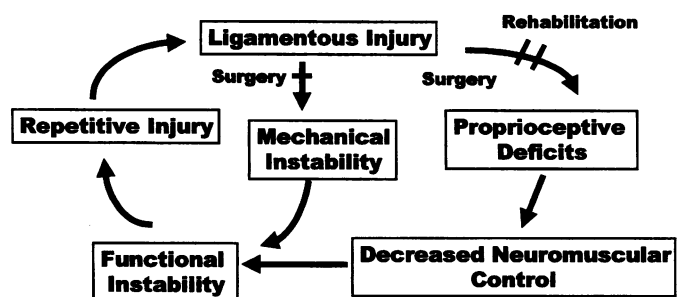


Figure 3. Shoulder functional stability paradigm. The paradigm demonstrates the cyclic progression of functional instability at the shoulder and the role of surgical intervention and rehabilitation in preventing functional instability. (Reprinted by permission from Scott Lephart and Timothy Henry, 1996, "The physiological basis for open and closed kinetic chain rehabilitation for the upper extremity." *Journal of Sport Rehabilitation*, 5(1):78.²²)

deficits. Blasier et al⁵³ noted decreased kinesthetic sense in subjects with hypermobility but no history of instability or injury. In the absence of mechanoreceptor trauma, these results again indicate that capsular laxity (resulting from hypermobility) decreases proprioception. Allegrucci et al⁵² focused on kinesthetic awareness in overhead athletes and reported decreased kinesthesia in the dominant limb of overhead athletes compared with the nondominant limb. This decrease may result from the general capsular laxity present in overhead athletes and indicates that increased capsular laxity may account for proprioceptive deficits.⁵² Sainburg et al⁸³ demonstrated that patients lacking proprioception were unable to perform multijoint movements that mimic a slicing gesture, suggesting that a proprioceptively deficient joint disrupts coordinated movement at other joints along the kinetic chain.

The deficits in proprioception after joint injury appear to contribute to alterations of the neuromuscular response vital to joint stability.²² Glousman et al⁷⁰ measured muscle activity during pitching using fine-wire EMG in subjects with anterior glenohumeral instability. They demonstrated increased compensatory supraspinatus and biceps brachii muscle activity in unstable shoulders to compensate for a lack of glenohumeral stability. In addition, Glousman et al⁷⁰ reported decreased subscapularis, pectoralis major, latissimus dorsi, and serratus anterior muscle activity during the late cocking phase of pitching in individuals with instability. This decreased activity is problematic, because the shoulder relies on activation by these muscles for anterior stability, especially in positions of vulnerability such as the late cocking phase of pitching.⁷⁰ Kronberg et al⁷¹ demonstrated decreased anterior and middle deltoid muscle activity with shoulder flexion and shoulder abduction in subjects with instability. This disrupted deltoid activity may alter the force couple action that exists between the deltoid and rotator cuff muscles and is vital to functional stability.

The mechanical instability from capsuloligamentous injury does not result in episodes of functional instability in all patients.²² Functional instability results from mechanical instability compounded by decreased proprioception and alterations in neuromuscular control. The lack of functional stability can make the athlete susceptible to reinjury and may account for the high rate of recurrence in shoulder dislocation injuries.⁸⁴

PROPRIOCEPTION AND NEUROMUSCULAR CONTROL AFTER FATIGUE

Similar to joint injury, muscle fatigue is believed to affect proprioception and neuromuscular control.^{54,57,59,85-87} Several mechanisms of fatigue have been reported as possible causes of decreased proprioceptive input, thereby affecting neuromuscular control. Unfortunately, no definitive conclusions can be drawn as to the exact mechanism resulting in decreased proprioception. As a result, we discuss several commonly described mechanisms.

Muscle fatigue is believed to desensitize muscle spindle threshold, thereby affecting joint position sense and the neuromuscular responses vital to joint stability.^{57,85} This desensitization results from changes in local metabolism at the muscle.⁸⁵ Pedersen et al¹⁸ reported that increased intramuscular concentrations of lactic acid, potassium chloride, bradykinin, arachidonic acid, and serotonin after fatiguing contractions may affect the muscle spindle system, thereby influencing proprioceptive acuity. Djupsjobacka et al⁸⁸⁻⁹⁰ noted that in-

creased intramuscular concentrations of several contractile substances resulting from muscle fatigue alter the muscle spindle output, as measured through reflex arcs.

The role of central factors cannot be overlooked when discussing the role of muscle fatigue. Central fatigue occurs at higher levels of the central nervous system, such as the cerebral cortex.⁹¹ The physiologic strain of fatigue can lead to psychological inhibition.⁹² The fatigue protocol may be taxing not only to the shoulder musculature but also to conscious awareness of proprioception.

An indirect mechanism independent of muscle fatigue but resulting from the bout of exercise to elicit fatigue is the increased ligamentous laxity that occurs with exercise.^{93,94} During cyclic loading, viscoelastic changes resulting from exercise decrease the stiffness properties of ligament.⁹⁵ This decrease in stiffness may desensitize the mechanoreceptors present within stabilizing structures, compromising proprioceptive feedback.⁹⁶ The desensitized mechanoreceptors, in combination with the decreased capsuloligamentous stiffness, may compromise stability in extremes of rotation (ie, positions of vulnerability). Researchers have investigated the effect of muscular fatigue on proprioception and neuromuscular control at the shoulder, elbow, knee, and ankle.^{54,57,59,85,97-100} Carpenter et al⁵⁴ demonstrated decreased proprioception after fatigue using TTDPM assessment. Detection latency increased by 171% for internal rotation and 179% for external rotation. Because of the decreased kinesthetic sense after fatigue, the researchers concluded that fatigue affects sensation of joint movement, decreases athletic performance, and increases fatigue-related shoulder dysfunction.⁵⁴ Myers et al⁵⁷ focused on the effect of fatigue on shoulder proprioception and neuromuscular control. Sixteen subjects exhibited decreased ability to actively reproduce joint position in both mid and end ranges of motion. Unlike the previous studies, Myers et al⁵⁷ also included a neuromuscular control measurement.

At the shoulder joint, Myers et al⁵⁷ measured neuromuscular control using the single-arm dynamic stability test. As evident by the number of compensatory events (any touch down to maintain stability), the authors reported a decreased ability to maintain the single-arm push-up position after a bout of isokinetic fatigue (1 compensatory event before fatigue, 14 after) and speculated that fatigue of the force couple musculature vital to dynamic stability was altered, decreasing the dynamic stability. Wickiewicz et al¹⁰¹ performed a kinematic analysis of glenohumeral motion after a bout of muscle fatigue and noted an increase in superior humeral migration at 45°, 90°, and 125° of abduction after fatigue.¹⁰¹ These results emphasize the importance of the dynamic stabilizers present at the shoulder joint and how fatigue may increase the risk of injury due to a loss of stability. Because few studies to date have examined shoulder neuromuscular control after fatigue, additional research is needed.

The implications from decreased proprioception and neuromuscular control after fatigue are 2-fold. First, afferent proprioceptive feedback integrated at the CNS elicits efferent neuromuscular responses as both spinal reflexes and preprogrammed responses vital to functional stability of the shoulder joint. Because fatigue hinders proprioceptive feedback from the shoulder to the CNS, the neuromuscular responses responsible for joint stability may be hindered, leading to joint instability and eventually joint injury. That joint injury can occur to both the musculoskeletal and

capsuloligamentous-stabilizing structures. Second, if an individual's ability to recognize joint position, especially in positions of vulnerability, is hindered, he or she may be prone to injury due to increased mechanical stress placed on both the static and dynamic structures responsible for joint stability.

RESTORATION OF PROPRIOCEPTION AND NEUROMUSCULAR CONTROL

After capsuloligamentous injury, the goal of management and rehabilitation should be restoration of functional stability at the shoulder joint. As previously stated, functional stability encompasses the interplay of both the mechanical restraints (joint capsule, ligamentous structures, and glenoid labrum) and dynamic restraints (neuromuscular responses by the shoulder musculature). To restore functional stability, both constituents must be restored. Figure 3 illustrates the roles that surgery and rehabilitation play in shoulder functional instability.

Surgical Management of Instability

Surgical management disrupts that vicious cycle of injury by restoring capsuloligamentous integrity and restoring proprioceptive capabilities. Surgical techniques such as variations of the capsular shift, Bankart procedures, and thermal capsular shrinkage address the capsuloligamentous trauma that results from injury, alleviating mechanical instability.^{102,103} Interestingly, surgical management also plays a significant role in restoring the proprioceptive capabilities of the shoulder joint after injury. Surgery retensions the capsuloligamentous structures, facilitating proprioceptive feedback by allowing mechanical stimulation of the afferents present within the joint capsule and ligaments.^{25,55}

As previously discussed, Lephart et al⁵⁵ measured both joint position sense and kinesthesia in normal individuals and those with unstable and surgically reconstructed shoulders. The subjects diagnosed with instability who underwent open or arthroscopic surgical intervention showed no significant difference in joint position sense or kinesthesia of the injured limb when compared with the contralateral limb. Therefore, restoration of capsular tension resulted in restoration of proprioceptive feedback. Zuckerman et al⁸² prospectively studied 30 individuals with unilateral glenohumeral instability of traumatic origin with both joint position sense and kinesthetic testing protocols 1 week before surgery and at 6 and 12 months after surgery. The authors demonstrated significant decreases in both joint position sense and kinesthesia before surgery and partial restoration by 6 months and full restoration by 12 months after surgery.⁸²

Thermal Capsular Shrinkage

A contemporary surgical procedure gaining popularity in the orthopaedic community is the use of thermal energy via radiofrequency devices and lasers to address mechanical instability (thermal capsular shrinkage).^{103,104} While thermal capsular shrinkage has been received with much enthusiasm, data concerning its efficacy are anecdotal.¹⁰⁵ No substantial clinical studies address the efficacy of thermal capsular shrinkage. Given that thermal energy denatures the collagenous infrastructure of the shoulder capsule,^{106–108} whether the mechanoreceptors present within the shoulder capsule are also altered is a topic of much controversy.

We⁶¹ measured joint position sense, kinesthesia, and shoulder function in subjects who underwent thermal capsular shrinkage for shoulder instability. We found no significant difference in kinesthesia or either active or passive reproduction of joint position sense 6 to 24 months after surgery. In addition, these subjects had returned to near-normal daily function at the time of testing. We concluded that the combination of normalized proprioception and the subject's ability to return to near-normal function after surgery suggests that thermal capsular shrinkage may provide an effective management option for treating glenohumeral instability. Thermal capsular shrinkage and its effect on proprioception, neuromuscular control, and function still need to be investigated prospectively.

Functional Rehabilitation

Whether surgical intervention or a conservative approach is chosen, a rehabilitation program is vital for return to function after shoulder joint injury. As with any injury, rehabilitation should address inflammation and pain reduction, a return to normal range of motion and flexibility, and restoration of strength through traditional rehabilitation exercises. We refer readers to several sources of traditional shoulder rehabilitation exercises.^{72,75,109,110} Traditional rehabilitation addressing the aforementioned aspects might be sufficient for return to activities of daily living but not for return to athletic activity.²³ As a result, Lephart and Henry²³ proposed adding "functional rehabilitation" to the traditional rehabilitation protocol.

Functional rehabilitation is believed to prepare an athlete for return to athletic competition by restoring the proprioceptive capability and neuromuscular control of the shoulder joint after injury. Functional rehabilitation is believed to increase the sensitivity of peripheral afferents present in both the capsuloligamentous and musculotendinous structures, reestablish afferent pathways, facilitate coactivation of the force couples, elicit preparatory and reactive muscle contractions, and increase muscle stiffness.⁴⁴ Functional rehabilitation should mimic the demands placed on the shoulder joint during athletic activity, making the transition to full activity less stressful for the athlete. To meet these goals, 4 facets of functional rehabilitation must be addressed: awareness of proprioception, dynamic-stabilization restoration, preparatory and reactive muscle facilitation, and replication of functional activities. We discuss each facet of functional rehabilitation individually, providing clinicians with valuable tools for reestablishing functional stability.

Unfortunately, many of these exercises we describe are discussed only in clinical journals, and reports of efficacy are limited to anecdotal evidence. As such, controlled scientific studies are needed to add a level of scientific efficacy.

Awareness of Proprioception. The goals of awareness of proprioception are to reestablish afferent pathways from the mechanoreceptors at the injured joint to the CNS and to facilitate supplementary afferent pathways as a compensatory mechanism for proprioceptive deficits that resulted from joint injury. Because the risk of injury aggravation with proprioception training is low, both kinesthesia and joint position sense training can be initiated early in rehabilitation. Early training of conscious awareness of proprioception is believed to lead eventually to unconscious awareness.⁴⁴ Proprioceptive information is appreciated by the injured athlete in the form of both

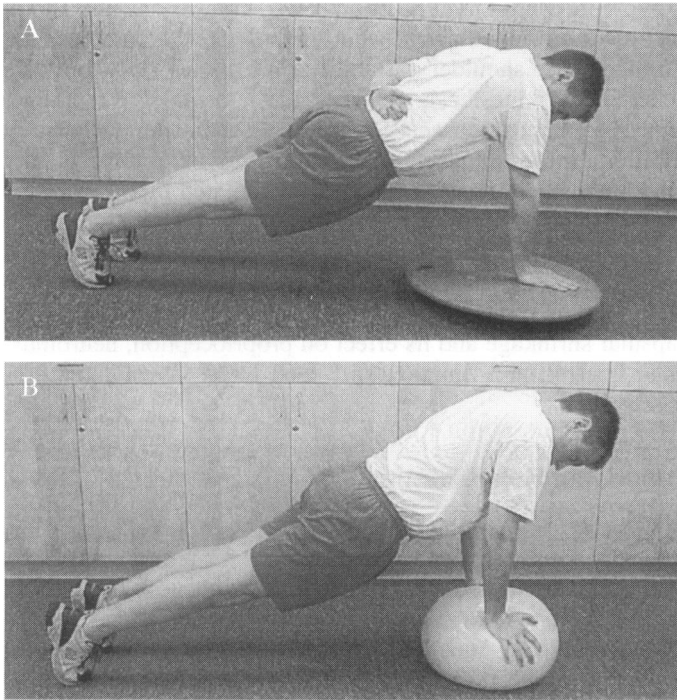


Figure 4. An individual performing upper extremity weightbearing exercises for both dynamic stabilization and preparatory-reactive muscle activation on A, wobble board and B, therapy ball.

joint position sense and kinesthesia. Therefore, rehabilitation should address both aspects.

Clinicians can implement joint position sense training with isokinetic exercises, proprioception testing devices, goniometry, and electromagnetic motion analysis. Joint position sense training can be simply performed by placing the athlete's upper extremity into a predetermined position, then instructing the athlete to reproduce the joint position as accurately as possible. Initially, trials can include visual cues (the athlete can see the limb position), progressing to the removal of visual cues through the use of a blindfold. Joint position sense trials should be performed within mid ranges of motion to stimulate musculotendinous mechanoreceptors as well as in end ranges of motion in positions of vulnerability to stimulate capsuloligamentous afferents. Trials can include both passive reproduction of joint position, in which the clinician, isokinetics, or a proprioception testing device moves the limb while the athlete signals when the joint position is reached, and active reproduction of joint position, in which the athlete actually reproduces the joint position through his or her own muscle contraction. The activity can be varied by having the athlete replicate paths of motion rather than joint position to add an element of functionality.

Kinesthesia training can also be easily performed by the clinician. By simply eliminating external cues via a blindfold and headphones, the clinician uses isokinetics, a proprioception testing device, or simple manual motion to administer the trials. The athlete's goal is to signal when joint motion is sensed, as quickly as possible once motion is initiated. Recording the degree of motion before joint motion detection is a means of quantifying progress.

Dynamic Stabilization. In this phase of rehabilitation, the primary goal is to reestablish the synergistic coactivation of force couples present at the shoulder. These force couples include the 2 present at the glenohumeral joint, as well as that

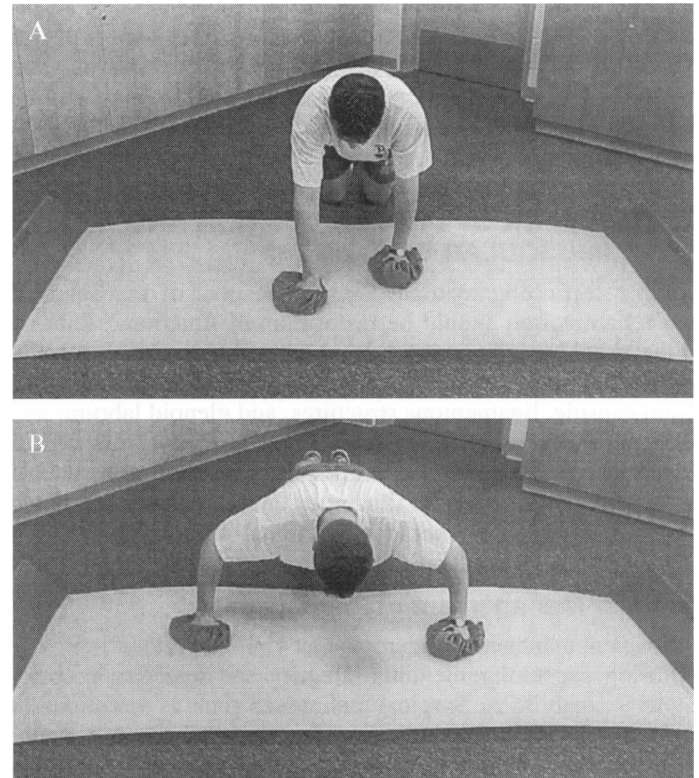


Figure 5. A, An individual in a limited upper extremity weightbearing position performing arm flexion on a slide board. B, An individual in a full push-up position performing horizontal flexion exercises on a slide board. Both exercises are for dynamic stabilization.

at the scapulothoracic articulation. By facilitating this coactivation of the force couples at the glenohumeral joint, dynamic stability is restored as the resulting vector forces centralize and compress the humeral head within the glenoid fossa. Also, contraction of the rotator cuff pulls on the glenohumeral joint capsule, applying tension, which results in increased stability.

It is commonly believed that weightbearing exercises in the upper extremity facilitate a level of coactivation of both the glenohumeral and scapulothoracic force couples.^{32,78} Until recently, the use of weightbearing exercises for coactivation of the force couple musculature was strictly anecdotal, with no scientific validity. However, Henry et al¹¹¹ performed a fine-wire EMG study to assess the level of coactivation of the 2 force couples present at the shoulder. Subjects in the study performed dynamic rehabilitation exercises, including a push-up, rhythmic stabilization, tracing circles on a slide board, horizontal motion on a slide board, and flexion motion on a slide board. Of the dynamic rehabilitation exercises, 4 exercises produced coactivation of the force couples. Those coactivation exercises included the push-up and the 3 slide board activities.¹¹¹ Thus, weightbearing exercises in the upper extremity are suited for re-establishing the glenohumeral coactivation necessary for dynamic stabilization.

As such, we recommend several exercises designed for reestablishing coactivation during rehabilitation. Simple weightbearing shifts on a table can be initiated early in the rehabilitation process due to the low risk of injury reagravation. Next, a simple tripod stance on a firm surface can be beneficial. Once an athlete is able to maintain the tripod position on a firm surface with ease, moving to some type of

unstable surface is the next logical progression (Figure 4). (The role of tripod-type exercises will be discussed further in the next section.) Additional exercises as described by Henry et al¹¹² are weightbearing activities on the slide board. A simple progression can include limited weightbearing on one's knees, progressing to a full push-up position. Motions can include circles, figures-of-8, and flexion exercises within the frame of the body (Figure 5A). As rehabilitation progresses and dynamic stability is restored, horizontal motion can be performed with the limb placed in positions of vulnerability (Figure 5B).

At the scapulothoracic joint, several exercises are suggested to facilitate synergistic contraction, providing a stable base of support for upper extremity movement. Wilk et al¹¹² described several exercises to reestablish the scapulothoracic contraction necessary to provide a stable base of support: isometric punches, push-ups, press-ups, and scapulothoracic rhythmic-stabilization techniques. A full description of these exercises is presented in the literature.^{32,112} Moseley et al⁷⁵ performed an EMG study focusing on scapular stabilization and strengthening exercises. They found that scaption exercises, rowing exercises, push-ups with a plus, and press-ups all provide substantial muscle activity for the scapular stabilizers.

Preparatory and Reactive Muscle Activation. The goals of this phase of rehabilitation are to reestablish the preparatory activation that provides joint stability through an increase in muscle stiffness, as well as to stimulate the reflexive contraction that results when a force acts upon the shoulder joint. Through the use of different types of joint perturbation, the shoulder joint is stressed with unexpected types of forces, similar to those experienced during athletic competition. However, full strength, range of motion, and dynamic stability must be obtained before initiating these exercises.

We recommend several exercises to address this phase of the functional rehabilitation. First, glenohumeral rhythmic-stabilization exercises should be performed. While rhythmic-stabilization exercises were not found to elicit coactivation, as commonly believed,¹¹¹ their usefulness should not be underestimated. The athlete lies supine with the elbow extended and the limb projecting upward in the scapular plane. The athlete is instructed to maintain this position while the clinician applies repeated joint perturbations in randomized directions. Several progressions can be incorporated, including progressing from a visual to a nonvisual condition, progressing from the scapular plane position to positions of function and vulnerability, and adding a medicine ball to increase the challenge of performing the task (Figure 6). Rhythmic-stabilization exercises are believed to be very beneficial because they include both preparatory muscle activity, as the athlete prepares for the joint perturbation, and reactive muscle activity as the athlete responds to the unexpected direction of force.

In addition to the rhythmic-stabilization exercises, weightbearing exercises (as described in the dynamic-stabilization restoration section of this manuscript) may have an important role in restoring both preparatory and reactive muscle activity. In addition to their coactivation capabilities, weightbearing exercises performed on unstable joints may elicit both preparatory activity to allow maintenance of the weightbearing position and reactive muscle contraction as the athlete responds to unexpected changes from the unstable surface. These exercises can be performed on any unstable surface, including wobble boards (Figure 4A), multiaxial devices, therapy balls (Figure 4B), and minitrampolines. Progressions can include

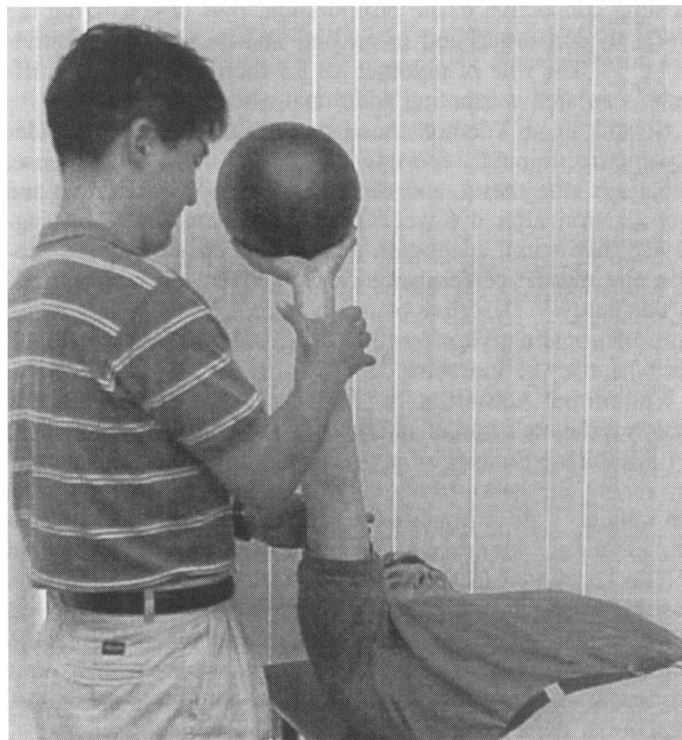


Figure 6. Rhythmic stabilization in which the clinician applies different joint perturbations while the individual tries to maintain joint stability. A medicine ball was added to increase the difficulty through increased resistance.

visual to nonvisual conditions and increasing the difficulty by manipulating the unstable surface.

Plyometrics play a vital role in rehabilitation of the athletic shoulder. Plyometrics incorporate stretch-shortening contractions. Stretch-shortening contractions are characterized by an eccentric preload in which elastic energy is stored in the series elastic component of muscle.¹¹³ This stored energy is then used by the muscle to perform a forceful concentric contraction. The eccentric stretching that occurs with stretch-shortening contractions stimulates the muscle spindle, which in turn activates the myotactic (stretch) reflex in the agonist extrafusal muscle fibers.¹⁷ The faster the muscle is stretched, the greater the concentric contraction.¹¹³ The ballistic nature of plyometrics means that restored dynamic stability is essential before a plyometric training program is initiated.

The benefits of plyometric training are numerous. First, athletic movement patterns at the shoulder, including the late cocking phase of pitching, use a quick eccentric stretch followed by a sudden forceful contraction (acceleration phase), a stretch-shortening contraction. Plyometrics recreate the type of eccentric-concentric contraction experienced during athletic activity, providing the vital functional component. Second, preparatory muscle activity is elicited during plyometric training as the athlete prepares for the eccentric load, followed by the reactive (reflexive) contraction from increased stimulation of the muscle spindle. Repeated plyometric training may elicit neural adaptation, increasing muscle spindle sensitivity. Finally, plyometric training may play a role in increasing muscle stiffness. In addition to eliciting preparatory muscle contraction that increases muscle stiffness, high-repetition, low-rest interval eccentric training like that found in plyometric training may increase muscle stiffness by increasing muscle tone and

causing connective tissue proliferation, thus desensitizing the Golgi tendon organ and increasing muscle spindle sensitivity.¹¹⁴⁻¹¹⁶ The role of plyometrics for increasing muscle stiffness is an area warranting additional research.

Swanik et al⁵⁸ demonstrated the effectiveness of shoulder plyometric training, reporting enhanced joint position sense, enhanced kinesthesia, and decreased time to peak torque and amortization after a 6-week plyometric program. They suggested that neural adaptation may have enhanced proprioception and muscle performance characteristics, as demonstrated in this study.⁵⁸ Descriptions of plyometric exercises appear in the functional activities section of this manuscript as well as elsewhere in the literature.^{117,118}

Functional Activities. The final facet of functional rehabilitation is the inclusion of activities that mimic athletic function. By mimicking the type of activities and forces experienced by the athlete, the return-to-play transition may be less stressful on the athlete.¹¹⁹ It is important to incorporate specificity when implementing functional activities. Therefore, the athlete should be trained in sport-specific positions of function. The position of function for a baseball player or tennis player is a position of vulnerability in abduction and external rotation, while the position of function for an interior lineman on a football team is just below shoulder level anterior to the thorax. Functional rehabilitation should reflect such positions.

Several rehabilitation exercises with modification mimic function for any athlete. The benefits of plyometric exercises and their ability to mimic functional activity have been previously discussed. Plyometrics exercises using a minitrampline and medicine ball or a simple piece of rubber tubing can mimic the throwing and serving motion in overhead athletes,

an interior football line using explosive chest-pass repetitions, or athletic activities that incorporate the powerful trunk motions of pitching, batting, and golf (Figure 7). Because of the amount of joint force exhibited on the shoulder, plyometric exercises should be incorporated only after full, pain-free range of motion, strength, and dynamic stability are achieved.

A second rehabilitation exercise that mimics functional activity is proprioceptive neuromuscular facilitation (PNF). PNF exercises are believed to build strength through functional planes of motion by incorporating both spiral and diagonal patterns of motion that demand neuromuscular coordination.⁴¹ The diagonal 2 (D2) flexion-extension PNF pattern is often used in the rehabilitation of overhead athletes due to the similarity between its plane of motion and the throwing and serving movement pattern. PNF exercises can be performed manually by the therapist or with rubber tubing or isokinetics (Figure 8). Padua et al⁷⁹ demonstrated the effectiveness of a 5-week manual PNF training study on function. After 5 weeks of PNF training, normal subjects showed a significant improvement in shoulder function as measured with the Functional Throwing Performance Index.^{78,79} These results demonstrate the importance of incorporating activities such as PNF exercises, which mimic function when preparing an athlete for return to competition.

CONCLUSIONS

Functional stability at the shoulder joint results from an interaction between the static and dynamic components of joint stability. The sensorimotor system plays an integral role by mediating static and dynamic components of afferent proprio-

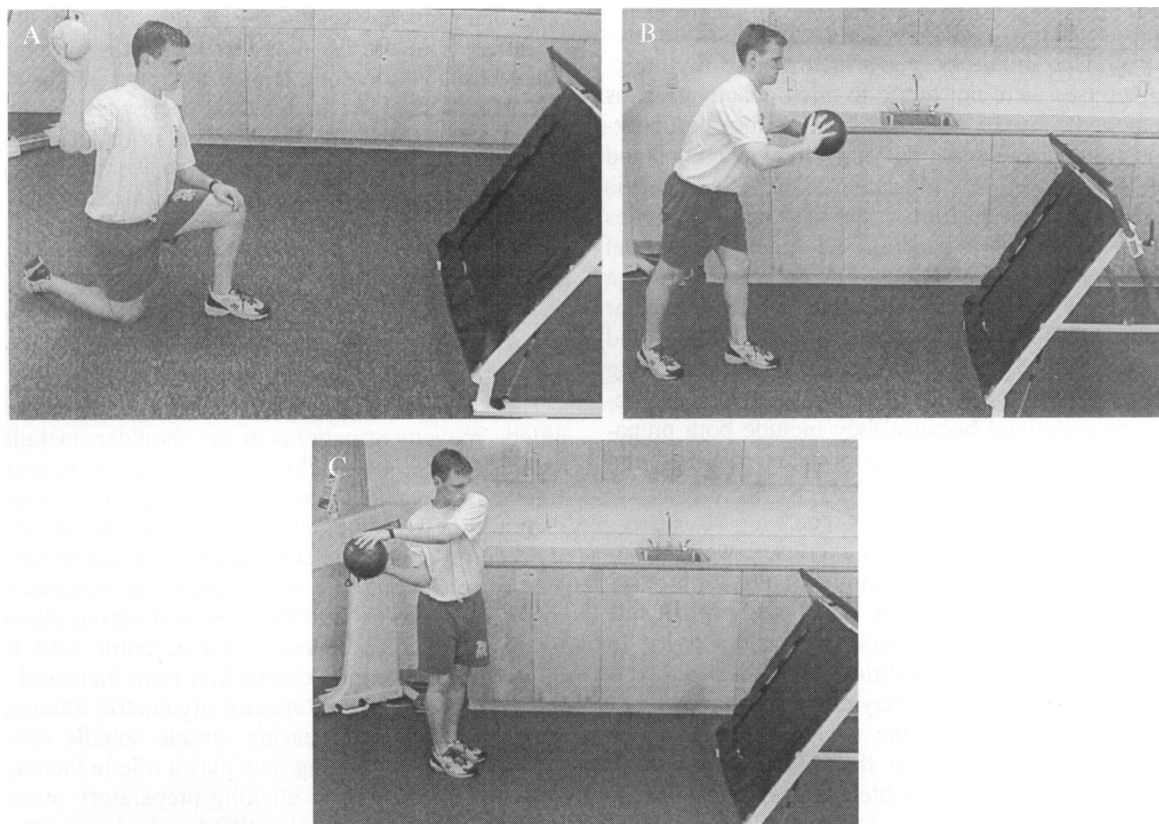


Figure 7. An individual performing plyometric A, pitching exercises, B, chest-pass exercises, and C, trunk-rotation exercises that mimic functional activities.

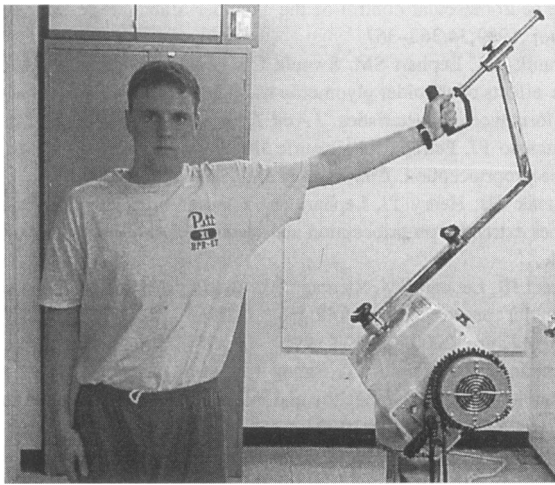


Figure 8. An individual performing diagonal 2 (D2) proprioceptive neuromuscular facilitation (PNF) exercises that mimic the functional plane of throwing on an isokinetic dynamometer.

ceptive information concerning joint position sense, kinesthesia, and sensation of resistance and the efferent neuromuscular responses that result. These neuromuscular responses are vital to both joint stability and coordinated movement patterns. The neuromuscular responses vital to joint stability include coactivation of the force couples, dynamic capsular tensioning, preparatory and reactive muscle contraction in the form of reflexes, and increased muscle stiffness. After capsuloligamentous injury, proprioceptive input appears to be disrupted, which in turn disrupts the efferent neuromuscular responses. This combination of increased capsuloligamentous laxity and decreased neuromuscular control results in a functionally unstable joint.

Restoration of functional stability in the athletic shoulder requires attention to both the stabilizing structures that are compromised, whether with surgical intervention or a conservative approach, and the neuromuscular responses vital to joint stability through a functional rehabilitation program. We have provided clinicians with the tools necessary for returning the athlete to competition by addressing functional rehabilitation through awareness of proprioception, facilitation of dynamic stabilization, restoration of preparatory and reactive muscle activity, and implementation of functional activities. The shoulder joint must have the ability to sense forces placed on the capsuloligamentous and musculotendinous structures and respond appropriately with efferent neuromuscular responses, providing much-needed functional stability to the inherently unstable joint.

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