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Proprioception and Neuromuscular Control of the Shoulder After Muscle Fatigue

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Objective: To examine the effects of fatigue on proprioception and neuromuscular control of the shoulder.

Design and Setting: Subjects were randomly assigned to either an experimental group or control group. Subjects were tested using either the active angle-reproduction or the single-arm dynamic stability test. The subjects were then fatigued using a dynamometer performing continuous, concentric rotation exercises of the shoulder. Once fatigued, the subjects were posttested using the same test. One week later, the subjects returned and were pretested, fatigued, and posttested using the other test.

Subjects: Thirty-two college-age (18 to 25 years) subjects (16 males, 16 females) with no history of glenohumeral instability or upper extremity injury volunteered for this study.

Measurements: Absolute angular error was measured using an electrogoniometer present within the isokinetic dynamometer, while sway velocity was measured using a force-plate system.

Results: Repeated-measures analysis of variance revealed a significant difference between the pretest and posttest values for absolute angular error in the experimental group, whereas no significant difference was revealed between pretest and posttest sway velocity for either the control or experimental group.

Conclusions: Fatigue of the internal and external rotators of the shoulder decreased proprioception of the shoulder, while having no significant effect on neuromuscular control.

Key Words: mechanoreceptors, joint position sense, force plate

Since proprioception is a component of neuromuscular control, the two terms are often used interchangeably and incorrectly. Proprioception is defined as the specialized variation of the sensory modality of touch that encompasses the sensation of joint movement (kinesthesia) and joint position,[1] whereas neuromuscular control is the unconscious motor efferent response to afferent sensory (proprioceptive) information.

Afferent proprioceptive feedback results from impulses transmitted by mechanoreceptors to the central nervous system (CNS), relaying information about joint position and joint movement sense.[1] A mechanoreceptor is a specialized neuroepithelial structure found in the skin and in articular, ligamentous, muscular, and tendinous tissue about a joint.[2] Mechanoreceptors transduce functional and mechanical deformation into frequency-modulated neural signals. An increase in deformation causes an increase in afferent discharge of neural signals back to the CNS.[3]

Several studies to date have examined proprioception of the shoulder. Smith and Brunolli[4] compared the proprioceptive feedback of the involved versus the uninvolved shoulders in individuals who had sustained anterior dislocations. They concluded that proprioceptive deficits existed within the involved shoulder. Lephart et al[1] reported similar results when comparing shoulder proprioception of normal, unstable, and surgically repaired shoulders. Like Smith and Brunolli,[4] Lephart et al[1] reported proprioceptive deficits in both threshold to detection of passive motion and passive reproduction of joint position in persons with unstable shoulders, while differences between those with normal and surgically repaired shoulders were nonsignificant.

Since mechanoreceptors, which are responsible for proprioceptive feedback causing neuromuscular responses, are present in the musculature surrounding the joint,[2] it is feasible to believe that, as a muscle fatigues, proprioceptive feedback is affected, and thereby, neuromuscular control and shoulder function are affected. To date, 3 studies have examined the effect of fatigue on shoulder proprioception. Voight et al[5] studied the effects of fatigue and the relationship of arm dominance to shoulder proprioception. Using both active and passive joint-angle reproduction, they concluded that fatigue significantly decreased one's ability to both actively and passively reproduce an angle.[5] Voight et al[5] believed that the decrease in ability after fatigue was due to "dysfunctional mechanoreceptors" in the internal and external rotators of the shoulder. Carpenter et al[6] used threshold to detection of passive movement to determine how fatigue affects proprioception of the shoulder. These researchers concluded that fatigue affects sensation of joint movement, decreases athletic performance, and increases fatigue-related shoulder dysfunction.[6] Pedersen et al[7] measured joint position sense of the shoulder. Unlike Voight et al,[5] who measured shoulder

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proprioception with humeral rotation, Pedersen et al[7] assessed proprioception with shoulder motion in the transverse plane. Like Voight et al,[5] Pedersen et al[7] reported a decrease in joint position-sense ability after fatigue. While there is debate as to whether fatigue affects proprioception,[8,9] some studies have shown decreased proprioceptive feedback after bouts of fatigue.[5–7,10,11]

To date, these studies have examined the effect of fatigue on shoulder proprioception, but no investigators have examined how fatigue affects neuromuscular control of the shoulder joint. The purpose of our study was to determine how muscle fatigue affects shoulder proprioception and neuromuscular control of the shoulder joint. A study of this nature, focusing on both afferent proprioceptive feedback and the efferent neuromuscular responses, will shed light on how fatigue affects proprioceptive feedback, and thereby, neuromuscular control of the shoulder.

METHODS

Subjects

Subjects consisted of 32 physically active college students (16 males, age = 21.82 ± 1.46 years, weight = 81.42 ± 19.27 kg, height = 181.31 ± 5.59 cm; 16 females, age = 20.82 ± 1.44 years, weight = 56.08 ± 6.95 kg, height = 164.95 ± 6.50 cm) with no history of glenohumeral pathology. Subjects were randomly assigned to either an experimental group or a control group. Following the group assignment, subjects signed an informed consent form approved by the Institutional Review Board at the University of North Carolina at Chapel Hill, which also approved the study, and were instructed about the testing and fatigue procedures.

Instrumentation

Subjects performed the active angle-reproduction test (AAR) on the Lido Multi-Joint II isokinetic dynamometer (Loredan Biomedical, Inc, West Sacramento, CA). This test measures proprioceptive feedback using active reproduction of joint position. Lephart et al[12] reported that active joint position assessment stimulates both joint and muscle mechanoreceptors and is a more functional assessment of afferent pathways. We positioned the supine subjects in 90° of glenohumeral abduction with 90° of elbow flexion (Figure 1A). A hook-and-loop strap secured the subject's humerus to a pad positioned on the lever arm of the dynamometer, while the wrist was also secured to the lever arm. The subjects wore a pneumatic air splint, a blindfold, and headphones with music to eliminate tactile, visual, and auditory cues (Figure 1B).

The subjects performed the single-arm dynamic stability (SADS) test on the Smart Balance Master long force plate (NeuroCom International, Inc, Clackamas, OR) with the New Balance Master Version 6.1 software package (NeuroCom International, Inc). The test measures neuromuscular control by calculating sway velocity, which is a measure of amplitude divided by time. The amplitude is the distance (in degrees) traveled away from one's center of gravity, while time is the duration of the trial (10 seconds). The subjects assumed a single-arm push-up position with the dominant hand placed in the center of the force plate while the nondominant arm was placed on the small of the back. Full extension of the elbow, torso, hips, and knees was considered a correct position for testing. The subject positioned his or her feet in the center of the Dynamic Stabilization Trainer (DST 360; Exertool, San Carlos, CA) multidirectional unstable platform (Figure 2). We positioned the 40.64-cm unstable platform away from the center of the force plate at a distance corresponding to a measurement from the floor to the acromioclavicular joint of each subject. The unstable platform increased the difficulty of maintaining the single-arm push-up position.

We conducted a separate reliability study for the SADS test on 18 healthy, college-age subjects in 2 testing sessions

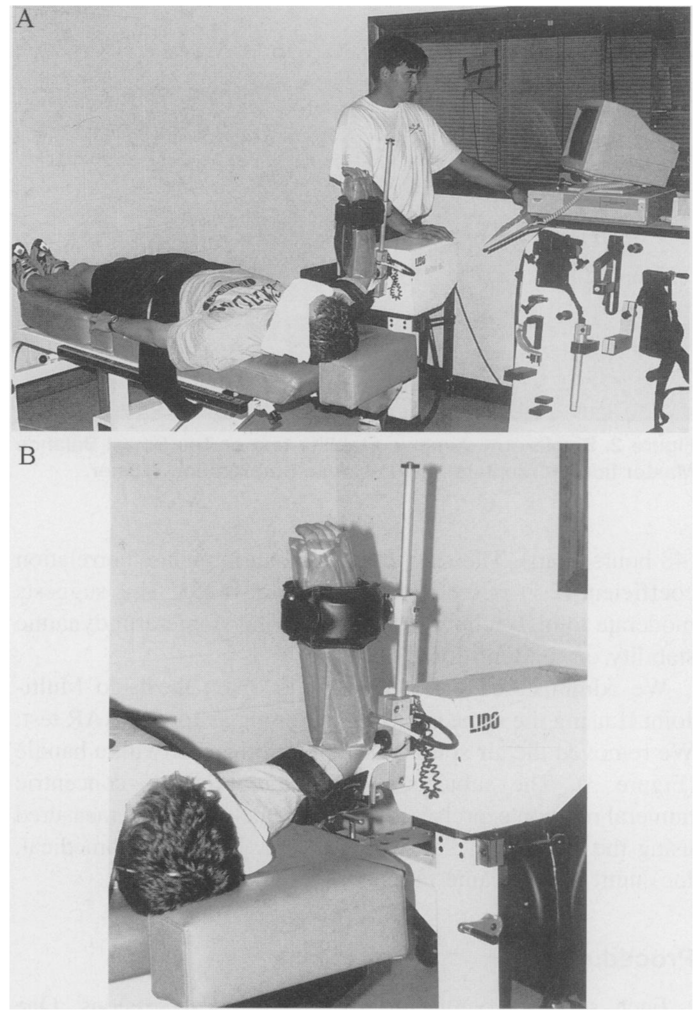

Figure 1. Active angle-reproduction test on the Lido Multi-Joint II. A, The supine subject is positioned in 90° of glenohumeral abduction and 90° of elbow flexion. B, A pneumatic air splint, blindfold, and headphones with music eliminate tactile, visual, and auditory cues.

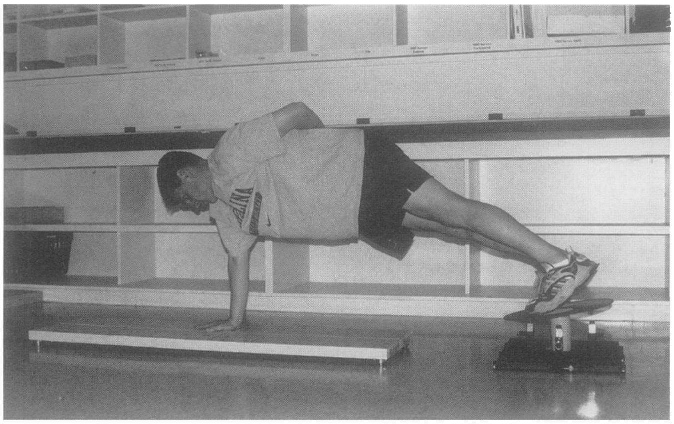

Figure 2. Single-arm dynamic stability test on the Smart Balance Master (long forceplate) and Dynamic Stabilization Trainer.

(48 hours apart). The results revealed an intraclass correlation coefficient (2,1) = 0.80 with an SEM of 0.253. This suggests moderate to high reliability for measuring single-arm dynamic stability on the long force plate.

We administered the fatigue protocol on the Lido Multi-Joint II using the same subject positioning as for the AAR test. We removed the air splint and replaced the cuff with a handle (Figure 3). The subjects performed continuous concentric humeral rotation exercises, and their peak torque was measured using the LIDOACT software package (Loredan Biomedical, Inc) until they became fatigued.

Procedures

Each subject volunteered to attend 2 test sessions. One session involved the proprioceptive testing procedure (AAR), and 1 session involved the neuromuscular control procedure (SADS). We counterbalanced the order of testing so that half the subjects performed AAR first, while half performed the SADS first. Before testing, all subjects performed a 2-minute warm-up activity using only the upper body to drive an ergometer. After the warm-up activity, we pretested the subjects using either the AAR or the SADS test.

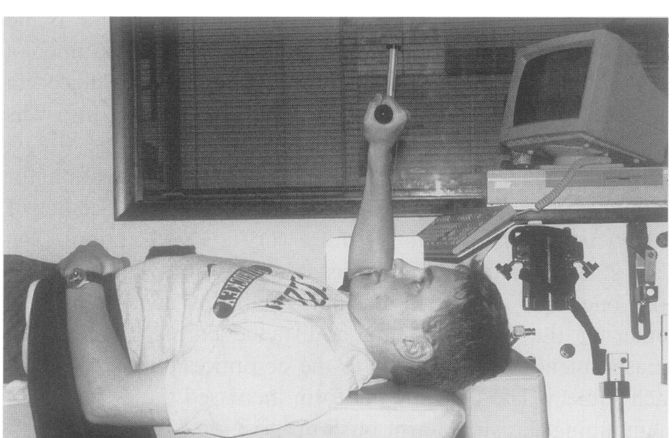

Figure 3. Fatigue set-up on the Lido Multi-Joint II.

The AAR Test

We administered the AAR test to the dominant arm of all subjects. Before testing, we calibrated the electrogoniometer to correspond to 0° of humeral rotation for the subject. After calibration, we manually rotated the humerus into either an internally or externally rotated position, placing it at 1 of 3 reference angles (30° of internal rotation, 30° of external rotation, or 75° of external rotation). Because the articular mechanoreceptors are best stimulated at end ranges of motion, whereas muscle spindles, due to their gamma motor-neuron innervation, allow for readjustment of muscle tension and joint position sense at all times during activity,[13,14] we chose the 3 reference angles to represent both directions of humeral rotation, as well as midrange and end range of motion. We used various speeds (1°/s to 5°/s) of placement in an attempt to prevent anticipation. Once the reference angle was obtained, we held the position for 10 seconds and then passively returned the limb to 0° of rotation at the same speed previously used. We then instructed the subject to actively reproduce the reference angle. We standardized the dynamometer speed at 300°/s to ensure unrestricted motion by the subject. The isokinetic electrogoniometer measured the range of motion for each trial, allowing us to calculate absolute angular error (the absolute difference between the reference angle and the angle reproduced by the subject). The subjects performed 3 trials at each reference angle using a randomized testing order.

The SADS Test

The SADS test began after the subject assumed a push-up position, with the dominant hand placed on the center of the force plate and the feet on the DST 360. Each trial began once the subject placed the nondominant limb on the small of the back and closed his or her eyes. We instructed the subjects to remain as stable as possible for the 10-second trial period. The subjects performed 3 trials, with a 30-second rest period between trials. Pilot testing revealed that the experimental group subjects were apt to fall during testing. We defined a fall as 1) any type of touch down by the subject to help stabilize, or 2) the subject's leaving the force plate completely. A fall resulting from a touch down meant added stabilization due to an increased base of support and thereby affected the sway velocity score. If the subject fell off the force plate completely, causing the force plate to no longer detect weight, the test was stopped automatically, and the Smart Balance Master calculated no sway velocity score. The investigator substituted a value of 3.55°/s for all trials involving a fall. A pilot study in which 12 subjects remained as unstable as possible without falling, as well as performing several falls on the force plate, revealed that a mean value of 3.55°/s represented a fall.

After the pretest, the experimental group subjects immediately performed the fatigue protocol, using continuous concentric internal and external rotation exercises of the shoulder as described by both Voight et al[5] and Carpenter et al.[6] We standardized the dynamometer speed at 180°/s. We set range-of-motion restrictions at 85° of external rotation and 75° of internal rotation to limit excessive ranges of motion. The subjects performed continuous repetitions until the fatigue criterion was reached: 3 consecutive repetitions achieving less than 50% of the subject's maximum peak torque for external rotation. Control subjects performed no fatigue protocol and remained inactive for 5 minutes between the pretest and posttest. Immediately after the fatigue or 5-minute interval, we posttested the subjects using the pretest procedure.

After a 1-week layoff, the subjects returned to perform the remaining testing protocol (either AAR or SADS). During the second session, the subjects remained as control or experimental subjects, with only the testing protocol being changed. At the end of the second session, we analyzed data on each subject for both tests.

Data Analysis

The data were analyzed using repeated-measures analyses of variance calculated by the Statistical Package for Social Sciences (version 7.5; SPSS, Inc, Chicago, IL). Data for the AAR test were analyzed using a 1-between, 2-within repeated-measures design, whereas data from the single-arm dynamic stability test were analyzed using a 1-within, 1-between, repeated-measures design. We performed post hoc analyses with a Tukey calculation. The number of falls was analyzed using a Wilcoxon signed rank test. An a priori α level of 0.05 was set.

RESULTS

Shoulder proprioception was measured using the AAR test and quantified with absolute angular error. The control group achieved a mean absolute angular error value of 5.42° ± 2.94° for the pretest while scoring 5.02° ± 2.59° for the posttest. The experimental group's pretest mean absolute angular error was 4.72° ± 2.43°, and the posttest mean was 5.58° ± 2.23°. Statistical analysis revealed a group-by-test interaction ($F_{1,30}$ = 5.38, P = .027). Post hoc analysis revealed a significant difference between the pretest and posttest values for the experimental group, but no such significant difference for the control group (Figure 4).

We measured neuromuscular control of the shoulder using the SADS test (Table). No significant difference existed between SADS results before and after fatigue ($F_{1,30}$ = 2.49, P = .125). The Wilcoxon signed rank test analysis revealed a significant increase in the number of falls after fatigue by the experimental group (P = .016), but no significant difference between pretest and posttest falls for the control group (P = .317).

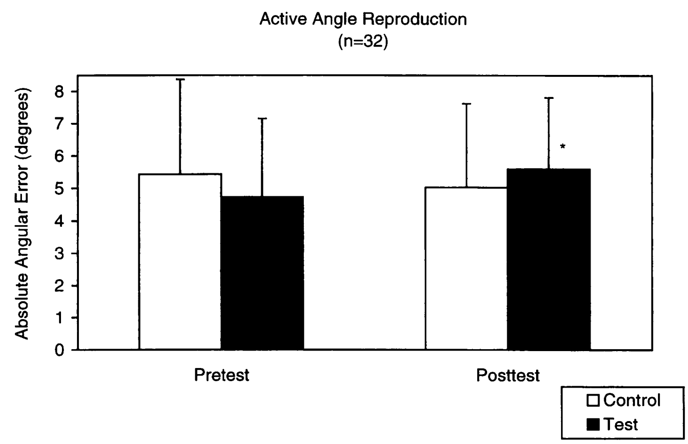

Figure 4. Pretest and posttest values (absolute angular error) for the AAR test. *Significant difference between pretest and posttest values.

Mean and SD Values for the Composite Sway Velocity and the Number of Falls for the Single-Arm Dynamic Stability Test

Group	Test	Falls	Mean Sway Velocity (°/s) (SD)
Control	Pretest	4	1.796 (0.651)
Control	Posttest	6	1.864 (0.685)
Experimental	Pretest	1	1.595 (0.496)
Experimental	Posttest	14*	2.095 (0.793)

*Significantly different from the number of falls exhibited by the experimental group during pretesting.

DISCUSSION

The purpose of our study was to determine whether fatigue had a significant effect on proprioceptive feedback and neuromuscular control of the shoulder. We hypothesized that fatigue would inhibit afferent proprioceptive feedback from the mechanoreceptors present in the muscle, thereby affecting neuromuscular control.

Shoulder Proprioception

Our results indicate that fatigue decreased proprioception of the shoulder as measured through joint position-sense assessment. Proprioceptive feedback regarding joint position results from mechanical stimulation of the mechanoreceptors present in the articular structures, muscles, and possibly skin.[2] Ruffini-type mechanoreceptors are predominant in all articular structures of the shoulder except the glenohumeral ligaments, where Pacinian corpuscle-type receptors are most abundant.[15] Muscle spindles and Golgi tendon organs are present in the muscle, with the muscle spindles more likely responsible for joint position sensation.[2] Nociceptors present in the skin at the joint may provide afferent feedback.[15] Since fatigue decreased the experimental group's ability to actively reproduce reference angles, we believe that muscle mechanoreceptors, specifically muscle spindles, are likely the primary receptors involved with joint position sense. As the subject moved into internal or external rotation, muscle spindles sensed changes in muscle length and relayed joint position sensation back to the CNS.[2,16–18]

The reason for this dysfunction is not completely understood. A possible reason for dysfunction may be changes in local metabolism at the muscle.[11] Pedersen et al[7] reported that increased intramuscular concentrations of lactic acid, KCl, bradykinin, arachidonic acid, and serotonin after fatiguing contractions may affect the muscle spindle system, and, thus, proprioceptive acuity. Djupsjöbacka et al,[19–21] in separate studies, reported that increased intramuscular concentrations of several contractile substances altered the muscle spindle output as measured through reflex arcs. Since local blood flow and metabolic changes are more pronounced at the muscle than in the articular structures, muscle mechanoreceptors may be more affected than articular mechanoreceptors.[11] This may cause one to rely primarily on proprioceptive information from the articular mechanoreceptors, thereby limiting joint repositioning ability. Both central and peripheral fatigue may also influence active angle reproduction. Central fatigue is due to influences of the CNS, whereas peripheral fatigue occurs at the level of the sarcomere and involves failure at the neuromuscular junction, sarcolemma, and transverse tubules.[22] The fatigue protocol may be taxing not only to the shoulder musculature but also to conscious joint position awareness. Unfortunately, the influences of central fatigue and peripheral fatigue are difficult to measure reliably.

Our findings support the "dysfunctional mechanoreceptor" theory proposed by Voight et al.[5] Muscle fatigue desensitized muscle spindle threshold, thereby decreasing afferent feedback to the central nervous system.[5] Carpenter et al[6] measured threshold to detection of passive motion after an isokinetic fatigue protocol. Threshold to detection of motion by the subjects increased after fatigue when compared with a control group. Carpenter et al[6] concluded that decreased proprioceptive sense after muscle fatigue might play a role in decreased athletic performance and shoulder dysfunction. We did not test threshold to detection of passive motion in our study because our isokinetic dynamometer's minimum velocity was 2°/s. Investigators often test threshold to detection of passive motion at a slower speed of 0.5°/s.[1,23,24]

Shoulder Neuromuscular Control

We quantified neuromuscular control by measuring the subject's ability to maintain the single-arm push-up position. The results of our study revealed no significant effect of fatigue on neuromuscular control of the shoulder joint and suggest that fatigue did not affect neuromuscular control when assessed by sway velocity. Although there was no significant effect on sway velocity, analysis of the number of falls revealed a significant increase in falls after fatigue in the experimental group, whereas no such difference existed in the control group.

It is difficult to definitively ascertain why the number of falls increased after fatigue compared with the control group. As shown in this study, fatigue decreased proprioception by affecting the mechanoreceptors present within the musculature of the shoulder. Neuromuscular control involves afferent proprioceptive feedback from peripheral mechanoreceptors. This afferent proprioceptive feedback is integrated at the CNS with input from both the visual and vestibular systems to produce spinal reflexes, cognitive programming, and balance, all of which affect muscle action through efferent responses.[25] Due to the compression of the humeral head in the glenoid fossa with the closed kinetic chain position, stimulation of the articular mechanoreceptors elicits a cocontraction response of the force-couple musculature.[26,27] Fatigue of the mechanoreceptors within the force-couple musculature affects cocontraction ability of the shoulder in the closed kinetic chain position, thereby affecting the subject's ability to maintain the single-arm push-up position. Again, we want to state that further research is needed to determine whether and how fatigue affected neuromuscular control in this study.

Clinical Significance

We believe the results from this study have clinical relevance. The subjects' ability to recognize joint position was hindered after a bout of isokinetic fatiguing exercise. The implications from decreased proprioception are threefold. 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.[25,28] 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. Second, if a person's ability to recognize joint position, and more importantly extremes in joint position, 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. Finally, Carpenter et al[6] concluded that decreased proprioceptive sense after muscle fatigue might play a role in decreased athletic performance. As a person fatigues, a decrease in athletic performance may place an individual in harm's way in terms of injury.

Clinicians should consider modifications to rehabilitation protocols after shoulder injury, as well as preventive programs for individuals who are unstable. Oftentimes, rehabilitation programs contain the traditional 3 sets of 10-repetition protocols for resistive training. Because the musculature responsible for providing dynamic stability of the shoulder has a continual stabilization function, clinicians should incorporate endurance training-type exercises for the dynamic stabilizers of the glenohumeral joint into rehabilitation programs.

CONCLUSIONS

Our results indicate decreased proprioceptive feedback after fatigue of the shoulder musculature, whereas the effect of fatigue on neuromuscular control was inconclusive. Even though these results shed light on the effect of fatigue on shoulder proprioception, additional research is needed to fully understand how fatigue, as well as diminished proprioception, affects the efferent neuromuscular responses by the musculature that provides joint stability. It is extremely important for a joint to sense forces placed on the articular and muscular structures and respond appropriately with efferent feedback to the muscles, providing much-needed dynamic joint stability to the inherently unstable shoulder joint.

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