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Voluntary activation deficits of the infraspinatus present as a consequence of pitching-induced fatigue

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Hypothesis: Neuromuscular inhibition of the infraspinatus would be greater and external rotation muscle force would be lower after a simulated game compared with pregame values.
Materials and methods: The sample included 21 uninjured, asymptomatic high school—aged baseball pitchers. Maximum volitional shoulder external rotation strength was assessed before and after a simulated game with a clinical dynamometer. Voluntary activation of the infraspinatus was assessed during strength testing by a modified burst superimposition technique. Performance-related fatigue was assessed by monitoring pitch velocity, and global fatigue was assessed by subject self-report before and after the game. Statistical testing included paired and independent t tests, with $\alpha \leq .05$.
Results: There was no difference between throwing and non-throwing shoulder external rotation strength ($P = .12$) or voluntary infraspinatus activation ($P = .27$) before the game. After the game, voluntary activation was significantly lower in the throwing limb compared with pregame activation levels ($P = .01$). Lower external rotation strength after the game approached statistical significance ($P = .06$). Pitch velocity was lower in the final inning compared with first-inning velocity ($P = .01$), and fatigue was significantly greater after the game ($P = .01$).
Conclusions: Voluntary infraspinatus muscle activation is a mechanism contributing to external rotation muscle weakness in the fatigued pitcher. Understanding mechanisms contributing to muscle weakness is necessary to develop effective injury prevention and rehabilitation programs. Treatment techniques that enhance neuromuscular activation may be a useful strategy for enhancing strength in this population.
Level of evidence: Basic Science Study, Kinesiology Study.

Keywords: Baseball; rotator cuff; muscle; neuromuscular

Shoulder injuries among preadolescent and high school—aged pitchers have become increasingly prevalent.[3] Epidemiologic studies have reported the incidence of shoulder pain to vary between 29% and 35% among 9- to 19-year-old boys and men.[8,9,19] Pitch volume over the course of a single game, season, and year has been identified as a significant risk factor for shoulder injury in this population.[8,9] One of the potential consequences of a high pitch volume is muscle fatigue, which has been proposed to increase injury vulnerability due to alterations in pitch mechanics and joint arthrokinematics.[11,12]

This study was approved by the Mayo Clinic Institutional Review Board (study number 10-001411).

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Fatigue may also impact muscle strength in the baseball athlete. Mullaney et al[11] tested isometric upper and lower extremity strength in 13 uninjured collegiate pitchers and 1 uninjured Minor League pitcher before and after pitching. Postgame shoulder strength tests showed significantly lower shoulder flexion (15%), internal rotation (18%), and adduction (11%) values compared with pregame measures.[11] The authors also reported an 11% decrease in throwing-arm external rotation strength after the pitching performance compared with baseline measures.[11] Although this change in external rotation strength was not statistically significant, it does represent a substantial degradation in posterior rotator cuff muscle performance over the course of a single outing. Furthermore, it is unclear what constitutes a clinically meaningful change in external rotation strength for the baseball athlete. The loss of external rotation strength associated with a single game outing may have a significant impact on the baseball athlete, because external rotation muscle weakness has been associated with throwing-related injuries that require surgery.[2] Thus it is imperative to develop effective injury prevention and rehabilitation programs that address external rotation strength in baseball athletes.

One mechanism that may contribute to rotator cuff muscle weakness is incomplete neuromuscular recruitment. A lack of central drive from the nervous system, known as failure of voluntary activation, has been documented in several muscles, including the quadriceps,[10] triceps brachii,[1] biceps brachii,[4] and ankle plantar flexors.[13] Recently, Stackhouse et al[16] assessed recruitment of the infraspinatus muscle in uninjured adults across several levels of external rotation effort and during fatigue. Voluntary activation was measured during a maximum volitional isometric contraction of the external rotators, with force recorded both during the voluntary effort and when an electrical stimulus was applied to the infraspinatus during the maximum volitional isometric contraction. Stackhouse et al reported that in the nonfatigued state, subjects showed a voluntary activation of 95%. With fatigue, however, there was a 46% drop in both external rotation force production and infraspinatus voluntary activation. They reported that the failure in activation for the infraspinatus in the fatigued state was greater than what had previously been reported for other upper and lower extremity muscles. They suggested that the infraspinatus may be more susceptible to failure of voluntary activation during fatigue than other muscles.[16]

Understanding the mechanisms underlying external rotation muscle weakness is critical for developing effective injury prevention and rehabilitation programs. The purpose of this study was to quantify the impact of fatigue on voluntary activation of the infraspinatus in uninjured high school–aged pitchers after a simulated game. We hypothesized that both voluntary activation of the infraspinatus and external rotation force in the dominant arm would be lower after pitching compared with pregame measures.

Materials and methods

Subjects

Twenty-five uninjured high school–aged pitchers were recruited for study participation. Subject consent and parental assent were obtained before the initiation of testing procedures. Inclusion criteria included age between 14 and 19 years; a minimum of 3 years' experience pitching in organized baseball; no injury to either upper extremity; and full, unrestricted participation in baseball activities. A QuickDASH Sports score of 10% or less was used as an objective measure of full sports participation. Exclusion criteria included current injury to either upper extremity, surgery to either upper extremity in the past year, prior surgery or injury to the dominant extremity that precluded a full return to baseball, current lower extremity or back injury, or vestibular dysfunction that limited pitching, as well as failure to meet all inclusion criteria.

Testing procedures

Maximum voluntary isometric external rotation strength and voluntary infraspinatus activation were assessed before and after a simulated pitching performance by a burst superimposition technique, as described by Stackhouse et al.[16] During testing, subjects were seated in a HUMAC NORM dynamometer (CSMi Medical Solutions, Stoughton, MA, USA), with hips and knees flexed to 90°. Stabilization belts were applied across the pelvis, torso, and shoulder to enhance stabilization during testing. The arm was positioned at 5° of shoulder internal rotation, 0° of forward flexion, 30° of shoulder abduction, and 90° of elbow flexion. The axis of rotation of the dynamometer was aligned with the long axis of the humerus through the ulnohumeral joint (Fig. 1). Subjects were instructed to perform 3 submaximum contractions and 2 maximum voluntary isometric contractions for 2 to 3 seconds in length as warm-up and become familiar with the testing procedure.

After approximately 5 minutes of rest, subjects were asked to perform a full-effort shoulder external rotation contraction for approximately 5 seconds. Subjects were given strong verbal encouragement and visual feedback during the testing to facilitate maximum volitional force production. When subjects had reached a force plateau during the contraction, an electrical stimulus was applied to the infraspinatus (3-pulse train, 600 μs pulses in length at 50 Hz) (Grass S48 stimulator; Grass Technologies, West Warwick, RI, USA). The stimulus was applied through 2 self-adhesive electrodes applied to the lower motor points of the infraspinatus along the medial border of the scapula and more laterally near the posterior deltoid border.[16] A second stimulus was delivered during the resting state after the force had returned to baseline.[16] If maximum volitional force output was achieved and no augmentation of force was observed with the application of the stimulus, testing was concluded for that limb. If augmentation was present during the application of the electrical stimulus, the test was repeated up to a maximum of 3 trials. Five minutes' rest was provided between tests. The trial with the highest volitional force production was chosen for analysis. Before the simulated pitching performance, the non-throwing shoulder was tested first and then the throwing shoulder. After pitching, only the throwing shoulder was retested. Electrode positioning on the throwing shoulder was outlined so that placement could be replicated after pitching.

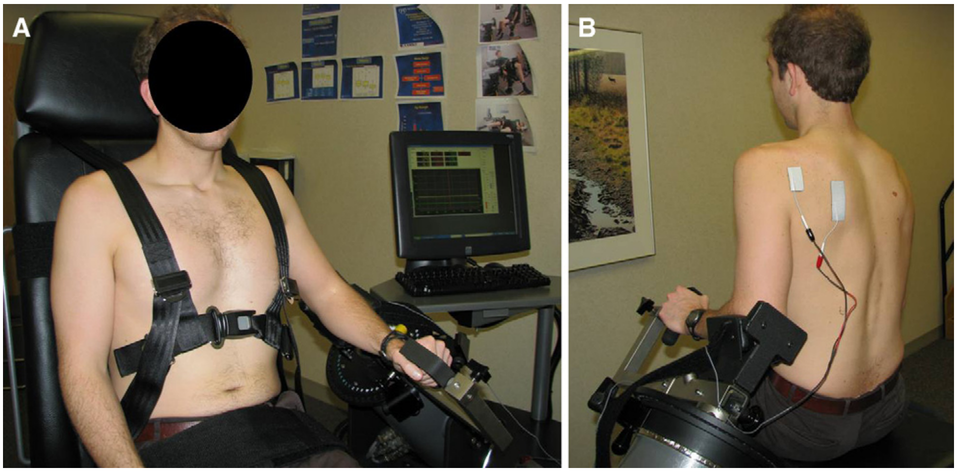

Figure 1 Anterior **(A)** and posterior **(B)** views of testing setup. The back support has been removed to facilitate viewing of electrode positioning for the posterior view.

The simulated game was conducted in an indoor biomechanics laboratory. Subjects threw from a mound to a target from a regulation distance of 60 ft 6 in. An examiner positioned behind the net recorded pitch velocity using a radar gun (Jugs Sports, Tualatin, OR, USA). Before initiating the game simulation, players were allotted 10 minutes for warm-up activities including stretching, jogging, and level-ground tossing. Subjects were also allotted 25 to 30 pitches off of the mound as part of their pregame warm-up. The simulated game consisted of 6 innings, with 10 to 15 pitches thrown per inning. This resulted in each subject throwing between 75 and 90 pitches, with the total number based on the subject's mean pitch count during the baseball season. In addition, 5 to 8 warm-up pitches were thrown before each inning. The type of pitch thrown (fastball, changeup, curve ball) was based on the percentage of each type of pitch typically thrown during a game outing for each subject. Subjects were asked to reproduce a normal game situation by individualizing rest between pitches, whereas between-inning rest time was standardized at 8 to 10 minutes. Subjects were asked to report fatigue level before and after the simulated game using a 10-point scale (0, no pain and/or fatigue; 10, unbearable pain and/or complete exhaustion).

Data management

Variables of interest included infraspinatus activation, maximum volitional external rotation strength, fatigue, and pitch velocity for fastballs thrown during the first and last innings. Activation of the infraspinatus was calculated as the difference in the augmented external rotation force production relative to the electrically elicited external rotation force production at rest by use of the following formula: Voluntary activation = 1−(Force augmentation from stimulus during isometric contraction/force of stimulus while at rest), where a value of 1.0 is considered full activation.[16]

All statistical testing was performed with commercially available software (SPSS, Chicago IL, USA).

Results

Data from 3 subjects could not be included because of equipment complications, and 1 subject was unable to complete the testing protocol because of intolerance to the electrical stimulation. This left a total of 21 subjects for the final sample. As a group, the subjects had a mean age of 16 years (range, 14-19 years) and had 7 years' pitching experience (range, 4-11 years). The mean weight was 79.3 kg (range, 55.8-120.2 kg), and the mean height was 1.8 m (range, 1.5-1.9 m). There were 19 right arm—dominant pitchers and 2 left arm—dominant pitchers. The mean time since the last game appearance as a pitcher was 5 weeks (range, 1-12 weeks). The mean pitch volume for the game simulation was 87 pitches (range, 75-90 pitches), with fastballs comprising 67% of the pitch mix (range, 40%-100%); curve balls, 25% (range, 0%-60%); and changeups, 8% (range, 0%-25%).

Self-reported fatigue was significantly higher after the simulated game (mean, 6; range, 3-7) compared with pregame values (mean, <1; range, 0-3) ($P < .01$). The change in pitch velocity was also statistically significant, because fastballs thrown in the final inning (mean, 63 mph; range, 40-75 mph) were slower than fastballs thrown in the first inning (mean, 65 mph; range, 40-78 mph) ($P = .01$).

There were no side-to-side differences in external rotation strength (Fig. 2) or voluntary activation before pitching (Fig. 3). Voluntary activation of the pitching arm was significantly lower after pitching compared with pregame activation levels ($P = .01$) (Fig. 3). External rotation strength of the pitching arm was also lower after the game simulation, with this change approaching statistical significance ($P = .06$) (Fig. 2).

Discussion

This is the first study to show voluntary activation failure of the infraspinatus as a consequence of fatigue induced by pitching. The drop in voluntary activation was both statistically and clinically significant. Studies reporting on the quadriceps have stated that 90% to 100% represents the

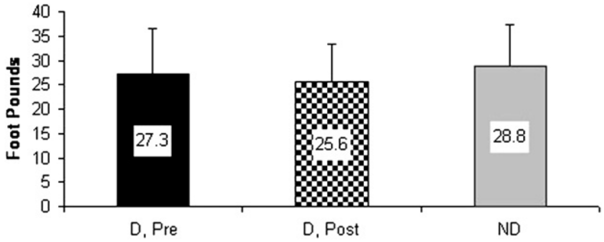

Figure 2 Peak volitional external rotation torque in dominant (D) and nondominant (ND) limbs. *Pre*, Before game; *Post*, after game.

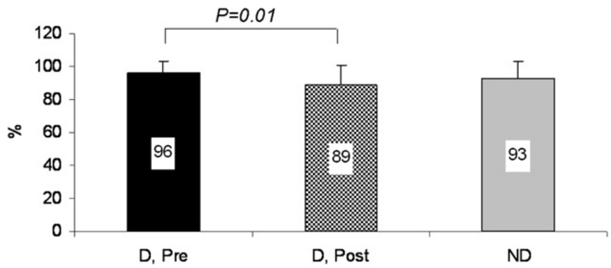

Figure 3 Voluntary activation of infraspinatus in dominant (D) and nondominant (ND) limbs. *Pre*, Before game; *Post*, after game.

range of normal voluntary activation values among the general population.[17,18] Conversely, values below 90% are considered clinically meaningful deficits. In this study the nonfatigued voluntary activation of the infraspinatus was 96%, and voluntary activation dropped to 89% in the fatigued state. This was accompanied by a 3% drop in external rotation force. In light of the relationship between external rotation strength, shoulder function, and injury risk in the overhead athlete,[2,20,21] identifying mechanisms contributing to impaired rotator cuff muscle performance may provide a meaningful opportunity to prevent injury in this at-risk population.

During pitching, the greatest infraspinatus muscle activity occurs during late cocking as the humerus is positioned in maximum external rotation.[7] Pitchers with chronic anterior glenohumeral instability exhibit less infraspinatus activity at this point of the pitching cycle when compared with uninjured pitchers.[5] Glousman et al[5] suggested that this reduction in muscle activity may be a protective mechanism to reduce the amount of external rotation of the shoulder and relative contribution of the infraspinatus to joint instability. We believe that a decrease in infraspinatus muscle activation due to fatigue also has the potential to contribute to less external rotation during late cocking and impair arm deceleration during follow-through. The potential impact of diminished infraspinatus muscle activation on external rotation is consistent with the findings described by Murray et al,[12] who assessed the effects of extended play on the pitching kinematics and kinetics in 7 Major League pitchers. They reported that over the course of a single game, pitchers showed changes in biomechanics that included decreases in maximum shoulder external rotation, knee angle at ball release, ball velocity, maximum distraction force at both the shoulder and elbow, and peak horizontal adduction torque. They stated that it was unclear whether the changes in pitching biomechanics were a consequence of fatigue or whether the decreases in ranges of motion and speeds of movement were protective mechanisms adopted to decrease joint loads and reduce injury potential.

It should not be assumed, however, that the changes in pitching mechanics described by Murray et al[12] equate to a lower injury risk for the fatigued pitcher. The arm functions as a kinetic chain, and it is possible that lower forces at the shoulder due to less external rotation are occurring at the expense of greater forces acting more distally. Furthermore, current technology limits the ability to accurately assess humeral head translations during pitching. Thus, glenohumeral arthrokinematics in the fatigued state that may contribute to pathologies such as anterior glenohumeral instability and posterior impingement cannot be quantified. Finally, changes in muscle activity during pitching are unknown, because previous studies evaluating the impact of fatigue on biomechanics did not include electromyographic data. Establishing the functional impact of lower voluntary activation of the infraspinatus is dependent on biomechanical studies that capture muscle activity during pitching, as well as determining whether alterations in muscle activity due to fatigue are contributing factors to subsequent injury.

The decline in muscle performance reported in this investigation occurred in a sample of uninjured, asymptomatic subjects after a single game. It is therefore possible that over the course of a season, the effects of fatigue may be cumulative and result in more pronounced changes in strength and voluntary activation. Wilkin and Haddock,[22] however, reported no change in rotator cuff strength over the course of a season when assessing isokinetic internal and external shoulder rotation strength in a sample of 9 uninjured collegiate pitchers. Their study was limited, however, by a small sample size. Furthermore, pitch volume and fatigue levels were not reported by Wilkin and Haddock to correlate the cumulative impact of pitching on strength. Studies that incorporate larger sample sizes and more comprehensive metrics of fatigue and throwing volume will be necessary to establish the impact of playing an entire season on rotator cuff muscle performance.

Identifying the etiology underlying muscle weakness is critical for the development of effective exercise interventions. Volitional, progressive resistance exercise may be used to enhance strength by increasing muscle cross-sectional area. This form of exercise has limited effectiveness, however, when muscle weakness is due to neuromuscular activation failure.[14] In these instances, interventions that enhance neural recruitment of muscle fibers are necessary to completely resolve strength deficits.[6] Neuromuscular electrical stimulation (NMES), biofeedback, and proprioceptive neuromuscular facilitation techniques are examples of treatment techniques that may be used to address voluntary activation deficits. In patients with knee injury, NMES has been established as an effective intervention for addressing quadriceps strength deficits due to voluntary activation failure. Few publications have described the impact of electrical stimulation on rotator cuff strength. Reinold et al[15] measured isometric shoulder external rotation force production in 39 patients after rotator cuff repair surgery. Both voluntary and electrically augmented force production was measured. Reinold et al reported that peak force production was 22% greater when the contraction was augmented with NMES compared with the volitional contraction. They subsequently advocated using NMES concomitantly with exercise to enhance force production and potentially minimize rotator cuff inhibition after repair surgery.[15] Additional work is necessary to determine the impact of rehabilitation and injury prevention exercise programs that use NMES to enhance rotator cuff strength in the overhead athlete.

There are limitations to this study. Voluntary activation was only assessed for the infraspinatus. Although the teres minor also contributes to shoulder external rotation force production, the teres minor is considered a secondary contributor to external rotation force. In addition, stimulating both muscles would have resulted in excessive activation of the trapezius and posterior deltoid. By stimulating only the infraspinatus, we were able to minimize accessory contraction of the surrounding musculature while producing an enhanced external rotation contraction. Another potential limitation was arm positioning during strength and activation testing. A more functional position for assessing rotator cuff strength and activation in this population would include placing the subject in the thrower's position, with 90° of abduction. We believed that this was a position of vulnerability, however, because there was tremendous potential to provoke an anterior subluxation of the glenohumeral joint with the application of the electrical stimulus. By positioning the arm by the side during testing, we were able to enhance glenohumeral stability during the testing process. Although differences in arm position may impact force production because of alterations in muscle length, it is unclear whether this may impact voluntary activation. Finally, the drop in force production (3%) that we observed was not equal to the drop in voluntary activation (6%). It is possible that there was compensatory muscle activity of the teres minor and surrounding musculature in response to lower infraspinatus recruitment, thus minimizing external rotation force deficits. Electromyographic assessment will be necessary to gain insight regarding external rotation force production in the fatigued and nonfatigued states.

Conclusions

Voluntary activation failure of the infraspinatus was present after pitchers had fatigue from pitching a simulated game. This was accompanied by lower shoulder external rotation force and slower pitch velocity. Addressing mechanisms underlying external rotation muscle weakness will enhance the effectiveness of injury prevention and rehabilitation exercise programs for the baseball pitcher.

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