Timing of Rotator Cuff Activation During Shoulder External Rotation in Throwers With and Without Symptoms of Pain

Sally Anne Hess, BPhty
Carolyn Richardson, BPhty (Hons), PhD
Ross Darnell, BAppSc, PGDipBiom, MSc, PhD
Peter Friis, MBBS, FACSP
David Lisle, MBBS, FRANZCR
Peter Myers, MBBS, FRACS, FAOrthA

Study Design: Fine-wire EMG rotator cuff onset time analysis in 2 matched groups of throwers with and without pain.

Objective: To identify if there is a difference in the activation patterns of the rotator cuff muscles during a rapid shoulder external rotation task between throwers with and without pain.

Background: The coordinated action of the rotator cuff is recognized as essential for glenohumeral joint control in the throwing athlete. Identification of abnormalities occurring in muscle activation patterns for injured athletes is relevant when prescribing rehabilitative exercises.

Methods and Measures: Twelve throwers with shoulder pain were compared to a matched group of 11 asymptomatic throwers. Participants were matched for age, height, body mass, and habitual activity. Fine-wire EMG electrodes were inserted into the subscapularis, supraspinatus, and infraspinatus. EMG activity was measured during a reaction time task of rapid shoulder external rotation in a seated position. The timing of onset of EMG activity was analyzed in relation to visualization of a light (reaction time) and to the onset of infraspinatus activity (relative latency).

Results: In the group with shoulder pain, the onset of subscapularis activity was found to be significantly delayed (reaction time, \( P = .0018 \); relative latency, \( P = .0005 \)) from the onset of infraspinatus activity when compared to the control group.

Conclusions: The presence of shoulder pain in these athletes was associated with a difference in the onset of subscapularis EMG activity during a rapid shoulder external rotation movement. This was an initial step in the understanding of the joint protection mechanisms of the glenohumeral joint and the problems that occur in throwers. This information may assist in providing future guidelines for more effective rehabilitation and prevention strategies for this condition. J Orthop Sports Phys Ther 2005;35:812-820.

Key Words: baseball, electromyography, throwing

Any overhead athletes suffer from disorders of the shoulder. The act of throwing has been seen as one of the major precipitators of shoulder injury as it pushes the arm to its physiological limits. With the large forces placed on the joint and the excessive motions required during throwing, the soft tissues surrounding the joint may be compromised. The mechanisms and adaptations of the musculoskeletal system and resultant shoulder pathology and pain are important aspects of treatment and prevention.

Although the precise mechanisms of injury in throwers are unclear, it is generally agreed that if the glenohumeral joint is not adequately stabilized by the rotator cuff, the actions of the prime movers of the arm can cause abnormal displacement of the humeral head. Using a cadaveric model, Sharkey and Marder demonstrated that if abduction occurs without the imposed forces of the teres minor, infraspinatus, and subscapularis, significant superior translation of the humeral head may occur. It would seem that an effective, coor-
Organized rotator cuff action is required to prevent impingement and likely shoulder pathology in throwing athletes.

Biomechanically, the act of throwing may be divided into 5 phases: the wind-up, cocking, acceleration, deceleration, and follow-through. The wind-up phase of throwing is the preparation phase, with the thrower initiating movement of the body onto the back leg and the arm commencing movement towards the cocking position. This phase sets the body and arm positions for the following phases of the throwing motion. During cocking, the arm moves towards full external rotation at about 90° abduction. The acceleration phase begins when the arm starts moving into internal rotation and concludes with the release of the ball. The deceleration phase commences with the release of the ball as the body begins to decelerate and absorb the unspent forces, with the follow-through continuing until the throwing action is complete. While the act of throwing involves the coordinated movement of the entire body, one of the most dynamic movements is that of shoulder external and internal rotation.11 During the wind-up to the cocking phases, the arm moves rapidly into external rotation prior to moving into internal rotation in the acceleration phase.

The rotator cuff muscles are active to a varying extent throughout the entire throwing motion.15,28,31,37 Previous studies have shown some rotator cuff muscle activity during the wind-up phase,5,15,16,19,28 with the activity levels of the rotator cuff peaking during the cocking phase, as the infraspinatus and teres minor provide external rotation and the subscapularis and supraspinatus assist in providing stability to the glenohumeral joint. It is thought that lack of coordination and control by the rotator cuff during this phase may result in excessive movement of the humeral head and added stress on the anterior stabilizing structures of the shoulder.12

Several models have been used previously to investigate the function of the rotator cuff in throwing athletes. Isokinetic equipment has been used to measure the peak torques generated during internal and external rotation of the shoulder.1,7,21,47 While these data provide important information about the strength characteristics of the shoulder rotators, they do not give any indication of how precisely the rotator cuff supports the glenohumeral joint during the fast, ballistic action of throwing.

EMG studies of the activation of the rotator cuff muscles have added markedly to the knowledge of muscle activity and their firing patterns during all phases of throwing.10,15,16,17,27,37 Studies using EMG data expressed as a percentage of maximal voluntary contraction have shown that subscapularis, supraspinatus, and infraspinatus are all active to varying degrees through the entire pitching motion.15,28,37 The wind-up phase of the throw has been deemed to be the most variable among individual athletes.19,37 While EMG studies have demonstrated rotator cuff muscle activity during this phase, the pattern and intensity of muscle activation is inconsistent.5,10,15,27 It may be possible that the preactivation of the rotator cuff muscles during the preparation of the throw is the important component in protecting the glenohumeral joint in the following phases. It is during the cocking phase that the glenohumeral joint is vulnerable to injury at the extremes of abduction and external rotation.5,3,16 The preactivation of the rotator cuff during the initiation of the wind-up phase may provide essential stability to the glenohumeral joint as the body moves from the wind-up to cocking phase.

To study the activation patterns of the rotator cuff muscles and determine their likely role in glenohumeral joint stability, a different type of EMG study was undertaken. Studying the timing of activation of the muscles during a concentric shoulder external rotation task could give some insight into the stabilization role of the muscles and whether they are recruited early (before the movement) to ensure joint protection through this stage of throwing.

The precise EMG assessment of the role of the individual rotator cuff muscles through timing of their actions presents methodological difficulties due to the complexity of the movement of throwing and the number of joints involved. To detect possible differences in rotator cuff activation patterns it was determined that this study would focus on muscle function of the shoulder joint in the predominant direction of movement (ie, external rotation). This plane was chosen due to the close link between the function of throwing and the movement of the glenohumeral joint into rotation during the wind-up and cocking phases. While it is important to gain an understanding of muscle activation at the point where injury occurs, by investigating the preactivation of the rotator cuff muscles, additional insight may be gained into the joint protection (motor control) mechanisms involved in the complex act of throwing and if differences can be detected in throwers who have pain.

For this study, the measurement of timing of activation of individual rotator cuff muscles, based on a reaction time task, was deemed appropriate. Reaction time is defined as “the interval between presentation of an unexpected stimulus and the initiation of a response.”44 Specifically, a premotor reaction time task (RTT), which represents the interval from the stimulus to “the first change in EMG,”44 was chosen, as it is considered to represent the central processes involved in making a response. Analysis of the reaction time can determine feedforward stabilization, which has previously been described as the early onset of muscles prior to movement and is a
preprogrammed response of the central nervous system.22,32,39

For this study, a RTT was chosen that would mimic the initiation of the rapid shoulder external rotation movement involved when initiating the throwing action, while controlling some of the variables of throwing, such as body and arm position. The purpose of this study was to compare the activation patterns of the rotator cuff musculature between throwers with and without pain using a defined model of a RTT.

METHODOLOGY

Subjects

Twelve symptomatic male throwers with shoulder pain (mean age, 29.5 years; age range, 22-41 years; mean height, 180 cm; height range, 170-195 cm; mean body mass, 83.8 kg; body mass range, 75-95 kg) and 11 matched male throwers without shoulder pain (mean age, 32.5 years; age range, 24-41 years; mean height, 178.5 cm; height range, 170-186 cm; mean body mass, 79.9 kg; body mass range, 62-110 kg) volunteered for this study. All subjects were competitive baseball players who played at least once a week and trained at least twice a week. Each subject was matched for age, height, and body mass, and for levels of activity in work, sport, and leisure settings, as determined by the Habitual Activity Questionnaire.4 Pitchers were not included in the study sample of players so that the sample would be more homogeneous.

The subjects with shoulder pain reported having symptoms of pain during throwing activities at training and in game situations, although they were able to continue to play. Subjects were excluded if they reported any signs or symptoms of cervical, thoracic, or upper limb pain other than specific shoulder pain. This was done to isolate the pathology to the structures of the glenohumeral joint and to eliminate other pathology that may affect the shoulder. A Modified Rowe Score43 was completed to estimate the participants’ functional disability. The maximum possible score available was excellent.90-100 The control group of subjects all reported scores in the excellent category, while the group with shoulder pain reported scores in the fair-to-good category.45-75

Physical examination by an experienced sports physiotherapist and sports physician was conducted and included tests for range of movement and signs of shoulder instability using the anterior and posterior drawer tests,14 apprehension and relocation tests,27 and the Hawkins-Kennedy impingement test.20 These standard clinical tests were included to assist in the interpretation of results rather than for data analysis.

In addition, pain levels were measured on a visual analogue scale (VAS) before, during, and after testing (a 0-to-10 scale, with 0 defined as no pain at all and 10 defined as the worst pain the subject could imagine). These were completed to ensure that subjects in both groups did not experience pain during testing. Subjects were to be excluded if they reported pain levels of greater than 1 at any stage. No subjects were excluded by the VAS responses.

Subjects were excluded from the study if they reported cervical, thoracic, or upper limb injury or problems requiring surgery, any previous fractures of the cervical or thoracic spine or the shoulder and upper limb, any previous shoulder dislocation, or any neurological or respiratory conditions.

The subjects who did not have shoulder pain were also excluded if they had cervical, thoracic, shoulder, or upper limb pain during the past year. They were also excluded if they had previously suffered any cervical, thoracic, or upper limb injury that had required any medical intervention.

The throwers with shoulder pain were excluded if they had previous treatment for shoulder pathology in the past year or if they had maintained an exercise regime for that pathology over the past year.

Prior to participation in this study, subjects read and signed a consent form explaining the study and risks associated with the use of fine-wire electrodes. The Medical Research Ethics Committee of the University of Queensland, Australia, approved this study.

Procedure and Measurement Techniques

Upon arrival to the laboratory, physical assessment was performed on each subject and VAS for pretesting pain levels was completed.

Fine-wire bipolar electrodes fabricated from Teflon-coated stainless steel wire (75 µm, 1 mm insulation removed; A-M Systems Inc, Everett, WA) inserted into a beveled-edged hypodermic needle (0.7 × 32 mm) and bent back at the ends, leaving the receptive ends staggered were used. Under ultrasound guidance, the fine-wire electrodes were inserted into the dominant arm subscapularis (lower section), supraspinatus, and infraspinatus, at the standard sites, as described by Morris et al.35 Nemeth et al.40 and Perotto.41 Insertion of the electrodes was performed by suitably qualified medical personnel.

A RTT of rapid shoulder external rotation was performed. The subject was positioned in sitting with the arm supported at 90° abduction, the elbow at 90° of flexion, and the palm of the hand flat on the plinth (Figure 1). The tester informed the subject of the movement required and passively performed the movement of shoulder external rotation to demonstrate that the forearm was to remain in the same plane of motion, for measurement purposes. The importance of the speed of movement upon visualization of the light was emphasized.
FIGURE 1. Starting position for the reaction time task of rapid shoulder external rotation in sitting.

The subject performed 3 test trials into shoulder external rotation prior to the collection of data. The subject then performed 10 repetitions of rapid shoulder external rotation in the sitting position. As usual practice for a RTT, the timing of the onset of the light switch was randomly varied among the repetitions. A uniaxial accelerometer (model 480C02; PCB Piezotronics, Inc, Depew, NY), which measured movement in the sagittal plane, was attached to the forearm to monitor the onset of arm movement during the RTT.

The EMG and the accelerometer data were collected on an AMLAB (AMLAB International Pty Ltd, Sydney, Australia), a multichannel data acquisition system utilizing Windows-based software and hardware installed on a personal computer. Data were sampled at 2000 Hz, with a 12-bit analog-to-digital conversion, and were digitally filtered (20-1000 Hz, sixth-order Butterworth filter, common-mode rejection ratio of 110 dB, and differential input impedance of 10 MΩ). A remote switch activated the AMLAB and the light. The AMLAB commenced recording for a period of 400 milliseconds prior to visualization of the light.

Measure of Reaction Time and Relative Latency

The timing of onset of EMG activity was analyzed in relation to visualization of the light (Figure 2). This determined the reaction time for each of the 3 muscles investigated. The relative latency of the onset of the EMG signal in relation to an agonist muscle was also analyzed (Figure 2). Hodges and Richardson investigated the feedforward mechanisms of the lumbar spine musculature by using the analysis of relative latency of EMG activity. For this study, the relative latency was analyzed in relation to timing of onset of the infraspinatus as the agonist for the external rotation movement.

Data Processing

All data were filtered by the software program and stored in a computer for future analysis. The timing of the onset of the EMG activity of each of the muscles was evaluated using an algorithm modified from that described by Di Fabio and confirmed visually. The EMG and accelerometer data were analyzed using a LabVIEW program to detect the onset point (Figure 3). The algorithm identified the onset as the point of the EMG and the accelerometer where the mean amplitude of 50 consecutive samples (25 milliseconds) exceeded the mean baseline activity by 2 standard deviations. The mean and standard deviations of the baseline activity were calculated from 50 milliseconds before the light stimulus.

Statistical Analysis

The statistical model to explain the differences among the timing of onset and relative latency times (including onset times relative to the accelerometer) has factors of group (pain/control), muscle (subscapularis, supraspinatus, infraspinatus) and the interactions of these factors. The random effects are subject and subject by muscle. The onset times were averaged across trials. The linear mixed-effects model was fitted using the linear mixed-effects (lme) function in R/SPM and the resulting 24-factor repeated-measures ANOVA table was examined for statistical significance. The ANOVA tables were first examined for significant interactions. In the presence of interactions, both group comparisons were made for individual muscles as well as comparing muscle onsets within groups using independent t tests. Because the number of possible tests is large, the uncorrected P values reported will be lower than the correct type I error rate. The strength of conclusions based on these P values were considerate of this. Comparisons of means for which P values exceeded .05 have not been reported. Assumptions regarding homogeneity of variance and normality were checked using residual diagnostic plots.

RESULTS

The descriptive statistics for the reaction times and relative latencies from the onset of infraspinatus EMG activity are presented in the Table.

There was a significant group-by-muscle interaction (reaction time, F2,43 = 7.31, P = .0018; relative latency, F2,20 = 11.48, P = .0005), with the onset of subscapularis EMG activity in the group with shoulder pain being 28.3 milliseconds later than the control group (Table). A significant difference in reaction time (t42 = -2.384, P = .0216) and relative latency (t20 = 4.7801, P = .0001) was observed between groups for the subscapularis, with the subscapularis being the earliest muscle activated in the control group when
compared to the onset of infraspinatus and supraspinatus EMG activity (Table; Figures 4 and 5). The subscapularis was also activated significantly earlier than the initiation of arm movement, as indicated by the onset of the accelerometer in the control group ($t_{203} = -3.5119, P = .0005$).

In 8 of 11 control subjects, the subscapularis was the first muscle activated in 80% to 90% of their 10 trials. The other 3 subjects demonstrated this pattern in 60% to 70% of the trials. In 8 of the 12 subjects with shoulder pain, the subscapularis was the last muscle activated in 90% of the trials. In the other 4 subjects, the subscapularis was activated last in 70% to 80% of the trials.

The physical assessment of the subjects with shoulder pain demonstrated positive anterior translational and relocation tests on all of the subjects in this group. This indicated an element of instability at the glenohumeral joint was present. Two of the subjects in the control group demonstrated increased anterior translation with the anterior drawer tests when dominant and nondominant arms were compared without any corresponding pain, while none of the subjects in that group demonstrated a positive relocation test.

**DISCUSSION**

This study investigated another facet of muscle activation for joint protection in the throwing athlete. Using a RTT, incorporating rapid shoulder external rotation in sitting, significant differences in the mean response times of the subscapularis between the control group and the group with shoulder pain were demonstrated.

Other EMG studies on throwers have used different methods of determining the patterns of rotator cuff activation. These studies have demonstrated variability and inconsistency in muscle activation during the wind-up phase of throwing, which has been suggested to be due to low firing intensities. The present study used a different experimental method that focused on the timing of preprogrammed muscle responses to a RTT. This method has been used previously for other joints, when individual muscle contributions to the joint protection mechanisms were the focus of the investigation. The addition of an accelerometer in the RTT allowed the onset of movement to be quantified, thus giving additional information on the early recruitment of the rotator cuff muscles prior to movement into external rotation. Comparisons of timing were completed with filtered rather than raw data, but this was consistent across groups and muscles.

In the control group, the subscapularis was the first muscle activated, occurring 50 milliseconds prior to the onset of movement into external rotation. This finding of a feedforward activation of the subscapularis is similar to previous studies on support and protection of the pelvic region, which demonstrated feedforward activation of the transversus abdominis and multifidus. Early muscle activation in these studies was argued to be related to a
FIGURE 3. (a) EMG data of a representative subject without shoulder pain. The heavy line notes the onset of subscapularis EMG activity. The dashed line notes the onset of infraspinatus EMG activity. (b) EMG data of a representative subject with shoulder pain. The heavy line notes the onset of subscapularis EMG activity. The dashed line notes the onset of infraspinatus EMG activity.

TABLE. Descriptive statistics (means ± SD) of reaction times and relative latencies from infraspinatus EMG activity (in milliseconds) of the shoulder muscles during shoulder external rotation in sitting. Data are presented for individuals with and without shoulder pain.

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<tr>
<th></th>
<th>Control Pain</th>
<th>Relative Latency</th>
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<tbody>
<tr>
<td>Subscapularis</td>
<td>236.7 ± 55.2</td>
<td>265.0 ± 73.0</td>
</tr>
<tr>
<td>Infraspinatus</td>
<td>262.7 ± 66.7</td>
<td>233.6 ± 78.4</td>
</tr>
<tr>
<td>Supraspinatus</td>
<td>262.8 ± 66.8</td>
<td>253.1 ± 73.9</td>
</tr>
</tbody>
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* Time between visual stimulus and onset of EMG activity.
† Time between onset of EMG activity of infraspinatus and the onset of EMG activity of the corresponding muscle.
‡ Onset of shoulder external rotation movement as determined by the accelerometer.

mechanism of joint protection. The early activation of the subscapularis may indicate a similar mechanism at the shoulder joint. Current anatomical and biomechanical research shows that subscapularis activity is essential for joint stability. Its early activation may contrib-
ute to glenohumeral joint stability by increasing the tension in the middle and inferior glenohumeral ligaments. This may improve the passive barrier to any anterior translation of the humeral head. In addition, the large amount of collagen in the subscapularis may enhance its role as a passive stabilizer by providing a barrier against anterior translation of the head of humerus. This contraction may also prevent anterior and superior translation of the humeral head by assisting with the centering motion described by Lippett and Matsen and Myers et al.

In contrast, there was a difference in pattern of activation in the group with shoulder pain. Early activation of the subscapularis did not occur and both infraspinatus and supraspinatus were activated prior to the subscapularis. This may be consistent with the hypothesis that there is dysfunction in the activation patterns of muscles that are linked to joint protection and support of the glenohumeral joint. The loss of feedforward activation of the subscapularis may contribute to a lack of support of the humeral head during the wind-up phase as it leads into the cocking phase.

The present results are in agreement with those reported by Glousman et al, who investigated activation patterns in throwers with shoulder instability and found differences in the pattern of activation when compared to the control group. They found that the magnitude of subscapularis muscle activity was decreased during the late cocking, acceleration, and follow-through phases of the throw. It was considered that this may allow unchecked shoulder external rotation during this phase. Other studies have also investigated the rotator cuff in pathological situations. Broström et al investigated the EMG activity during shoulder external rotation in subjects with generalized joint laxity. These authors found the subscapularis to have lower activation levels and slower activation in individuals with a history of glenohumeral dislocation. Gamulin et al performed a histomorphometric study of the subscapularis muscle in patients with recurrent dislocations and found that it had variable changes in the ratio of fiber types, as is usually seen with disuse atrophy. They also found interstitial fibrosis indicative of a scarring process. These results may be consistent with the hypothesis that the subscapularis is an important muscle in shoulder support and is dysfunctional in individuals with shoulder pathology.

In the present study, clinical tests of the subjects with shoulder pain demonstrated shoulder instability. This adds further support to the hypothesis that the differences found in activation of the subscapularis are closely related to the loss of joint support mechanisms.

While this study has provided some additional information on the activation of the rotator cuff, there were several limitations. Due to the invasive methodology used and the strict inclusion and exclusion criteria involved in matching the groups, only a small sample size was recruited. Additional comparisons between groups and muscles might have reached statistical significance if a larger sample size had been tested with greater statistical power.

In addition, throwing is a complex task, with external rotation at the glenohumeral joint being only 1 aspect of a movement that involves the entire body. Assessment of shoulder muscle control and its effect on the glenohumeral joint has been studied in

**FIGURE 4.** Graphical representation of the mean ± SD of the reaction time (in milliseconds) of the glenohumeral muscles during shoulder external rotation in sitting (*P = .0005 for subscapularis compared to infraspinatus in the pain group; *P = .0216 for subscapularis compared to infraspinatus in the control group).

**FIGURE 5.** Graphical representation of mean ± SD of the relative latency from infraspinatus onset of EMG activity (0 ms) to the onset of subscapularis and supraspinatus EMG activity during shoulder external rotation in sitting (*P = .0001 for the control group compared to the pain group for subscapularis).
an artificial environment using a single plane of movement. One aspect of the complex muscle function and dysfunction at the shoulder has been highlighted in the findings of this study. However, further studies are required to increase our understanding of how these muscles function in more complex tasks, such as throwing and also to quantify the dysfunction in pathological and pain conditions of the shoulder.

Furthermore, by utilizing fine-wire EMG, only 1 section of each muscle was accessed. Different sections of the subscapularis have been shown to have varying function.5 Further study of the different sections of the subscapularis would give additional insight into the role the various sections of the muscle have for glenohumeral joint support.

This study does not provide information about whether this pattern of activation in the group with shoulder pain occurs as a result of injury or is a causative factor in the development of injury. Alternatively, it may also be possible that the change in the timing of activation could be a compensatory response to lessen pain.

CONCLUSIONS

The finding of early activation of subscapularis prior to the onset of other rotator cuff muscles, enhanced current knowledge of this muscle’s primary role in the support and protection of the glenohumeral joint. The results of this study suggest that activation of subscapularis prior to the onset of the other rotator cuff muscles may be preprogrammed for joint support.

The difference in activation of subscapularis in the group with shoulder pain is interesting, as it may reflect that throwers with pain may lose part of the glenohumeral joint support mechanisms. This was an initial step in the understanding of the joint protection mechanisms of the glenohumeral joint and the problems that occur in throwers. Understanding these mechanisms of joint support may lead to more effective prevention and rehabilitation strategies for overhead athletes with shoulder pathology.

ACKNOWLEDGEMENTS

The authors would like to thank the Physiotherapy Research Foundation (Australia), the Dorothy Hopkins Award, and the APA Manual Therapy Special Interest Group (Queensland Branch) for the financial assistance given to this project.

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