Effects of Muscle Fatigue on 3-Dimensional Scapular Kinematics

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ABSTRACT. Tsai N-T, McClure PW, Karduna AR. Effects of muscle fatigue on 3-dimensional scapular kinematics. Arch Phys Med Rehabil 2003;84:1000-5.

Objective: To determine the effects of fatigue during an external rotation task on 3-dimensional scapular kinematics.

Design: A single-group, pretest-posttest measurement design.

Setting: Research laboratory.

Participants: Thirty healthy subjects.

Interventions: Not applicable.

Main Outcome Measures: Three-dimensional scapular kinematics were recorded with a Polhemus magnetic tracking device during arm elevation in the scapular plane.

Results: There was a significant fatigue effect for all scapular rotations in the early to middle phases of humeral elevation. Significantly less posterior tilting (up to 90° of elevation), external rotation (up to 120° of elevation), and upward rotation (up to 60° of elevation) were observed. Additionally, there were fair to good correlations (*r* range, .39–.60) between the changes in scapular posterior tilting and the amount of muscle fatigue.

Conclusions: Fatigue in shoulder external rotation altered the scapular resting position and the movement of posterior tilting in the early range during arm elevation in the scapular plane. Observed changes in scapular kinematics may affect the amount of area in the subacromial space and facilitate impingement. Data regarding changes produced by fatigue of the external rotators may also help with the development of a model of diminished rotator cuff function.

Key Words: Biomechanics; Fatigue; Rehabilitation; Shoulder.

THREE-DIMENSIONAL SHOULDER motion is accomplished by a coordinated movement of all 3 diarthrodial joints of the shoulder girdle. This synchronous motion is controlled by passive soft tissue support and active muscular control. A change in either of these mechanisms may alter normal kinematic patterns. This may lead to shoulder problems, because optimal scapular positioning is believed to be necessary for ideal muscle lengths, force production, and assisting with glenohumeral joint stability.[1,2] Specifically, alterations in scapular kinematics have been associated with shoulder pathologies, such as impingement, rotator cuff tears, and instability.[3-8]

Although many studies of scapular motion have been restricted to 2 dimensions, several recent studies have examined scapular motion about 3 axes: upward/downward rotation (axis of rotation perpendicular to the infraspinatus fossae), anterior/posterior tipping (axis of rotation parallel to the scapular spine), and internal/external rotation (axis of rotation aligned with a vertical axis). In general, the scapula demonstrates a pattern of progressive upward rotation, external rotation, and posterior tipping as the humerus is elevated.[9-11]

Recently, scapular muscle fatigue during an elevation task was found to alter scapular kinematics.[12,13] Muscle fatigue may be 1 factor in the development of neck and shoulder discomfort during static work postures and repetitive arm movements.[14,15] Several factors, such as arm position, repetitive work with and without pauses, torque level, and work pace, have been investigated to determine their effects on muscle fatigue and discomfort.[14,16,17]

The infraspinatus and teres minor muscles are considered the primary external rotators of the glenohumeral joint.[18] Additionally, these 2 muscles have been studied and described as having other functions with respect to the glenohumeral joint, such as contributing to arm abduction,[19-21] prevention of anterior joint instability,[22-24] and production of force couples around the glenohumeral joint for dynamic stabilization.[25-27] Simultaneous contraction of the rotator cuff muscles produces a moment that assists in arm elevation as well as a downward-directed joint reaction force that acts to neutralize the upward shear force produced by the deltoid muscle contraction. This dual function is facilitated by the wide tendinous insertions of these muscles above and below the humeral head's center of rotation.[28]

Due to the multiple functions of the infraspinatus and teres minor muscles at the glenohumeral joint, a deficiency of these 2 muscles may result in problems other than just causing weakness in shoulder external rotation. The purpose of this study was to examine the effect of fatigue of these muscles on scapular 3-dimensional movements. Specifically, we hypothesized that there would be alterations in scapular motion patterns when the infraspinatus and teres minor were fatigued and that the amount of change would be linearly related to the level of muscle fatigue.

METHODS

Study Design and Participants

A 1-group pretest-posttest measurement design was used, with 1 investigator performing the entire testing procedure. Thirty subjects who indicated that they had no history of cervical or shoulder pain or pathology and who showed no range of motion restriction were recruited for this study. Based on previous kinematic data,[29] the power to detect a difference of greater than 2° is better than 85%. There were 16 women and 14 men, with a mean age of 28±6 years, a mean height of 170±9cm, and a mean mass of 65±11kg. The dominant shoulder was tested for each subject. Approval for this study was obtained from the internal review board of MCP Hahnemann

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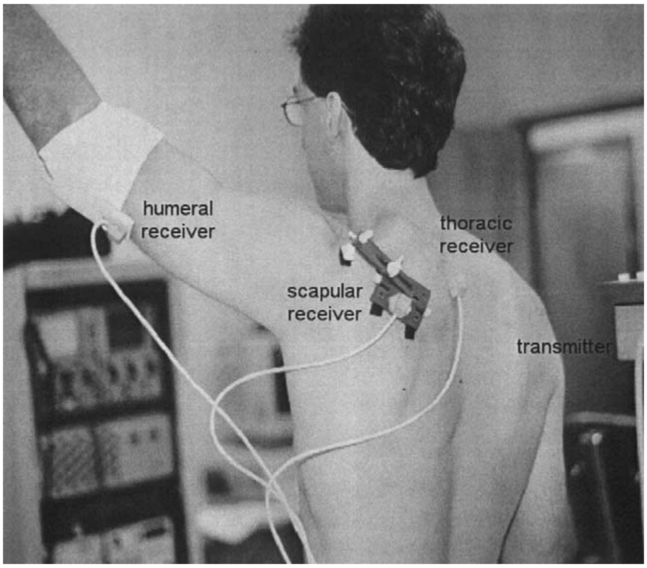

Fig 1. Experimental placement of the Polhemus transmitter and receivers.

University. Each subject was informed of the nature and details of the study and signed a consent form before participation.

Kinematics

Kinematics were measured with a Fastrak magnetic tracking device,[a] which included a system electronics unit, a transmitter, 3 receivers, and a digitizing probe.[30] The transmitter contains a series of coils that emit low-frequency magnetic fields that are detected by corresponding coils in the receivers and digitizer. The electronics unit then converts these signals into position and orientation data that are sent to the serial port on a computer. We have developed a method for using this system to noninvasively assess dynamic 3-dimensional scapular kinematics in vivo.[29] We validated our surface mounting technique by comparing measurements with those made with an additional receiver attached directly to the scapula with bone pins. Details of this method and its validation are presented elsewhere.[29] Root mean square errors ranged from 3° to 5° and tended to be much lower for elevation angles below 120°.

Briefly, the subjects stood with their thoracic spine and dominate shoulder and arm exposed. The transmitter was set up by leveling it on a plastic stand behind the subject. The first receiver was positioned on the thorax at T3 by using double-sided tape. The second receiver was placed on an orthoplast device that was positioned on the distal humerus with elastic straps. The final receiver was positioned over the scapula after the receiver was mounted on a specially machined plastic jig. The base of this so-called scapular tracker has a hinge joint that conforms to the spine of the scapula and a lightweight adjustable arm that extends and contacts the posterolateral acromion (fig 1). Both the base and arm of the tracker were attached to the skin with adhesive-backed Velcro® strips.

An anatomically appropriate axis was derived for each segment by digitizing bony landmarks.[10,29] The scapula landmarks were the acromioclavicular (AC) joint (superior portion), the interior angle, and the root of the scapular spine (intersection of medial border and scapular spine) (fig 2). The humeral landmarks were the center of the humeral head and the medial and lateral epicondyles. The thoracic landmarks were the sternal notch and the spinous processes of T1 and T7. All landmarks were surface points and could thus be located directly with a digitizer connected to the magnetic tracking device, except for the center of the humeral head. This was defined as the point on the humerus that moved the least with respect to the scapula when the humerus was moved through short arcs ($<$45°) of midrange glenohumeral motion and was calculated by using a least-squares algorithm.[31]

Standard matrix transformation methods were used to determine the rotational matrix of the humerus and scapula with respect to the thorax.[10] Humeral rotations were represented by using a standard Euler angle sequence in which the first rotation defined the plane of elevation, the second rotation described the amount of elevation, and the last rotation represented the amount of internal/external rotation.[32] Scapular rotations were represented by using an Euler angle sequence of internal/external rotation (axis of rotation aligned with a vertical axis), upward/downward rotation (axis of rotation perpendicular to the scapular plane), and anterior/posterior tipping (axis of rotation parallel to the scapular spine) (fig 2).

Torque Measurements

A KinCom dynamometer[b] was used to measure maximal isometric torque production during shoulder external rotation. Isometric torque measurements were made with the arm at the side at 45° of internal rotation and the elbow at 90° of flexion, because this position was found to best isolate the infraspinatus muscle.[33] The forearm and wrist were kept in the neutral position. The dorsal side of the wrist joint was placed on a pad that was connected to the dynamometer arm. Subjects warmed up with several submaximal contractions and 1 maximal isometric contraction of the shoulder external rotators. Subjects were instructed to stand still, to keep their trunk from leaning forward or backward, and to push as hard as they could. The average resistive torque during a 4-second maximal isometric contraction was recorded.

Pilot Study

An electromyographic pilot study was performed on an additional set of 15 subjects to determine the relationship between muscle fatigue and reduction in isometric torque production (mean age, 26±5y). Stainless steel, bipolar, and preamplified electrodes (common-mode rejection ratio [CMRR], $>$100dB; bandwidth, 6–29kHz; 300–380 gain) were used. An Instech Myoamplifier system[c] was used to bandpass filter the data with a Bessel high-pass filter (10Hz) and a Butterworth low-pass filter (750Hz). The system has a CMRR of greater than 100dB. Raw electromyographic activity was sampled at 1000Hz, and then the mean power frequency (MPF) of the signal was calculated. An 8% decrease in the MPF of electromyographic data was used as an indication of muscle fatigue.[34] Six surface electromyography electrodes were used to monitor the following shoulder muscles: biceps brachii; anterior, middle, and posterior parts of the deltoid; infraspinatus; and upper trapezius muscles. Electrode placement was based on recommendations by Cram et al.[35] Surface electromyography and isometric torque data were collected simultaneously.

Maximal voluntary contraction during external rotation was performed as described above. Also, an additional abduction isometric strength test was performed with the arm at 90° of elevation in the scapular plane. The subject then performed the fatigue protocol (described below) 4 times, and the strength tests for both shoulder abduction and external rotation were performed immediately after each fatiguing exercise. Only the infraspinatus and upper trapezius muscles showed a decrease of

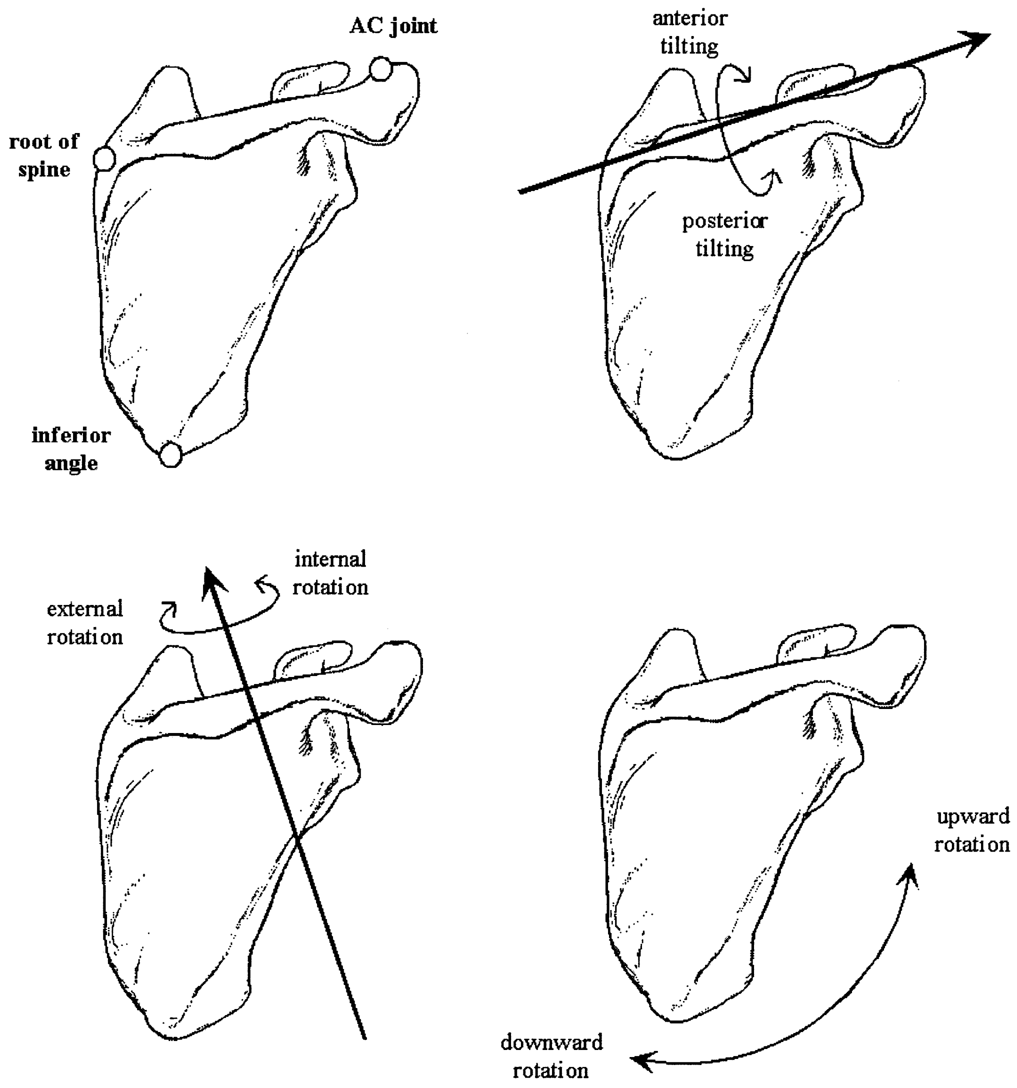

Fig 2. Schematic identification of scapular landmarks and axes of rotation.

MPF in both external rotator and abductor strength testing as a result of the fatigue protocol. Additionally, only the infraspinatus muscle reached the criterion of an 8% decrease in MPF during shoulder external rotator strength testing. After the fourth fatigue cycle, there was a 10% decrease in the infraspinatus MPF, which was associated with a decrease in the torque of the shoulder external rotators that was greater than 25%. Therefore, a decrease more than of 25% of external rotator torque was set as the criterion for muscle fatigue.

Fatigue Protocol

The fatiguing exercise was performed with a Thera-band.[d] This rubber material is typically used in the clinic for resistance exercise. A green band with medium resistance was used in this study. One end of the Thera-band was attached to a fixed object, and subjects held the other end. The subjects externally rotated their shoulders from 45° of internal rotation to neutral against the resistance of the Thera-band and then returned to 45° of internal rotation at a rate of approximately 1Hz. Subjects were asked to repeat this task without elevating their arm or retracting their scapula. When the subjects could not perform the task anymore, their muscle strength was remeasured on the KinCom. If a there was a decrease in torque from the baseline measurement that was greater than 25%, the subjects were considered as being fatigued and stopped exercising with the Thera-band. If the drop was 25% or less, subjects were not considered fatigued, and, as such, then continued exercising with the Thera-band until their torque production was reduced more than 25% from baseline.

Experimental Protocol

Three repetitions of maximum arm elevation in the scapular plane (40° anterior to the frontal plane) were performed (trial 1) while data were collected continuously at a rate of approximately 10Hz. The investigator gave verbal feedback to control the timing of arm elevation. Output data were monitored in real time to ensure that the scapular plane was maintained during testing. To assess reliability, 3 additional repetitions were performed after a 5-minute rest interval, but before fatigue began (trial 2). Next, external rotation strength was tested on the KinCom. After these baseline kinematic and torque measurements were completed, the fatigue protocol was performed. When the criterion of 25% torque reduction was achieved, the subject repeated the 3 repetitions of scapular plane elevation motion (trial 3).

Data Analysis

For each repetition of humeral elevation, data at every 30° increment were calculated by linear interpolation, with the primary humeral rotation serving as the independent variable. Additionally, the minimum and maximum elevation points were recorded. These data were averaged over the 3 repetitions of humeral elevation performed for each trial. To evaluate intrasession reliability, data from the 2 prefatigue trials were compared (trials 1 and 2). The intraclass correlation coefficient ($ICC_{3,1}$) and standard error (SE) of the measurement were used to determine the intrarater reliability for all 3 scapular rotations.[36] Paired *t* tests were used to distinguish significant differences between the scapular positions before (trial 2) and after (trial 3) the fatiguing exercise. The relationships between the scapular motions and the decreases in muscle strength caused by the fatiguing exercise were tested with Pearson product-moment correlation coefficients. An α level of .05 was set for all comparisons.

RESULTS

The $ICC_{3,1}$ values for measurements of scapular motions were analyzed at the minimal, 30°, 60°, 90°, 120°, and maximal humeral elevations. All the ICC values were above 0.9, and the SE of measurement for each point ranged from 1.0° to 2.6°.

There was a significant effect of fatigue on the scapular resting position for all rotations. For posterior tilting, significant changes were found up to 90° of humeral elevation. The biggest mean difference was approximately 4° at the beginning of arm elevation, with the scapula more anteriorly titled after fatigue (fig 3A). For external rotation, significant changes were observed up to 120° of humeral elevation. However, the biggest change was only 2.4° at the beginning of arm elevation, so that the scapula became more internally rotated after fatigue (fig 3C). For upward rotation, significant changes were found up to 60° of humeral elevation. The biggest mean difference was 2.5° at the beginning of arm elevation, with the scapula more downwardly rotated at the starting position after fatigue (fig 3B).

There were statistically significant relationships between the changes of scapular posterior tilting and the decrease of external rotation torque production, due to the fatiguing exercise, at all positions except the maximal humeral elevation. The correlation coefficients (*r*) were .60 at minimal position, .59 at 30°, .58 at 60°, .45 at 90°, and .39 at 120° of humeral elevation, with significant changes (fig 4). No significant difference was found for the other 2 scapular rotations.

DISCUSSION

The results of this study indicate that scapular kinematics can be temporarily altered with fatigue of the external rotators. All 3 rotations were altered after the fatiguing exercise; however, the maximal increase was no more than 4°. However, for posterior tilting, this represented almost a 50% change in rotation after the fatiguing exercise. This is consistent with other studies showing small changes in scapular kinematics with fatigue,[12,13] resistance level,[37,38] passive positioning,[37,39] posture,[40,41] and muscle strengthening.[42]

Clinically, the overhead athlete commonly exhibits posterior shoulder pain and external rotator weakness, resulting in shoulder dysfunction believed to be secondary to a force-coupled imbalance between the anterior and posterior rotator cuff musculature.[43,44] An imbalance such as this has been shown in professional baseball pitchers, who have a low ratio of external to internal rotation strength.[45] Fatigue of the shoulder external rotators could further aggravate this imbalance. Also, because we observed a correlation between the amount of fatigue of the external rotators (based on torque production) and changes in scapular kinematics, activities such as athletics and overhead work that require highly strenuous repetitive motion may result

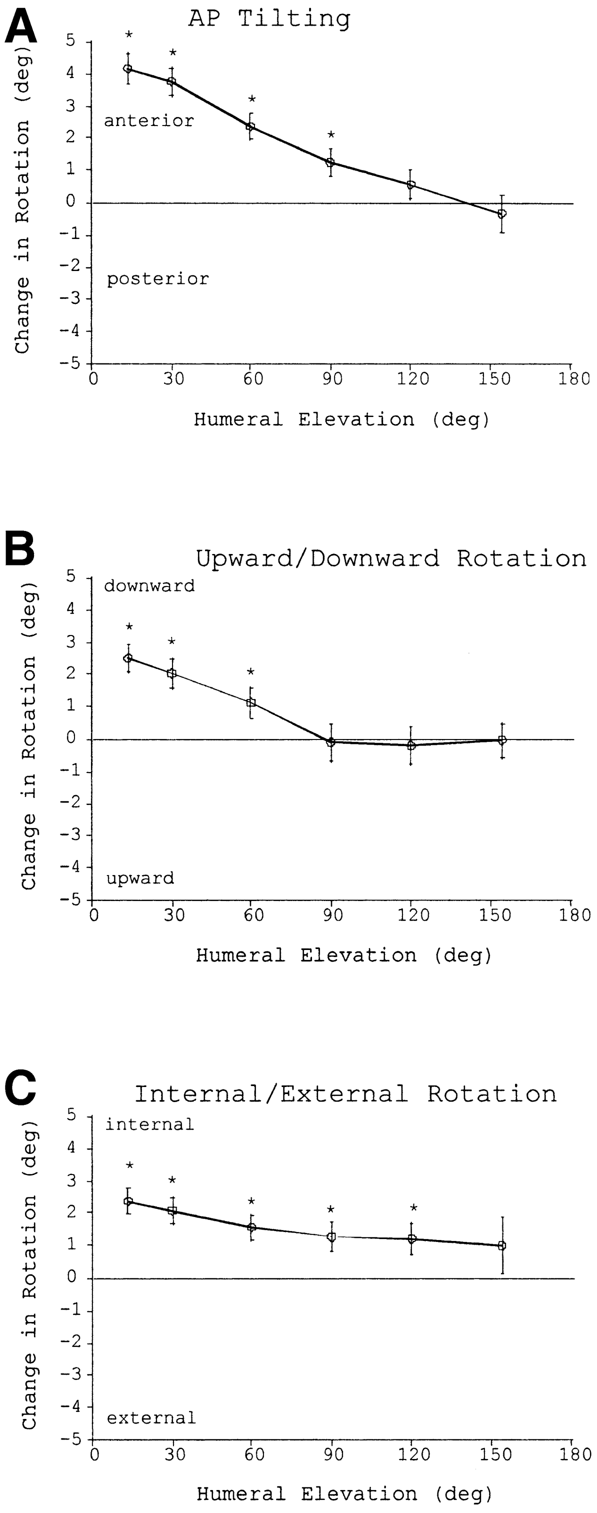

Fig 3. Mean change in 3-dimensional scapular rotations due to fatigue protocol (data represent after minus before): (A) anterior/posterior (AP) tilting, (B) upward/downward rotation, and (C) internal/external rotation. Error bars represent the SE of the mean. ****P*<.05.

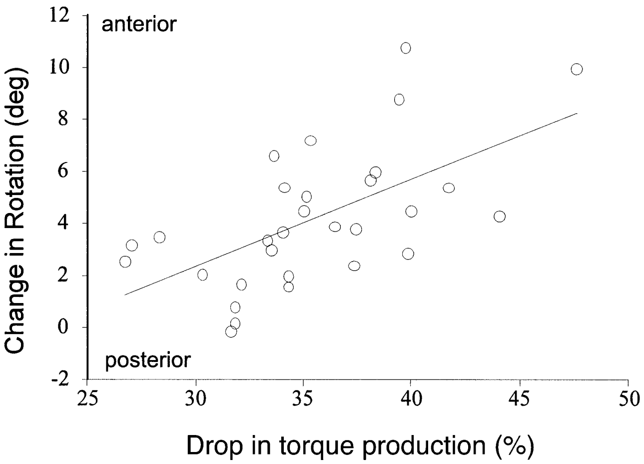

Fig 4. Representative correlation between scapular anterior/posterior tilting and percentage decrease of external rotation torque production. This example is at the minimal position of humeral elevation (r=0.6, P<.01).

in even more pronounced alterations in scapular motion patterns.

Recent studies[3,46] have shown that patients with impingement syndrome have significantly more anterior tilting when compared with asymptomatic subjects. This increase in anterior tilting is of the same magnitude as found in our study. It has been suggested that small changes in anterior/posterior tilting may be functionally analogous to anatomic changes in acromial morphology, resulting in alterations of soft tissue compression in the subacromial space.[3,46]

Kuechle et al[20] have shown that during elevation in the scapular plane, the infraspinatus and teres minor moment arms are largest during the initial part of the motion. Additionally, Sharkey et al[28] have also found that these 2 muscles are most effective in arm elevation during the first 90° of humeral elevation in the scapular plane. These results may help to explain why most of the significant changes in scapular orientation in our study were found in the initial phases of humeral elevation.

At the same time that the infraspinatus and teres minor muscles are applying a force to the humerus, they are also applying a force to the scapula. If the humerus has been stabilized by other muscles, then the force of the internal rotators could directly influence scapular motion. Additionally, a disruption in the balance between internal and external rotation torques may result in compensatory activity from scapulothoracic muscles to help maintain scapular stability. It is unknown whether the observed changes in scapular orientation are a primary result of direct force alterations of the infraspinatus and teres minor muscles or are secondary to compensatory changes in the activity of other muscles.

Several limitations of our study must be acknowledged. Although significant differences were found, the magnitude of these changes did not differ much from the errors we found in our validity and reliability studies. Although our pilot study indicated that the fatigue protocol primarily targets the infraspinatus and teres minor muscles, there were some smaller indications of fatigue in other muscles that may have contributed to the observed alterations in scapular position. For example, Jenp et al[47] have shown that both the supraspinatus and posterior deltoid may show significant activity levels in our testing position. Additionally, the electromyographic activity of some key muscles, such as the supraspinatus, lower trapezius, and serratus anterior, was not monitored in our study. Although it is possible that unbalanced rotator cuff forces caused by fatigue may have influenced humeral internal rotation, subjects were asked to keep their thumbs up during the entire protocol, which resulted in their maintaining roughly the same amount of internal rotation after the fatigue protocol, as determined from our kinematic data. Another limitation is that subjects were healthy and between the ages of 20 and 42 years. It is not known whether the observed effects would also be seen in older subjects or in patients with shoulder pathologies. Finally, although we found excellent reliability of our kinematic measurements, it is possible that the sensors slipped during the fatiguing protocol due to skin motion or sweat. One way we could have checked this was by measuring kinematics well after the fatigue effect would have worn off (at least an hour).

CONCLUSION

This study showed that small but potentially clinically significant changes in scapular kinematics were found after an external rotation fatigue protocol. The altered scapular 3-dimensional movements occurred in the first part of arm elevation in the scapular plane. The fair to good correlation (r range, .39–.60) between the changes in scapular posterior tilting and the reduction in muscle strength suggest that the larger the muscle imbalance between internal and external shoulder rotators due to the muscle fatigue, the greater the alteration in scapular posterior tilting. It is possible that even larger differences in scapular motion patterns might be observed in activities that result in more substantial fatigue of these muscles, such as work-related motions and overhead athletics.

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Suppliers

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b. Chattanooga Group, 4717 Adams Rd, Hixson, TN 37343.
c. Instech Laboratories, 5209 Militia Hill Rd, Plymouth Meeting, PA 19462-1216.
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