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Roles of deltoid and rotator cuff muscles in shoulder elevation

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Abstract

Objective. The objective of this study was to measure abduction moment arms of the supraspinatus, subscapularis, infraspinatus, and deltoid (anterior, middle, and posterior portions) muscles during humeral elevation in the scapular plane (abduction).
Design. Moment arms were measured by conducting an *in vitro* experiment.
Background. The moment arm of a muscle represents its mechanical advantage, which is an important determinant of muscle function.
Methods. Measurements were made on 10 fresh frozen cadaveric specimens. Tendon excursions were measured as the humerus was elevated in the plane of the scapula. The principle of virtual work was used to estimate the muscle moment arm of each muscle by computing the slope of the tendon excursion *versus* joint angle relationship.
Results. Moment arms were affected by joint angle in a non-linear fashion. The anterior deltoid, middle deltoid, subscapularis, and infraspinatus muscles had abduction moment arms throughout most of the range of motion studied. The posterior deltoid had an adduction moment arm. Internal and external humeral rotation affected the elevation moment arms of all six muscles.
Conclusions. Abduction moment arm magnitudes of the muscles studies vary throughout the arc of elevation. This study was limited by considering broad muscles to have a single line of action.

Relevance

The positive elevation moment arms of the infraspinatus and subscapularis muscles indicate that they can elevate the arm in addition to acting as stabilizers. Thus this study suggests a biomechanical explanation for the clinical success of conservative treatment for rotator cuff tears. © 1997 Elsevier Science Ltd. All rights reserved.

Key words: Rotator cuff, moment arms, shoulder, deltoid, biomechanics

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Introduction

The ability of a muscle to move a joint is partially determined by the torque it generates about the joint. Torque is the product of the muscle's force and moment arm. Muscles with larger moment arms can generate more torque than muscles with smaller moment arms given the same muscle force. Moment arm magnitude represents the mechanical advantage of a muscle at a joint. Accurate measurement of muscle moment arms can assist in understanding muscle function. Although many authors have used electromyography (EMG) to study shoulder muscles in sports and in rehabilitation programs[1–4], the quantitative interpretation of EMG data during dynamic conditions is problematic[5]. Knowledge of the moment arm of a muscle in specific planes of movement helps in understanding its role in those motions.

There are several methods to study the moment arm of muscles across the glenohumeral joint. The geometric method has been used by some authors to measure the perpendicular distance from the centre of rotation to the muscle's line of action either directly on anatomical specimens[6,7] or indirectly on radiographs[8,9]

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The drawbacks of this type of measurement are that it can only be done at discrete joint angles and the joint centre of rotation must be known. However, the moment arms may vary as a function of joint angle[9,10]. An alternative method is to use the principle of virtual work to derive the moment arm from the relationship between tendon excursion and joint angle[11,12]. This method can reflect changes in moment arm with joint angle. Otis et al.[10] applied this method to the shoulder, but restricted the allowable shape of the moment arms to be linear with joint angle.

The purpose of this study was to describe the effect of elevation angle and humeral internal/external rotation on moment arms of six shoulder muscles during elevation of the humerus in the scapular plane. The supraspinatus, infraspinatus, and subscapularis muscles of the rotator cuff were measured. The deltoid muscle was divided into three entities: anterior, middle, and posterior portions.

Methods

Ten fresh frozen cadaveric shoulders were prepared by scapulothoracic and sternoclavicular disarticulation. There were five right shoulders and five left from four males and five females, and mean age was 67 (range 40–89). Specimens were visually examined after dissection to ensure they were free of rotator cuff tears, limited range of motion, arthritis, or bony metastasis.

The humerus was marked with a Steinmann pin directed parallel to the ulna in 90° of elbow flexion for reference of the anterior aspect. The humerus was transected just distal to the deltoid insertion. The skin and all muscles except the deltoids and the rotator cuff were dissected free and carefully removed. The deltoid was then detached from its origin on the clavicle, acromion, and scapular spine. Its muscle belly was cut away, leaving only the tendon. The supraspinatus, subscapularis, infraspinatus, and teres minor were elevated from their origins at the scapula to the insertions at the joint capsule, and were then carefully transected 1 cm proximal to their musculotendinous junction. The joint was vented and the coracoacromial ligament preserved. Fifty pound test nylon lines were sutured to the anterior, middle, and the posterior deltoid origins and the mid-point of the musculotendinous portion of each cuff tendon (except the teres minor), using the modified Mason–Allen (Gerber) method[13]. Three eye-hooks were fixed to the midpoints of the origins of the individual portions of the deltoid muscle. Eye-hooks were also placed in the centres of the supraspinous, infraspinous, and subscapular fossae to simulate the origins of the supraspinatus, infraspinatus, and subscapularis muscles. The nylon lines were passed through the corresponding eyehooks to re-establish the line of action of each muscle (Figure 1). After mounting the scapula, all nylon lines were routed through holes in a Plexiglas guide to potentiometers (3500S-2-103, Bourns Corp., Riverside, CA, USA; resistance tolerance ±3%, linearity tolerance ±0.2%). Each string was wrapped around a cylinder on a potentiometer shaft, and a 250-g weight was hung on the end of each string. The potentiometers were powered by ±10V power supply and the voltage across each was sampled by an A/D converter (DT2801A, Data Translation, Marlboro, MA, USA). The 10-turn potentiometers were calibrated and checked before use to ensure they did not reach their endpoints during testing.

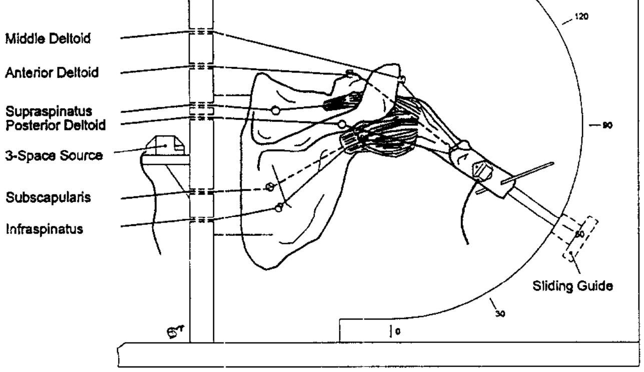

Figure 1. Experimental set-up.

A six degree of freedom magnetic tracking device (3SPACE Tracker, Polhemus, Colchester, VT, USA) was used to measure the glenohumeral angles and for digitization. The absolute accuracy of this system was better than 1 mm and the angular accuracy was less than 0.5 degree[14]. The 'source' of the 3SPACE was attached to the Plexiglas table and the 'sensor' was attached to the humeral shaft. A second 'sensor' was used for digitization. The 'scapular plane' was defined as the plane containing the centre of the glenoid and the superior and the inferior angles of the scapula. 'Elevation' was defined as abduction in the scapular plane (glenohumeral angle from a neutral hanging posture). This angle is different from total arm elevation, because of the shoulder rhythm.

A glass-fibre rod was inserted into the humeral intramedulary canal and fixed with pins and bone cement. The reference Steinmann pin was replaced by a thinner glass-fibre pin, and the scapula was mounted onto a Plexiglas table with plastic bolts and bone cement. The plane of the scapula was kept perpendicular to the ground when mounting. A vertical Plexiglas guide was placed coplanar to the scapular plane. A sliding guide was fastened to the distal end of the intramedullary rod. It was used to control the plane of elevation and the degree of internal and external humeral rotation during the trial; it moved along the Plexiglas guide plane (Figure 1). The humerus was elevated from zero degrees (hanging position) to maximal elevation in the scapular plane in each of five axial humeral rotation conditions: neutral rotation, 30 and 60 degrees internal, and 30 and 60 degrees external rotations. Neutral internal/external rotation was defined to be where the AP plane of the humerus (determined from flexion of the forearm) was perpendicular to the scapular plane. The elevation was achieved both by the hanging weights and with light assistance by the experimenter's hand holding on the gliding guide. Three trials were performed for each test. Each trial took 10 s and data were collected in real time at 30 Hz. After testing, the joint was disarticulated, and the articular surfaces of the glenoid and humeral head were digitized (25 points on humeral head and 17 on the glenoid) with a second 3SPACE sensor. A sphere was fitted to the digitized points on the humeral head. The centre of the sphere was computed relative to the sensor fixed to the humerus. Thus the location of the centre of the sphere, which is an estimate of the centre of the humeral head, was estimated from the humeral sensor throughout the motion. The maximum superior–inferior travel of the centre of the sphere during each trial was computed.

Tendon excursions were measured by rotation of the potentiometers, and the glenohumeral elevation angle was determined from the 3SPACE tracking data. Polynomial regression was used to model the relationship between tendon excursion and elevation angle. A limit on the order of the polynomial was used (sixth order) to avoid overfitting the data. The lowest order polynomial satisfying the requirement that the root mean square error be less than 0.5 mm was selected for each muscle of each specimen. The polynomial regression was analytically differentiated to give the instantaneous moment arm, i.e. the slope of the excursion vs. joint angle (in radians)[12]. Figure 2 shows data (measured and fitted) for one trial. Moment arms were computed at 1-degree intervals by numerically evaluating the differentiated polynomials. Note that the sign convention was that positive moment arms indicate agonist function (abduction) and negative represent antagonist function (adduction). All trials were examined for technical faults such as the nylon line catching or slipping. Problematic trials were repeated, and trials were only excluded from the analysis if it was not possible to successfully complete them after several attempts.

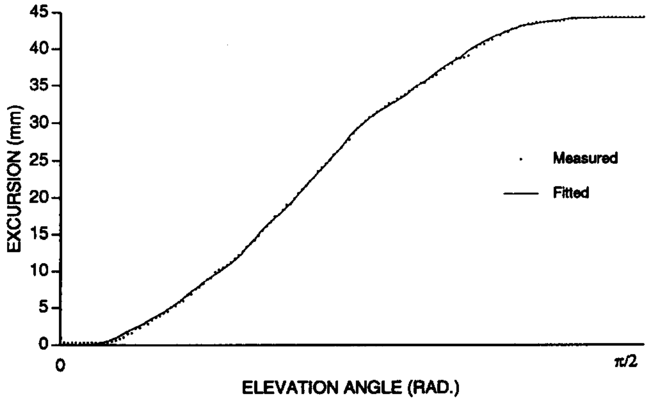

Figure 2. Tendon excursion–elevation angle relationship for a single trial. The moment arm is computed by differentiating the polynomial fitted to the data.

Statistical analysis included computing means and standard deviations at one degree increments. A three-way ANOVA model was used to test whether the abduction angle (at 10-degree increments), axial humeral rotation angle, and interactions significantly affected each muscle's moment arm (specimen was used as a blocking variable). P values less than 0.05 were considered significant.

Results

The abduction moment arms in scapular plane elevation are shown in Figure 3. Elevation angle, internal/external rotation, and the interaction between the two angles all affected elevation moment arms at the $P<0.0001$ level of significance. The elevation moment arm varied continuously with the elevation angle in all six muscles. The supraspinatus and middle deltoid had the two largest abduction moment arms. The peak supraspinatus value of 30 mm occurred at 30 degrees and remained above 20 mm up to 70 degrees glenohumeral elevation. The middle deltoid had a 13-mm moment arm at 0 degree and increased up to 27 mm at 60 degrees and 32 mm at 90 degrees. The anterior portion of deltoid had a small moment arm at small angles of glenohumeral elevation but became progressively larger with increasing arm elevation. The posterior deltoid was an important adductor due to its negative moment arm, but its adduction moment arm decreased with arm elevation. The abduction moment arm of the infraspinatus was small at 0 degree abduction but increased to 10 mm at 15 degrees and remained rather constant thereafter to maximal elevation. The abduction moment arm of the subscapularis decreased with arm elevation from 8.8 mm at 0 degree to 0 mm at 63 degrees.

The internal/external rotation of the humerus influenced the abduction moment arms of all six muscles (Figure 4). The abduction moment arms increased with external rotations and decreased with internal rotation in the anterior deltoid and subscapularis muscles. The infraspinatus moment arm decreased with external rotation and increased with 30 degree internal rotation. The moment arm of the supraspinatus decreased with both internal and external rotations. The moment arms of the middle deltoid and the posterior deltoid changed significantly with rotations, but the magnitude of changes were too small to have clinical significance.

The superior–inferior movement of the humeral head was small. The average superior-inferior translation of the centre of the humeral head was 3.1 mm (1.8 mm SD).

The moment generating potential of the muscles was determined at a glenohumeral angle of 0 degrees. Ignoring the length–tension and force–velocity properties of muscle, the ability to generate abduction moment was assumed to be the product of the moment arm, physiological cross-sectional area (PCSA), and the maximum isometric stress limit of muscle. The PCSA values were taken from Veeger et al.[15]. and Karlsson and Peterson[16]; the maximum stress limit was 63 N cm^{-2}[17]. The maximum moment potentials for the supraspinatus, infraspinatus, subscapularis, anterior deltoid, middle deltoid, and posterior deltoid were 6.2, 2.6, 7.6, 0.5, 8.0–16.5 Nm respectively. Maximum abduction moment is obtained by assuming inactive adductors, giving 24.9 Nm maximal abduction strength.

Discussion

This study shows that abduction moment arms of the muscles studied were not constant throughout the range of motion; rather, they changed with angle in a non-linear fashion. This is in contrast to the report of Otis et al.[10], which showed linear relationships between moment arms and glenohumeral angle.

This study suffers from the inherent limitations of cadaver studies: the age of specimens is not representative of the whole population of clinical interest, a relatively small number of specimens were studied, and *in vitro* kinematics may differ from *in vivo* conditions. Although the first two limitations are

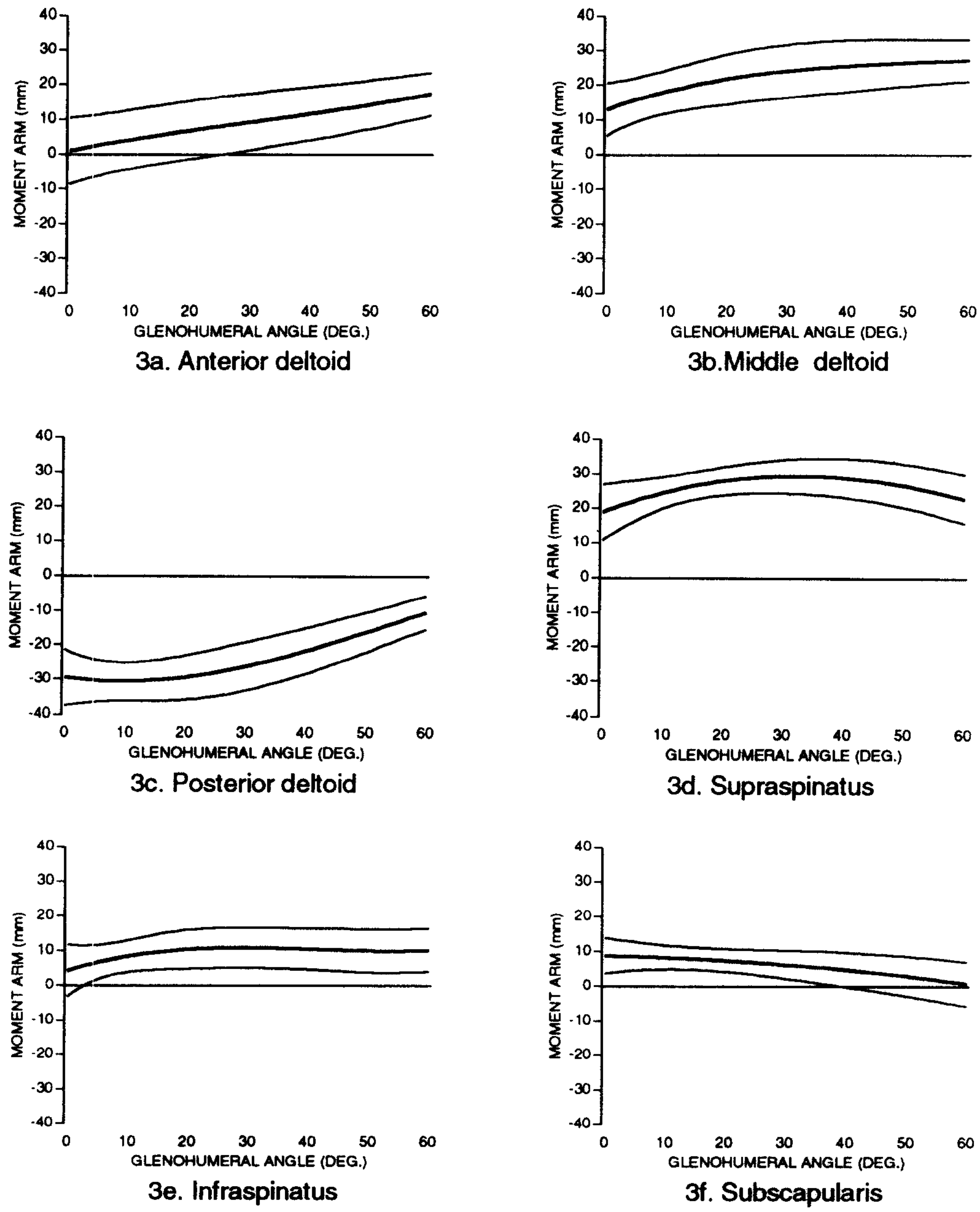

Figure 3. Average elevation moment arms (millimetres) for the six muscles tested (supraspinatus, infraspinatus, subscapularis, and anterior, middle, and posterior deltoid) with no internal or external rotation of the humerus. Note average moment arm lines are bounded by ±1 standard deviation lines.

difficult to surmount, it is possible to compare kinematics to reported *in vivo* motions at the glenohumeral joint. The normal kinematics in shoulder elevation was described by Poppen and Walker[18]. From studying the radiographs of active elevation in the scapular plane on 12 normal subjects, they found that superior translation of the humeral head was about 3 mm in the initial 30 degrees of shoulder elevation and then 1.1 ± 0.5 mm upward or downward for every 30 degrees elevation, and the centre of rotation was within 6 mm from the geometric centre. In our study, the movement of the humeral head was within this range. Typically, the humeral head moved about 1 mm upward in the first 30 degrees of elevation, then about 2 mm downward in the next 30 degrees, and 1 mm upward in the last 30 degrees.

The interpretation of these results is also limited by an inherent limitation of the virtual work method of moment arm measurement: muscle lines of action are unknown. Additionally, calculations of total joint moment generating capability do not include the length–tension and force–velocity properties of muscle. The analysis of individual muscular contribution to joint moment is therefore an approximation, but one that explains important aspects of shoulder function.

The data analysis techniques used in this study eliminate some of the limitations of previous studies of shoulder musculature moment arms. Otis et al.[10] used second-order polynomials to fit the abduction angle to excursion for the deltoid muscle; therefore it was impossible to detect any non-linear effects for the

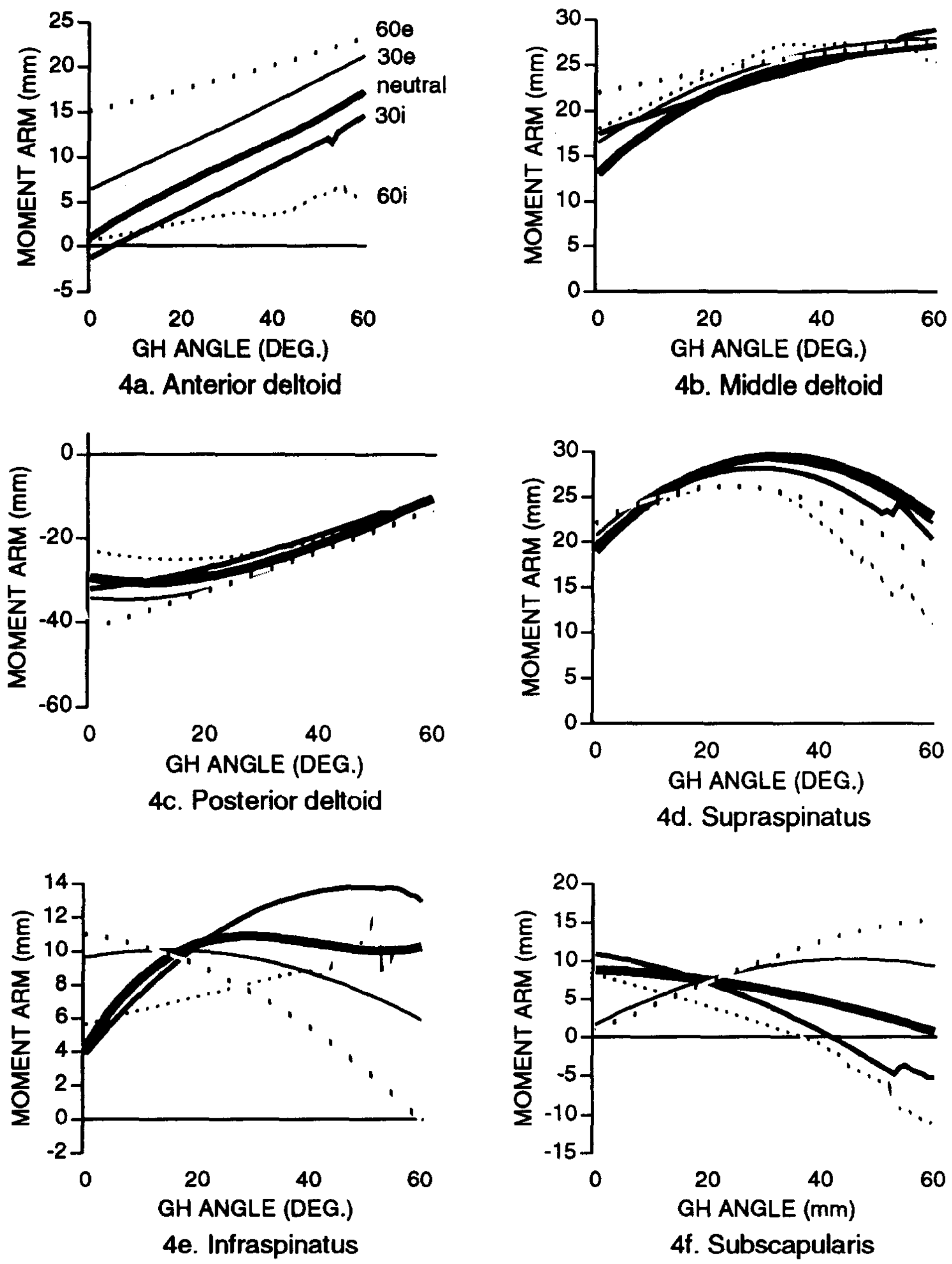

Figure 4. Average elevation moment arms at different internal and external rotation angles (60° external, 30° external, neutral, 30° internal, and 60° internal).

rotator cuff muscles in that study. In contrast, this current study fitted the excursions with polynomials of up to sixth order, which allows the moment arms to be represented by fifth-order polynomials. The results reported here are less likely to be artefacts of the data fitting procedure, because the data is not forced to be represented by low order polynomials.

The middle portion of deltoid and the supraspinatus are generally thought to be the two most important abductors[2,9,19,20]. The supraspinatus was believed to be more important in initiating elevation, and the middle portion of the deltoid more important for elevation of the arm at higher angles of abduction. Some authors attributed this to the relatively smaller moment arm of the deltoid at lower angles of elevation[10]. This study found the middle deltoid had a smaller moment arm at the first 50 degrees of elevation but increased to become larger than the supraspinatus after 50 degrees glenohumeral elevation. Even though the middle deltoid has 30% less moment arm at the beginning, its physiological cross-sectional area is more than twice as large as the supraspinatus[6,9]. Theoretically it can generate a large torque to elevate the arm even at the beginning; therefore the deltoid and the supraspinatus may both play an important role in the initiation phase. Moreover the supraspinatus moment arm maintains significant moment producing capability throughout the range of motion. The interpretation that both the supraspinatus and middle deltoid can generate abduction moment throughout the elevation range of motion is consistent with the *in vitro* simulation study of McMahon et al.[21], which concluded that the supraspinatus alone is sufficient for abduction.

Several studies have reported an abduction moment arm for the anterior portion of the deltoid[9,10]. It was found to have a large moment arm exceeding the middle portion of the deltoid after 90 degree abduction[9]. Otis et al.[10] reported a smaller moment arm that became positive after 15 degree elevation. The results of the present study indicated a positive anterior deltoid moment arm, but one smaller than for the middle deltoid. The posterior portion of deltoid was also found to have a small positive abduction moment arm in one study[9] and a negative one in another study[10]. The present study found a negative abduction moment arm for the posterior deltoid. The negative moment arm suggests that the posterior deltoid acts as an antagonist during abduction, but it gradually loses the antagonist mechanical function at higher elevation angles.

The role of the infraspinatus and the subscapularis in abduction and elevation is not very clear in the literature. Inman et al.[19] found them to be active throughout abduction, but they considered these two muscles to be depressors. This concept was supported by subsequent moment arm studies using the geometric method on radiographs[8,9,20]. These muscles were found to have small moment arms and were thus thought to have little contribution to abduction. Under this concept, Kronberg et al.[2] considered both the infraspinatus and the subscapularis to be stabilizers in abduction, even though the activity of the infraspinatus was found to be as high as the supraspinatus during abduction in EMG study. Townsend et al.[4] also found that the subscapularis had the highest EMG activity during elevation in the scapular plane. In a nerve block study, the abduction torque was found to decrease 25–45% after selectively paralysing the infraspinatus[22]. Furthermore the infraspinatus-teres minor, and subscapularis were found to have equal contribution to abduction as the supraspinatus in an *in vitro* dynamic model[23].

An analysis of muscle moment arms can provide additional insight. If the infraspinatus and subscapularis muscles really contribute to abduction, their moment arms should not be zero. This study indicates the abduction moment arm of the infraspinatus in neutral rotation was small in the first 15 degrees elevation, increased to about 10 mm afterward, and maintained that value throughout the remaining range of elevation. The subscapularis was found to have a small and decreasing moment arm with shoulder elevation and changed from an abductor to an adductor at about 60 degrees glenohumeral elevation. The subscapularis might act as a stabilizer in abduction in neutral rotation, but it had a significantly larger abduction moment arm in external rotation.

The broad origins of the infraspinatus and subscapularis muscles suggest that the inferior and superior portions of these muscles may have different actions. The superior portions may play a more important role in generating abduction torque, and the inferior portions may enhance stability. Otis et al.[10] reported that the superior portions of the infraspinatus and subscapularis have larger abduction moment arms than the middle or inferior portions. The inferior portions of these muscles may play more of a role in preventing superior movement of the humeral head, due to their inferior-superior lines of action. This study did not separate these muscles into superior and inferior portions. Thus the moment arms presented here may represent an underestimate of the mechanical advantage of the superior portions of the muscle.

Although the moment arms of the infraspinatus and supraspinatus were less than half of the supraspinatus, they have more than twice as large physiological cross-sectional area as the supraspinatus[6,7,9]. Therefore it is theoretically possible for them to generate large abduction torques. Moreover the internal/external rotation of the humerus can significantly influence the magnitudes of the abduction moment arms of these two rotators. In theory it may be possible to elevate the arm even with the existence of a tear at the supraspinatus tendon by strengthening other rotator muscles and by rotating the humerus to get an optimal position. The data presented here suggest a biomechanical explanation for the clinical success of conservative treatment for rotator cuff tear[1].

Nerve block studies have also been used to investigate the abductor mechanism[20,24,25]. The axillary nerve supplies the three portions of deltoid and the suprascapular nerve supplies the supraspinatus and the infraspinatus muscles. Blocking the suprascapular nerve produced a decrease of abduction torque similar to blocking the axillary nerve[25]. Using the moment-generating potentials of each muscle computed from the moment arms of this study, the suprascapular nerve block should reduce maximal abduction strength 35%. The axillary block should reduce it 34%. Thus, the moment arms reported here help explain the results of nerve block experiments.

Acknowledgements

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