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The relevance of the moment arm of shoulder muscles with respect to axial rotation of the glenohumeral joint in four positions

David K. Kuechle, Stephen R. Newman, Eiji Itoi, Glen L. Niebur, Bernard F. Morrey, Kai-Nan An *

Biomechanics Laboratory, Division of Orthopaedic Research, Mayo Clinic and Mayo Foundation, 200 First Street SW, Rochester, MN 55905, USA

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Abstract

Objective. This study was undertaken to determine the efficiency of the shoulder girdle muscles during axial humeral rotation based on measurements of the moment arms.

Design. The instantaneous muscle moment arms of 10 shoulder muscles, including the three portions of the deltoid, the rotator cuff muscles, teres major, and the thoracohumeral muscle group, were measured during four specified glenohumeral rotations.

Background. Axial humeral rotation is a commonly performed movement during activities of daily living and is a targeted motion of shoulder rehabilitation, particularly in those protocols emphasizing rotator cuff strengthening. An understanding of the function of the movers and stabilizers of the shoulder requires such basic information of muscle moment arms.

Methods. The instantaneous moment arm values of the muscles were derived from the slope of the plot of tendon excursion versus glenohumeral joint rotation angle. Motion studied included axial rotation with the humerus elevated 90° in the coronal, scapular, and sagittal planes, as well as in the neutral position with the arm at the side.

Results. Based on the findings, with the humerus in both neutral and elevated positions, the infraspinatus is potentially the most powerful external rotator, followed by teres minor and posterior deltoid. Subscapularis and possibly pectoralis major are the most effective internal rotators in this position.

Conclusions. The moment arm in providing axial humeral rotation of 10 shoulder muscles in four planes were obtained. In general, the teres minor and infraspinatus had the largest moment arms in external rotation, and the subscapularis had the largest moment arm in internal rotation. The muscle function for axial humeral rotation was found to be modified by the plane of arm elevation.

Relevance

The data could be used for developing exercise programs in physical therapy.

1. Introduction

The moment arm or lever arm of a muscle is the perpendicular distance between the joint center of rotation and muscle line of force. Shoulder muscle moment arm has been the subject of a number of previous papers, yet precise definition has proven elusive, due in part to the complexity of the articulation, as well as to the limitations in measurement techniques [1–5]. Nevertheless, an understanding of the function of the movers and stabilizers of the shoulder requires such basic information on the internal and external forces involved. The purpose of this study is to measure the instantaneous moment arms of 10 shoulder muscles during glenohumeral rotation at four selected positions.

The majority of previous shoulder moment arm studies have been performed during elevation, usually in the scapular plane [1–5]. Only two authors, to our knowledge, have investigated axial humeral rotation [1,4]. Bassett et al. [1] used serial cross-sectional data in five specimens with the shoulder in a position of 90° of abduction and 90° of external rotation in order to measure the moment arm geometrically. From this single position, the short head of biceps, coracobrachialis

* Corresponding author.

E-mail address: an@mayo.edu (K.-N. An).

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and posterior deltoid were determined to be the main external rotators. The primary limitations of the serial cross-sectional technique are that it only permits evaluation of a single joint configuration per specimen, and it describes a dynamic situation in a static manner.

Jiang et al. [4] utilized tendon excursion and joint displacement data to calculate moment arm, a technique described previously by An et al. [6]. Jiang studied five specimens with the humerus in neutral abduction and joint position maintained by an external fixation device. Teres minor and infraspinatus were found to be the primary external rotators, while subscapularis was the main internal rotator. Supraspinatus and the deltoid were not thought to contribute to humeral rotation. Although axial humeral rotation has not been the subject of many moment arm studies, it is nevertheless a worthy topic for investigation. It is a commonly performed movement during daily activities and is a targeted motion of shoulder rehabilitation, particularly in those protocols emphasizing rotator cuff strengthening. In addition, the rotational motions studied currently fully complement a previous project from our biomechanics laboratory which investigated glenohumeral elevation and horizontal flexion, allowing definition of a comprehensive shoulder exercise program [7].

In the current study, we calculated instantaneous shoulder muscle moment arm during axial humeral rotation at four select positions from tendon excursion and joint displacement data. In addition, we attempted to determine the potential contribution of individual muscles to standard shoulder rehabilitation movements using physiologic cross-sectional area and electromyographic data.

2. Methods

Twelve fresh frozen cadaveric specimens were chosen (seven right, five left) from subjects ranging in age from 33 to 80 years with a mean age of 59 years. Shoulders with evidence of degenerative changes were not included in the study. Specimen preparation followed carefully defined steps and began with transsection of the humerus just distal to the deltoid tuberosity. The skin and subcutaneous tissue, pectoralis minor, trapezius and coracobrachialis muscles were dissected free and removed. Latissimus dorsi, pectoralis major, and triceps were divided at the musculotendinous junction and the muscle bellies were removed. The remaining musculature, including the supraspinatus, infraspinatus, teres major and minor, subscapularis, and the anterior, middle, and posterior portions of the deltoid were isolated and identified.

Using Dacron line (Cabela's™), a Bunnell stitch was placed in the superficial aspect of the musculotendinous junction of each muscle at the midpoint of the insertion into bone. The specimen was mounted on an acrylic testing frame, and the Dacron line was passed through the lubricated hole in the backboard best approximating the orientation of the muscle fibers (Fig. 1). Each Dacron line was wrapped around the axle of an assigned electropotentiometer (Bourns, Riverside, CA, USA) mounted on the rear of the testing frame. A sensor from an electromagnetic tracking device (3Space Tracker™, Polhemus, Colchester, VT, USA) was affixed to the humerus, while the magnetic source was mounted adjacent to the scapula. The 3-Space Tracker™ measures the three-dimensional position and orientation of a sensor relative to a source based on low-frequency magnetic field technology. The position and orientation of the humeral head with respect to the glenoid were monitored at 30 Hz by the 3Space Tracker™.

Each of the 10 muscles studied was monitored by a potentiometer. With the specimen mounted on the acrylic frame, and the tensioned Dacron line wound around the potentiometer shaft, movement of the humerus caused a rotation of the potentiometer shaft corresponding to the linear excursion of the specified tendon. Data taken simultaneously by the 3Space Tracker™ allowed calculation of the three-dimensional position of the humerus with respect to the glenoid, and hence, determination of the angle subtended by the humerus during the specified motion [8]. The plot of tendon excursion versus joint angle yielded a curve, the slope of which at any given point defined the instantaneous moment arm vector. Muscles that demonstrated tendon shortening during a motion were defined as agonists and consequently were assigned a moment arm less than 0. Conversely, antagonists displayed tendon lengthening during movement and therefore had moment arms greater than 0.

Motion of the humerus with respect to the scapula was defined according to the Eulerian Angle System based on a X–Z'–X'' rotation sequence. The first rotation

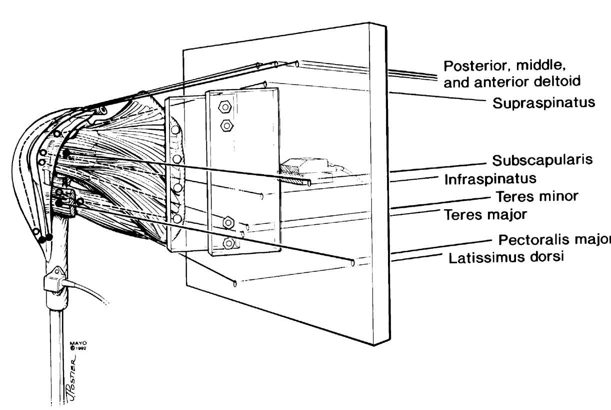

Fig. 1. A diagramatic representation of the experimental set-up, with the shoulder specimen mounted on the plexiglas testing frame and the Dacron lines threaded through their corresponding holes. (Illustration used with permission of Mayo Foundation.)

around the X-axis delineated the plane of elevation. The second rotation about the Z'-axis determined the angle or amount of elevation. The third rotation about the X''-axis corresponded to axial humeral rotation. The glenohumeral neutral position was defined by placing the humeral shaft parallel to the vertebral border of the scapula, with the anterior aspect of the humerus perpendicular to the plane of the infraspinatus fossa on the scapula. In this experiment, the scapula was rigidly fixed. Thus, only glenohumeral and not humerothoracic rotation was measured.

At the completion of the experiment, the shoulder was disarticulated and the 3Space Tracker™ was used as a spatial digitizer to define a reference coordinate system, as well as the geometric center of the glenoid and the humeral head. The centers of the glenoid and of the humeral head were calculated using a least-squares regression analysis from multiple digitized points taken on the glenoid and humeral head.

Axial humeral rotation was studied with the humerus in the neutral position, as well as at the intersections of three vertical planes (coronal, scapular, and sagittal) with one horizontal plane (90° elevation) (Fig. 2). All vertical planes were referenced to the plane of the scapula, which was described by a line connecting the point of intersection of the spine and vertebral border of the scapula and the center of the glenoid. The coronal plane was defined as 30° posterior to the scapular plane and the sagittal plane as 60° anterior. The horizontal plane selected corresponded to 90° of elevation. The scapula was inclined 30° and the glenohumeral joint was

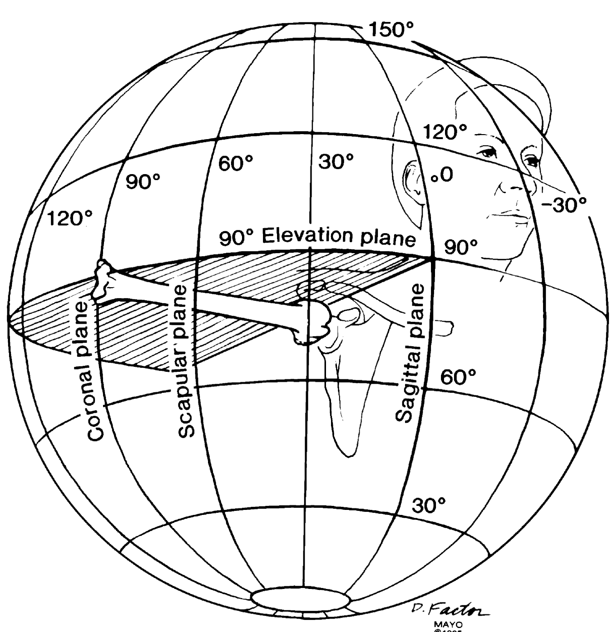

Fig. 2. A global representation of shoulder motion demonstrating the planes of motion studied. (Illustration used with permission of Mayo Foundation.)

elevated 60° based on previous reports describing relative contributions of the scapulothoracic and glenohumeral joints to shoulder motion [9–12]. Thus, in the horizontal plane corresponding to 90° of elevation, axial rotation was measured at the intersections with the coronal, scapular, and sagittal planes. The scapula was fixed in 0° inclination during rotation in the neutral position. The movement consisted of axial humeral rotation from a position of maximal internal to maximal external rotation, which defines the third Eulerian Angle [13].

The same investigator (DKK) performed all of the glenohumeral motions in all specimens. In order to minimize variation between specimens during data collection, an acrylic guide with an adjustable base was used to control motion along the specified planes. These collection techniques were found to be quite reproducible. 3Space Tracker™ data were gathered in real time at 30 data points per second; each range of motion was measured over 5 s. Potentiometer data were obtained simultaneously. The precise glenohumeral position in orientation was subsequently calculated from the kinematic data collected. The kinematic data were converted into screw axis rotations. We then plotted excursion versus the screw axis rotation. Using generalized cross validation splines, the excursion versus screw axis plot was smoothed and differentiated. The slope of this plot at any given point was the instantaneous moment arm for the muscle studied. The moment arm data were multiplied by a ratio of the average humeral head radius to the humeral head radius of the specimen studied to correct for variation in humeral head size. The normalized data for all specimens were then averaged for each degree of motion. The graphs thus generated represent the mean moment arm of a minimum of four specimens at each position.

3. Results

Overall, during external rotation teres minor and infraspinatus were measured to have the greatest amount of tendon shortening and were therefore calculated to have the largest agonist (external rotator) moment arms. Conversely, subscapularis, pectoralis major, and latissimus dorsi tendons were found to lengthen the most and thus had the largest antagonist or internal rotator moment arms (see Figs. 3–6 and Table 1).

With the humerus elevated 90°, the greatest negative value of the moment arm was teres minor regardless of plane, followed by infraspinatus and supraspinatus in the posterior plane (Figs. 3–6). Similarly, subscapularis had the greatest positive moment arm in all planes, followed by pectoralis major, latissimus dorsi and teres major. Supraspinatus and the three portions of the deltoid had both positive and negative values of the

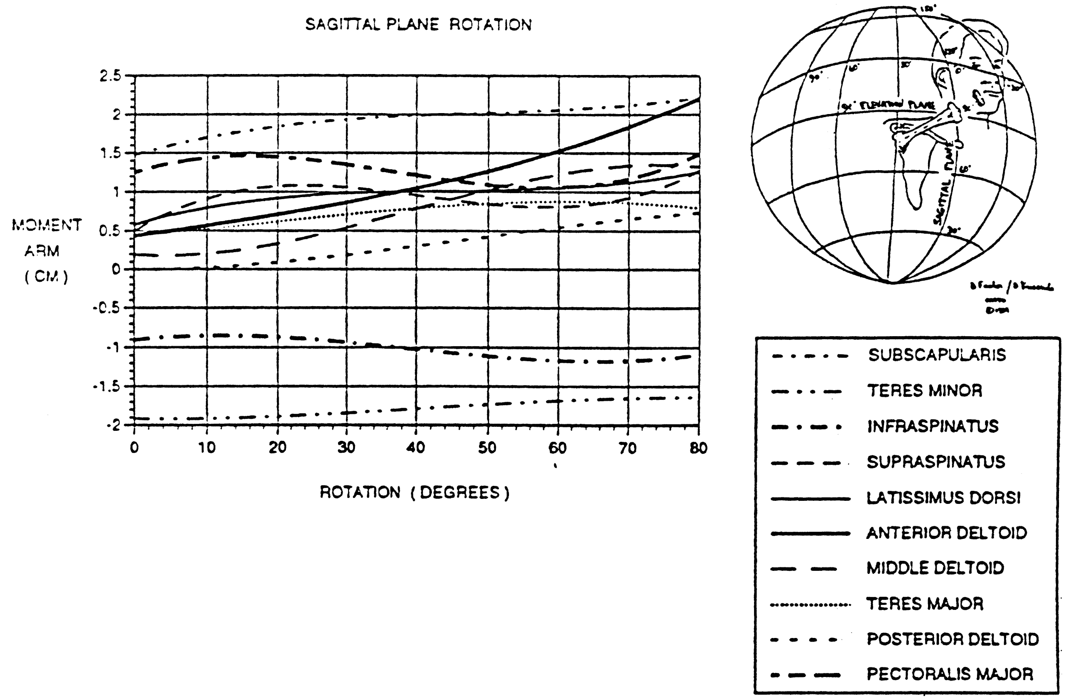

Fig. 3. Instantaneous moment arms with the humerus elevated 90° in the sagittal plane. Positive moment arm represents internal rotation, and negative moment arm represents external rotation. (Illustration used with permission of Mayo Foundation.)

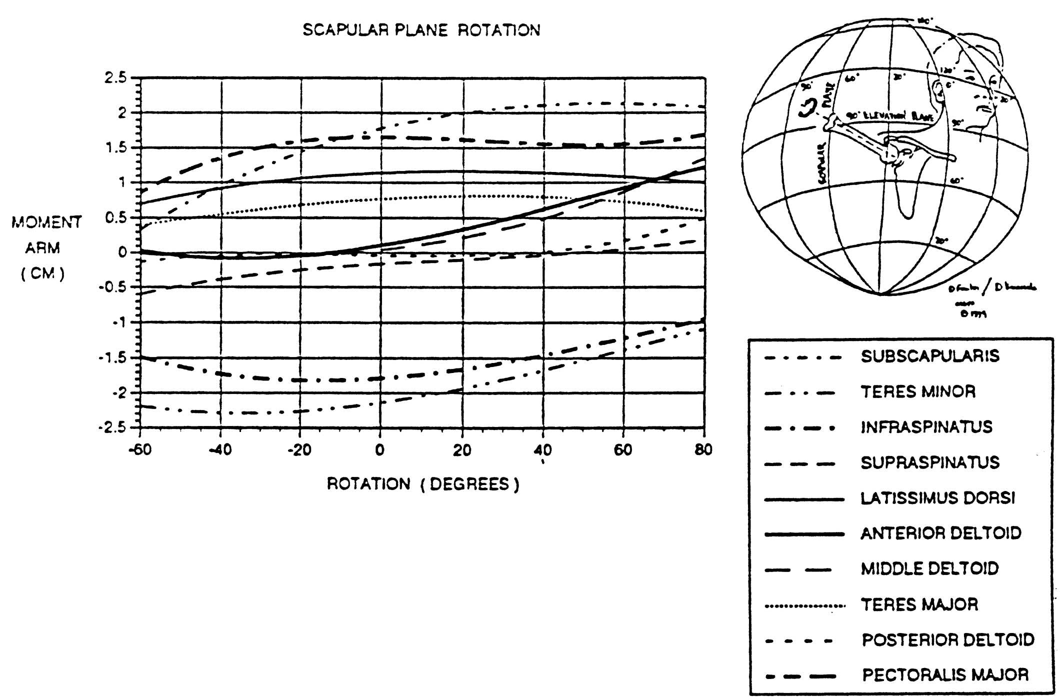

Fig. 4. Instantaneous moment arms with the humerus elevated 90° in the scapular plane. Positive moment arm represents internal rotation, and negative moment arm represents external rotation. (Illustration used with permission of Mayo Foundation.)

moment arm, being positive (internal rotators) in the anterior planes and negative (external rotators) in the posterior planes.

In general, as the plane of humeral rotation was moved from anterior in the sagittal plane to posterior in the coronal plane, the negative value (external rotator)

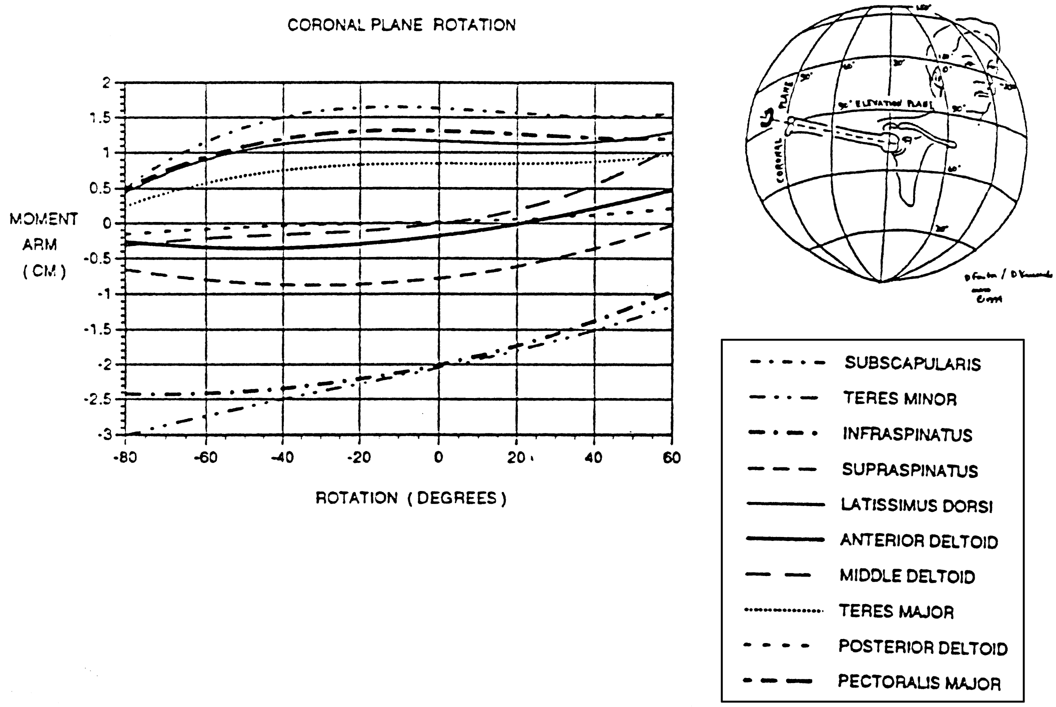

Fig. 5. Instantaneous moment arms with the humerus elevated 90° in the coronal plane. Positive moment arm represents internal rotation, and negative moment arm represents external rotation. (Illustration used with permission of Mayo Foundation.)

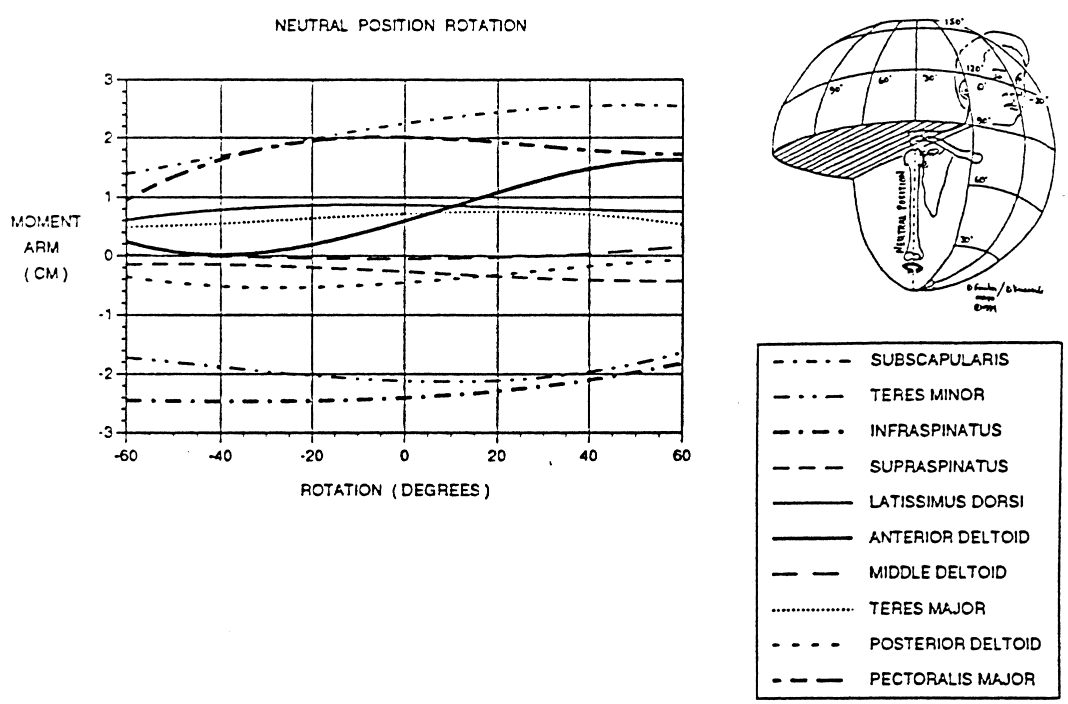

Fig. 6. Instantaneous moment arms with the humerus elevated 90° in neutral elevation. Positive moment arm represents internal rotation, and negative moment arm represents external rotation. (Illustration used with permission of Mayo Foundation.)

of the moment arm became dominant, while the positive value (internal rotator) became decreased. This trend held true for teres minor (mean moment arm sagittal plane: −1.8 cm; coronal plane −2.1 cm), infraspinatus (−1.0; −1.9 cm), supraspinatus (1.0; −0.7 cm), anterior deltoid (1.2; −0.1 cm), subscapularis (2.0, 1.5 cm),

Table 1
Average shoulder muscle moment arms (average moment arm and standard deviation for shoulder muscles during four motions.)[a]

	Neutral rotation (cm)	Sagittal rotation (cm)	Scapular rotation (cm)	Coronal rotation (cm)
SC (S.D.)	2.18 (0.52)	1.98 (0.54)	1.75 (0.40)	1.53 (0.48)
TMi (S.D.)	−2.00 (0.29)	−1.77 (0.26)	−1.94 (0.29)	−2.06 (0.34)
IS (S.D.)	−2.34 (0.29)	−1.03 (0.53)	−1.61 (0.26)	−1.94 (0.29)
SP (S.D.)	−0.27 (0.33)	0.95 (0.39)	−0.14 (0.19)	−0.68 (0.44)
LD (S.D.)	0.82 (0.25)	1.01 (0.35)	1.09 (0.24)	1.13 (0.25)
AD (S.D.)	0.68 (0.39)	1.17 (0.77)	0.32 (0.24)	−0.11 (0.29)
MD (S.D.)	−0.02 (0.07)	0.84 (0.40)	0.26 (0.18)	0.11 (0.19)
TMa (S.D.)	0.67 (0.33)	0.77 (0.40)	0.73 (0.26)	0.81 (0.29)
PD (S.D.)	−0.39 (0.33)	0.35 (0.38)	0.01 (0.08)	0.04 (0.19)
PM (S.D.)	1.84 (0.47)	1.24 (0.41)	1.56 (0.33)	1.22 (0.29)

[a] SC – subscapularis, TMi – teres minor; IS – infraspinatus; SP – supraspinatus; LD – latissimus dorsi; AD – anterior deltoid; MD – mid deltoid; TMa – teres major; PD – post deltoid; PM – pectoralis major.

middle deltoid (0.8; 0.1 cm), and posterior deltoid (0.4; 0.0 cm). The remaining muscles, latissimus dorsi (1.0 cm; 1.1 cm), pectoralis major (1.2 cm; 1.2 cm) and teres major (0.8 cm; 0.8 cm) remained relatively constant throughout.

With the arm at the side in the neutral position, the moment arms were similar (Fig. 6). The greatest negative moment arm was observed in the infraspinatus (mean moment arm: −2.3 cm), followed by teres minor (−2.0 cm), posterior deltoid (−0.4 cm), and supraspinatus (−0.3 cm). Subscapularis (2.2 cm), followed by pectoralis major (1.8 cm), latissimus dorsi (0.8 cm), anterior deltoid (0.7 cm), and teres major (0.7 cm) had the greatest positive moment arms. A mean moment arm of the middle deltoid was approximately equal to 0 in this position. As the humerus was externally rotated from maximal internal rotation, the positive value of the moment arms of subscapularis and anterior deltoid progressively increased while the moment arm of the supraspinatus became slightly more negative. The remaining muscles were relatively unchanged by rotation.

Comparing the neutral versus the elevated positions, infraspinatus, posterior deltoid, subscapularis, and pectoralis major demonstrated maximum mean rotation moment arms with the humerus in neutral. The mean moment arm for teres minor was not remarkably different in the scapular or coronal planes or the neutral position. The maximal moment arm for the remaining muscles occurred with the humerus elevated, and the neutral position moment arm represented either an intermediate or lesser value.

4. Discussion

Shoulder muscle moment arm during axial humeral rotation has been reported by Jiang et al. and Bassett et al. [1,4]. Jiang et al. calculated moment arm values from tendon excursion and joint displacement data, similar to the current study. The authors found infraspinatus and teres minor to have the greatest negative values of moment arm (−2.1 and −2.0 cm, respectively), while subscapularis had the greatest positive moment arm (2.3 cm). The supraspinatus and deltoid showed zero moment arm during rotation.

Our data trends were similar. We also found teres minor and infraspinatus to have the greatest negative values of mean moment arm (−2.0 and −2.3 cm, respectively), being almost identical. In addition, the subscapularis showed the greatest positive mean moment arm at 2.2 cm. The moment arm of the middle deltoid was almost 0. However, we found the posterior deltoid and supraspinatus to have a slightly negative moment arm, and the anterior deltoid to have a lesser positive moment arm in contrast to the previous results.

Bassett et al. [1] determined the biceps and coracobrachialis to have the greatest negative moment arm at a position of 90° of elevation and 90° of external rotation in the coronal plane. Posterior deltoid and supraspinatus showed small negative values, while infraspinatus and teres minor showed almost zero values. The authors also reported latissimus dorsi, teres major, pectoralis major, subscapularis and anterior deltoid to have the positive moment arms. In this study, with the arm positioned similarly at 90° elevation in the coronal plane, even with the arm maximally externally rotated, we found teres minor and infraspinatus to have the greatest negative moment arms. The subscapularis, pectoralis major, latissimus dorsi, and teres major had the greatest positive moment arms. The moment arms of the three deltoid components were close to zero, although at maximal external rotation, all showed some positive moment arms.

The better agreement of the current study with the results of Jiang et al., rather than with those of Bassett et al., likely reflects the greater similarity in experimental design [4,1]. To our knowledge, no author has studied axial rotation with the humerus elevated 90° in the scapular or sagittal planes.

Muscle force production is a function not only of moment arm, but also of muscle size, length–tension relationships, and EMG activity. Acknowledging that joint motion is far more complex than simply a summation of the forces of the surrounding muscles, rising instead from a precise coordination and timing of these forces, additional information may nevertheless be gained by relating muscle moment arm to the other components of force production. This concept has been explored by other authors, most notably Howell et al. [1–3], who described the terms "relative force" and "relative torque". Relative force is the product of muscle size (defined by its physiologic cross-sectional area) and EMG signal during a given motion. Similarly, relative torque is the product of relative force and moment arm. Bassett et al. defined the term "potential moment" as the product of moment arm, physiologic cross-sectional area, and a constant relating cross-sectional area to muscle force (Table 2) [1].

A linear relationship between muscle cross-sectional area and torque production has long been recognized [2]. While considerable variation exists in the reported values for the constant describing this relationship, the value using the current study is 4.7 kg/cm^2 as determined by Ikai and Fukunaga [14]. Cross-sectional area data for the shoulder musculature were recently measured by Veeger [15] and is listed in Table 2.

The potential moment data reflect the trends found in the moment arm data (Tables 1 and 2). By virtue of its larger size, infraspinatus is the most efficient external rotator, regardless of position, followed by teres minor, posterior deltoid (neutral position), and supraspinatus (coronal plane). Similarly, subscapularis and pectoralis major are the most effective internal rotators, again independent of position, followed by latissimus dorsi, teres major, and the three components of the deltoid (sagittal plane).

There are a couple of limitations in this study. First, the moment arm of each muscle was determined by the cable attached to a certain portion of the muscle attachment. When measuring the deltoid, three cables were used to represent three portions of the muscle as it has wide extension of origin. However, in subscapularis, for example, only one cable was attached to the middle portion of the muscle, which may have neglected the function of the other portions of the muscle. Second, the scapula was fixed and the humerus was moved in this experiment. In the living body, the scapula moves on the thorax with the movement of the arm. The major movement of the scapula, abduction/adduction in the coronal plane, occurs with a certain rhythm known as the scapulothoracic rhythm. Thus, the abduction angle of the arm relative to the thorax can be estimated once the glenohumeral angle is known. For example, 60° elevation in this experiment represents 90° elevation of the arm relative to the thorax. However, the scapula also moves slightly in the sagittal and horizontal planes. Therefore, the estimated relationship between the humerus and the scapula may not exactly be the same as the one in vivo. This also is a limitation of the study.

Potential moment and potential torque data may assist with the identification of rehabilitation exercises best able to strengthen the shoulder musculature. Those muscles contributing most to external (infraspinatus, teres minor and posterior deltoid) and internal rotation (subscapularis, pectoralis major) produced either their largest or second largest potential moment value during neutral rotation. There exists a functional antagonism of internal and external rotators. Therefore, the above-mentioned order of functional effectiveness should be restricted on the isolated function. Although potential moment and potential torque data may assist with the identification of rehabilitation exercises best able to strengthen the shoulder musculature, the difference between isolated function and combined function with agonism–antagonism should be kept in mind when generating an exercise plan for physiotherapy.

Table 2
PCSA[a] and potential moment[b] for shoulder muscles during four motions

	PCSA (cm^2)	Neutral rotation (kg cm)	Sagittal rotation (kg cm)	Scapular rotation (kg cm)	Coronal rotation (kg cm)
SC	13.51	139.7	127.0	108.0	95.3
TMi	2.92	−27.4	−24.7	−27.4	−30.1
IS	9.51	−102.8	−44.7	−76.0	−93.9
SP	5.21	−7.4	23.3	−4.9	−17.2
LD	8.64	33.3	41.0	44.3	45.5
AD	7.38	28.4	47.1	10.2	−8.1
MD	9.08	−0.8	35.4	8.5	0.4
TMa	10.02	31.6	36.3	33.0	37.7
PD	9.45	−17.8	15.1	−0.4	0.4
PM	13.65	118.1	80.3	100.2	79.0

[a] PCSA – physiologic cross-sectional area (based on [15]).
[b] Potential moment = PCSA × constant × moment arm; constant = 4.7 kg/cm^2 [14].

Acknowledgements

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References

[1] Bassett RW, Browne AO, Morrey BF, An KN. Glenohumeral muscle force and moment mechanics in a position of shoulder instability. J Biomech 1990;23:405.
[2] deLuca CJ, Forrest WJ. Force analysis of individual muscles acting simultaneously on the shoulder joint during isometric abduction. J Biomech 1973;6:385.
[3] Howell SM, Imobersteg AM, Seger DH, Marone PJ. Clarification of the role of the supraspinatus muscle in shoulder function. J Bone Joint Surg A 1986;68:398.
[4] Jiang CC, Otis JC, Warren RF, Wickiewicz TL. Muscle excursion measurements and moment arm determinations of rotator cuff muscles. Trans ORS 1988;13:441.
[5] Poppen NK, Walker TS. Forces at the glenohumeral joint in abduction. Clin Orthop 1978;135:165.
[6] An KN, Takahashi K, Harrigan TP, Chao EYS. Determination of muscle orientation and moment arms. J Biomech Eng 1984;106:280.
[7] Kuechle DK, Newman SR, Itoi E, Niebur GL, Morrey BF, An KN. Shoulder muscle moment arm during horizontal flexion and elevation. J Shoulder Elbow Surg. 1997;6:429.
[8] An KN, Jacobsen MC, Berglund LJ, Chao EYS. Application of a magnetic tracking device to kinesiologic studies. J Biomech 1988;21:613.
[9] Freedman L, Munro RR. Abduction of the arm in the scapular plane: scapular and glenohumeral movements A roentgenographic study. J Bone Joint Surg A 1966;18:1503.
[10] Howell SM, Galinat BJ, Renzi AJ, Marone PJ. Normal and abnormal mechanics of the glenohumeral joint in the horizontal plane. J Bone Joint Surg A 1988;70:227.
[11] Inman VT, Saunders JR, Abbott LC. Observations on the function of the shoulder joint. J Bone Joint Surg 1944;26:1.
[12] Poppen NK, Walker TS. Normal and abnormal motion of the shoulder. J Bone Joint Surg A 1976;58:195.
[13] Browne AO, Hoffmeyer P, Tanaka S, An KN, Morrey BF. Glenohumeral elevation studied in three dimensions. J Bone Joint Surg B 1990;72:843.
[14] Ikai M, Fukunaga T. Calculation of muscle strength per unit of cross-sectional area of human muscle by means of ultrasonic measurements. Int Zangewandte Physiol 1968;26:26.
[15] Veeger HE, Van der Helm FC, Van der Woude LH, Pronk GM, Rosendal RH. Inertia and muscle contraction parameters for musculoskeletal modelling of the shoulder mechanism. J Biomech 1991;24:615.