Glenohumeral mechanics: A study of articular geometry, contact, and kinematics

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Stereophotogrammetry was used to investigate the functional relations between the articular surface geometry, contact patterns, and kinematics of the glenohumeral joint. Nine normal shoulder specimens were elevated in the scapular plane by using simulated muscle forces in neutral rotation (NR) and starting rotation (SR). Motion was quantified by analyzing the translations of the geometric centers of the humeral head cartilage and bone surfaces relative to the glenoid surface. In both NR and SR, the ranges of translations of the center of the humeral head cartilage surface were greatest in the inferior-superior direction (NR 2.0 ± 0.7 mm, SR 2.9 ± 1.2 mm). Results of this study also show that joints with less congruence of the articular surfaces exhibit larger translations, and elevation in SR yields greater translations than in NR. Kinematic analyses with the humeral head bone surface data yielded larger values of translation than analyses that used the cartilage surface data, suggesting that similar overestimations may occur in radiographic motion studies. Results of this study demonstrate that small translations of the humeral head center occurred in both SR and NR. The proximity of the origin of the helical axes to the geometric center of the humeral head articular surface confirmed that glenohumeral elevation is mainly rotation about this geometric center with small translations. (J Shoulder Elbow Surg 2001;10:73-84.)

INTRODUCTION

Functional stability of diarthrodial joints is believed to be important in maintaining the health and longevity of their articular cartilage surfaces.[31] The glenohumeral joint has minimal bony constraint, allowing it the largest range of motion of any major diarthrodial joint in the human body.[1,15,20,22,47] In general, glenohumeral joint stability is provided by both static (ligamentous restraints and articular surface contacts) and dynamic (muscular loading) components. Alterations in either the anatomy of the joint or deficiencies in the intrinsic biomechanical properties of the ligamentous and/or capsular components can cause motion abnormalities and focal contact stresses to develop.[8,29,35,37] These sites of high contact stresses may initiate focal lesions to develop on the articulating surfaces and will tend to exacerbate the rate of cartilage degeneration leading to osteoarthritis.[21,31]

While recent studies have characterized the stress-strain laws and intrinsic properties of articular cartilage and capsular ligaments,[6,29-31,42] differing opinions exist concerning normal or abnormal glenohumeral joint kinematics. Some researchers believe that the normal glenohumeral joint behaves as a "ball and socket," allowing only small translations possible due to deformation of the articulating surfaces and small differences in their radii.[22,33] Others feel that the joint is relatively unconstrained, allowing larger translations through the range of motion.[20] This lack of consensus has motivated a number of differing approaches on the development and refinement of treatment interventions aimed at improving shoulder mechanics.

The earliest shoulder studies documented the motion of the clavicle, scapula, and upper portion of the sternum.[9,10] Later, classic radiographic studies investigated glenohumeral motion in the frontal[25] and scapular[19] planes, as well as motion in normal and abnormal joints.[33] Poppen and Walker[33] reported that in normal shoulders, the geometric center of the humeral head did not exhibit translations of more than 1 or 2 mm through the midrange of motion. A more recent in vivo radiographic study of patients with anterior instability found that anterior translation of the humeral head occurred during motion in the horizontal plane.[23] The same study demonstrated that in healthy subjects,

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in the position of maximum extension and external rotation (ie, the cocked stage of the throwing motion), the center of the humeral head was positioned approximately 4 mm posterior to the center of the glenoid cavity. A cadaver study of passive manipulation of the humerus documented excessive translations of the humeral head on the glenoid at the extremes of cross-body motion.[20] Recently, a technique to reproduce the position of the humerus with respect to the glenoid in space was described in a study that demonstrated that the maximum humeral elevation occurred in a plane anterior to the scapular plane.[1] More recently, an optical stereophotogrammetry (SPG) technique has been used in our laboratory to quantify the 3-dimensional kinematics of the normal glenohumeral joint and the effect of anterior capsular tightening on joint mechanics.[5,27] These SPG studies have shown that the normal shoulder exhibits very small translations of the center of the humeral head during elevation in the scapular plane, and that tightening of the anterior capsular structures results in a posterior translation and shift in glenoid contact when compared with the results in untightened shoulders.[39]

While a number of previous studies have separately analyzed the geometry of the joint[24,28,36,38] and its motion characteristics,[19,20,25,33] very little quantitative data exist relating the 3-dimensional kinematics of the glenohumeral joint to its articular geometry. An earlier SPG study has shown that on average, the radii of curvature of mating glenoid and humeral head cartilage surfaces are closely matched.[38] However, in individual joints, a greater radius mismatch can exist. The primary hypothesis of this study is that the amount of translation of the humeral head on the glenoid is related to the conformity of the articulating surfaces (ie, larger translations occur in joints with lesser conformity of the articulating surfaces).

A certain degree of external rotation is necessary to elevate the humerus fully.[11] However, it has been observed clinically that patients who are prone to dislocate anteroinferiorly tend to compensate by elevating their arms in less external rotation. Therefore, the second hypothesis of this study is that the clinically defined neutral position (ie, zero external rotation or NR) provides greater stability during elevation than a position of external rotation.

Soslowsky et al[38] demonstrated that whereas the articulating glenohumeral cartilage surfaces on average are very conforming, there is a large difference in the radii of the humeral head and glenoid bone surfaces. Thus the third hypothesis of this study is that because the bone and cartilage surfaces have different topographies and thus different geometric centers, a significant difference exists in results of kinematic analyses that use cartilage surface data when compared with those that use subchondral bone surface data. In this study, the effects of articular surface congruence differences in kinematic analyses with articular cartilage and subchondral bone surface data are quantified.

MATERIALS AND METHODS

The experimental protocol was based on the technique developed by Soslowsky et al.[39] A brief description of the methodology and modifications to the original protocol is provided. The soft tissues surrounding the glenohumeral joints of 9 fresh frozen human cadaveric shoulders (average age 50 years, range 42 to 59 years; 4 lefts and 5 rights; 2 right-left pairs) were dissected away while the deltoid, rotator cuff tendons, glenohumeral capsule, subacromial bursa, and coracoacromial and coracohumeral ligaments were maintained. Specimens were regularly moistened with physiologic saline solution with protease inhibitors during dissection, preparation, and testing to retard specimen degradation. Only normal shoulders (defined as those without rotator cuff tears, fractures, or visual signs of arthritis) were used in this study.

Six flexible cables, 3 simulating rotator cuff muscles (supraspinatus, subscapularis, and a combined infraspinatus and teres minor), and 3 simulating the anterior, middle, and posterior heads of the deltoid were attached to 6 adjustable worm gear mechanisms each in series with a calibrated spring scale (Figure 1, *A*). Care was taken during dissection to identify, expose, and establish the origins and insertions of all 6 simulated muscles to establish their lines of action. For the subscapularis and infraspinatus, which have broad origins on the scapula, at the time of dissection, an eyehook was placed midway (in the inferior-superior span of the muscle origin) at the medial border of the scapula to provide a line of action for the muscle. Once the lines of action had been determined, the muscles were resected immediately proximal to the musculotendinous insertions of the rotator cuff tendons and the humeral shaft insertions of the 3 heads of the deltoid.

A Dacron strip was sutured onto the articular and bursal surfaces of the tendinous insertion of each rotator cuff tendon. The Dacron strip was then looped over a thin cylindrical metal rod to provide uniform loading across the width of the tendon. Each flexible cable was passed through the cylindrical rod, threaded through an eyehook that was carefully positioned to pass through the anatomic line of action for that muscle (Figure 1, *B*), and attached in series to a calibrated spring scale and worm gear mechanism (Figure 1, *A*).

A bicortical screw was placed transversely through the humerus at the insertion of each head of the deltoid. A channel suspended above from a semicircular plate allowed precise positioning of the origin of each head of the deltoid, without sacrificing the integrity of the acromion (Figure 1, *B*). A flexible cable was threaded around each cortical insertion screw, passed through its respective channel, and again attached in series to a calibrated spring scale and worm gear mechanism. For the first 2 specimens, before humeral condyle resection, a Kirschner wire was placed distal to the deltoid insertions and parallel to the condylar axis to help visually maintain constant humeral rotation during elevation. A lightweight humeral alignment plate was used for the last 7 specimens and was maintained parallel to a vertical surface representing the scapular plane. This design more

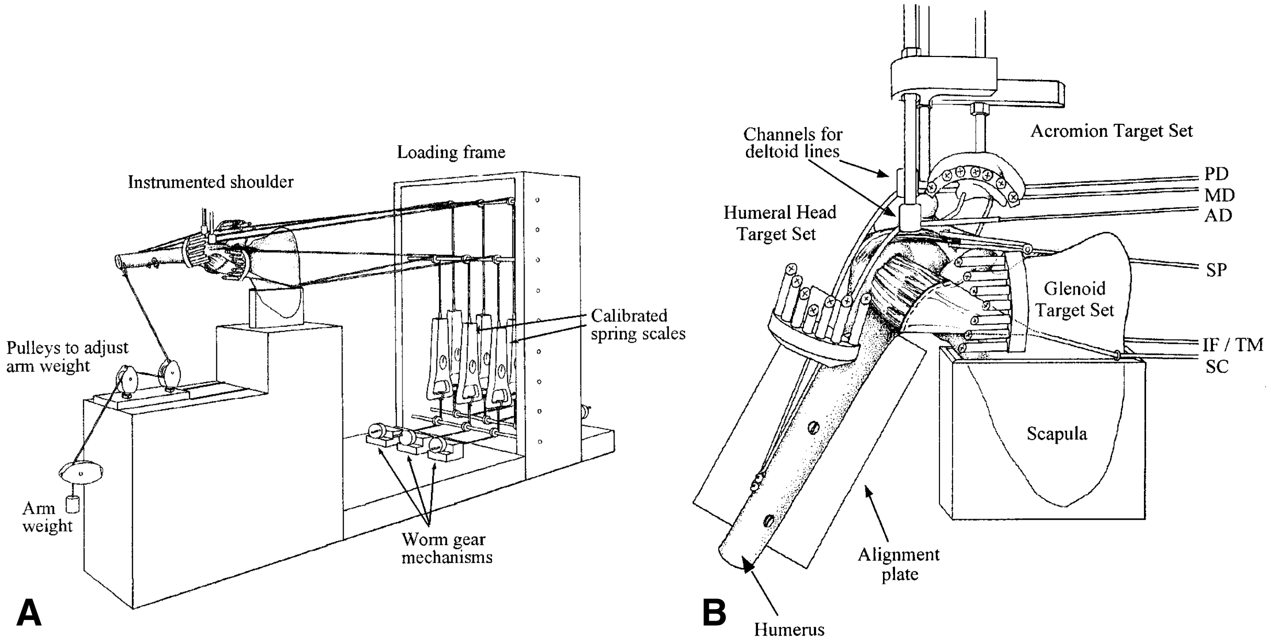

Figure 1 Shoulder rig **(A)** and schematic of instrumented shoulder **(B)**. Simulated muscles included the subscapularis *(SC)*; supraspinatus *(SP)*; infraspinatus/teres minor *(IF/TM)*; anterior deltoid *(AD)*; middle deltoid *(MD)*; and posterior deltoid *(PD)*.

accurately ensured that a constant amount of external rotation was maintained at higher elevations. During the experiment, the amount of glenohumeral abduction was measured with a goniometer centered behind the humeral head and aligned with the shaft of the humerus. In the final analysis, the precise magnitude of glenohumeral abduction was obtained from the SPG kinematic analysis (see below). The lower portion of the scapula was rigidly fixed with the plane of the scapula at a 20° anterior tilt, and with its medial border vertical, representing its position in the body at 0° of elevation (Figure 1, *B*). Arm weight was simulated by attaching a 3.2-kg mass at a fixed distance from the center of rotation of the humeral head,[39,45] and its line of action was adjusted for each position of elevation to account for the effects of gravity and physiologic scapular tilt.[39] In addition, the contribution of glenohumeral elevation to total arm elevation was determined from previous studies[16,19,33,39] so that motion at the glenohumeral joint represented the reported total arm elevation.

Codman[11] demonstrated that to achieve maximal elevation of the humerus, the arm had to be rotated externally by a certain amount to allow the greater tuberosity to pass below the acromion. For each of the 9 specimens in this study, this amount of external rotation was determined by passively elevating the arm. This characteristic degree of external rotation was called *starting rotation* (SR) and averaged 18° ± 4° from the clinically defined neutral rotation NR (corresponding to 0° of external rotation).[41] The ranges of applied muscle loads were based on anatomic, mechanical, and electromyographic data, following the protocol developed by Flatow et al[18] and Soslowsky et al.[39] By coordinating the tension on each simulated muscle to maintain SR, the humerus was elevated in 10° increments from zero to maximum elevation in the scapular plane. The arm was brought down to zero elevation, and the range of elevation repeated in NR (zero external rotation) in the scapular plane. Repeatability in joint positioning in the lateral-medial (L-M), inferior-superior (I-S), and posterior-anterior (P-A) directions was found to be 0.15 mm, 0.35 mm, and 0.2 mm, respectively.

The kinematic analysis of the glenohumeral joint motion was accomplished optically with SPG by using precision optical targets attached to the humerus and glenoid (Figure 1, *A*), as described previously.[3,38,39] Once the ranges of motion were completed, the joint was disarticulated, and the topographies of the humeral head and glenoid cartilage and subchondral bone surfaces were quantified with SPG.[3,39] The articular layer thickness was also determined in 7 of the specimens with the method described by Ateshian et al.[3] The accuracy of the SPG measurements in our system has been previously determined to be 90 µm at a 95% confidence level in the least favorable direction.[3]

Spheres that best approximated the humeral head and glenoid cartilage and subchondral bone surface data were fitted to the geometric surfaces. Deviations from sphericity[38] were less than 1% of the radius of the surface, indicating that the humeral head and glenoid surfaces may in fact be represented by portions of spheres. The centers of curvature of the spheres fitted to the cartilage and bone surfaces of the humeral head were used to determine the translation of the humeral head on the glenoid at various angles of elevation. Contact analyses were performed with the proximity technique described earlier,[4,37,39] and the finite helical axis parameters were calculated with the technique[40,44] to complete the kinematic description of the glenohumeral joint motion.

Paired Student *t* tests were performed to compare the ranges of translation in SR and NR, the ranges of translation with cartilage surface data and subchondral bone surface data, and the radii of matched humeral head and glenoid cartilage and subchondral bone surfaces. Linear correlation coefficients were calculated to determine the correlation, if any, between cartilage surface congruence and ranges of translation.

RESULTS

Articular geometry

The average radii of the humeral head and glenoid articular surfaces were 25.5 ± 1.5 mm and 27.2 ± 1.6 mm, respectively. The difference in the radii of curvature of matching humeral head and glenoid cartilage surfaces was 1.7 ± 1.5 mm (range –1.2 to 3.8 mm). There was one joint in which the radius of curvature of the humeral head cartilage surface (R_H) was greater than that of the articulating glenoid cartilage surface (R_G) (ie, R_H-R_G = 1.2 mm).

Mathematical spheres were also fitted to the humeral head and glenoid subchondral bone surfaces. The average radii of curvature for the humeral head and glenoid bone surfaces were 25.2 ± 0.7 mm and 33.4 ± 3.4 mm, respectively. There was no statistical difference between the radii of curvature of the humeral head cartilage and humeral head subchondral bone surfaces. The glenoid subchondral bone surfaces had significantly larger ($P < .005$) radii of curvature than the corresponding glenoid cartilage surfaces. All glenoid subchondral bone surfaces had a larger radius of curvature than the matching humeral head bone surfaces.

Translation of the humeral geometric center

The position of the center of the humeral head cartilage surface at 90° was taken as a reference position for reporting humeral head translations. The position of 0° was not selected as the reference position because all joints had been vented and, as such, subluxated inferiorly at 0°. For each 10° increment of elevation, the deviation of the center of the humeral head from the reference position was calculated and averaged over the number of specimens. Results for left shoulders were converted to right-shoulder equivalents for comparison purposes.

In SR, along the L-M, I-S, and P-A directions, the translation values resulted in root-mean-square (rms) deviations of 0.26 mm, 0.68 mm, and 0.41 mm, respectively (Figure 2). These motions were considered small in relation to the size of the joint (<3% of R_H). In NR, the center of curvature of the humeral head also remained relatively stationary (rms of deviations in L-M = 0.19 mm, I-S = 0.59 mm, and P-A = 0.32 mm) through the range of motion (Figure 3).

The range of translation is defined as the difference between the maximum and minimum excursion of the humeral head center of curvature relative to the glenoid in each of the 3 anatomic directions. The average ranges of translation in SR, as derived from the cartilage surfaces, were 0.9 ± 0.2 mm in L-M, 2.9 ± 1.2 mm in I-S, and 2.2 ± 1.1 mm in P-A. The average ranges of translation in SR, as derived from the subchondral bone surfaces, were 1.1 ± 0.3 mm in L-M, 3.5 ± 1.0 mm in I-S, and 2.4 ± 1.1 mm in P-A.

The average ranges of translation in NR for the cartilage surfaces of the humeral head were 0.7 ± 0.3 mm in L-M, 2.0 ± 0.7 mm in I-S, and 1.2 ± 0.6 mm in P-A. The average ranges of translation in NR for the subchondral bone surfaces of the humeral head were 0.9 ± 0.3 mm in L-M, 2.7 ± 0.7 mm in I-S, and 1.4 ± 0.7 mm in P-A.

Statistical comparison of the ranges of humeral head translation demonstrated that bone surface data generally yielded larger values than those obtained with the use of cartilage surface data (Figure 4). In SR, along the I-S direction, the range of bone surface translation was significantly larger ($P < .05$) than that for the cartilage surface. In NR, along all 3 directions, the bone surface data yielded significantly higher ranges of translation than the cartilage data (I-S and P-A: $P < .05$; L-M: $P < .005$).

Effect of congruence

Congruence of a joint can be defined as the difference in the radii of curvature of its articulating surfaces. Of the 54 ranges of translation (9 specimens × 3 directions × 2 modes) for the cartilage surface data, only 4 cases (3 in I-S and 1 in P-A; all 4 in SR) had a range of translation that exceeded 4.0 mm. Of these 4, 2 of the 3 cases in I-S were in joints that had the largest mismatch between glenoid and humeral head cartilage radii of curvature. The third case in I-S was in a joint that was subluxated inferiorly at the zero position and demonstrated only 2.8 mm of translation between 30° and 180°. A moderately high correlation ($r = 0.7$) was found between incongruence and I-S translation, with less congruent joints demonstrating larger ranges of translation as well as shifts in contact (Figure 5). No correlation was seen between incongruence and ranges of translation in the P-A and L-M directions, and none existed between the congruence of the joint and the maximal elevation achieved in either SR or NR.

Effect of humeral rotation

Comparison of the ranges of translation of the center of the humeral head cartilage surface demonstrated that elevation in SR yielded consistently larger translations than elevation in NR (Figure 6). In the L-M direction, whereas the SR values demonstrated a trend toward being larger than in NR, the difference was only significant at the level of $P = .06$. In the I-S and P-A directions, however, the ranges of translation in SR were significantly higher ($P < .005$) than in NR. These larger translations consequently led to anteroinferiorly shifted contact patterns on the glenoid cartilage surface, especially in less congruent joints (Figure 5). In NR, the ranges of transla-

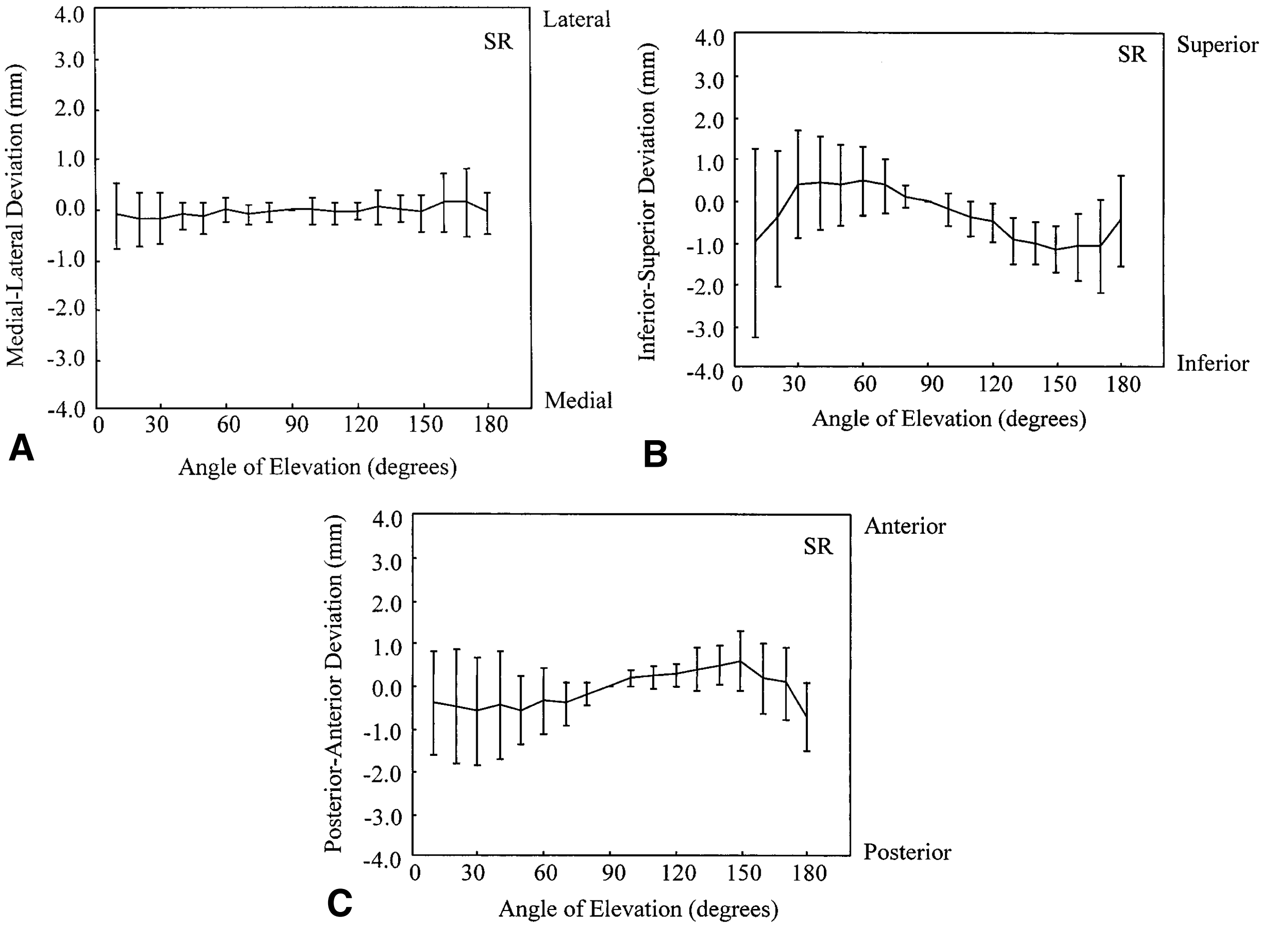

Figure 2 Line graphs showing the position of the center of the humeral head cartilage surface in starting rotation *(SR)* in medial-lateral **(A)**, inferior-superior **(B)**, and posterior-anterior **(C)** directions. Data represent means ± standard deviations.

tion of the humeral head cartilage surface were less than 3.0 mm for all joints in all directions. Maximum elevations of 180° in 5 specimens, 170° in 1 specimen, 160° in 2 specimens, and 150° in 1 specimen were achieved in SR. When arm elevation was performed in NR, maximum elevation equivalent to 160° in 1 specimen, 140° in 4 specimens, 130° in 3 specimens, and 120° in 1 specimen were achieved. As expected, all specimens reached higher elevation in SR than in NR. However, no significant correlation was noted between the maximum elevation in SR and that in NR.

Helical axis analysis

The finite helical axis for each 30° increment in elevation was plotted for each specimen in relation to its humeral head articular cartilage geometric center. The proximity of the helical axes to this geometric center represents the ball-and-socket nature of the joint. The helical axes for a more congruent and a less congruent joint are shown in Figure 7.

DISCUSSION

This study was performed to test the following hypotheses:

1. The amount of translation of the humeral head on the glenoid is related to the conformity of the articulating surfaces. The results of this study partially support this hypothesis because a moderately high correlation was found between incongruence and I-S translation.
2. The clinically defined neutral position (ie, zero external rotation or NR) provides greater stability during elevation than a position of external rotation (ie, SR). This hypothesis was supported by the finding that translations in the I-S and P-A directions were significantly higher in SR than in NR.
3. Due to the difference in cartilage and bone surface topography, a significant difference exists in the results of kinematic analyses with the use of cartilage surface data when compared with those that used

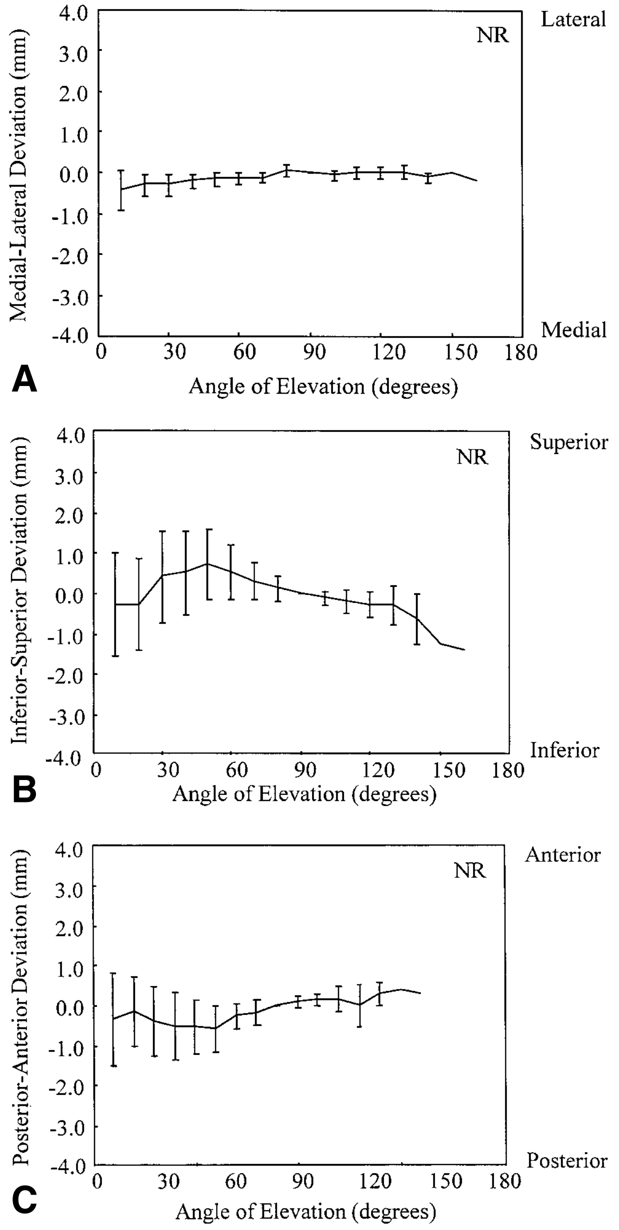

Figure 3 Line graphs showing the position of the center of the humeral head cartilage surface in neutral rotation *(NR)* in medial-lateral **(A)**, inferior-superior **(B)**, and posterior-anterior **(C)** directions. Data represent means ± SD.

bone surface data. This hypothesis was also supported by the results of this study because a significantly greater translation was observed in the I-S direction when using translation data derived from the centers of curvature of subchondral bone surfaces rather than of cartilage surfaces.

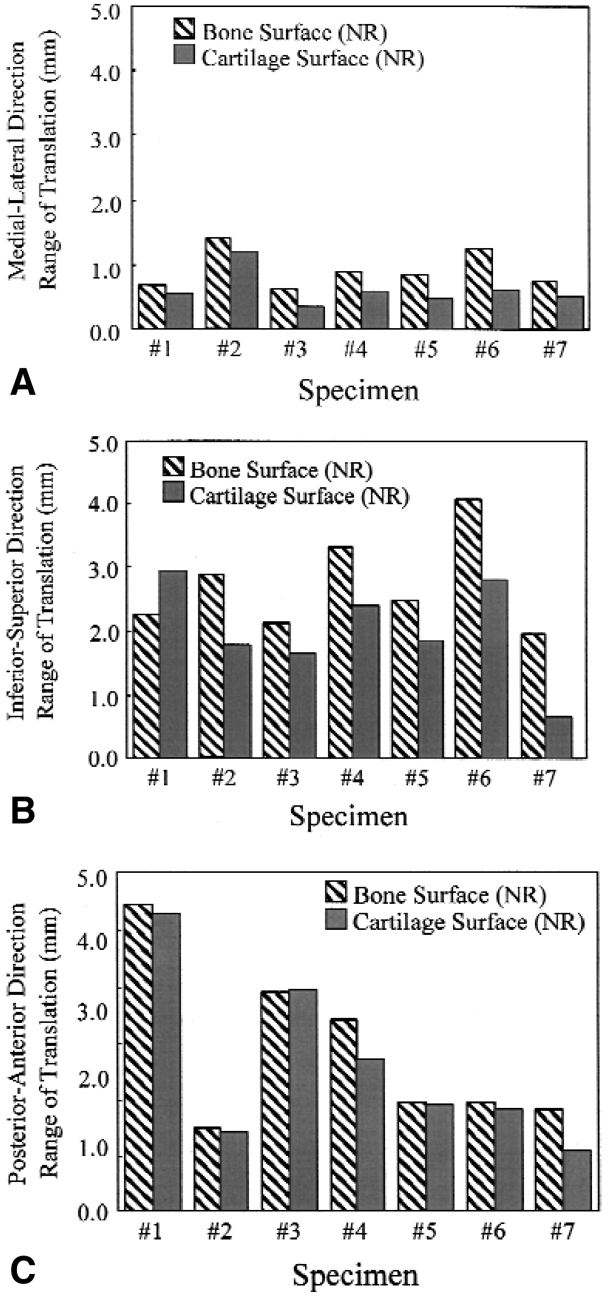

Figure 4 Bar graphs showing ranges of translations in neutral rotation *(NR)* for the medial-lateral **(A)**, the inferior-superior **(B)**, and the posterior-anterior **(C)** directions. The *solid bars* represent ranges of translation obtained from the cartilage surface data, whereas the *hatched bars* represent ranges of translations obtained from the subchondral bone surface data.

A more complete understanding of the mechanics of a joint is obtained when the articular geometry, kinematics, and contact patterns are studied together, rather than in isolation, allowing examination of the interactions among the various factors. In the shoulder, as in all other diarthrodial joints, the articular cartilage surface geometry (representing the structure) influences the contact areas and kinematics (representing the function) of the joint.

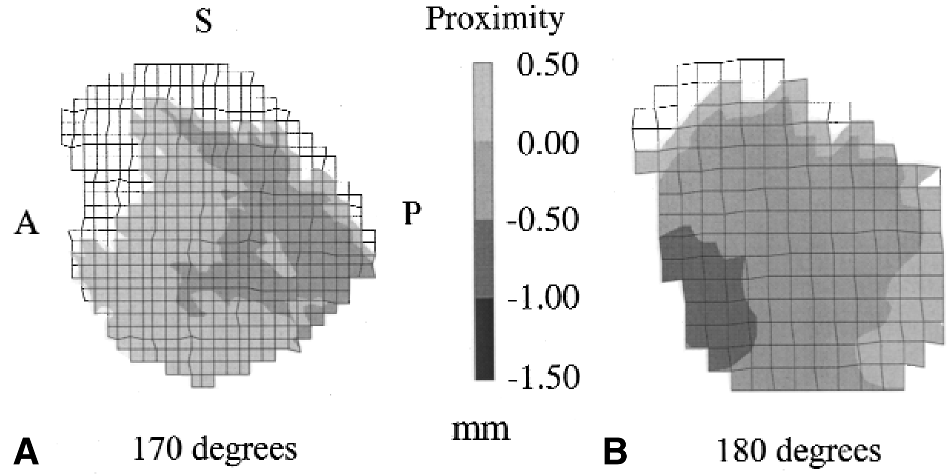

Figure 5 Glenoid contact maps for a more congruent joint showing more evenly distributed contact **(A)** and a less congruent joint showing anteroinferiorly shifted contact **(B)**. The *grid* represents the photographic grid that was projected onto each specimen. *A,* anterior; *S,* superior; *P,* posterior.

An issue of debate among researchers and clinicians is whether the glenohumeral joint behaves as a closely conforming joint, or whether large differences exist between the radii of articulating glenoid and humeral head surfaces. This study investigates the relations that exist among these factors in the glenohumeral joint.

Congruence, a measure of the conformity between two surfaces, can be defined as the difference in the radii of curvature of the humeral head and the glenoid. The closer this difference is to zero, the more congruent is the joint. Our laboratory has previously reported that although there is a range of congruence, on average the glenoid and humeral cartilage surfaces are closely conforming.[38] Although the current study of 9 shoulders found a small difference between the average radii of the humerus (25.5 mm) and glenoid (27.2 mm) cartilage surfaces, a prior larger study, which was designed to investigate the articular anatomy, examined 32 shoulders and found minimal difference between the average for the humerus (25.0 mm) and glenoid (24.9 mm) cartilage surfaces. However, individual shoulders can and do have variations in conformity. The results suggest that within a range of glenohumeral congruence, there may be a range of translations that does not subject the surfaces to abnormal loading (eg, edge loading on the glenoid, or smaller contact areas). The larger ranges of translations occurring in joints with reduced congruence, however, may lead to more detrimental loading conditions.

The glenohumeral joint surface geometry is considered less of a stabilizing factor because of the smaller surface area of the glenoid in comparison with the humeral head and the apparent shallowness of the glenoid. Before the advent of technology such as open MRI, which now allows visualization of cartilage surfaces through a range of motion, radiography was the standard technique used to study the geometry and kinematics of the glenohumeral joint.[19,25,33] Plain radiographs, however, depict only the bony surfaces. The subchondral bone surfaces are less congruent than the true articulating cartilage surfaces because of the varying cartilage thickness.[38] Results of this study comparing both bone and cartilage surfaces confirm the findings of Soslowsky et al,[38] which demonstrate that the articulating cartilage surfaces are much more conforming than suggested by the underlying subchondral bone surfaces. This re-emphasizes why some investigators, on studying only the glenohumeral bone surfaces, have concluded that the joint is not very conforming. Thus, if the stabilizing role of the articulating surfaces of the glenohumeral joint is less than in other joints, it is not because of the incongruence in the joint that is incorrectly perceived when observing the bony geometry, but rather it is the result of the smaller surface area of the glenoid in comparison with the humeral head. The perception of incongruence sometimes also arises from mathematical artifact. Several of the previous studies of glenohumeral geometry have relied on a limited number of measurements on each surface.[28,36] Whereas on the humeral head, the choice of a limited number of measurements does not dramatically affect the determination of the radius, on the glenoid (which represents a smaller portion of a spherical surface), the use of a limited number of measurement points coupled with the noise inherent in all such measurements could lead to large errors (eg, up to 25% of the actual value) in the determination of the glenoid radius of curvature.

Ranges of translation of the humeral head center can be considered quantitative measures of the func-

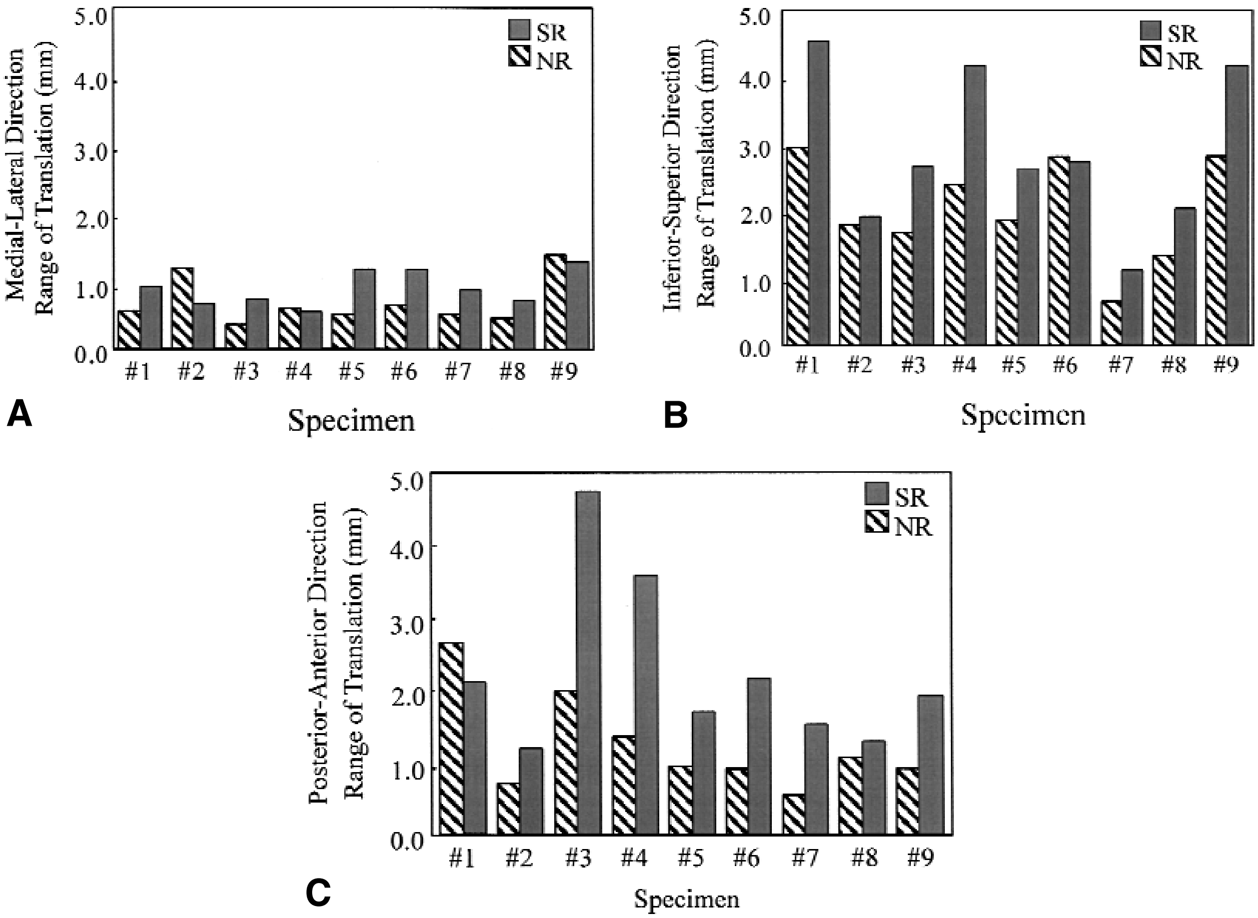

Figure 6 Bar graphs showing ranges of translations in neutral rotation *(NR)* and starting rotation *(SR)* for the medial-lateral **(A)**, inferior-superior **(B)**, and posterior-anterior **(C)** directions. The *hatched bars* represent ranges of translations in NR, whereas the *solid bars* represent ranges of translation in SR.

tional stability of the glenohumeral joint in the 3 principal anatomic directions. Results of the current study demonstrate that during active elevation of the humerus in the scapular plane with the use of simulated muscles, there are small translations in all 3 anatomic directions in SR and NR. In both NR and SR, translations in the L-M direction are expectedly very small because of the restraint provided by the capsuloligamentous and muscular tissues in the lateral direction and the glenoid surface in the medial direction. The position of the center of the humeral head in the I-S direction is in agreement with the observations of Poppen and Walker,[33] who reported that the humeral head initially migrated superiorly and thereafter remained fairly constant ("moving only one millimeter or at most two millimeters upward or downward between each successive position"). The position of the humeral head center at the upper extreme of motion in this study is in agreement with results from radiographic[43] and stereophotogrammetry contact[39] studies that demonstrate a posterior position of the humeral head and a posterior shift of contact on the glenoid at higher elevations.

This study demonstrates that the position of external rotation, SR, is associated with higher ranges of translation than NR. Elevation in SR increases the P-A range of translation by almost 100% over that in NR. Therefore, while SR allows the glenohumeral joint a greater range of motion than NR (ie, higher maximal elevation), it also represents a mode of elevation in which the humeral head may be functionally less stable. We believe that in SR, the posterior head of the deltoid is substantially less effective because of a reduction of its moment arm about the axis of rotation. Furthermore, the inferior glenohumeral ligament provides an anterior restraint only against large humeral head translations, whereas the externally rotated middle deltoid provides a continuous restraint in the posterior direction through the range of motion.[6,43] The resulting asym-

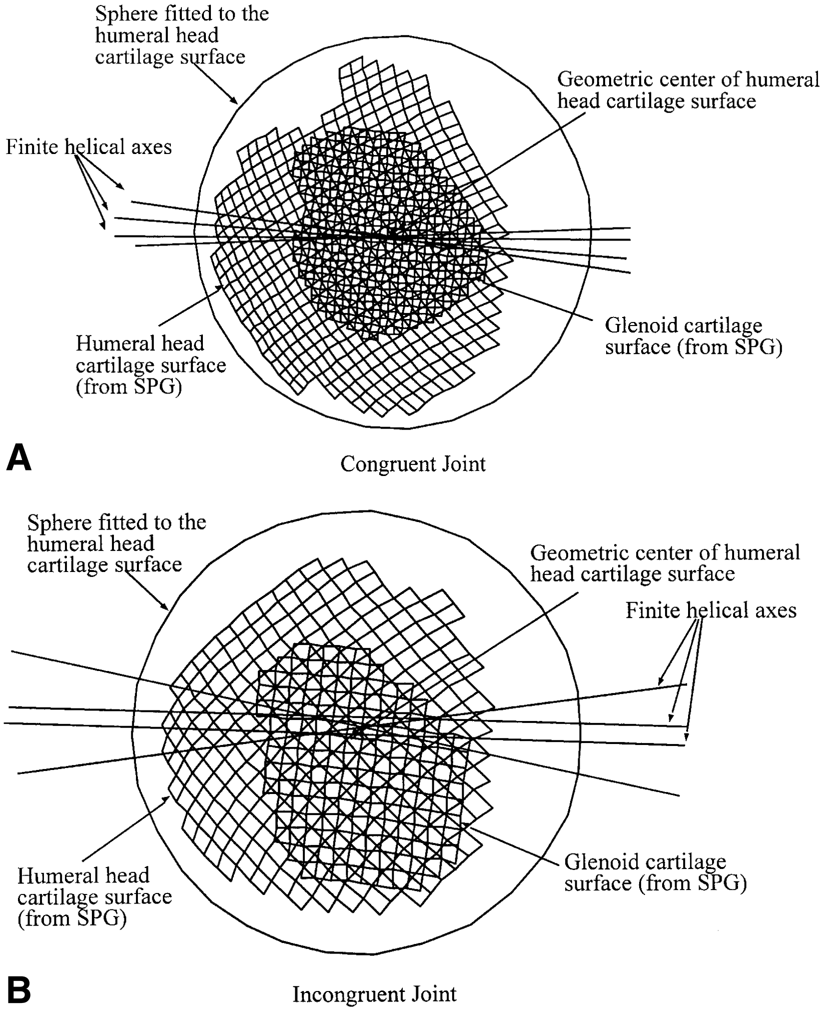

Figure 7 Helical axes for a more congruent joint **(A)** and a less congruent joint **(B)**. *SPG,* Stereophotogrammetry.

metric action of the deltoid provides less dynamic stability, thereby allowing a greater range of translation. In NR, the deltoid functions more symmetrically, thereby maintaining the humeral head in a more stable position. This interpretation may explain why patients who tend to dislocate anteriorly, compensate by elevating their arms in relatively less external rotation (ie, avoiding the apprehension position). The center of the humeral head exhibits characteristic tracking patterns through the range of motion. The superior translation in the first 60° of elevation can be attributed to centering of the initially inferiorly subluxated humeral head. This inferior laxity at the zero position may be the result of either the relatively unloaded states of the muscles and/or loss of the intraarticular "vacuum effect" (all joints in this study were vented before kinematic testing to avoid artifact caused by accidental venting and to provide a consistent baseline for a subsequent study). At higher elevations, inferior translation could be caused by the inferiorly directed lines of action of the infraspinatus and subscapularis, as suggested by Poppen and Walker.[34]

The rms deviations for the center of the humeral head in the L-M, I-S, and P-A directions are shown in Figure 2. In our study, a larger-than-average incongruence in a joint was associated with larger anteroinferior translation of the humeral head and an anteroinferior shift of contact on the glenoid in that particular joint (Figure 5).

Larger ranges of translation may occur in joints with decreased congruence and/or abnormal musculoligamentous structure. Because of the surface area disparity between articulating glenoid and humeral head surfaces,[38] a loading imbalance exists, wherein through a range of motion, the glenoid surface is subjected to a higher duty cycle (duration of loading) than the humeral head. Large translations could cause altered loading, contact areas and contact stresses on the articular surfaces, and may predispose the more frequently loaded glenoid surface to early cartilage degeneration.[14,32]

Several studies have presented methods for evaluation of the finite helical axis parameters from target position data[2,40,44,46] and have determined the effect of target measurement noise on these parameters.[12,46] Woltring et al[46] demonstrated that stochastic errors in the determination of the position and direction of the finite helical axis are inversely proportional to the finite rotation magnitude. Smoothing of noisy target data and choosing larger rotation increments between positions are techniques used to reduce the stochastic error in the determination of the helical axis parameters. In this study, increments of 30° between positions were used for helical axis parameter determination, and no smoothing of the target data was performed. The proximity of the helical axes to the center of curvature of the humeral head cartilage surface (Figure 7) indicates that elevation in the scapular plane is primarily rotation about the geometric center of the humeral head with small translations. For pure planar rotation, in the absence of all translations, the helical axes would superpose on one another. The observed deviation of the helical axes from this ideal configuration (Figure 7) can be attributed to the small translations of the humeral head center and to slight deviations from purely planar motion.

Harryman et al[20] have reported that excessive translations occurred, especially at the extremes of passive cross-body motion. Results of the current study demonstrate that during elevation in the scapular plane, small translations of the center of the humeral head occur in all 3 anatomic directions. These reported differences must be viewed with respect to the following two factors: (1) different motions are being compared (scapular plane elevation in the current study and cross-body motion in the Harryman study[20]) and (2) passive manipulation of the humerus results in significantly larger translations of the humeral head (especially at the extremes of motion) than those obtained with simulated muscle forces.[26] Although passive manipulation of the humerus is an important clinical diagnostic tool, establishment of a baseline for normal shoulder function requires consideration of the motion of the articulation in an active mode rather than in a passive mode. Most recently, investigators have conducted experiments to study not only the active role of the muscles, but also to simulate this active role in a dynamic mode.[13,48] The complexity of designing control systems to replicate the muscle loading of the shoulder has necessitated the use of fixed ratios of loading across the muscles (typically based on their physiologic cross-sectional areas). These approximations of relative muscle activity have led to some surprising results. For example, Wuelker et al[48] reported that in normal shoulders, 11 mm of superior translation of the humeral head center occurred during dynamic humeral abduction. In a separate study, Boardman et al[7] reported that in their dynamic model of simulated rotator cuff pathology, no significant difference was found between the kinematics of the shoulders before and after the cuff tears had been created. However, recent results of active models, as well as our clinical experience, suggest that tears of the rotator cuff do alter the kinematics of the shoulder joint.[17] We believe that further improvements in dynamic modeling of the shoulder musculature need to be made before results from these experiments are considered representative of normal shoulder function.

It should be considered that our articular geometry measurements were made with the surfaces in an unloaded state, and it is likely that cartilage deformations during load bearing make the joint even more conforming. In addition, although passive manipulation may occur during stretching exercises or physical examination, most physiologic arm functions involve active range of motion, during which the translations are significantly smaller.[26]

This study also demonstrates that the differences in cartilage and bone anatomies cause a significant difference in results obtained from kinematic analyses of bone surface and cartilage surface data. Given that the subchondral bone and the cartilage surface of the humeral head have different geometric centers, even if the head were undergoing pure rotation without translation about the center of its true (cartilage) articular surface, the center of the subchondral bone as seen on radiographs would appear to be translating. Thus kinematic analyses that use bone surfaces yield larger translation values compared with those obtained with the use of the articular cartilage surfaces. The result, which demonstrates that kinematic analyses that use bone surfaces consistently overestimate the average translation more than 25% in the I-S direction over values obtained with the use of cartilage data, suggests that results of radiographic motion studies of joint articulation should be interpreted with caution.

In conclusion, information relating the mechanics of the joint to its geometry has been provided. While the glenohumeral joint may be relatively free of large bony constraints, its articular surface geometry and other normal functioning static and dynamic soft tissue restraints provide stability to the joint. Thus, under normal conditions, the inherently stable glenohumeral joint allows for small translations of the humeral head on the glenoid. This study demonstrates that the glenohumeral joint cartilage surfaces are more congruent than the corresponding bone surfaces. The amount of humeral head translation depends not only on joint congruence but also on the amount of humeral external rotation. A position of zero external rotation (NR) resulted in smaller translations than a position of external rotation (SR), and joints with reduced congruence demonstrated larger (though still small) values of translation in the I-S direction. Finally, caution must be exercised in the use of plain radiographs for kinematic analyses because the values of translation obtained from bone surface data are significantly larger than those obtained from cartilage surface data. This quantitative study provides an understanding of the kinematics of the normal glenohumeral joint and its relation to the topography of the articular surfaces, and it provides a baseline on which future studies of abnormal joint mechanics and experimental surgical techniques can be performed.

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