Contact forces in the subacromial space: Effects of scapular orientation

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The purpose of this study was to examine the effects of scapular orientation on clearance in the subacromial space. Eight glenohumeral joints from fresh-frozen human cadavers were secured to an Instron mechanical testing machine via a custom-made translation table. Forces were applied to simulate rotator cuff and deltoid contraction. Superior translation of the glenohumeral joint was simulated, and the distance before the development of significant subacromial contact force was measured. Specimens were tested at varying orientations of scapular posterior tilting, upward rotation, and external rotation. Results demonstrated no significant effect of posterior tilting and external rotation. Subacromial clearance was found to decrease with an increase in upward rotation, which is contrary to what was expected. These results suggest that changes in upward rotation observed in patients with impingement syndrome may serve to open the subacromial space. Future work needs to focus on confirming these results and determining contact location. (J Shoulder Elbow Surg 2005;14:393-399.)

Elevation of the arm is not accomplished by motion at a single articulation but, rather, is a combination of both glenohumeral and scapulothoracic motion. There appears to be a consensus among clinicians that abnormal control of scapular motion may be associated with an increased risk of subacromial compression of the rotator cuff tendons. Fu et al[7] proposed that, if the synchronous pattern of motion between the scapula and humerus is disrupted, the rotator cuff tendons might become impinged under the coracoacromial arch. In the clinic, alterations of scapular movement patterns have been found to be associated with muscle weakness,[26] fatigue,[3] and paralysis.[23] Differences in kinematics between patients with impingement syndrome and healthy individuals have also been documented in scientific studies.[18,20,21,35] This may be, in part, due to the fact that alterations in scapular orientation can affect the amount of clearance in the subacromial space, as demonstrated with magnetic resonance imaging (MRI).[32]

A myriad of investigators have studied scapular kinematics, with techniques ranging from simple 2-dimensional methods, such as goniometers[4] and radiographs,[28] to more sophisticated 3-dimensional approaches involving magnetic tracking devices[24] and MRI.[9] However, only a few studies have looked at the biomechanical consequences of altered scapular kinematics. A number of investigators have developed methods of simulating glenohumeral translations to study instability.[13,22,34] For example, by testing a specimen before and after removal of a ligament, the contribution of that ligament to joint stability can be determined. Although investigators have primarily focused on anterior, posterior, and inferior translations, several investigations from the Hospital for Special Surgery (New York, NY, USA) have reported simulating superior translations. For a given force, superior translations were close to an order of magnitude lower than inferior translations and were not increased by subsequent capsular venting[33] or glenohumeral ligament sectioning.[34] Translations were only increased by sectioning of the coracoacromial ligament and surgical alterations of the acromion.[25] These studies have provided a foundation for developing a cadaveric model of subacromial contact forces. Although there is clinical and biomechanical evidence as to where this contact takes place,[6] it is not clear how scapular orientation affects these patterns.

The goal of this experiment was to study the effect of scapular orientation on subacromial contact forces in a cadaveric model. A superiorly directed translation was applied to the humerus, and the resulting forces were measured. On the basis of current clinical thought, our hypothesis was that clearance in the

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subacromial space is increased with posterior tilting, external rotation, and upward rotation.

MATERIALS AND METHODS

Eight human glenohumeral joints (mean age, 76 years) were harvested from fresh cadavers and dissected to the level of the rotator cuff. Specimens were stored frozen and thawed just before experimentation. On the humerus, all soft tissue between the rotator cuff and distal condyles was removed. On the scapula, the inferomedial portions of the infraspinatus, teres minor, and subscapularis were resected. The glenohumeral capsule was vented, thus eliminating any effects of intraarticular pressure.

Joints were tested on a mechanical testing machine (Instron, Canton, MA), by use of a method similar to a method developed previously for testing cadaveric glenohumeral joints.[16,17] Both the scapula and humerus were potted in appropriately sized fixtures with quick-setting epoxy. For the entire experiment, the Instron was considered as the thoracic reference frame, and the humerus was maintained horizontally at 90° of humerothoracic elevation and maximal internal rotation. The humerus was secured to a biaxial translational table fixed to the Instron load frame, thus allowing off-axis translations. The joint mediolateral and anteroposterior axes were aligned with the table axes, and the superoinferior axis was aligned with the Instron actuator. Translations were monitored with linear potentiometers (Novotechnik, Southborough, MA). The scapula was potted in a specially designed rotation jig that allowed for accurate and reproducible angular positioning of the scapula based on the standard Euler angle sequence of external rotation, upward rotation, and posterior tilting (Figure 1).[15] This rotation jig was mounted directly to the Instron actuator (Figure 2).

Four muscle forces were simulated in this experiment: subscapularis, supraspinatus, combined infraspinatus–teres minor complex, and middle deltoid. For the rotator cuff muscles, Dacron cord (Berkley, Spirit Lake, IA, USA) was sewn directly into the tendinous insertions. For the middle deltoid, a single line of action was taken from a bolt placed near the deltoid tuberosity. Lines of action for these muscles were maintained with pulleys located near their scapular origins. For each muscle, the Dacron cord was run from the insertion site, over the pulley at the origin site, to a hanging weight of 25 N. It is important to point out that the position of maximum internal rotation was achieved by passively rotating the humerus and then locking it at that position on the jig, not by applying higher forces to the subscapularis.

Before each test, the humeral head was centered in the glenoid cavity by adjusting the anteroposterior and superoinferior translations until the head was in its most medial location, which represented the deepest portion of the glenoid socket (Figure 3). The experimental procedure consisted of loading the simulated muscles and then translating the joint superiorly at a rate of 1 mm/s up to 125 N of force. The force level was selected based on pilot data, where we were looking for a force level high enough to achieve contact between the humerus and acromion but low enough to avoid significant deformation of the acromion. Before the protocol began, specimens were positioned in neutral orientation and preconditioned for 25 cycles to 125 N.

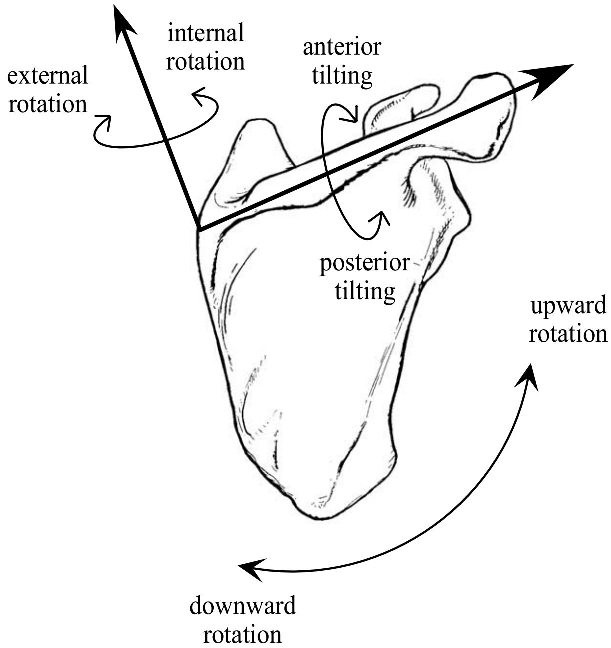

Figure 1 Drawing of the 3 Euler angles representing scapular orientation: internal/external rotation, upward/downward rotation, and anterior/posterior tilting.

At the end of each trial, the scapula was reoriented and the test repeated. Scapular rotations were varied by $\pm$ 5° and $\pm$ 10° from a neutral position determined from in vivo data collected in our laboratory.[24] Consequently, for the purposes of the current study, the neutral position was rounded off to be 0° of posterior tilting, 30° of upward rotation, and −40° of external rotation. Because we set the scapular plane in that study to be between 35° and 40° anterior to the coronal plane, the neutral position for external rotation was set as the scapular plane (0° in the coordinate system of the current study). This resulted in the following scapular orientations: upward rotation, 20°, 25°, 30°, 35°, and 40°; posterior tilting, −10°, −5°, 0°, 5°, and 10°; and external rotation, −10°, −5°, 0°, 5°, and 10°. Testing order within each rotation was determined with a Latin square design to help control for order effects. An additional test in the neutral position was performed after completion of testing to assess measurement reliability.

To isolate the forces resulting from contact in the subacromial space, specimens were retested under all orientation conditions with the coracoacromial ligament cut and the entire acromion removed. The differences in forces between these trials and the experimental trials were used to determine the forces resulting from contact with the subacromial arch. This method of superposition is often used in biomechanical experimentation.[30] We defined the subacromial clearance as the amount of translation that occurred at 20 N of subacromial contact force.

SPSS (SPSS Inc, Chicago, IL) was used for statistical analysis. Reliability was assessed with the intraclass correlation coefficient [ICC(3,1)].[29] A repeated-measures analy-

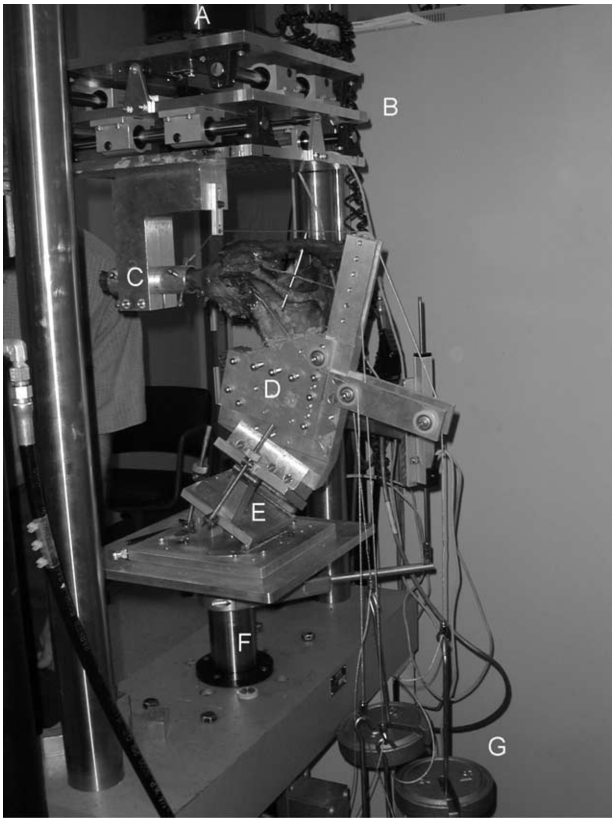

Figure 2 Photograph of experimental setup, showing a glenohumeral joint mounted onto an Instron via a custom-designed translation table: load cell (*A*), x-y translation table (*B*), humeral mount (*C*), scapular mount (*D*), scapular orientation device (*E*), Instron actuator (*F*), and hanging weights (*G*).

sis of variance was performed for each scapular rotation, with one within subject factor (amount of scapular rotation). A priori comparisons (or contrasts) between group means were planned for the experiment. To determine the effects of scapular orientation, polynomial contrasts were used to test for linear trends. The acceptable rate for a type I error was chosen as 5% for all tests.

RESULTS

As expected, during the initial translation period of most trials, the force data before and after removal of the acromion were very similar. It was only after larger displacements were achieved that these 2 curves diverged (Figure 4, *A*). Once the difference between these 2 curves was calculated, it was relatively straightforward to determine the displacement at 20 N (Figure 4, *B*). This displacement value was defined as the subacromial clearance. The reliability of this clearance measurement was found to be excellent, with retesting of the neutral position resulting in an ICC(3,1) of 0.96.

There was no significant effect of either external rotation (P = .59) or posterior tilting (P = .86) on subacromial clearance (Figure 5, *A* and *C*). However, there was a significant effect of upward rotation ($P < .001$) (Figure 5, *B*). A follow-up contrast revealed a significant linear relationship, with a decrease in subacromial clearance resulting from an increase in scapular upward rotation (P = .013). Careful examination of the data reveals that this pattern was consistent across all specimens. Data from a representative specimen are presented in Figure 6.

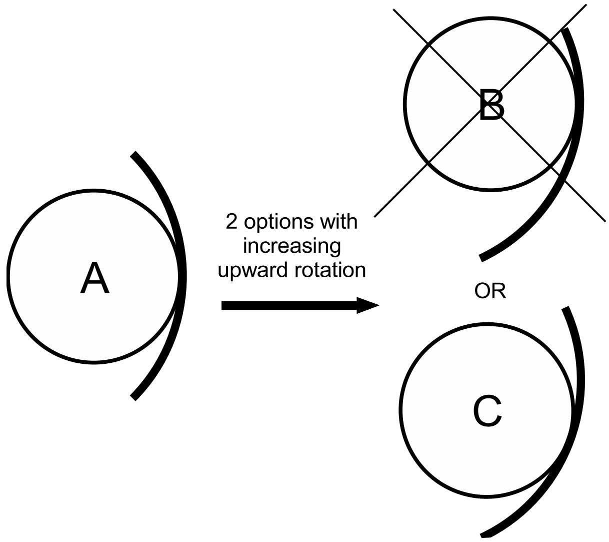

Figure 3 *A*, Location of the most medial location of the humeral head, with the glenoid aligned vertically. As the glenoid was upwardly rotated, this point could either be adjusted (*B*) or remain the same (*C*). The latter method (*C*) was used for this study.

DISCUSSION

Impingement syndrome is one of the most commonly diagnosed shoulder conditions. It is characterized by a mechanical compression of the soft tissues in the subacromial space with symptoms that typically include shoulder pain, stiffness, tenderness, and weakness. Although the etiology of rotator cuff disease is still not completely understood, many researchers and clinicians believe that there is an association between subacromial contact and the development of rotator cuff disease. On the basis of existing literature and previous work in our laboratory, we believe that shoulder movement patterns, especially those of the scapula, may play a key role in the impingement syndrome. If the relationship between scapular motion and shoulder impingement syndrome can be determined, it is possible that novel methods for modifying motion patterns may be developed, which may relieve patient symptoms and potentially help prevent the progression of rotator cuff disease.

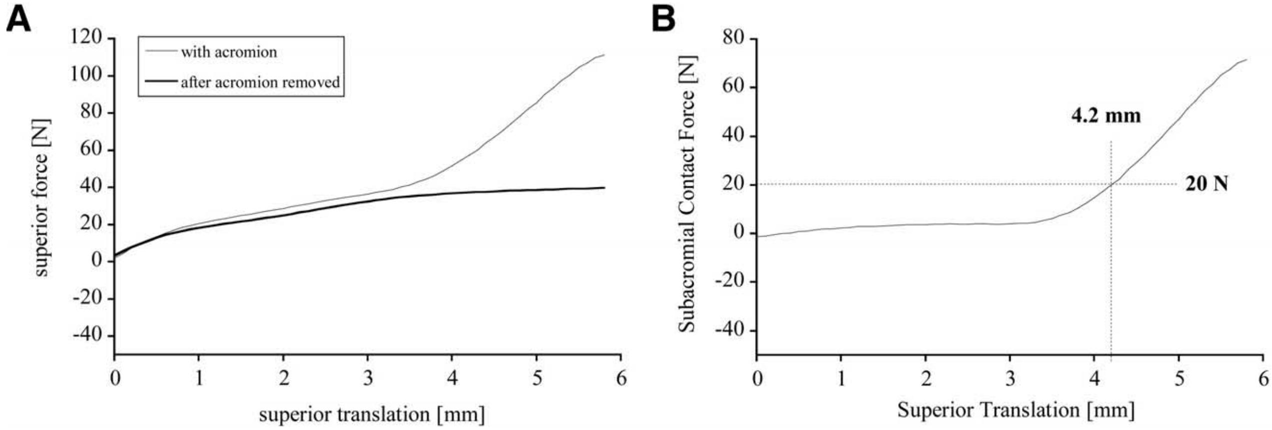

Figure 4 Representative plots of forces measured before and after removal of acromion (**A**) and subacromial contact forces (**B**), defined as force during intact condition minus force during resected condition.

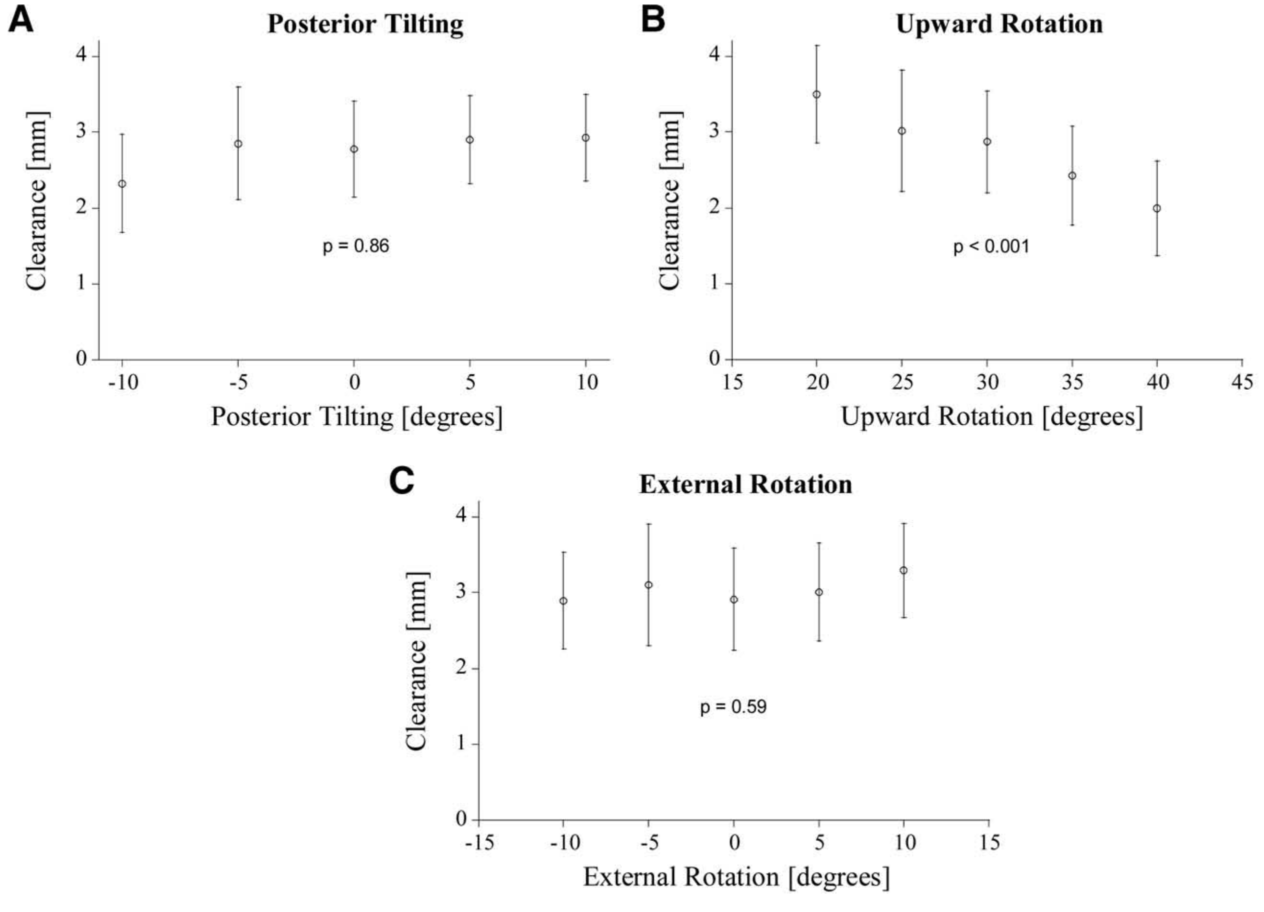

Figure 5 Mean ± SEM of subacromial clearance as a function of posterior tilting (**A**), upward rotation (**B**), and external rotation (**C**).

Although previous cadaveric studies have examined the effects of altering scapular kinematics, these investigations have focused on glenohumeral instability, not impingement.[11,14,36] Only Solem-Bertoft et al[32] have looked at the effects of scapular kinematic on subacromial clearance. With the use of MRI in an

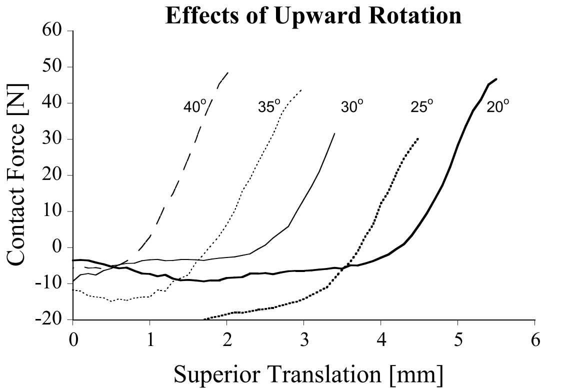

Figure 6 Representative plot of contact force versus superior translation for 5 different scapular upward rotation angles. This is the force during the intact condition minus the force during the resected condition.

in vivo setting, they demonstrated that scapular protraction serves to reduce the clearance in the subacromial space. Recent studies of subacromial clearance have not explicitly studied scapular motion but have either examined the effects of total humeral elevation in vivo[1,8,31] or the effects of glenohumeral motion in a cadaveric model.[2,6]

Several in vivo studies have examined the differences in scapular kinematics between patients with impingement syndrome and healthy control subjects during arm elevation, with techniques as varied as surface digitization,[21] surface-mounted sensors,[12,20] imaging techniques,[5,10] and Moire topographic analysis.[35] As might be expected with such a wide range of techniques, the results are extremely varied. With regard to posterior tilting, half of the studies demonstrated a decrease in posterior tilting with the impingement syndrome[5,20,21] whereas the other half demonstrated no significant difference.[10,12,35] Of the 4 studies that looked at external rotation, only 1 found a significant difference (increased internal rotation with the impingement syndrome).[20] Whereas 2 studies demonstrated a decrease in upward rotation with the impingement syndrome,[5,20] 3 studies showed no significant differences.[10,12,21]

Previous discussions have speculated on the effects of scapular orientation on subacromial contact. For example, Ludewig and Cook[20] found less posterior tilting in patients with the impingement syndrome and suggest that this may negatively affect their performance. Because the subacromial space is relatively small,[6] even a subtle change in dimension could result in compression of the subacromial tissues during glenohumeral elevation.[8,27] However, until we have a better understanding of the biomechanical effect of altered scapular orientation, it will be difficult to interpret the results from scapular kinematic studies. Specifically, at the present time, we do not know whether altered motions patterns observed in patients with pathologies are detrimental (ie, cause the pathology) or beneficial (ie, help compensate for the pathology).

Despite previous discussion in the literature, our data do not support the concept that changes in scapular external rotation and posterior tilting significantly affect the amount of clearance in the subacromial space (for the position of 90° of humeral elevation with maximal internal rotation). Although power is always a consideration when no significant difference is detected, many more samples would have been needed, given the small difference in means and the fact that the *P* values were greater than .5 in both cases. We did find a shift in clearance with upward rotation; however, it was not consistent with what was expected. Our original hypothesis was that increasing upward rotation would serve to increase clearance in the subacromial space, presumably by rotating the lateral portion of the acromion out of the way of the superiorly translating humeral head. However, our results run contrary to this hypothesis. Visual confirmation of a decrease in subacromial clearance with an increase in upward rotation can be observed in Figure 7. On the basis of these results, the decease in upward rotation found in patients with impingement syndrome may serve to open up the subacromial space. If this were the case, then kinematic differences in these patients might be compensatory in nature. However, this speculation is probably premature and needs to be confirmed by other models.

With a study of this nature, in which the orientation of the scapula is altered, one question that must be considered is whether the selection of the zero translation point would artificially influence the results. As shown in Figure 3, there were 2 methods that we considered for selecting the most medial portion of the glenoid. By selecting the same medial point for all trials (situation C), if anything, an increase in upward rotation would have resulted in a more inferior position, thus potentially increasing subacromial clearance (compare situations B and C in Figure 3). Consequently, we are confident that our findings of decreasing subacromial clearance with an increase in upward rotation are not an artifact of our starting point.

One of the major limitations of this study is that no measurements were made of contact location. Consequently, decreases in subacromial clearance might not be detrimental, if the load is transferred from a pathologic area to a less painful area. To overcome this problem, a technique such as stereophotogrammetry[6] or pressure measuring film photography[19] would have to be used. In addition, for the present study, changes in scapular orientation were made independently. For instance, while the upward rotation was altered, external rotation and posterior tilting remained constant. In theory, this study may have

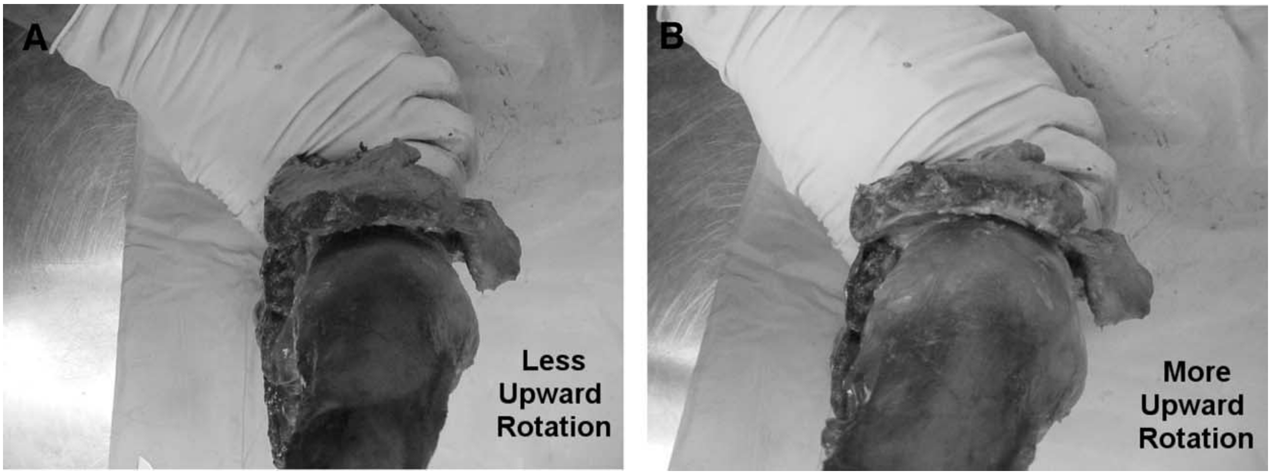

Figure 7 Photographs demonstrating decrease in subacromial space going from a position of less upward rotation (**A**) to more upward rotation (**B**).

missed important effects of combination patterns. We also only considered a single humeral orientation: 90° of elevation in the scapular plane, with maximal internal rotation. Although there are clearly other important positions, on the basis of MRI data, Graichen et al[8] suggest that in order to examine compression of the "supraspinatus tendon at its most vulnerable part . . . comparisons of acromiohumeral distance between patients with impingement syndrome and healthy subjects should focus on abduction angles of 90 degrees and smaller and in particular on 90 degrees with internal rotation." It might be important for future studies to address more functional positions.

Finally, one of the fundamental assumptions of the use of superposition in our model is that the contribution of the capsule (and concavity compression) would be the same both before and after removal of the acromion. Therefore, by subtracting the forces between these 2 conditions, only the subacromial contact forces would remain. Although our jig allowed for accurate repositioning of our specimens, it is possible that the force imposed by the surgical removal of the arch resulted in a shift of the bone with respect to the potting material or deformation of the bone itself, which could weaken the assumptions of superposition. We offer 2 checks of our data to support the contention that our model is valid. The first is that we performed an additional test in the neutral position and after the protocol and found excellent reliability (ICC = 0.96) when compared with the initial neutral test. Second, although the contact force should initially be zero or perhaps slightly positive (Figure 4, *B*), repositioning errors could result in negative initial contact forces (Figure 6). To quantify this effect, the mean contact force at 0 mm of translation was calculated. The average of all trials was less than 2 N, indicating that overall, good repositioning was achieved. In fact, of the 108 acceptable trials, only 1 was observed to have an excessive (<-20 N) negative force at this position (25° case in Figure 6).

In conclusion, scapular orientation affects the subacromial space as measured by the subacromial clearance distance. Interestingly, upward rotation of the scapula led to a decrease in subacromial clearance distance, a finding opposite of that predicted. In addition, posterior tilting and external rotation of the scapula had no effect on subacromial clearance, again opposite of contemporary thought. Future studies should address the effects of other humeral positions, as well as surgical interventions such as acromioplasty.

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