Three-Dimensional Acromioclavicular Joint Motions During Elevation of the Arm

The shoulder girdle is composed of the sternoclavicular (SC), acromioclavicular (AC), and glenohumeral (GH) joints. Scapulothoracic motion occurs through combined SC and AC joint motions.11 The AC joint is a diarthrodial, planar joint comprised of the distal end of the clavicle articulating with the acromion process of the scapula, and may include a fibrocartilaginous disk.29 The angular motions of the AC joint are described as scapular movement with respect to the clavicle, including upward/downward rotation about an axis directed perpendicular to the scapular plane facing anterior and somewhat medial, internal/external rotation about an approximately vertical axis, and anterior/posterior tipping or tilting about an axis directed laterally and somewhat anteriorly (FIGURE 1). The joint capsule, reinforced by the superior and inferior AC ligaments, and the surrounding musculature, maintains stability at the AC joint.23,28 Additionally, the coracoclavicular ligaments (conoid and trapezoid) stabilize and limit motions of the AC joint.

AC joint injuries are common in young active populations.3 Frequent injuries include traumatic sprains, distal clavicle fractures, AC joint arthrosis, or atraumatic osteolysis of the distal clavicle.5,13,28 It is important to consider the proximity of the subacromial space (which is just lateral and inferior to the AC joint) when diagnosing shoulder injuries. Symptoms of subacromial pathology, such as rotator cuff impingement, can be very similar to symptoms of AC joint pathology.28 Pain with abnormal AC joint motion is a cause of weakness and loss of shoulder function.2,5,26 Additional research into the biomechanics of the AC joint has revealed ways to alter surgical techniques to improve patient outcomes.2,34

To date, few studies have been published on AC joint kinematics in human subjects.4,11,27 Historically, Inman et al11 were the first to look at specific AC joint kinematics 2-dimensionally. Using a...
A more recent investigation reported on AC joint translatory and rotational positions at multiple static positions of humeral abduction measured via a vertically open magnetic resonance imaging unit. They hypothesized that this amount of motion was allowed by posterior rotation of the clavicle at the SC joint, creating a slackening of the coracoclavicular ligaments. It appears from their manuscript that these data were from a single subject.

Conway’s investigation used a static sliding device that described the change in position of the root of the spine of the scapula, linearly relative to an arbitrarily determined point on the clavicle, to identify range of motion at the AC joint. These values were then converted to angular measures. Findings indicated that approximately 30° of upward rotation and 8° of external rotation occurred at the AC joint during a combined movement of full humeral flexion and external rotation. While these studies contributed valuable information regarding AC joint movement, data were provided for only 2 rotations. Because motion at the AC joint occurs in 3 dimensions, a more comprehensive analysis is needed to fully describe joint motion. Recently, research has focused on 3-D methods to examine motions of the shoulder girdle.

#### TABLE 1
Demographics for All Included Participants (n = 30)

<table>
<thead>
<tr>
<th></th>
<th>Mean (SD)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>25.2 (3.5)</td>
<td>23.0-28.0</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>174.6 (9.9)</td>
<td>154.9-188.0</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>71.2 (12.3)</td>
<td>49.9-99.8</td>
</tr>
</tbody>
</table>

### METHODS

#### Subjects

Eligible subjects were between 18 and 40 years of age and presented with no pathology on their dominant shoulder based on self-reported history and a clinical screening exam (range of motion, impingement, and provocative tests). A total of 33 volunteers were initially screened for the study. One was excluded due to inability to stand for 45 minutes, another was excluded due to a past history of shoulder pathology on the dominant shoulder, and the third participant was excluded due to soft tissue visually interfering with clavicle sensor tracking. Subsequently, 30 (16 male, 14 female) of the 33 subjects recruited were used in our analysis (Table 1). All subjects were informed of the purpose and risks/benefits of this study and completed University-approved informed-consent documentation. The protocol for this study was approved by the University of Minnesota Institutional Review Board, Human Subjects Committee.

#### Specimens

Eight fresh-frozen cadaver specimens, ranging in age at time of death from 31 to 81 years (average age, 63 years), were also tested. For either shoulder to be included, there had to be no evidence of radiographic and bone pin study, these authors described approximately 30° of upward rotation at the AC joint with full flexion or abduction of the arm. They hypothesized that this amount of motion was allowed by posterior rotation of the clavicle at the SC joint, creating a slackening of the coracoclavicular ligaments. It appears from their manuscript that these data were from a single subject.

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joint degeneration, based on a passive-motion exam by a physical therapist, radiographic screening, and examination by an orthopedic surgeon, as well as no known past medical history of shoulder problems. One left shoulder was excluded due to severe scapular crepitus during passive motion. One right shoulder was excluded due to loss of tracking (pin loosening), and another right shoulder was excluded because of a major range of motion restriction, leaving a total of 13 shoulders for analysis from the 8 specimens. Cadaver specimens included intact hemitorsos or full bodies including bilateral upper extremities, such that the shoulders were not dissected away from the rest of the body.

**Instrumentation**

Three-dimensional motion data were collected using the Flock of Birds miniBIRD electromagnetic tracking system (Ascension Technologies, Burlington, VT) and associated Motion Monitor software (Innovative Sports Training, Chicago, IL). The manufacturer reports static accuracy (root-mean-square [RMS]) of 1.8 mm for position and 0.5° for orientation within 76.2 cm of the transmitter. The total number of sensors available with this system is 7, with 5 used for this study. One sensor was used as a digitizing stylus, with known tip offsets for identifying anatomical landmarks.

**Procedures**

**Subjects** Subjects were asked to stand in a neutral position with the transmitter directly behind the shoulder joint being tested. Three-dimensional kinematic data were collected from 4 sensors placed on specific anatomical segments. One was taped on the sternum, inferior to the sternal notch; one was located at the mid clavicle; one on the posterior medial acromion; and the last sensor was attached to a cuff secured with Velcro right above the epicondyles of the humerus (FIGURE 2). These sensor coordinates were then realigned to anatomical coordinate systems by palpating and digitizing various anatomical landmarks. On the clavicle, superior and inferior SC joint and anterior and posterior AC joint landmarks were used to define the long axis, along with a custom device to identify a third landmark. The center of the humeral head was estimated as a humeral landmark by rotating the arm passively to 10 different positions. At the completion of digitizing, participants assumed a neutral standing position and angular values were recorded with the arm at rest at their side.

With a vertical planar surface for reference, subjects were instructed to perform 3 repetitions of shoulder scapular plane abduction. Participants were given verbal timing cues to control for speed of motion (3 seconds up and 3 seconds down). Electromagnetic sensors were not removed between repetitions.

**Specimens** Cadaver specimens were thawed prior to testing, and 2.5-mm-diameter Steinmann pins were placed by an orthopedic surgeon into the lateral clavicle, distal spine of the scapula and deltoid insertion of the humerus. The electromagnetic sensors were then rigidly attached to the pins via a nonferrous housing (FIGURE 3). A sensor was also attached to the sternum with tape. Landmarks were digitized for development of anatomical coordinate systems, as described for subjects above. Three repetitions of scapular plane abduction were completed passively by a physical therapist while the specimens were stabilized in an upright posture to allow for normal gravitational resistance during motion. Stabilization was accomplished with a wooden back support and stabilization belts around the lower torso.

**Data Reduction**

The local coordinate systems of the sensors relative to the transmitter were transformed to clinically meaningful axis systems based on the digitized anatomical landmarks. To describe AC joint motion, scapular axes were described relative to clavicular axes. The clavicular x-axis was created from the SC joint (midpoint of superior and inferior SC joint landmarks) and the AC joint (midpoint of anterior and posterior AC joint landmarks).
landmarks) oriented laterally. Using an adjustable-length triangular frame with one end of the base placed at the SC joint and the other end at the AC joint, a third point (apex of the triangle) was digitized, while the triangular frame was leveled in the vertical plane incorporating the long axis of the clavicle. The y-axis was oriented anteriorly perpendicular to this plane. The z-axis was oriented superiorly perpendicular to the x-axis and y-axis. The scapular, trunk, and humeral axis systems were established as previously described.15,17 The trunk axes were aligned with the cardinal planes.

The clavicular recommended standard coordinate system31 assumes vertical orientation of the clavicular z-axis (relative to the thorax) in the resting position, with the arms at the side by using the trunk vertical axis as the clavicular vertical axis. Our software did not allow this process during data collection, and, because there is not a third point on the clavicle to create this vertical orientation, we used a custom device to establish the vertical reference. In cases where there was greater than a 4° deviation of the clavicular superior/inferior axis from the superior/inferior axis of the thorax in the rest position, postprocessing was used to realign the clavicular superior/inferior axis coincident with the thorax superior/inferior axis in the standing rest position. This threshold was established based on previously reported between-day reliability values (3°-4°).15

The primary motions of interest in our study were at the AC joint. Scapular orientation relative to the clavicle was found by rotation about z (internal/external), rotation about y' (downward/upward), and rotation about x'' (anterior/posterior tilting) (z, y', x'' Cardan angles). Clavicular, scapular, and humeral orientation relative to the trunk were described as previously reported.15,17 Left-sided data were converted to right side equivalence. For ease of interpretation, AC joint upward rotation values were multiplied by −1 to create positive values for upward rotation. AC joint internal rotation and posterior tilting were also positive values.

Data were originally collected at a 100-Hz sampling rate. Angular values were extracted for each subject and specimen at every 5° increment of active or passive humeral elevation relative to the trunk, starting at 30° up to 90°. Beyond 90°, less-accurate tracking of the clavicle surface sensors has been previously identified.15 Values were also extracted for live subjects in the resting standing position.

**Data Analysis**

**Subject’s Active-Motion Data** A 2-way analysis of variance (ANOVA), with subjects and trials as factors, was used to analyze the consistency of the 3 trials for the dependent measures. The ANOVA results were used to calculate the intraclass correlation coefficient (ICC3,1) as a measure of within-session reliability for positions of the AC joint ([BMS – EMS]/[BMS + (k – 1)EMS]).25 The standard error of the measurement (SEM) was calculated using the square root of the within-subject mean-square error.9 Calculations were performed at humerothoracic positions of rest, 30°, 60°, and 90° of humeral elevation for each dependent variable (internal/external rotation, upward/downward rotation, and anterior/posterior tilt positions at the AC joint) during scapular plane abduction.

Descriptive statistics were averaged across subjects and trials (mean, SD) for all 3 dependent variables during scapular plane abduction at rest and every 5° increment from 30° to 90° of humeral elevation. Normality was verified by testing skewness and kurtosis on each dependent variable at 30°, 60°, and 90° of elevation.7 The possibility of velocity and age as potential covariates were tested using a Pearson correlation matrix with all dependent variables for 30°, 60°, and 90° humeral elevation angles. Correlation coefficients greater than 0.60 were considered possible confounders,25 and in such cases the use of an ANCOVA was planned. Average velocity was calculated for the phases of motion from 30° to 60° and 60° to 90°. Age and velocity were not found to be significant covariates with AC joint motions during humeral scapular plane abduction. The strongest correlation (0.45) was for velocity with AC joint internal/external rotation during scapular plane abduction at 90°. These values fell below the correlation cutoff point of 0.6025; therefore, ANCOVA analyses were not performed.

To determine any difference in AC joint motion across elevation angles during subject’s active scapular plane abduc-

### TABLE 2

**RELIABILITY FOR AC JOINT POSITION DURING ACTIVE SCAPULAR PLANE ABDUCTION AT SPECIFIC ANGLES OF HUMEROThorACIC ELEVATION**

<table>
<thead>
<tr>
<th>Joint Position/Humerothoracic Elevation Angle</th>
<th>SEM (°)</th>
<th>ICC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal/External rotation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30°</td>
<td>0.9</td>
<td>0.98</td>
</tr>
<tr>
<td>60°</td>
<td>1.1</td>
<td>0.98</td>
</tr>
<tr>
<td>90°</td>
<td>1.2</td>
<td>0.99</td>
</tr>
<tr>
<td>Tilting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30°</td>
<td>0.9</td>
<td>0.98</td>
</tr>
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<td>0.98</td>
</tr>
<tr>
<td>90°</td>
<td>1.2</td>
<td>0.98</td>
</tr>
<tr>
<td>Upward rotation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30°</td>
<td>0.9</td>
<td>0.98</td>
</tr>
<tr>
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</tr>
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<td>90°</td>
<td>1.2</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Abbreviations: AC, acromioclavicular; ICC, intraclass correlation coefficient, model 3,1.
tion, 1-way repeated-measures ANOVAs were performed with humeral angle as the factor (rest, 30°, 60°, and 90°). In the presence of a significant main effect, a Tukey-Kramer follow-up test was completed for each pairwise comparison across humeral elevation angles. The overall level of significance was $P < .05$. All analyses were completed using the NCSS 2000 statistical software (NCSS, Kaysville, UT).

**Passive Data from Cadaver Specimens** Descriptive statistics were also averaged across specimens and trials (mean, SD) for all 3 dependent variables during scapular plane abduction at every 5° increment from 30° to 90° of passive humeral elevation in cadavers. These data are presented descriptively from 30° to 90°. Statistical comparisons were not completed on the passive cadaver data due to the low number of specimens ($n = 8$).

**RESULTS**

The within-session ICCs during scapular plane abduction ranged from 0.94 to 0.99 with the SEM between 0.9° and 2.0° (TABLE 2). Descriptive statistics across humeral elevation angles are provided in FIGURES 4 through 6. In general, the pattern of motion was for the scapula to upwardly rotate, internally rotate, and posteriorly tilt relative to the clavicle at the AC joint as the arm was elevated from rest to 90° scapular plane abduction.

**Subject’s Active Scapular Plane Abduction**

During scapular plane abduction there were significant differences across humeral elevation angles for AC joint internal rotation ($F = 3.28$; $df = 3.87$; $P = .02$), upward rotation ($F = 23.14$; $df = 3.87$; $P < .01$), and posterior tilting ($F = 9.09$; $df = 3.87$; $P < .01$) (FIGURES 4-6). Post hoc analyses indicated that pairwise differences were significant for all comparisons except for internal rotation, in which rest was not different from 30° elevation, and posterior tilting, where 30° elevation was not different from 60° elevation. During scapular plane abduction from rest to 90°, the mean change at the AC joint was approximately 4.3° of internal rotation, approximately 14.6° of upward rotation, and approximately 6.7° of posterior tilting.
Passive Cadaver Scapular Plane Abduction

Average AC joint motions during passive cadaveric scapular plane abduction at varying angles of humeral elevation (30°-90°) are also shown in Figures 4 through 6. Although there were offsets in passive upward rotation and posterior tilt position, passive cadaver AC joint motions were generally similar in direction to active trials in human subjects. Descriptively, from 30° to 90° of passive cadaver humeral elevation there was a mean of 2° of AC joint internal rotation, to the AC joint and a second line along the AC joint, which is critical in relating SC and AC joint motions to overall scapular motion on the thorax, keeping in mind that SC joint kinematics involve clavicular motion relative to the sternum and AC joint kinematics involve scapular motion relative to the clavicle. The angle between a line from the root of the spine of the scapula to the AC joint and a second line along the clavicular long axis in the transverse plane is represented by AC joint internal rotation values (Figure 7A). This angle is critical in relating SC and AC joint contributions to scapulothoracic movement, knowledge of these joint component motions is important in understanding shoulder kinematics in healthy and disease states. Historically, limited attempts have been made to track the clavicle during dynamic motions, resulting in limited AC joint data for comparison. Using surface sensors we were able to describe the 3-D motion occurring at the AC joint during scapular plane abduction of the humerus up to 90°, with a high level of within-session reliability, although the reliability with removal and replacement of sensors or redigitizing was not determined. Within-session ICCs were consistently above 0.94, with SEMs of approximately 2° or less.

Previous to this study, descriptions of AC joint motion were limited primarily to 2-dimensional methods. Inman et al., using radiographs, proposed that a total of approximately 30° of upward rotation was seen at the AC joint throughout humeral elevation with most of the motion occurring in the early and late phases. Extrapolating from their graphical results, between rest to 90°, about 12° of upward rotation at the AC joint was found during coronal plane abduction. These findings compare favorably to our results of 14.6° of AC joint upward rotation during scapular plane abduction. Conway measured superior/inferior (upward/downward rotation) and anterior/posterior (internal/external rotation) changes in position. At the AC joint, during full flexion and external rotation of the humerus, both upward rotation (approximately 30°) and external rotation (approximately 8°) were measured. Conway’s findings agree with the 30° of upward rotation during full elevation reported by Inman et al. Conway’s study depicts a decrease in internal rotation while our results show an increase of approximately 4°. This difference may be due to the range over which data were recorded. External rotation of the scapula on the thorax can occur after 90° of humeral elevation; however, we did not analyze data beyond 90° due to limitations in surface clavicular tracking. Comparison to Conway’s data is further limited as only end range data were available and their subjects performed flexion with full external rotation of the humerus, preventing extraction of data for the same motion or portion of the range of motion over which we tested. Sahara et al.’s data describe only total rotation and do not allow for comparisons of specific component motions. Differences across study results may relate to 2-D versus 3-D analyses, varying sample sizes and populations, varying motions tested, and varying measurement technologies. None of these past studies investigated AC joint tilting motion during elevation of the arm.

Motion of the scapula relative to the thorax must be the result of a mechanical coupling between movements at the SC and AC joints. To analyze this it is necessary to compare component joint motions to overall scapular motion on the thorax, keeping in mind that SC joint kinematics involve clavicular motion relative to the sternum and AC joint kinematics involve scapular motion relative to the clavicle. The angle between a line from the root of the spine of the scapula to the AC joint and a second line along the clavicular long axis in the transverse plane is represented by AC joint internal rotation values (Figure 7A). This angle is critical in relating SC and AC joint contributions to scapulothoracic motion.

**DISCUSSION**

As scapulothoracic motion during humeral elevation is comprised of both AC joint and SC joint movement, knowledge of these joint component motions is important in understanding shoulder kinematics in healthy and disease states. Historically, limited attempts have been made to track the clavicle during dynamic motions, resulting in limited AC joint data for comparison. Using surface sensors we were able to describe the 3-D motion occurring at the AC joint during scapular plane abduction of the humerus up to 90°, with a high level of within-session reliability, although the reliability with removal and replacement of sensors or redigitizing was not determined. Within-session ICCs were consistently above 0.94, with SEMs of approximately 2° or less.

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tions. If the AC joint internal rotation angle were 0° (scapular plane parallel with the clavicular long axis; FIGURE 7B), clavicular elevation and scapular upward rotation would be directly coupled, as well as clavicular posterior rotation and scapular posterior tilting, and clavicular retraction and scapular external rotation (TABLE 3). The 1:1 coupling of retraction and external rotation assumes that the SC and AC vertical axes are parallel, which is a theoretical approximation. If the AC internal rotation angle were 90° (FIGURE 7C), these couplings would change. Elevation of the clavicle would be directly coupled with scapular anterior tilting, posterior rotation of the clavicle would be coupled with scapular upward rotation, and clavicular retraction would still be coupled with scapular external rotation (TABLE 3). The AC joint internal rotation angle in our sample averaged 68°. Considering that 68° is approximately 75% of 90°, theoretically a combination of 75% of the 90° coupled motions and 25% of the 0° coupled motions would occur with clavicular and scapular motion (TABLE 3). Accordingly, clavicular elevation will be coupled approximately 75% with scapular anterior tilting and approximately 25% with scapular upward rotation. Posterior rotation of the clavicle will be coupled approximately 75% with scapular upward rotation and approximately 25% with scapular posterior tilting (TABLE 3).

During scapular plane abduction, from 30° to 90° of humeral elevation in these same subjects, we measured the clavicle to be retracting 6°, elevating 6°, and posteriorly rotating 10° at the SC joint. Without any movement at the AC joint, this clavicular motion would be associated with the scapula externally rotating (assuming 1:1 coupling), anteriorly tilting (75% coupling of elevation to anterior tilting and 25% coupling posterior rotation to posterior tilting) and upwardly rotating (25% coupling of elevation and 75% coupling of posterior rotation) (TABLES 3 and 4). Of course the AC joint is not a rigid link. Therefore, our measured data for AC joint internal rotation over this range would partially offset the coupling of clavicular retraction and scapular external rotation, with a net result of scapular external rotation on the thorax from 30° to 90° humeral elevation (TABLE 4). The AC joint posterior rotation that we measured over this range would also offset the anterior tilting.

### TABLE 3

Hypothetical Listing of SC Joint Couplings With ST Motion on the Thorax at Varying Angles of AC Joint Internal Rotation

<table>
<thead>
<tr>
<th>AC Internal Rotation Angle</th>
<th>0°</th>
<th>90°</th>
<th>68°</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC retraction</td>
<td>100% ST external rotation</td>
<td>100% ST external rotation</td>
<td>100% ST external rotation</td>
</tr>
<tr>
<td>SC elevation</td>
<td>100% ST upward rotation; 0% ST anterior tilting</td>
<td>100% ST anterior tilting; 25% ST upward rotation</td>
<td>75% ST anterior tilting; 25% ST upward rotation</td>
</tr>
<tr>
<td>SC posterior rotation</td>
<td>100% ST posterior tilting; 25% ST upward rotation</td>
<td>100% ST upward rotation; 75% ST posterior tilting</td>
<td>0% ST posterior tilting</td>
</tr>
</tbody>
</table>

**Abbreviations:** AC, acromioclavicular; SC, sternoclavicular; ST, scapulothoracic.

### TABLE 4

SC and AC Joint Couplings With Predicted ST Motion on the Thorax During Scapular Plane Abduction From 30° to 90°

<table>
<thead>
<tr>
<th>Measured SC Rotation</th>
<th>Hypothetical Coupled ST Rotations</th>
<th>Measured AC Rotation</th>
<th>Predicted ST Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>6° retraction</td>
<td>-6° external rotation</td>
<td>+4° internal rotation</td>
<td>Z° external rotation</td>
</tr>
<tr>
<td>6° elevation, 10° posterior rotation</td>
<td>-4.5° anterior tilting, +2.5° upward rotation</td>
<td>+4° posterior tilting</td>
<td>2° posterior tilting</td>
</tr>
<tr>
<td>6° elevation, 10° posterior rotation</td>
<td>+1.5° upward rotation, +7.5° upward rotation</td>
<td>+7° upward rotation</td>
<td>16° upward rotation</td>
</tr>
</tbody>
</table>

**Abbreviations:** AC, acromioclavicular; SC, sternoclavicular; ST, scapulothoracic.
ing associated with clavicular motion, with a net result of posterior tilting of the scapula on the thorax (TABLE 4). Finally, the upward rotation associated with clavicular motions would be complementary to the upward rotation measured at the AC joint, resulting in 16° of upward rotation of the scapula on the thorax (TABLE 4). These scapulothoracic motion patterns predicted through measured SC and AC joint data are consistent with previous descriptions of scapulothoracic kinematics over this range of motion in the literature,17,22 and our measured data for scapular motion on the thorax in the current sample. Understanding how SC and AC joint rotations are coupled with scapulothoracic motion in healthy subjects is a basis for future investigations of abnormal coupling of motions in patients with pathology and also shows us how the SC and AC joint each plays a critical role in the overall kinematics of the shoulder girdle.

When comparing passive motion in cadaver specimens to subjects’ active motion during scapular plane abduction, there are similar patterns with regard to the general directions of motion during progressive humeral elevation (AC joint internal rotation, upward rotation, and posterior tilting). The use of an upright cadaver model for capturing passive motion allowed for true passive AC joint motion to be captured under normal gravitational forces using a direct bone-fixed technique. The similarity of motion patterns between the active and passive conditions suggests that motion and position are influenced at least in part by passive tension in the soft tissues, joint capsule, and ligaments as well as the shape of the thorax. There appeared to be a difference in excursion for AC joint posterior tilting with more posterior tilting occurring passively in the cadavers, and a more posterior position at low humeral elevation angles. This might mean that the deltoid as the prime mover of the glenohumeral joint and/or pectoralis minor muscle may pull the AC joint into more anterior tilting during active motion, offsetting the passive contributions to posterior tilting. The position of the AC joint in active and passive conditions at low humeral elevation angles was similar for internal rotation, which suggests that low levels of muscular activity with the arms relaxed at the side may not substantially affect this initial position. Initially, the AC joint was less upwardly rotated in passive cadaver testing, which may be due to no upper trapezius activation on the joint. Because of the small sample for cadaver analysis, these differences also may simply relate to sample variation, as well as different skin tension between active and passive testing, or skin motion artifact with the use of surface sensors actively and direct bone-fixed measurement passively. In a similar cadaveric analysis of passive shoulder motion, Fung et al10 have also demonstrated similar patterns of motion for the SC joint and scapula on the thorax as compared to active movements, although the magnitudes of motion are diminished early in the range of motion compared to active measurements in live subjects. Alternatively, passive motion could have been measured in vivo in our study; however, full muscle relaxation during such testing can be difficult to obtain.

In this study we used surface sensors for in vivo testing, and palpation to establish local anatomical coordinate systems. Subsequently, there is a potential error in the description of AC joint positions associated with palpation or with surface sensors not precisely tracking underlying bone movement. The palpation error was minimized by having the same person digitize each subject. The validity of our group average measurements is supported by the high within-session reliability of the measurements, past literature describing scapular and clavicular kinematics with surface sensors,17,21 and the ability of the coupled SC/AC joint motions to predict scapular motion on the thorax. Nevertheless, the lack of between-session reliability data with removal and replacement of sensors and redigitizing of landmarks is a limitation of the study. Further, no direct validation of AC joint measurement with surface sensors is available. Because of skin motion artifact, the rotations reported in our study could be underrepresented or overrepresented. Not all individual subjects followed the average patterns of motion. In individual subjects, with motion between 30° and 90° of humeral elevation, 67% demonstrated a pattern of AC joint internal rotation and 73% demonstrated patterns of increased AC joint upward rotation and increased AC joint posterior tilting. With the small magnitudes of AC joint motion reported, on an individual subject basis for small increments of humeral elevation, the errors of measurement may exceed the recorded joint displacements and thus use of this technique for single-subject analyses is not recommended.

However, we compared our average surface motions measured from 30° to 90° at the AC joint with average motions measured on a small sample (n = 9) of participants in an ongoing bone-fixed motion study.18 That study used the same electromagnetic instrumentation, experimental techniques, axis orientations, and anatomical landmarks as the current surface motion study.18 The bone-fixed measurement was completed similarly to the methods used for the cadaver samples in this investigation, with pin placements completed under local anesthetic and skin released around the pin placement sites. Subjects completed 2 active trials of scapular plane abduction motion. The bone-fixed measurements from 30° to 90° scapular plane abduction were 4° internal rotation (4° for the surface sensors in this study), 6° upward rotation (7° for surface sensors in this study), and 7° posterior tilting (4° for surface sensors in this study). Given that between-subject variation is present and these data sets are 2 different samples of subjects, the general descriptions of AC joint motion are quite similar, providing further support for the validity of our surface measures. Despite the availability of direct bone-fixed tracking, noninvasive surface measures are still important to consider for their ability...
to be used on larger samples and patient populations, as well as the potential ability to follow subjects over time or before and after interventions.

At the present time, our interpretation of AC joint kinematics is limited to that occurring for scapular plane abduction to 90° humeral elevation. Further investigation is needed and ongoing in this area of validating and improving surface tracking techniques, in particular for tracking clavicular motions. Alternative methods of measurement are available in the literature for tracking SC joint elevation and retraction; however, tracking axial rotation of the clavicle is challenging noninvasively.

Our subjects represented a relatively young, healthy population with no history of shoulder dysfunction. Subsequently, results should not be generalized to other age demographics or to those with pathologies. A healthy population was needed to identify “normal” kinematics of the AC joint, as postural and degenerative changes can occur with aging. We only used dominant arms in this study (29 right, 1 left), which may limit the generalizability as well.

Further, the motions in this study were only analyzed to 90° of humeral elevation, due to concerns with quality of clavicular surface tracking above that range.

Clinical Implications

The results of this study demonstrate the relationships of the scapula relative to the clavicle during humeral elevation in healthy subjects. For arm elevation to occur without impingement, the clavicle and scapula must allow clearance of the humeral head underneath the acromion and AC joint. This study identifies that, in healthy subjects, clavicular motions from the SC joint, coupled with corresponding scapular motions relative to the clavicle from the AC joint, are associated with scapular motion on the thorax believed necessary to accommodate clearance of the humeral head as the arm elevates, as well as to maintain the scapula on the thorax. As discussed previously, with an AC joint internal rotation angle of approximately 68°, clavicular elevation couples predominately with anterior tilting of the scapula. Anterior tilting of the scapula during humeral elevation is believed to effectively decrease the space for the humeral head and rotator cuff soft tissues under the acromion. Therefore, posterior tilting of the scapula at the AC joint is necessary to overcome the normal clavicular elevation and results in posterior tilting of the scapula on the thorax. Injury to the AC joint may result in the disruption of normal scapulothoracic motion, which in turn can result in decreased shoulder function. Several studies have shown increased internal rotation and decreased upward rotation and posterior tilting of the scapula in subjects with impingement. These changes in scapulothoracic motion could be the result of increased or decreased motion at the AC and SC joints. The lack of posterior tilting identified in impingement could be the result of decreased posterior tilting at the AC joint or excess elevation of the clavicle at the SC joint. The decreased upward rotation of the scapula identified in impingement could be due to decreased elevation or posterior rotation at the SC joint, or decreased upward rotation of the AC joint. Increased internal rotation of the scapula on the thorax observed in impingement may be due to increased internal rotation at the AC joint or decreased retraction at the SC joint. Posterior tilting at the AC joint appears to be a critical component motion because normal clavicular motions during humeral elevation do not substantively contribute to scapular posterior tilting on the thorax.

Initially, the results demonstrating AC joint internal rotation during scapular plane abduction may seem contradictory to data describing external rotation of the scapula on the thorax near end range humeral elevation. It is possible that at higher ranges of elevation the AC joint may show a pattern of external rotation rather than internal rotation; but it is more likely that scapular external rotation on the thorax at higher angles of humeral elevation is a function of clavicular retraction at the SC joint. As noted above, because clavicular retraction is occurring throughout elevation, the AC joint internal rotation can offset and reduce the effect of this SC joint retraction on scapulothoracic external rotation rather than result in a pattern of scapular internal rotation. It should also be noted that patterns of both scapulothoracic internal rotation and external rotation have been reported in the literature, and that this motion is the most variable of scapulothoracic motions. As measurement capabilities continue to evolve, future studies directed at examining AC joint motions at higher humeral elevation angles and in subjects with shoulder pathology, such as impingement, AC joint separation, or glenohumeral instability, would be beneficial. This would further elucidate the role of the AC joint in overhead activities and may lead to new insights into shoulder pathologies and their treatment.

CONCLUSION

To our knowledge, this research provides the first dynamic 3-D data for in vivo AC joint kinematics during active humeral elevation. There is measurable motion of the scapula toward internal rotation, upward rotation, and posterior tilting relative to the clavicle at the AC joint during humeral scapular plane abduction from rest to 90°. The relationships between coupled motions occurring at the SC and AC joints are integral to understanding the biomechanics of the shoulder girdle. Upward rotation of the scapula on the thorax is associated in a complementary fashion with SC and AC joint motions, whereas AC joint internal rotation and posterior tilting offset the SC joint motions of elevation and retraction. These data provide an expanded foundation to assess pathological mechanisms and rehabilitative strategies for patients with shoulder pathology.
KEY POINTS

FINDINGS: Three-dimensional motion occurs at the acromioclavicular joint during humeral abduction in the scapular plane, including internal rotation, upward rotation, and posterior tilting.

IMPLICATION: Normal or abnormal motions at the acromioclavicular joint will affect the position of the scapula on the thorax. Scapulothoracic position is often assessed in cases of shoulder pathology.

CAUTION: This investigation used surface motion tracking, which is subject to errors from skin motion artifact. Testing also occurred only through a limited range of elevation in scapular plane abduction.

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