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In vivo measurement of subacromial space width during shoulder elevation: Technique and preliminary results in patients following unilateral rotator cuff repair

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Abstract

Background. The shoulder's subacromial space is of significant clinical interest due to its association with rotator cuff disease. Previous studies have estimated the subacromial space width to be 2–17 mm, but no study has measured in vivo subacromial space width during shoulder motion. The purpose of this study was to measure the in vivo subacromial space width during shoulder elevation in patients following rotator cuff repair.

Methods. Biplane X-ray images were collected during shoulder elevation of 11 patients who had undergone rotator cuff repair. Glenohumeral joint motion was measured from the biplane X-ray images for each subject's repaired and asymptomatic, contralateral shoulders. The joint motion data were combined with subject-specific CT models to measure the subacromial space width during shoulder motion.

Findings. Subacromial space width decreased with shoulder elevation, ranging from 2.3 to 7.4 mm in the repaired shoulder and 1.2–7.1 mm in the contralateral shoulder. Subacromial space width in the repaired shoulder was only 0.5 mm less than the contralateral shoulder when averaged over 10–60° of glenohumeral elevation.

Interpretation. The results indicate that the humerus in the repaired shoulder is positioned more cranially on the glenoid than in the contralateral shoulder. It is unclear if these subtle differences in subacromial space width are due to the surgical procedure or post-operative stiffness, or if subacromial impingement contributed to the development of the rotator cuff tear. Future research will ascertain if these results represent a transient response to the surgery or a more fundamental difference in rotator cuff function between repaired and contralateral shoulders.

Keywords: Shoulder; Subacromial space; Rotator cuff; In vivo

1. Introduction

Rotator cuff tears are a common shoulder injury, affecting approximately 30–40% of individuals over age 60, having a significant impact on function, comfort, and quality of life. A decrease in the subacromial space – i.e., the space between the humerus and the acromion occupied by the rotator cuff's supraspinatus tendon – may result in pathologic contact between the supraspinatus tendon and acromion. This phenomenon, known as subacromial impingement, is widely believed to be an etiologic factor in the development of rotator cuff tears (Bigliani and Levine, 1997; Neer, 1972, 1983). This concept has led to the development of surgical procedures designed to increase the subacromial space. These procedures – commonly referred to as acromioplasty or subacromial decompression – involve the removal of any projection or bone

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spurs from the anterior, inferior or anterolateral portion of the acromion to create a flat undersurface of the acromion, and are often performed in conjunction with surgical repair of a rotator cuff tear. However, the role of acromioplasty and its effect on the subacromial space have been questioned, with alternative approaches advocated that include rotator cuff repair without acromioplasty (Budoff et al., 1998; Goldberg et al., 2001) as well as acromioplasty alone without rotator cuff repair (Cordasco et al., 2002).

Given the clinical importance of the subacromial space, previous research efforts have measured the subacromial space in humans under a wide variety of testing conditions. These previous studies have measured the subacromial space under in vivo conditions with various imaging modalities, including three-dimensional (3D) computed tomography (Lochmuller et al., 1997), clinical radiographs (van de Sande and Rozing, 2006; van de Sande et al., 2006; Lehtinen et al., 2000; Petersson and Redlund-Johnell, 1984), ultrasound imaging (Girometti et al., 2006; Azzoni et al., 2004), and MRI (Pappas et al., 2006; Graichen et al., 1998, 1999b,a, 2001, 2005; Hinterwimmer et al., 2003; Roberts et al., 2002; Solem-Bertoft et al., 1993). Additional studies have estimated the subacromial space width based on shoulder kinematics as measured using skin-mounted sensors (Tsai et al., 2003; Thigpen et al., 2006; Ludewig and Cook, 2002; Nawoczenski et al., 2003). In addition, measurements of the subacromial space have also been recorded during operative procedures (Tillander and Norlin, 2002) and in various experiments using cadaveric shoulder specimens (Karduna et al., 2005; De Wilde et al., 2003; Flatow et al., 1994). The previous in vivo studies have reported the subacromial space width to range from approximately 2 to 17 mm. This wide range of subacromial space width measurements reflects differences in age, gender, shoulder position, shoulder pathology, and the measurement technique and its associated accuracy. It has also been shown that muscle activity (in particular, adducting and abducting muscle activity) has a significant effect on subacromial space width (Graichen et al., 2005, 2003). For example, Hinterwimmer and colleagues reported that adducting muscle forces increased the subacromial space from 32% to 138% over 30° to 150° of shoulder elevation when compared with abducting muscle forces (Hinterwimmer et al., 2003). Similarly, Graichen and colleagues reported a significant decrease in average subacromial space width from 6.7 mm to 4.9 mm in male subjects when 90° abduction was combined with abducting muscle activity (Graichen et al., 2001). These data clearly indicate that muscle forces have a significant effect on the subacromial space width. Unfortunately, many of the previous studies reported subacromial space width under passive (i.e., without any apparent muscle activity) and static conditions. The authors are unaware of any previous study that has accurately measured the 3D, in vivo subacromial space width during dynamic shoulder motion. Thus, the purpose of this study was to measure the 3D subacromial space width during shoulder elevation using a novel, accurate in vivo measurement technique.

2. Methods

Following IRB approval and informed consent, 11 subjects – 9 male, 2 female, average (standard deviation) age: 63.2 (10.7) – enrolled in the study. Each subject had been diagnosed by ultrasound with an isolated supraspinatus tear and had failed conservative treatment. To minimize subject variability, patients with partial-thickness tears, multi-tendon tears, or significant labral or glenohumeral joint pathology were excluded. All subjects had an asymptomatic contralateral shoulder and denied prior history of injury, pain, limited motion, or surgery. The subjects were tested at 12–16 weeks post-surgery.

At arthroscopy the glenohumeral joint and rotator cuff were examined and the supraspinatus tear identified. An acromioplasty was performed, the greater tuberosity was lightly abraded, and the rotator cuff tear was repaired using a double-row technique (Lo and Burkhart, 2003). Postoperatively, patients wore a sling for 6 weeks. Continuous passive motion was started the day after surgery and progressed for 4–6 weeks. The sling was discontinued at 6 weeks and active motion begun. At 10–12 weeks, progressive resistance training was initiated.

2.1. Testing Setup

Subjects were positioned with their glenohumeral joint centered within a unique biplane X-ray system (Tashman and Anderst, 2003). The system consists of two 100 kW pulsed X-ray generators (EMD Technologies CPX 3100CV, Quebec, Canada) and two 30 cm image intensifiers (Shimadzu AI5765HVP, Kyoto, Japan), optically coupled to synchronized high-speed video cameras (Phantom IV, Vision Research, Wayne, NJ, USA), configured at a 60° angle in a custom gantry to enable a variety of motion studies. Subjects wore a lead-lined thyroid shield and protective vest during testing to minimize X-ray exposure.

2.2. Testing procedures

Biplane X-ray images were acquired at 60 Hz for 2 s while subjects elevated their shoulder in the frontal plane from full adduction to approximately 120° of elevation (Fig. 1). Subjects began with their arm in a fully-adducted position, resting comfortably at their side (Fig. 1a). Shoulder elevation was performed with the subject holding a 3-pound hand weight or a weight that was consistent with the subject's stage of rehabilitation. The ending position was approximately 120° of humerothoracic motion, i.e., the angle formed between the humerus and the torso (Fig. 1b). Subjects were instructed to elevate their shoulder at a frequency of approximately 0.25 Hz, so that the motion from the starting position to the ending position took approximately 2 s. Thus, biplane X-ray images were

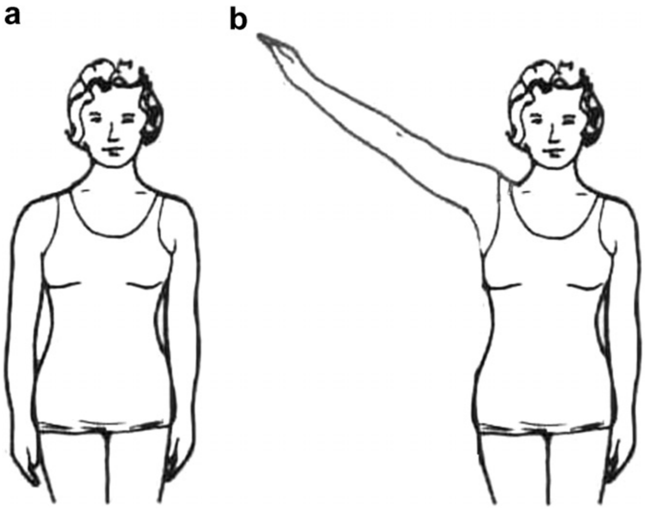

Fig. 1. Subacromial space width was measured while subjects elevated their shoulders in the frontal plane from a fully-adducted position (a) to approximately 120° of elevation (b).

acquired only while the subjects were elevating their shoulders. Subjects were given time to practice each shoulder action with no X-ray generation prior to data collection. Three trials were performed for each shoulder, with a minimum of 3 min between trials to minimize fatigue. The order of shoulder testing (i.e., repaired and contralateral) was balanced across all subjects.

Following testing, bilateral computed tomography (CT) scans of each subject's entire humerus and scapula were acquired. The scans were performed on a LightSpeed16 system (GE Medical Systems, Waukesha, WI, USA), in axial mode with 1.25 mm slice spacing, 18 cm field of view and 512 × 512 pixel image size. This corresponded to an in-plane resolution of approximately 0.35 mm per pixel. The humerus and scapula were manually isolated from other bones and soft tissue (ImageJ 1.32J, http://rsb.info.nih.gov/ij). Using custom software, the CT volume was then interpolated using a feature-based interpolation technique and scaled to have cubic voxels with dimensions similar to the 2D pixel size in the biplane X-ray images (Bey et al., 2006).

2.3. Measuring glenohumeral joint motion

The 3D position and orientation of the humerus and scapula were tracked from the biplane X-ray images using a model-based tracking technique (Bey et al., 2006). This technique determines the 3D position and orientation of a given bone by optimizing the correlation between two digitally reconstructed radiographs (produced from the CT-based 3D bone model) and the two biplane X-ray images. This computationally intensive algorithm was accelerated by parallelizing its calculations on a cluster of thirteen microcomputers (3.4 GHz Pentium 4, Silicon Mechanics iServ R100, Seattle, WA, USA). This decreased the time required to track a scapula from approximately 8 hours on a personal computer to approximately 40 min on the parallel processing system. Using this technique, the 3D position and orientation of the humerus and scapula was determined independently for all frames of each trial. This technique is supported by a validation study that has demonstrated an in vivo, dynamic accuracy of better than 0.4 mm and 0.5° (Bey et al., 2006).

Transformations between each bone's 3D position and anatomical axes were determined from the CT-based bone models using custom software (based on Open Inventor 5.0, Mercury Computer Systems, Chelmsford, MA, USA) that was developed to manually locate specific anatomical landmarks and construct standardized anatomical coordinate systems (Wu et al., 2005). To minimize side-to-side variability in kinematic measures due solely to anatomical axis locations, the same anatomical landmark locations identified on the humerus and scapula of the repaired shoulder were used for the contralateral shoulder. This was accomplished by mirror-imaging the contralateral shoulder CT-based bone models, manually co-registering these bone models with the repaired shoulder's CT-based bone models, and then automatically transferring the anatomical landmark locations to the contralateral shoulder's CT-based bone models. Rotations of the humerus relative to the glenoid were calculated using a standard Euler angle sequence in which the first rotation defined the plane of elevation, the second rotation described the amount of elevation, and the third rotation represented the amount of internal/external rotation (Karduna et al., 2001).

2.4. Measuring subacromial space width

Subacromial space width was measured with custom software based on a previously reported technique for characterizing the interactions of articulating surfaces (Anderst and Tashman, 2003). This method combines joint motion measured from the biplane X-ray images with the subject-specific CT bone models. Briefly, the CT-based bone models were first converted into 3D surface models constructed of contiguous triangular tiles. A typical humerus or scapula model contained approximately 70,000 triangles of 0.5 mm^2 each. To avoid unnecessary calculation, two specific regions of interest were identified: the acromion's caudal surface and the humeral head (including both the greater and lesser tuberosities). After co-registering the surface models with the kinematic data, the custom software calculated the 3D distance from every surface-triangle centroid on the humeral head to every surface-triangle centroid on the acromion. The overall minimum value of all these distances was taken to be the subacromial space width (Fig. 2). This process was repeated for all frames of every trial, providing a time-series of subacromial space width data at each point in time. This process required only 2–3 min per trial on a single personal computer. The subacromial space width was averaged across all trials in 5° increments from 15° to 75° of glenohumeral elevation.

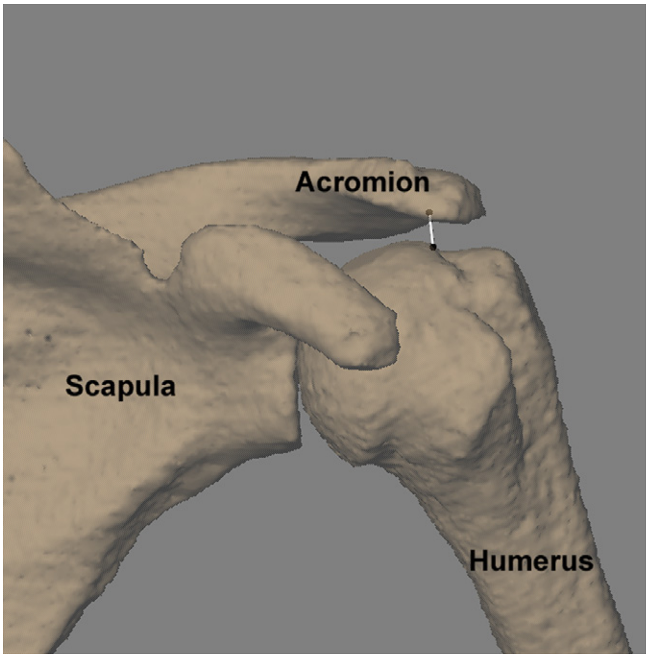

Fig. 2. Subacromial space width (indicated by the white bar connecting the two black spheres) was determined by calculating the shortest distance between the humerus and acromion for each frame of every trial.

In addition, these kinematic and subacromial space data allowed us to determine the range of elevation angles where the minimum distance between the humerus and acromion passed through the anatomical region occupied by the supraspinatus tendon's insertion site. This was accomplished by using custom software to visually identify the two instances in the trial where the contact point on the humerus (i.e., the black sphere located on the humerus in Fig. 2) was located at the medial border and the lateral border of the supraspinatus tendon's insertion site. This region has been previously referred to as the supraspinatus tendon's "footprint" (Curtis et al., 2006) and occupies the interval between the medial border of the humeral head's articular cartilage and the greater tuberosity's lateral most prominence.

2.5. Statistical analysis

The effects of shoulder condition (repaired vs. contralateral), elevation angle, and their interaction on subacromial space width was assessed with a repeated measures two-way ANOVA. Post-hoc comparisons were performed with a Fisher's test with Bonferonni correction for multiple comparisons. Significance was set at $P < 0.05$.

3. Results

Average subacromial space width ranged from 2.3 to 7.4 mm in the repaired shoulders, and ranged from 1.2 to 7.1 mm in the contralateral shoulders (Fig. 3). Subacromial space width decreased with elevation angle in both the repaired and contralateral shoulders, with elevation angle having a statistically significant effect upon subacromial space width ($P < 0.001$). The average (standard deviation) elevation angle where the minimum distance between the humerus and acromion passed through the anatomical region occupied by the supraspinatus tendon's insertion site ranged from 27.7° (6.8°) to 36.1° (6.5°) for all shoulders. For both the repaired and contralateral shoulders, the minimum subacromial space width occurred at a glenohumeral elevation angle of 60° (Fig. 3). At this elevation angle, the supraspinatus tendon has passed under the acromion and therefore the small measurement of subacromial

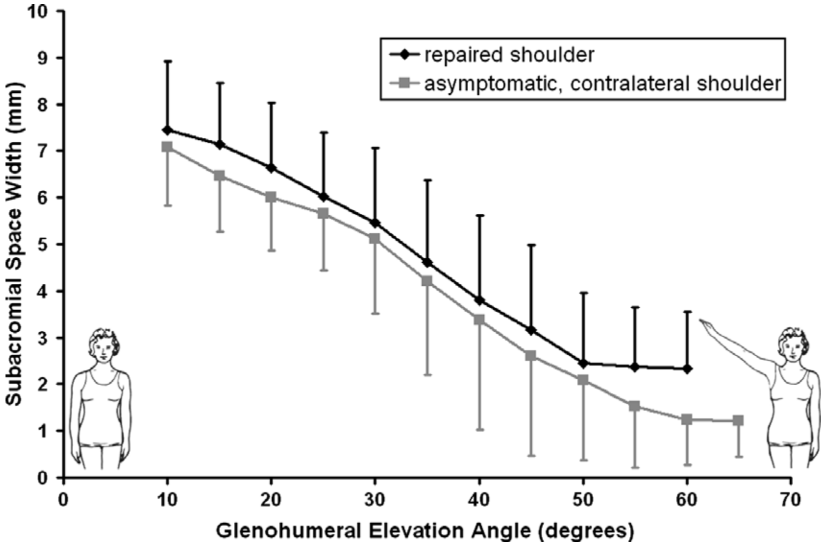

Fig. 3. Subacromial space width in the repaired shoulders was significantly greater than in the contralateral shoulders ($P < 0.001$). In general, subjects were able to elevate their contralateral shoulder higher than their repaired shoulder. Thus, additional data beyond 60° of glenohumeral elevation were available for the contralateral shoulder.

space width (i.e., 1–2 mm) represents the proximity of the greater tuberosity to the acromion.

Subacromial space width was greater in the repaired shoulder (on which the acromioplasty had been performed) than in the unoperated, contralateral shoulder. On average (standard deviation), the difference in subacromial space width between shoulders was 0.5 (0.2) mm. This difference in subacromial space width between shoulders was also statistically significant ($P = 0.001$). The interaction between shoulder (repaired vs. contralateral) and elevation angle was also statistically significant ($P = 0.003$).

4. Discussion

By applying accurate, state-of-the-art motion measurement techniques, we were able to report the subacromial space width during dynamic shoulder motion. Specifically, this study demonstrated a decrease in subacromial space width with increasing elevation angle. The study also found significant differences in the subacromial space width between the repaired and contralateral shoulders of patients who have had rotator cuff repair surgery. Given that the rotator cuff repair surgery included an anterior acromioplasty, it was not surprising that subacromial space width in the repaired shoulder was greater than that in the contralateral shoulder.

The data reported here are in reasonable agreement with the results reported by Graichen and colleagues using static MRI (Graichen et al., 2001). Specifically, for seven male subjects Graichen reported an average subacromial space width of: (1) 8.2 mm (range: 6.9–10 mm) at 30° of humerothoracic abduction and (2) 6.7 mm (range: 3.5–8.8 mm) at 90° of humerothoracic abduction (Graichen et al., 2001). By comparison, the current study reported an average subacromial space width in the contralateral shoulders of 6.0 mm at 20° of glenohumeral elevation (corresponding to approximately 30° of humerothoracic elevation) and 1.2 mm at 60° of glenohumeral elevation (corresponding to approximately 90° of humerothoracic elevation). Although the subacromial space width values reported in this study are consistently lower than the values reported by Graichen and colleagues, it is important to recognize that muscle activity has been shown to have a significant effect on subacromial space width (Hinterwimmer et al., 2003; Graichen et al., 2005, 2001). In particular, abducting muscle forces were shown to decrease subacromial space width from 6.7 mm to 4.9 mm with the shoulder positioned in 90° abduction (Graichen et al., 2001). Thus, abducting muscle activity during shoulder elevation could help to explain, at least in part, why the values reported in the current study are consistently lower than those reported by Graichen and colleagues. Discrepancies between the current data and the results reported by Graichen are also likely due to differences in subject age, experimental techniques, and other factors.

The difference in subacromial space width between the repaired and contralateral shoulders was, on average, only 0.5 mm. This is interesting in that intuitively one might expect a greater difference since the acromioplasty often involves resecting more than this amount of the anterior acromion. Thus, we expected that the difference in subacromial space width between the repaired and contralateral shoulders should have been in the range of 2–5 mm. However, conventional kinematic data from this study (i.e., three-dimensional position and orientation of the humerus relative to the scapula; not reported here) indicate that the humerus in the repaired shoulder is more cranially located on the glenoid than the contralateral shoulder, either due to the surgical procedure (specifically, suturing the torn supraspinatus tendon back down to the greater tuberosity), post-operative stiffness, and/or rotator cuff dysfunction. However, in the absence of pre-operative data, these explanations are speculative. In contrast to these data, Tillander and Norlin used a custom designed intraoperative probe to measure the subacromial space before and after performing an arthroscopic subacromial decompression in 30 patients (Tillander and Norlin, 2002). Their results indicated a subacromial space width of 8 mm before decompression and 16 mm after subacromial decompression. It is plausible that differences in surgical technique may help to explain, at least in part, the appreciable differences between the current study's data and the data reported by Tillander and Norlin.

It is possible that the subacromial space width data at glenohumeral elevation angles of greater than approximately 35–40° may have limited clinical significance. The reason for this is that at elevation angles beyond an average of 36.1°, the shortest distance between the acromion and the humeral head no longer passes through the region occupied by the supraspinatus tendon. Rather, the shortest distance is from the lateral edge of the acromion to the greater tuberosity (Fig. 4). In this arm position (and at higher elevation angles), the relative proximity of the humerus and scapula suggest that the supraspinatus tendon may have already passed underneath the acromion and thus the tendon is no longer at risk of impingement by the acromion. Thus, limiting the reported data to the range of glenohumeral elevation angle values of less than 40° would suggest that the clinically relevant subacromial space width varied from only approximately 4.2 mm to 7.4 mm in the repaired and contralateral shoulders of this population (Fig. 3).

The patient-specific bone models were generated from CT scans and therefore neglected the articular cartilage. Previous research has reported the thickness of the humeral head's articular cartilage to average 1.44 mm (range: 0.65–2.03 mm), with the thinnest cartilage located at the superior border of the humerus (Soslowsky et al., 1992). Thus, at elevation angles lower than an average of approximately 28°, it is likely that the data overestimate the true subacromial space width by the thickness of the humeral head's articular cartilage (i.e., from 0.65 to 1.44 mm). Although relying on CT scans for the patient-specific bone models is a limitation, the same experimental approach was used

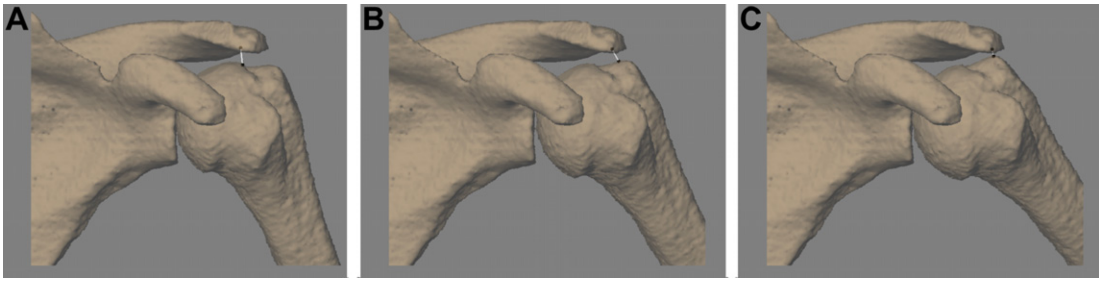

Fig. 4. Subacromial space width – indicated by the white bar connecting the two black spheres – decreased with elevation angle. These images correspond to elevation angles and subacromial space widths of: (A) 28°, 6.1 mm, (B) 35°, 4.1 mm, and (C) 43°, 2.0 mm. At glenohumeral joint elevation angles of greater than approximately 35–40°, the greater tuberosity was the location on the humerus that was in closest proximity to the acromion. Thus, the measurement of subacromial space width may be of modest clinical significance since in these arm positions it is likely that the supraspinatus tendon has "cleared" the acromion and may no longer be at risk of impingement at these (and higher) elevation angles.

throughout the entire study and therefore does not change the relative differences between repaired and contralateral shoulders.

The in vivo accuracy of techniques used for measuring the subacromial space width is often not reported. Measures of repeatability are often reported, but highly repeatable measurements may have limited accuracy due to bias (i.e., an offset in reported measurement). Given that the current study (and previous studies) have reported the subacromial space width to range from 3 to 10 mm over the elevation range most often associated with impingement, a 1–2 mm change in the position of the humerus relative to the scapula may be clinically significant since it represents a 10–67% decrease in subacromial space. The measurement technique reported here has been shown to be accurate to within 0.4 mm and 0.5° in a rigorous validation study that accurately simulated in vivo testing conditions (Bey et al., 2006).

This study has several limitations. The sample size was relatively small, but on-going research will test additional subjects and will also test control subjects with normal shoulders. The testing was performed at 3–4 months post-surgery when subjects may have been at various stages of rehabilitation and full functional recovery may not yet have been achieved. In addition, differences in muscle forces and muscle activation patterns (neither of which were quantified in this study) between subjects may have resulted in differing kinematics. However, this study will test these same subjects at 12 and 24 months post-surgery to assess long-term changes in shoulder function. The study is also limited by a lack of pre-operative data, so it is impossible to characterize the effect of the rotator cuff surgery on subacromial space width. The rationale for not testing patients pre-operatively was that we wanted to minimize subject variability by insuring that patients with only a full-thickness supraspinatus tendon tear – as confirmed by visual inspection during surgery – enrolled in the study. Finally, the study assumes a normal contralateral shoulder as the subjects were asymptomatic in that shoulder. This may be an invalid assumption since Yamaguchi and colleagues found a significant number of rotator cuff tears in asymptomatic shoulders of patients undergoing surgery for symptomatic rotator cuff tears (Yamaguchi et al., 2001).

The strength of this technique is that it provides accurate 3D measures of in vivo subacromial space width during shoulder motion. Previously published results demonstrating the importance of muscle activity on the subacromial space width suggest that subacromial space width should be measured during conditions of physiologic muscle activity. Furthermore, given that it is widely believed that subacromial impingement results from repetitive motion (versus static position) of the supraspinatus tendon under the acromion, the most clinically relevant measurements of the subacromial space width would be made during shoulder motion. The authors believe that this is the first study to measure the 3D, in vivo, subacromial space under conditions of shoulder motion and physiologic muscle forces. Future research will involve testing additional patients as part of an on-going study that is focused on understanding the effects of rotator cuff repair on long-term shoulder function. In addition, future research efforts will also characterize the subacromial space width in a population of subjects with normal shoulder function, i.e., asymptomatic with no history of shoulder injury or shoulder surgery. These data will allow us to determine if the subacromial space width in the asymptomatic, contralateral shoulder of patients undergoing unilateral rotator cuff repair is significantly different from normal, control shoulders.

5. Conclusions

This study used a state-of-the-art biplane X-ray system to provide accurate, in vivo measurements of subacromial space width during shoulder elevation. These measurements were made in both the repaired and asymptomatic, contralateral shoulders of patients at 3–4 months after rotator cuff repair. The subacromial space width in the repaired shoulder (in which approximately 2–5 mm of the acromion had been removed by acromioplasty) was only 0.5 mm less than the asymptomatic, contralateral shoulder when averaged over 10–60° of glenohumeral elevation. These data indicate that the humerus in the repaired shoulder is positioned more cranially on the glenoid than in the contralateral shoulder. It is unclear if these subtle differences in subacromial space width are due to the surgical procedure or post-operative stiffness, or if subacromial impingement was an etiologic factor contributing to the development of the rotator cuff tear. Future research will analyze these patients at additional time points (1 and 2 years post-surgery) to determine if these results represent a transient response to the surgery or a more fundamental difference in rotator cuff function between repaired and contralateral shoulders.

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