Coracohumeral Distances and Correlation to Arm Rotation

An In Vivo 3-Dimensional Biplane Fluoroscopy Study

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Background: Reduced coracohumeral distances have been reported to be associated with anterior shoulder disorders such as subscapularis tears, biceps tendon injuries, and leading edge supraspinatus tears.

Purpose: To determine the variability in coracohumeral distance as a function of arm rotation in healthy male subjects. The null hypothesis was that no differences in coracohumeral distance would exist with respect to arm rotation.

Study Design: Descriptive laboratory study.

Methods: A total of 9 male participants who had full range of motion, strength, and no prior surgery or symptoms in their tested shoulders were enrolled in this institutional review board–approved study. Computed tomography scans of the shoulder were obtained for each subject. A dynamic biplane fluoroscopy system recorded internal and external shoulder rotation with the arm held in the neutral position. Three-dimensional reconstructions of each motion were generated, and the coracohumeral distance and coracoid index (lateral extension of the coracoid) were measured.

Results: The mean coracohumeral distance in neutral rotation was 12.7 ± 2.1 mm. A significantly shorter minimum coracohumeral distance of 10.6 ± 1.8 mm was achieved ($P = .001$) at a mean glenohumeral joint internal rotation angle of 36.6° ± 19.2°. This corresponded to a reduction in coracohumeral distance of 16.4% (range, 6.6%-29.8%). The mean coracoid index was 14.2 ± 6.8 mm. A moderate correlation ($R = -0.75$) existed between the coracohumeral distance and coracoid index.

Conclusion: Coracohumeral distance was reduced during internal rotation. Decreased coracohumeral distance was correlated with larger coracoid indices.

Clinical Relevance: This study provides a reference value for coracohumeral distance in the healthy male population. Knowledge of how coracohumeral distance varies over the range of arm internal-external rotation may improve the clinical diagnosis and treatment plan for patients with anterior shoulder pathology, specifically subcoracoid impingement. Imaging of the coracohumeral distance during internal rotation with the hand at approximately midline should be considered to assess patients with anterior shoulder pain.

Keywords: shoulder; biplane fluoroscopy; coracohumeral distance; subcoracoid impingement; coracoid index

Subcoracoid impingement, while relatively uncommon in clinical incidence when compared to subacromial impingement, has been increasingly diagnosed in patients with anterior shoulder pain and tenderness.[7-9,11,27] However, studies have suggested that subcoracoid impingement may not be as rare as once thought.[6,8,12,22,26,33] In fact, one study reported that 19% of patients with combined subscapularis, supraspinatus, and infraspinatus tears had subcoracoid impingement,[26] and another reported subcoracoid impingement as a postoperative complication in 5.1% of patients following rotator cuff repair and anterior acromioplasty.[36]

Subcoracoid impingement has been defined as the encroachment of the posterolateral coracoid process upon the lesser tuberosity of the humerus.[12] This mechanism is common in patients who repetitively engage in activities involving forward flexion, adduction, and internal rotation because this position reduces coracohumeral distance and potentially impinges the intervening soft tissue structures.[6,8-10,12,22,27] This compression of the soft tissues between the lesser tuberosity and coracoid tip has been termed the *roller-wringer effect*[25] and reportedly can lead to progressive degeneration and injury to the rotator cuff, specifically subscapularis tendon tears, long head biceps tendon injuries, and anterior shoulder pain.[11,13,26,30,33,34]

Anatomic variations of the humerus and scapula, specifically lesser tuberosity prominences and coracoid length/orientation, respectively, can decrease coracohumeral distance.[10,12,13,16,17] Modern imaging techniques have a role in the evaluation of coracohumeral distance, lending to the diagnosis and treatment of patients with subcoracoid impingement.[9,32,37] The coracoid index, or lateral extension of the coracoid process, is subject to individual variation,

and the coracohumeral interval is affected by dynamic arm positions.[33] No specific imaging positions have been described to help interpret coracohumeral distance. Therefore, the purpose of this study was to determine the variability in coracohumeral distance and coracoid index as a function of arm rotation in healthy male subjects. Our null hypothesis was that there would be no differences in coracohumeral distance with respect to shoulder rotation.

METHODS

All participants provided written consent approved by our institutional review board prior to participation. Nine healthy male subjects (mean age $\pm$ standard deviation [SD], 28.7 $\pm$ 6.1 years; height, 1.84 $\pm$ 0.05 m; weight, 91.1 $\pm$ 8.4 kg; body mass index [BMI], 26.9 $\pm$ 2.7 kg/m^2) participated. All subjects underwent a detailed shoulder examination by a shoulder specialist to exclude preexisting pathology in the tested shoulder. It should be noted that the contralateral shoulder in all subjects had shoulder pathology. A total of 4 right shoulders (all dominant sides) and 5 left shoulders (1 dominant, 4 nondominant) were tested.

A high-resolution computed tomography (CT) scan (Aquilion 64; Toshiba America Medical Systems, Tustin, California) of the tested shoulder was collected. The CT scan was used for 3-dimensional (3D) geometry reconstruction of the scapula and humerus. The sequence of axial images from the scan (approximate voxel size, 0.5 $\times$ 0.7 $\times$ 0.7 mm) was obtained using standard 120 kVp and 200 mA techniques with sharp-bone CT reconstruction. The coracoid index was determined in the axial CT view by drawing a line tangential to the glenoid face and then measuring the projection of the coracoid process beyond the line in the slice where this distance was greatest (Figure 1).[8]

Each subject performed 2 motions in a biplane fluoroscopy system (Figure 2): (1) internal rotation with the subject in neutral position and (2) external rotation with the subject in neutral position. Neutral position was defined as the subject in a seated position with the back straight, arm hanging by his side, elbow flexed to 90° so that the forearm was pointing straight ahead parallel to the floor, and thumb pointed up. For internal rotation, subjects rotated their forearm to their abdomen over the course of 1 second. For external rotation, the subject externally rotated their forearm as far away from their abdomen as possible over the course of 1 second. In both movements, subjects were instructed to keep the elbow against the trunk throughout the entire movement. To minimize

Figure 1. Axial computed tomography image demonstrating measurement technique of the coracoid index.

Figure 2. The biplane fluoroscopy system consisting of 2 synchronized C-arms with the subject's shoulder positioned in the 3-dimensional viewing area.

radiation exposure, a single trial for each motion was recorded.

The biplane fluoroscopy system consisted of 2 synchronized BV Pulsera C-arms (Philips Medical Systems, Best,
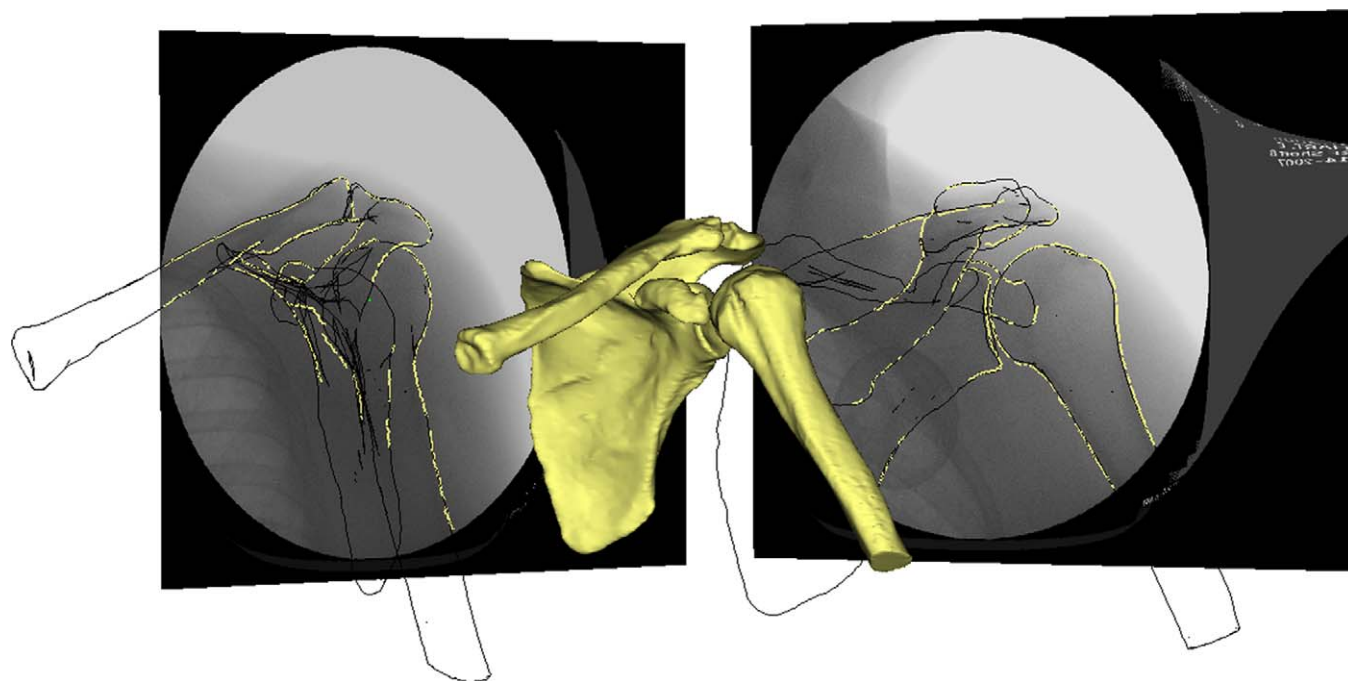
Figure 3. Position and orientation for the bone geometries during an internal rotation frame. The algorithm matched the detected bone contours (yellow) from the calibrated biplane fluoroscopy images with the projected bone contours (black).

the Netherlands) with 30-cm image intensifiers. The C-arms were modified under US Food and Drug Administration guidelines and Colorado Radiation Safety Regulations. Data were collected at 30 Hz with the x-ray generators in a pulsed fluoroscopy mode (8-ms pulses) at 60 mA and 60 kV. Image distortion correction, focal position, and accuracy validation of the biplane fluoroscopy system were established using the procedures as previously reported.[15,19]

The biplane fluoroscopy system was previously validated using standard validation techniques.[4,18,20] Using cadaveric shoulders, with tantalum beads (1.6 mm) inserted for reference measurement, accuracy and precision (mean $\pm$ SD)[2] relative to bead tracking were calculated: 0.2 $\pm$ 0.5 mm, 0.3 $\pm$ 0.3 mm, and 0.3 $\pm$ 0.4 mm for anterior-posterior, superior-inferior, and distraction-compression translations, respectively, and 0.1° $\pm$ 0.8°, 0.2° $\pm$ 0.2°, and 1.7° $\pm$ 1.2° for glenohumeral plane of elevation, elevation angle, and internal-external rotation, respectively. Results were consistent with similar studies using biplane fluoroscopy technology.[1,4,24,28] The difference between tantalum bead ("gold standard") and bone-contour tracking was found to be 0.2 $\pm$ 0.3 mm, −0.01 $\pm$ 0.1 mm, and −0.05 $\pm$ 0.1 mm for respective translations and 0.1° $\pm$ 0.1°, 0.3° $\pm$ 0.2°, 0.1° $\pm$ 0.3° for respective rotations.[4,14]

Data reduction followed the same 4-step process as outlined previously[5,14,15]: 3D bone geometry reconstruction of the humerus and scapula from CT data, coordinate system assignment and geometry transformation, determination of bone position and orientation in the biplane fluoroscopy data, and postprocessing to extract the shoulder kinematics.

In summary, the 3D geometries of the scapula and humerus were extracted from the CT data (Mimics;

Materialise Inc, Plymouth, Michigan). Determination of the bone position and orientation from the biplane fluoroscopy data were performed using Model-Based RSA software (Medis Specials BV, Leiden, the Netherlands).[20,21] Data were analyzed at 10 Hz. Contours were automatically extracted from the biplane fluoroscopy images and manually assigned to the humerus and scapula for each frame. Subsequently, a fully automatic 6-degree-of-freedom contour-matching optimization algorithm determined the 3D bone position and orientation, which optimally matched the detected contours with the projected contours from the imported bone geometries (Figure 3).

Coordinate systems and 3D glenohumeral rotations were determined following the International Society of Biomechanics standards[39] as closely as possible. The lateral-medial axis for the scapula was determined by a line drawn between the trigonum spinae (root of the spine of the scapula) and the angulus acromialis (junction of the posterior and lateral borders of the acromion) (Figure 4). The lateral-medial axis of the humerus was directed parallel to a line connecting the medial and lateral humeral epicondyles, which was estimated based on the bicipital groove,[33,34] with the superior-inferior axis along the central canal of the shaft.[3,23] Internal-external glenohumeral joint rotation was described through the use of Euler angles as the rotation of the humerus about its superior axis.[39] A position of 0° of glenohumeral internal-external rotation was defined as the glenohumeral rotation found with the arm in the neutral position, as described above.

Coracohumeral distance was measured using custom software (Matlab; The MathWorks, Natick, Massachusetts, USA) that derived the minimum distance between the
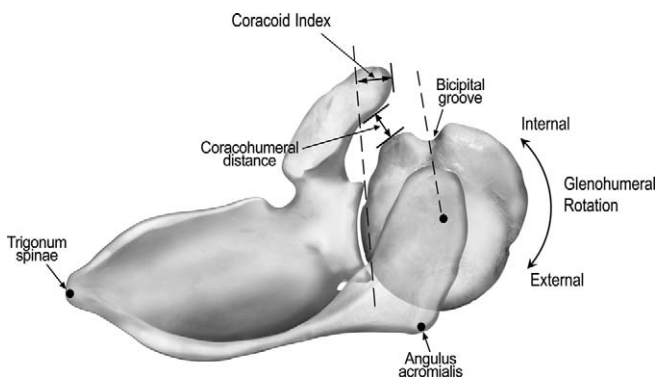
Figure 4. Superior view of the shoulder illustrating internal-external glenohumeral rotation calculated based on the bicipital groove and a line passing through the angulus acromialis and trigonum spinae. Coracohumeral distance and coracoid index are also visualized.

proximal humerus (generally the lesser tuberosity) and coracoid process for each tracked frame. Subsequently, the minimum coracohumeral distance with its corresponding glenohumeral rotation angle was determined. In addition, the difference between the coracohumeral distance with the arm in neutral rotation and the minimum coracohumeral distance was calculated. Lastly, the coracohumeral distances were extracted for every 10° of glenohumeral rotation from 60° of internal rotation to 50° of external rotation for every subject.

Statistical Analysis

A 1-way analysis of variance (ANOVA) was performed to determine the statistical differences between coracohumeral distances at varying degrees of glenohumeral internal-external rotation (60° internal to 50° external rotation). Nonpaired t tests were performed to test the coracohumeral distance measures and coracoid index for laterality (right vs left) and hand dominance (dominant vs nondominant). A paired t test was performed to compare the coracohumeral distance with the arm in neutral rotation and the minimum coracohumeral distance. Lastly, a linear regression analysis was performed to determine the relationship between the coracoid index and minimum coracohumeral distance and coracohumeral distance with the arm in neutral rotation.

RESULTS

Coracohumeral distance was significantly affected by the glenohumeral rotation angle ($P = .033$) (Figure 5). No significant differences in any of the coracohumeral distances and coracoid indexes existed when comparing laterality or hand dominance (Table 1). For all subjects, mean coracohumeral distance at neutral rotation was 12.7 ± 2.1 mm (range, 10.5-16.1 mm). As the arm underwent internal rotation from neutral, there was a mean decrease in the coracohumeral distance of 2.1 ± 1.3 mm. During internal rotation, a minimum coracohumeral distance of 10.6 ±
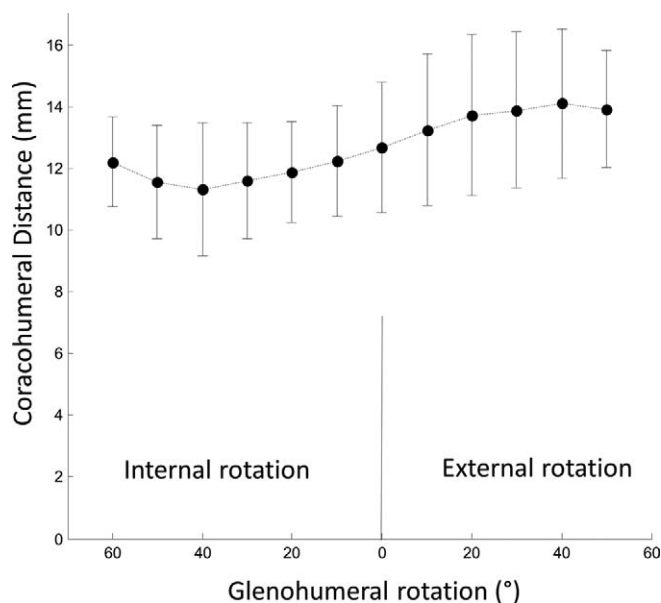

Figure 5. Mean coracohumeral distance across all subjects as a function of glenohumeral rotation angle. Error bars represent standard deviations.

1.8 mm (range, 7.4-12.4 mm) was reached, which was significantly less than the coracohumeral distance at neutral ($P = .001$). This minimum distance was achieved at a mean internal rotation angle of 36.6° ± 19.2° (range, 6.0°-59.0°).

The mean coracoid index was 14.2 ± 6.8 mm (range, −3 to 19.2 mm). Based on the regression analysis, a significant correlation was found between the coracohumeral distance at neutral rotation and coracoid index ($R = -0.75$; $P = .021$). The regression predicted that an increase in coracoid index of 1 mm would decrease the coracohumeral distance by 0.2 mm.

DISCUSSION

Our data indicated that changes in glenohumeral rotation affect the coracohumeral distance, resulting in the rejection of our null hypothesis. With internal rotation of the arm, the coracohumeral interval was narrowed in this subject population. On average, the coracohumeral distance decreased by 16% during internal rotation. This is consistent with what is seen clinically in patients with shoulder pain from subcoracoid impingement, where internal rotation, or forward flexion, adduction, and internal rotation frequently cause pain. Therefore, this relationship suggests the need to image and evaluate the shoulder in a position where the shoulder is internally rotated if a patient is suspected of having subcoracoid impingement.

Subcoracoid impingement is typically a clinical diagnosis of exclusion. While imaging measurements are not the sole criterion to diagnose subcoracoid impingement, our data, in combination with previous studies' findings, suggest that imaging can play a key role in delineating shoulder pathology.[13,32] Previous studies have reported that the coracohumeral distance is significantly decreased in patients with

TABLE 1
Measured Variables Stratified by Lateral Shoulder Side and Hand Dominance[a]

Shoulder Population	Coracohumeral Distance at Neutral, mm	Minimum Coracohumeral Distance, mm	Internal Rotation Angle at Minimum Coracohumeral Distance, deg	Change in Coracohumeral Distance, mm	Coracoid Index, mm
Right (n = 4)	12.3 ± 2.5	10.4 ± 1.9	35.3 ± 26.8	1.9 ± 1.5	16.7 ± 2.8
Left (n = 5)	13.0 ± 2.0	10.7 ± 2.0	37.6 ± 14.1	2.2 ± 1.2	12.2 ± 8.7
Dominant (n = 5)	11.9 ± 2.3	9.8 ± 2.1	36.2 ± 23.3	2.2 ± 1.4	17.1 ± 2.5
Nondominant (n = 4)	13.6 ± 1.7	11.5 ± 0.8	37.0 ± 16.2	2.0 ± 1.3	10.7 ± 9.2
Total (n = 9)	12.7 ± 2.1	10.6 ± 1.8	36.6 ± 19.2	2.1 ± 1.3	14.2 ± 6.8

[a]Data are shown as mean ± standard deviation. Nonpaired t tests were performed between right and left and between dominant and nondominant. No significant differences were found between groups.

subcoracoid impingement when compared to the normal healthy population.[10,13,25,30,35,38] Measuring the coracohumeral distance using plain radiographs, CT, or magnetic resonance imaging (MRI) allows the clinician to more objectively predict cases of impingement when compared to population norms. A narrowed coracohumeral distance on preoperative MRI or CT studies is consistent with subcoracoid impingement and may support dynamic arthroscopic examination of the coracohumeral space and the anatomic structures in this location (upper subscapularis tendon, long head biceps tendon, anterior edge of supraspinatus) and potentially support surgical decompression with a coracoplasty or lesser tuberoplasty.[11-13,29,35]

Values for coracohumeral distance ranging from 4.0 mm to 6.8 mm at internal rotation have been put forth as potential thresholds for indicating subcoracoid impingement.[10,12,26,31,35] However, the combined specificity and sensitivity of these values in predicting true subcoracoid impingement cases has been problematic.[13] While narrowed coracohumeral distance may be associated with subcoracoid impingement, it does not prove causality or justify a diagnosis of subcoracoid impingement when present without symptoms. Given the fact that our data demonstrated a reduction in coracohumeral distance as internal rotation increased, we agree with Okoro et al[32] that measuring coracohumeral distance during internal rotation (elbow flexed 90° with hand midline and slightly off abdomen) allows for better approximation of anatomic relationships encountered during subcoracoid impingement.

A moderate correlation existed between the coracoid index and coracohumeral distance at neutral position ($R = -0.75$) and at minimum coracohumeral distance during internal rotation ($R = -0.46$). Therefore, an increased coracoid index is likely to be associated with a decrease in coracohumeral distance. We suggest measuring the coracoid index when analyzing clinical images because it can be a potential indicator for a narrowed subcoracoid space.

Limitations existed in this study. First, no women were tested. Debate still exists on the influence of sex on coracohumeral distance. Some studies have reported smaller coracohumeral distances in women,[13,37] while others reported no differences in coracohumeral distance or incidence of subcoracoid impingement between sexes.[7,12,34,38] While it is unclear whether differences exist between sexes, our data only reflect the male population. Secondly, biplane fluoroscopy and CT imaging do not depict the soft tissue structures within the coracohumeral interval (articular cartilage, articular capsule, subscapularis muscle and tendon, and subcoracoid bursa). While none of these structures plays a role in measuring coracohumeral distance, it is important to note that subcoracoid impingement can occur without coracohumeral narrowing, resulting instead from bony compression caused by increased, or folded, soft tissue structures with the subcoracoid space.[10,33,34] Lastly, due to radiation exposure limits, we were unable to examine the combination of internal rotation, forward flexion, and adduction, which has been associated with decreased coracohumeral distance.[6,8-10,12,22,27] It could be argued that additional forward flexion during imaging may be useful in re-creating a pathologic position.

CONCLUSION

Coracohumeral distance was affected by arm position and was narrowest with internal rotation of the shoulder joint. Therefore, the amount of internal rotation must be taken into account when analyzing coracohumeral distance in clinical imaging. For patients suspected of having subcoracoid impingement, we recommend that CT and MRI analyses be taken with the shoulder internally rotated so that the hand is approximately midline and slightly off the abdomen in patients with a normal BMI. We believe this position best represents the ability of radiologic technologists to position the patient within a scanner where it is difficult to ensure precise angles. Our data can serve as a baseline for the normal healthy male population, which can help in the interpretation of the risk for subcoracoid bony impingement. Further studies of symptomatic individuals will allow a better understanding of the relationship between the coracohumeral distance and subcoracoid pathology.

REFERENCES

1. Anderst W, Zauel R, Bishop J, Demps E, Tashman S. Validation of three-dimensional model-based tibio-femoral tracking during running. *Med Eng Phys*. 2009;31:10-16.
2. ASTM. *E177-08 Standard Practice for Use of the Terms Precision and Bias in ASTM Test Methods*. West Conshohocken, PA: ASTM International; 2008.
3. Balg F, Boulianne M, Boileau P. Bicipital groove orientation: considerations for the retroversion of a prosthesis in fractures of the proximal humerus. *J Shoulder Elbow Surg*. 2006;15:195-198.
4. Bey MJ, Zauel R, Brock SK, Tashman S. Validation of a new model-based tracking technique for measuring three-dimensional, in vivo glenohumeral joint kinematics. *J Biomech Eng*. 2006;128:604-609.
5. Braun S, Millett PJ, Yongpravat C, et al. Biomechanical evaluation of shear force vectors leading to injury of the biceps reflection pulley: a biplane fluoroscopy study on cadaveric shoulders. *Am J Sports Med*. 2010;38:1015-1024.
6. Dines DM, Warren RF, Inglis AE, Pavlov H. The coracoid impingement syndrome. *J Bone Joint Surg Br*. 1990;72:314-316.
7. Ferreira Neto AA, Almeida AM, Maiorino R, Zoppi Filho A, Benegas E. An anatomical study of the subcoracoid space. *Clinics (Sao Paulo)*. 2006;61:467-472.
8. Ferrick MR. Coracoid impingement. A case report and review of the literature. *Am J Sports Med*. 2000;28:117-119.
9. Freehill MQ. Coracoid impingement: diagnosis and treatment. *J Am Acad Orthop Surg*. 2011;19:191-197.
10. Friedman RJ, Bonutti PM, Genez B. Cine magnetic resonance imaging of the subcoracoid region. *Orthopedics*. 1998;21:545-548.
11. Gaskill TR, Braun S, Millett PJ. Multimedia article. The rotator interval: pathology and management. *Arthroscopy*. 2011;27:556-567.
12. Gerber C, Terrier F, Ganz R. The role of the coracoid process in the chronic impingement syndrome. *J Bone Joint Surg Br*. 1985;67:703-708.
13. Giaroli EL, Major NM, Lemley DE, Lee J. Coracohumeral interval imaging in subcoracoid impingement syndrome on MRI. *AJR Am J Roentgenol*. 2006;186:242-246.
14. Giphart JE, Brunkhorst JP, Horn NH, Shelburne KB, Torry MR, Millett PJ. Effect of plane of arm elevation on glenohumeral kinematics: a normative biplane fluoroscopy study. *J Bone Joint Surg Am*. 2013;95:238-245.
15. Giphart JE, Elser F, Dewing CB, Torry MR, Millett PJ. The long head of the biceps tendon has minimal effect on in vivo glenohumeral kinematics: a biplane fluoroscopy study. *Am J Sports Med*. 2012;40:202-212.
16. Goldthwait JE. An anatomic and mechanical study of the shoulder joint. Explaining many of the cases of painful shoulder, many of the recurrent dislocations and many of the cases of brachial neuralgias or neuritis. *Am J Orthop Surg*. 1909;6:579-606.
17. Gumina S, Postacchini F, Orsina L, Cinotti G. The morphometry of the coracoid processits aetiologic role in subcoracoid impingement syndrome. *Int Orthop*. 1999;23:198-201.
18. Hurschler C, Seehaus F, Emmerich J, Kaptein BL, Windhagen H. Comparison of the model-based and marker-based roentgen stereophotogrammetry methods in a typical clinical setting. *J Arthroplasty*. 2009;24:594-606.
19. Kaptein BL, Shelburne KB, Torry MR, Giphart JE. A comparison of calibration methods for stereo fluoroscopic imaging systems. *J Biomech*. 2011;44:2511-2515.
20. Kaptein BL, Valstar ER, Stoel BC, Reiber HC, Nelissen RG. Clinical validation of model-based RSA for a total knee prosthesis. *Clin Orthop Relat Res*. 2007;464:205-209.
21. Kaptein BL, Valstar ER, Stoel BC, Rozing PM, Reiber JH. A new model-based RSA method validated using CAD models and models from reversed engineering. *J Biomech*. 2003;36:873-882.
22. Kragh JF Jr, Doukas WC, Basamania CJ. Primary coracoid impingement syndrome. *Am J Orthop (Belle Mead NJ)*. 2004;33:229-232.
23. Kummer FJ, Perkins R, Zuckerman JD. The use of the bicipital groove for alignment of the humeral stem in shoulder arthroplasty. *J Shoulder Elbow Surg*. 1998;7:144-146.
24. Li G, Van de Velde SK, Bingham JT. Validation of a non-invasive fluoroscopic imaging technique for the measurement of dynamic knee joint motion. *J Biomech*. 2008;41:1616-1622.
25. Lo IK, Burkhart SS. The etiology and assessment of subscapularis tendon tears: a case for subcoracoid impingement, the roller-wringer effect, and TUFF lesions of the subscapularis. *Arthroscopy*. 2003;19:1142-1150.
26. Lo IK, Parten PM, Burkhart SS. Combined subcoracoid and subacromial impingement in association with anterosuperior rotator cuff tears: an arthroscopic approach. *Arthroscopy*. 2003;19:1068-1078.
27. Martetschlager F, Rios D, Boykin RE, Giphart JE, de Waha A, Millett PJ. Coracoid impingement: current concepts. *Knee Surg Sports Traumatol Arthrosc*. 2012;20:2148-2155.
28. Massimini DF, Warner JJ, Li G. Non-invasive determination of coupled motion of the scapula and humerus—an in-vitro validation. *J Biomech*. 2011;44:408-412.
29. Mulyadi E, Harish S, O'Neill J, Rebello R. MRI of impingement syndromes of the shoulder. *Clin Radiol*. 2009;64:307-318.
30. Nove-Josserand L, Boulahia A, Levigne C, et al. Coracohumeral space and rotator cuff tears [in French]. *Rev Chir Orthop Reparatrice Appar Mot*. 1999;85:677-683.
31. Nove-Josserand L, Edwards TB, O'Connor DP, Walch G. The acromiohumeral and coracohumeral intervals are abnormal in rotator cuff tears with muscular fatty degeneration. *Clin Orthop Relat Res*. 2005;(433):90-96.
32. Okoro T, Reddy VR, Pimpelnarkar A. Coracoid impingement syndrome: a literature review. *Curr Rev Musculoskelet Med*. 2009;2:51-55.
33. Patte D. The subcoracoid impingement. *Clin Orthop Relat Res*. 1990;(254):55-59.
34. Radas CB, Pieper HG. The coracoid impingement of the subscapularis tendon: a cadaver study. *J Shoulder Elbow Surg*. 2004;13:154-159.
35. Richards DP, Burkhart SS, Campbell SE. Relation between narrowed coracohumeral distance and subscapularis tears. *Arthroscopy*. 2005;21:1223-1228.
36. Suenaga N, Minami A, Kaneda K. Postoperative subcoracoid impingement syndrome in patients with rotator cuff tear. *J Shoulder Elbow Surg*. 2000;9:275-278.
37. Tan V, Moore RS Jr, Omarini L, Kneeland JB, Williams GR Jr, Iannotti JP. Magnetic resonance imaging analysis of coracoid morphology and its relation to rotator cuff tears. *Am J Orthop (Belle Mead NJ)*. 2002;31:329-333.
38. Tasu JP, Miquel A, Rocher L, Molina V, Gagey O, Blery M. MR evaluation of factors predicting the development of rotator cuff tears. *J Comput Assist Tomogr*. 2001;25:159-163.
39. Wu G, van der Helm FC, Veeger HE, et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—part II: shoulder, elbow, wrist and hand. *J Biomech*. 2005;38:981-992.