Dynamic Three-Dimensional Shoulder Kinematics In Patients With Massive Rotator Cuff Tears: A Comparison of Patients With And Without Subscapularis Tears

Yuji Yamada
Kyoto Tachibana University
Yoshihiro Kai (kai-y@tachibana-u.ac.jp)
Kyoto Tachibana University
Noriyuki Kida
Kyoto Institute of Technology University
Hitoshi Koda
Kansai Welfare Science University
Hitoshi Ikeda
Ikeda Orthopedic & Rehabilitation Clinic
Minoru Takeshima
Department of Orthopedics, Tanabe Central Hospital
Kenji Hoshi
Hiroshima International University
Kazuyoshi Gamada
Hiroshima International University
Toru Morihara
Marutamachi Rehabilitation Clinic

Research article

Keywords: 3D-to-2D registration technique, massive rotator cuff tears, subscapularis tear, shoulder kinematics, center of humeral head, superior-inferior translation

Posted Date: November 2nd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-1014199/v1

Abstract

Background: Massive rotator cuff tears (MRCTs) with subscapularis tears cause severe shoulder dysfunction. This study aimed to examine the influence of subscapularis tears on 3D shoulder kinematics during scapular plane abduction in patients with MRCTs.

Methods: Fifteen patients were enrolled and were divided into two groups: supraspinatus and infraspinatus tears either with subscapularis tear (Torn Subscapularis group: 10 shoulders) or without subscapularis tear (Intact Subscapularis group: 5 shoulders). Single-plane fluoroscopic images during scapular plane elevation and computed tomography-derived 3D bone models were matched to the fluoroscopic images using 2D/3D registration techniques. Changes in 3D kinematic results were compared.

Results: The humeral head center at the beginning of arm elevation was significantly higher in the Torn Subscapularis group than in the Intact Subscapularis group (1.8 ± 3.4 mm vs. −1.1 ± 1.6 mm, respectively, $P < 0.05$). In the Torn Subscapularis group, the center of the humeral head migrated superiorly, then significantly downward at 60° arm elevation ($P < 0.05$). In the Intact Subscapularis group, there was no significant difference in the superior-inferior translation of the humeral head between the elevation angles.

Conclusions: In cases of MRCT with a torn subscapularis, the center of the humeral head showed a superior translation at the initial phase of scapular plane abduction, subsequently, there was inferior translation. These findings suggest that the subscapularis muscle plays an important role in determining the glenohumeral joint’s dynamic stability in a superior-inferior direction in patients with MRCTs.

Background

Rotator cuff tear is a common shoulder disorder. The main symptoms are pain, restricted range of motion, muscle weakness, and other functional impairments. The rotator cuff's primary function is to dynamically stabilize the shoulder joint by compressing the humeral head into the glenoid cavity and maintaining the centripetal position of the humeral head.[1,2,3] Burkhart[4] states that the balance of force couples in the transverse and coronal planes is important in maintaining the glenohumeral (GH) joint’s stability and function. The balance of forces in the transverse plane is maintained by the subscapularis muscles located anteriorly and the infraspinatus and teres minor muscles located posteriorly.[1,4] In the coronal plane, the force couple is formed mainly by the supraspinatus and deltoid muscles.[5,6] Rotator cuff tears disrupt the balance of the force couples, affecting the kinematics of the GH joint, resulting in the loss of ability to elevate the arm.[4,7,8]

Some patients with massive rotator cuff tears (MRCTs) lose the ability to elevate the arm due to secondary changes such as muscle atrophy,[9] fatty infiltration,[10] and osteoarthritis.[11] This condition is called pseudoparalysis and is associated with abnormal glenohumeral (GH) joint kinematics, including superior migration of the humeral head on arm elevation.[12,7,8] Collin et al.[12] classified MRCTs into five types and investigated their relationship to active motion. They reported that a tear in the supraspinatus and entire subscapularis (type B) or supraspinatus, infraspinatus, and superior subscapularis (type C) were risk factors for developing pseudoparalysis.[12] Furthermore, these patients had difficulty recovering elevation function in a rehabilitation program.[13] Sahara et al.[14] reported that although abnormal GH kinematics were identified in pseudoparalysis, no significant difference in tear type between patients with and without pseudoparalysis. Although subscapularis tears are considered a risk factor for pseudoparalysis,[13] some patients with MRCTs can perform active elevation.[14,15] The influence of subscapularis tears on GH kinematics in patients with MRCTs without pseudoparalysis is unclear.

Previous studies have used cadaveric simulations,[7,6,16] two-dimensional (2D) or three-dimensional (3D) static radiographs,[17,18,19] and dynamic 3D analysis using the 3D-to-2D registration technique to measure joint kinematics in rotator cuff tears.[20,21,22,14] The 3D-to-2D registration technique allows accurate measurement of joint kinematics based on matching a bone model created from computed tomography (CT) images to X-ray fluoroscopic images. High in-plane accuracy is a strong point of these techniques employing single-plane radiographic imaging, with a reported accuracy of 0.47 mm and 1.53 mm for in-plane and out-of-plane translations, respectively, and 0.76° and 3.72° for in-plane and out-of-plane rotations, respectively.[23] Previous studies[20,22] that used this method limited tear sizes to medium or large rotator cuff tears. None of the studies we found analyzed the effect of subscapularis tears on joint dynamics.

Knowledge of the effect of subscapularis muscle tears on GH kinematics may also provide important information for determining an effective treatment strategy. This study aimed to examine the effect of subscapularis tears on 3D glenohumeral kinematics during scapular plane abduction in patients with MRCTs without pseudoparalysis. We hypothesized that MRCTs with a torn subscapularis would exhibit greater translation of the humeral head relative to the glenoid cavity than MRCTs without such a tear.

Methods

Subjects

This study recruited patients with MRCTs involving at least two tendons, including the supraspinatus (SSP) and infraspinatus (ISP), with or without the subscapularis (SSC). MRCTs were confirmed by magnetic resonance imaging (MRI) in all patients. Exclusion criteria included a concurrent neuromuscular disorder, a history of surgery on the shoulder joint, a score greater than 3 on the numerical pain rating scale during arm elevation, and an inability to elevate the arm by at least 140°.

A total of 15 patients (15 shoulders, mean age 76.1 years) were divided into two groups: 10 shoulders in the SSP and ISP with SSC tears (Torn SSC group; mean age, 75.0 ± 7.4 years), and 5 shoulders in the SSP and ISP tears (Intact SSC group; mean age, 78.4 ± 2.3 years). The demographic data for the two groups are shown in Table 1. The Institutional Review Board approved the study protocol, and all subjects gave their written informed consent before participation.

Image evaluation

T1-weighted and T2-weighted MR images were obtained (3.0-T, X-series; Philips Healthcare, Best, Netherlands). in the coronal oblique, sagittal oblique, and axial planes. The tear sizes were measured using MRI. For the SSP and ISP, we used the classification of DeOrio and Cofield.[24] A greater than 5 cm retraction in the coronal plane was defined as a massive tear. For the SSC, we used the modified Lafosse's classification[25] as follows: type I, a partial tear of the upper one-third of the SSC; type II, a complete tear of the upper one-third of the SSC; type III, a complete tear of the upper two-thirds of the SSC; and type IV, a complete tear of the entire width of the SSC. Fatty infiltration of the SSP, ISP, and SSC muscles was graded using the 5-point semiquantitative scale described originally by Goutallier et al.[10] and modified for MRI analysis by Fuchs et al.[26] as follows: 0, normal; 1, some fat streaks; 2, fatty degeneration of less than 50% but still more muscle than fat; 3, fatty degeneration of 50% (equal fat and muscle); and 4, fatty infiltration of more than 50%. Moreover, the radiologic evaluation for cuff tear arthropathy was classified into six types according to Hamada et al.[11]: Grade 1, acromiohumeral interval (AHI) ≥ 6 mm; Grade 2, AHI ≤ 5 mm; Grade 3, AHI ≤ 5 mm, with acetabulization; Grade 4A, glenohumeral arthritis, without acetabulization; Grade 4B, glenohumeral arthritis, with acetabulization; Grade 4A, humeral head collapse, which is characteristic of cuff tear arthropathy. The imaging evaluation data for the two groups are shown in Table 1.

Image acquisition and 3D modeling

Scapular plane abduction was recorded using a flat panel radiography/fluoroscopy (R/F) system (SONIALVISION Safire, Shimadzu, 0.286 × 0.286 mm/pixel) and fluoroscopic images were acquired in a single anterior-posterior direction. Patients elevated the arm in the scapular plane (30° anteriorly to the frontal plane) from a natural hanging position to a maximum elevation over 3 seconds, with the elbow joint extended while standing. The distance from the tube of the flat panel R/F system to the target shoulder was 1500 mm, and the sampling rate was 7.5 frames/second.

CT was then used to obtain 0.5 mm tomographic images of the humerus and scapula. A 3D bone model of the humerus and scapula was created from the tomographic images using segmentation software (3D-Doctor, Able Software Corp., Lexington, MA, USA). The 3D bone models were converted to a polygonal surface model, and a smoothing process was applied using a 3D mesh processing software (MeshLab; www.meshlab.net/). A single experienced researcher embedded the local coordinate system of the glenoid and humerus onto the 3D bone models using the 3D-Aligner software (GLAB Corp., Higashihiroshima, Japan). Humerus coordinates were set with their origin at the center of the humeral head, a y-axis parallel to the humeral shaft, and an x-axis passing through the center of the intertubercular groove.[27] Scapular coordinates were set with their origin at the center of the scapular glenoid cavity, a y-axis parallel with a line connecting the topmost and lowermost edges of the glenoid cavity, and a z-axis parallel to a line connecting the anterior-most and posterior-most edges of the glenoid cavity.[27]

Model-image registration

JointTrack (open-source software; www.sourceforge.net/projected/jointtrack) was used to match the completed 3D bone model with the fluoroscopic images. The 3D bone model was matched to each fluoroscopic image. Outlines in the 3D bone model were matched to outlines in the fluoroscopy images. We used the greater tubercle, lesser tubercle, humeral head, and humeral shaft as landmarks when matching the humerus. We used the acromial process, coracoid process, glenoid cavity, scapular spine, superior angle, medial margin, and inferior angle as landmarks when matching the scapula (Fig. 1).

Data processing

The 3D shoulder kinematics were obtained using the 3D-Joint Manager software (GLAB Corp., Higashihiroshima, Japan). For the 3D joint orientation, the position of the distal bone in the local coordinate system of the proximal bone was calculated by the Euler angle.[28] Humeral elevation was defined as rotation about the z-axis. Scapular motion was defined as anterior-posterior tilt about the x-axis, internal-external rotation about the y-axis, and upward-downward rotation about the z-axis. Internal-external humeral rotation relative to the scapula was defined as rotation about its y-axis. The humeral head translation (in the superior-inferior, anterior-posterior, and medial-lateral directions) was calculated as the position of the humeral head center relative to the glenoid center. All kinematics data were measured from the beginning to the end of arm elevation. We also measured translation on each axis three times and calculated the root-mean-square (RMS) error to investigate measurement error. The RMS error observed in this study was an in-plane error of 0.12 mm and an out-of-plane error of 0.61 mm, which are comparable to previous validation studies.[23]

Statistical Analysis

Image evaluation and kinematics results were compared between the intact and Torn SSC groups. The Mann–Whitney U test was used to compare age, fatty infiltration, and glenohumeral and scapular rotation angles at the beginning and end of arm elevation. Chi-square tests were used to analyze categorical data such as gender and rotator cuff tear arthropathy. The effect of the subject group (Torn SSC group and Intact SSC group) on the GH kinematics in the three directions of translation of the humeral head were analyzed using a two-factor linear mixed-effects model. When a significant interaction between the subject group and arm elevation angle was observed, posthoc Bonferroni correction was used for further significance testing. The software used for statistical processing was SPSS Statistics 24 (IBM, Japan), and the significance level used was 5%.

Results

GH positions

A significant nonlinear interaction was found for superior-inferior translation between the two independent factors, indicating that the subject group effect on superior-inferior translation depended on elevation angle ($F = 3.85$, $P < 0.05$). The humeral head in patients in the Torn SSC group was positioned significantly more superiorly than in the Intact SSC group at the beginning of arm elevation (−1.1 ± 1.6

mm in the Intact SSC group vs. 1.8 ± 3.4 mm in Torn SSC group, $P < 0.05$) (Table 2). In the Torn SSC group, the center of the humeral head had migrated superiorly by 2.3 ± 3.9 mm at 50° arm elevation, then showed significant inferior translation (1.5 ± 3.9 mm) at 60° arm elevation ($P < 0.05$). In the Intact SSC group, there was no significant difference in superior-inferior translation between each arm elevation. Superior-inferior translation of the humeral head during arm elevation is shown in Fig. 2.

In both groups, anterior translation relative to the glenoid cavity was observed in the initial phase of arm elevation, then the humeral head gradually migrated posteriorly with increasing elevation. However, there was no significant interaction between the two independent factors in the anterior-posterior translation models ($F = 0.62$, $P = 0.43$) (Table 3). Moreover, there was no significant interaction between the two independent factors in the medial and lateral translation of the humeral head ($F = 0.03$, $P = 0.86$) (Table 4).

Rotation

There was no significant difference in GH abduction angle between the intact and Torn SSC groups at the beginning and end of arm elevation, even though the GH abduction angle was slightly smaller in the Torn SSC group at the end of elevation (Table 5). There was no significant difference in the GH external rotation angles at the beginning and end of arm elevation between the two groups.

The scapula showed upward rotation, posterior tilting, and external rotation in both groups during arm elevation. The upward scapular rotation at the end of arm elevation was significantly greater in the Torn SSC group (52.1° ± 10.6°) than in the Intact SSC group (42.0° ± 5.5°, $P < 0.05$) (Table 5). However, no significant difference was found at the beginning of elevation. There were no significant differences in posterior tilting and external rotation of scapular between the two groups at the beginning and end of arm elevation (Table 5).

Discussion

Previous studies have reported that tears of the subscapularis in MRCTs are a risk factor for the development of pseudoparalysis.[13,12] However, some studies suggest that tear size only is not enough to predict the ability to elevate the arm.[14,15] Furthermore, despite the abnormal joint kinematics affecting arm elevation, the effect of SSC tears on GH kinematics remained unclear. We found that an SSC tear led to greater superior migration of the humeral head center, which then migrated inferiorly as the elevation progressed. Our study is the first to show the effect of SSC tears on GH kinematics in patients with MRCTs using 3D kinematics analysis with 3D-to-2D registration technique.

Burkhart[4] reported that MRCTs with a Torn SSC failed to maintain the coronal plane force couple and showed obvious superior migration of the humeral head into contact with the subacromial surface. These patients showed “Captured Fulcrum Kinematics,” in which the undersurface or anterior end of the acromion was used as a fulcrum to elevate the shoulder.[4] In the present study, the humeral head was located significantly more superiorly at the beginning of arm elevation in the Torn SSC group than in the

Intact SSC group. However, the ability to elevate the arm was maintained. This result may support Burkhart's theory[4] that the superiorly migrated humerus head creates a fulcrum on the acromion’s undersurface.

Regarding the resultant force applied to the humeral head during arm elevation, the vertical force on the glenoid cavity is greatest at 90° elevation and the shear force acting superiorly on the humeral head is greatest between 30° and 60° elevation.[2,29] Because the force of the deltoid muscle causes the upward shearing force on the humeral head to be greatest in the initial phase of the arm elevation, the rotator cuff must exert its greatest force by 60° of elevation and hold the humeral head in the glenoid cavity.[2] In the present study, the humeral head migrated superiorly up to 50° of elevation and inferiorly at 60° of elevation in the Torn SSC group, consistent with the importance of the downward action of the humeral head against the upward shear force at 50°–60° of elevation to enable active elevation in patients with MRCTs with SSC tears.

In contrast, the Intact SSC group showed no superior migration of the humeral head relative to the glenoid on arm elevation. Kijima et al.[20] and Millet et al.[22] observed GH kinematics of medium tears with an Intact SSC and reported that the humeral head did not show significant superior migration in patients with or without symptoms. Kozono et al.[21] found slight superior migration of the humeral head during active arm elevation in patients with large or massive tears (it is unknown if these were with or without SSC tears) compared to healthy subjects. However, there was no significant difference in humeral head position between the two groups. Thus, the presence or absence of SSC tears in patients with MRCTs may affect the dynamic stability of the glenohumeral joint in the superior and inferior directions.

There was no significant difference in the anterior-posterior and medial-lateral translation of the humeral head between the Intact SSC group and the Torn SSC group. Cadaveric studies investigating the effect of rotator cuff tears on GH motion have shown that tears involving the upper half of the SSC lead to anterosuperior translation,[30] while supraspinatus and infraspinatus tears lead to posterior translation.[31] In contrast, Kozono et al.[21] observed anterior-posterior and medial-lateral migration of the humeral head in vivo and found no significant difference between patients with massive tears and healthy subjects. In their study, both groups showed a slight anterior translation after the beginning of the arm elevation.[21] In the present study, the humeral head was located anteriorly at the beginning of arm elevation in both groups and gradually migrated posteriorly as elevation progressed. The alterations in GH motion shown in this study may be characteristic of massive tears in vivo.

The Torn SSC group had a slightly smaller GH abduction angle and a greater upward rotation of the scapula (i.e., reduced scapulohumeral rhythm) compared to the Intact SSC group. Miura et al.[32] measured 3D scapular kinematics in patients with MRCTs and showed that the GH abduction angle was significantly smaller and the upward rotation of the scapula was greater than in the elderly people without rotator cuff tears. Simulation studies using cadavers show that as the size of the rotator cuff tear increases, so does the force the deltoid muscle needs to exert to elevate the arm.[33,34] Furthermore, electromyographic studies have shown significantly increased muscle activity in the upper trapezius and the serratus anterior muscle that rotates the scapula in patients with MRCTs.[35] These previous studies[33,34,35,32] support our findings and suggest a compensatory increase in upward rotation of the scapula to compensate for the GH abduction torque compromised by the rotator cuff tear.

This study has several limitations. First, we only studied MRCT cases capable of active arm elevation. Patients with pseudoparalysis were excluded because the study required that we compare humeral head migration at different arm elevation angles. Secondly, intact rotator cuff and other shoulder muscle activities that affect GH kinematics were not investigated using electromyography or other methods. Finally, we were unable to secure a good sample size to improve the statistical power of the study because the target was very severe MRCTs. In the future, we need to use electromyographic and simulation analysis. This will enable investigation of the compensatory functions involved in active arm elevation and comparison of joint dynamics with patients with pseudoparalysis.

Conclusion

We hypothesized that MRCTs with a torn subscapularis would exhibit greater translation of the humeral head relative to the glenoid cavity than MRCTs without such a tear. In cases of MRCT with a torn subscapularis, the center of the humeral head showed a superior translation at the initial phase of scapular plane abduction, subsequently, there was inferior translation. These findings suggest that the subscapularis muscle plays an important role in determining the dynamic stability of the glenohumeral joint in a superior-inferior direction in patients with MRCTs.

List Of Abbreviations

CT	Computed tomography
MRCT	Massive rotator cuff tears
MRI	Magnetic resonance imaging
RMS	Root-mean-square
GH	glenohumeral
ISP	infraspinatus
SD	standard deviation
SSC	subscapularis
SSP	supraspinatus

Declarations

Conflict of interest: None

IRB: The Institutional Review Board of Kyoto Prefectural Rehabilitation Hospital for the Disabled approved the study protocol (No. 11).

Acknowledgments: The authors would like to thank H. Itou for providing technical assistance with the experiments. We also thank Y. Miura and H. Fukushima for their leading expertise on shoulder rehabilitation.

Ethics approval and consent to participate: This study has been approved by the Institutional Review Board of Kyoto Prefectural Rehabilitation Hospital for the Disabled approved the study protocol (No. 11).

Consent for publication: All the patients agreed that we use their data for the study and publish our draft in the “J Orthop Surg Res” journal. We obtained written informed consents from all the patients.

Availability of data and materials: All data generated or analyzed during this study are included in this published article.

Competing interests: The authors declare that they have no competing interests.

Funding: Not applicable.

Authors' contributions: YY, YK, KN, KH, HK, GK, and TM contributed to the conception and design of the study. YY, YK, and TM performed acquisition of data. YY, YK, KN, and TM conducted data analysis, and YY, YK, MT, and TM contributed to data interpretation and preparation of the manuscript. All authors read and approved the final version of the manuscript.

References

1. Burkhart SS. Arthroscopic treatment of massive rotator cuff tears. Clinical results and biomechanical rationale. Clin Orthop Relat Res 1991;267:45-56.Inman VT, Saunders JB, Abbott LC. Observations of the function of the shoulder joint. 1944. Clin Orthop Relat Res 1996;330:3-12. doi:10.1097/00003086-199609000-00002Lippitt S, Matsen F. Mechanisms of glenohumeral joint stability. Clin Orthop Relat Res 1993;291:20-28. doi:10.1097/00003086-199306000-00004
2. Burkhart SS. Fluoroscopic comparison of kinematic patterns in massive rotator cuff tears. A suspension bridge model. Clin Orthop Relat Res 1992;284:144-152.
3. Halder AM, Zhao KD, Odriscoll SW, Morrey BF, An KN. Dynamic contributions to superior shoulder stability. J Orthop Res 2001;19:206-212. doi:10.1016/S0736-0266(00)00028-0
4. Parsons IM, Apreleva M, Fu FH, Woo SL. The effect of rotator cuff tears on reaction forces at the glenohumeral joint. J Orthop Res 2002;20:439-446. doi:10.1016/S0736-0266(01)00137-1Mura N, O’Driscoll SW, Zobitz ME, Heers G, Jenkyn TR, Chou SM, et al. The effect of infraspinatus disruption on glenohumeral torque and superior migration of the humeral head: A biomechanical study. J

Shoulder Elbow Surg 2003;12:179-184. doi:10.1067/mse.2003.9Thompson WO, Debski RE, Boardman ND, Taskiran E, Warner JJ, Fu FH, et al. A biomechanical analysis of rotator cuff deficiency in a cadaveric model. Am J Sports Med 1996;24:286-292. doi:10.1177/036354659602400307

5. Warner JJP, Higgins L, Parsons IM, Dowdy P. Diagnosis and treatment of anterosuperior rotator cuff tears. J Shoulder Elbow Surg 2001;10:37-46. doi:10.1067/mse.2001.112022
6. Goutallier D, Postel JM, Bernageau J, Lavau L, Voisin MC. Fatty muscle degeneration in cuff ruptures. Pre- and postoperative evaluation by CT scan. Clin Orthop Relat Res 1994;304:78-83.
7. Hamada K, Yamanaka K, Uchiyama Y, Mikasa T, Mikasa M. A radiographic classification of massive rotator cuff tear arthritis. Clin Orthop Relat Res 2011;469:2452-2460. doi:10.1007/s11999-011-1896-9
8. Collin P, Matsumura N, Lädermann A, Denard PJ, Walch G. Relationship between massive chronic rotator cuff tear pattern and loss of active shoulder range of motion. J Shoulder Elbow Surg 2014;23:1195-1202. doi:10.1016/j.jse.2013.11.019
9. Collin PG, Gain S, Nguyen Huu F, Lädermann A. Is rehabilitation effective in massive rotator cuff tears? Orthop Traumatol Surg Res 2015;101:S203-205. doi:10.1016/j.otsr.2015.03.001
10. Sahara W, Yamazaki T, Inui T, Konda S. Three-dimensional kinematic features in large and massive rotator cuff tears with pseudoparesis. J Shoulder Elbow Surg 2020. doi:10.1016/j.jse.2020.07.021
11. Wieser K, Rahm S, Schubert M, Fischer MA, Farshad M, Gerber C, et al. Fluoroscopic, magnetic resonance imaging, and electrophysiologic assessment of shoulders with massive tears of the rotator cuff. J Shoulder Elbow Surg 2015;24:288-294. doi:10.1016/j.jse.2014.05.026
12. Konrad GG, Markmiller M, Jolly JT, Ruter AE, Sudkamp NP, McMahon PJ, et al. Decreasing glenoid inclination improves function in shoulders with simulated massive rotator cuff tears. Clin Biomech 2006;21:942-949. doi:10.1016/j.clinbiomech.2006.04.013
13. Dennis DA, Mahfouz MR, Komistek RD, Hoff W. In vivo determination of normal and anterior cruciate ligament-deficient knee kinematics. J Biomech 2005;38:241-253. doi:10.1016/j.jbiomech.2004.02.042
14. Keener JD, Wei AS, Kim HM, Steger-May K, Yamaguchi K. Proximal humeral migration in shoulders with symptomatic and asymptomatic rotator cuff tears. J Bone Joint Surg Am 2009;91:1405-1413. doi:10.2106/JBJS.H.00854
15. Yamaguchi K, Sher JS, Andersen WK, Garretson R, Uribe JW, Hechtman K, et al. Glenohumeral motion in patients with rotator cuff tears: A comparison of asymptomatic and symptomatic shoulders. J Shoulder Elbow Surg 2000;9:6-11. doi:10.1016/s1058-2746(00)90002-8
16. Kijima T, Matsuki K, Ochiai N, Yamaguchi T, Sasaki Y, Hashimoto E, et al. In vivo 3-dimensional analysis of scapular and glenohumeral kinematics: comparison of symptomatic or asymptomatic shoulders with rotator cuff tears and healthy shoulders. J Shoulder Elbow Surg 2015;24:1817-1826. doi:10.1016/j.jse.2015.06.003

17. Kozono N, Okada T, Takeuchi N, Hamai S, Higaki H, Shimoto T, et al. Dynamic kinematics of the glenohumeral joint in shoulders with rotator cuff tears. J Orthop Surg Res 2018;13:9. doi:10.1186/s13018-017-0709-6
18. Millett PJ, Giphart JE, Wilson KJ, Kagnes K, Greenspoon JA. Alterations in glenohumeral kinematics in patients with rotator cuff tears measured with biplane fluoroscopy. Arthroscopy 2016;32:446-451. doi:10.1016/j.arthro.2015.08.031
19. Matsuki K, Matsuki KO, Yamaguchi S, Ochiai N, Sasho T, Sugaya H, et al. Dynamic in vivo glenohumeral kinematics during scapular plane abduction in healthy shoulders. J Orthop Sports Phys Ther 2012;42:96-104. doi:10.2519/jospt.2012.3584
20. DeOrio JK, Cofield RH. Results of a second attempt at surgical repair of a failed initial rotator-cuff repair. J Bone Joint Surg Am 1984;66:563-567. doi:10.2106/00004623-198466040-00011
21. Lafosse L, Jost B, Reiland Y, Audebert S, Toussaint B, Gobezie R. Structural integrity and clinical outcomes after arthroscopic repair of isolated subscapularis tears. J Bone Joint Surg Am 2007;89:1184-1193. doi:10.2106/JBJS.F.00007
22. Fuchs B, Weishaupt D, Zanetti M, Hodler J, Gerber C. Fatty degeneration of the muscles of the rotator cuff: assessment by computed tomography versus magnetic resonance imaging. J Shoulder Elbow Surg 1999;8:599-605. doi:10.1016/s1058-2746(99)90097-6
23. Saka M, Yamauchi H, Yoshioka T, Hamada H, Gamada K. Scapular kinematics during late cocking of a simulated throwing activity in baseball players with shoulder injury: A cross-sectional study using a 3D-to-2D registration technique. J Sport Rehabil 2015;24:91-98. doi:10.1123/jsr.2013-0056
24. Hébert LJ, Moffet H, McFadyen BJ, Dionne CE. Scapular behavior in shoulder impingement syndrome. Arch Phys Med Rehabil 2002;83:60-69. doi:10.1053/apmr.2002.27471
25. Poppen NK, Walker PS. Forces at the glenohumeral joint in abduction. Clin Orthop Relat Res 1978;135:165-170. doi:10.1097/00003086-197809000-00035
26. Su WR, Budoff JE, Luo ZP. The effect of anterosuperior rotator cuff tears on glenohumeral translation. Arthroscopy 2009;25:282-289. doi:10.1016/j.arthro.2008.10.005
27. Oh JH, Jun BJ, McGarry MH, Lee TQ. Does a critical rotator cuff tear stage exist?: a biomechanical study of rotator cuff tear progression in human cadaver shoulders. J Bone Joint Surg Am 2011;93:2100-2109. doi:10.2106/JBJS.J.00032
28. Miura Y, Kai Y, Morihara T, Fukushima H, Furukawa R, Sukenari T, et al. Three-dimensional scapular kinematics during arm elevation in massive rotator cuff tear patients. Prog. Rehabil Med 2017;2. doi:10.2490/prm.20170005
29. Dyrna F, Kumar NS, Obopilwe E, Scheiderer B, Comer B, Nowak M, et al. Relationship between deltoid and rotator cuff muscles during dynamic shoulder abduction: A biomechanical study of rotator cuff tear progression. Am J Sports Med 2018;46:1919-1926. doi:10.1177/0363546518768276
30. Hansen ML, Otis JC, Johnson JS, Cordasco FA, Craig EV, Warren RF. Biomechanics of massive rotator cuff tears: implications for treatment. J Bone Joint Surg Am 2008;90:316-325. doi:10.2106/JBJS.F.00880

31. Hawkes DH, Alizadehkhaiyat O, Kemp GJ, Fisher AC, Roebuck MM, Frostick SP. Shoulder muscle activation and coordination in patients with a massive rotator cuff tear: an electromyographic study. J Orthop Res 2012;30:1140-1146. doi:10.1002/jor.22051

Tables

Due to technical limitations, tables 1 to 5 are only available as a download in the Supplemental Files section.

Figures

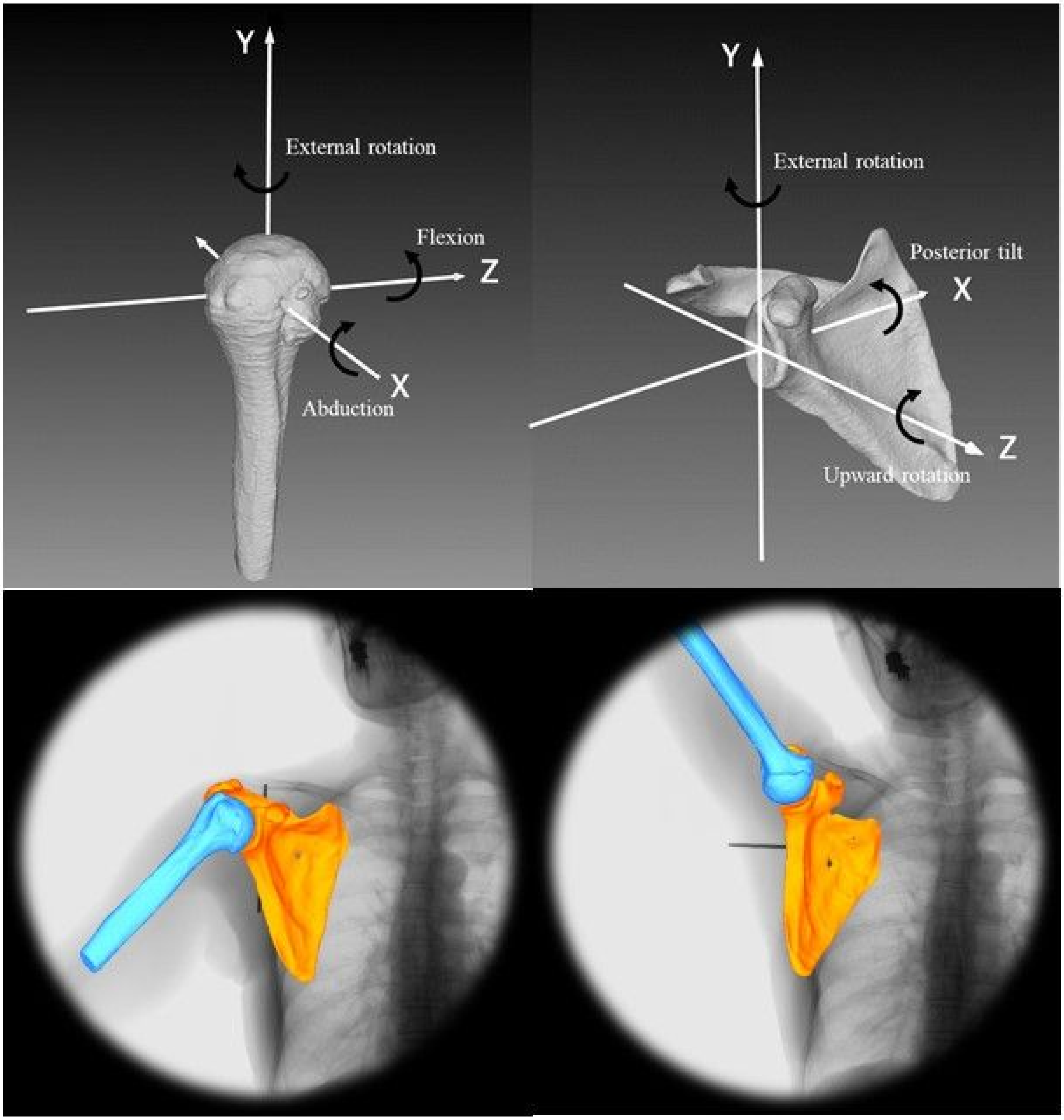

Figure 1

Figure 1

Matching the three-dimensional (3D) bone model and fluoroscopic images Fluoroscopic images are acquired, a 3D bone model of the humerus and scapula is created using the computed tomography images, and the bone model is matched with outlines on the fluoroscopy images.

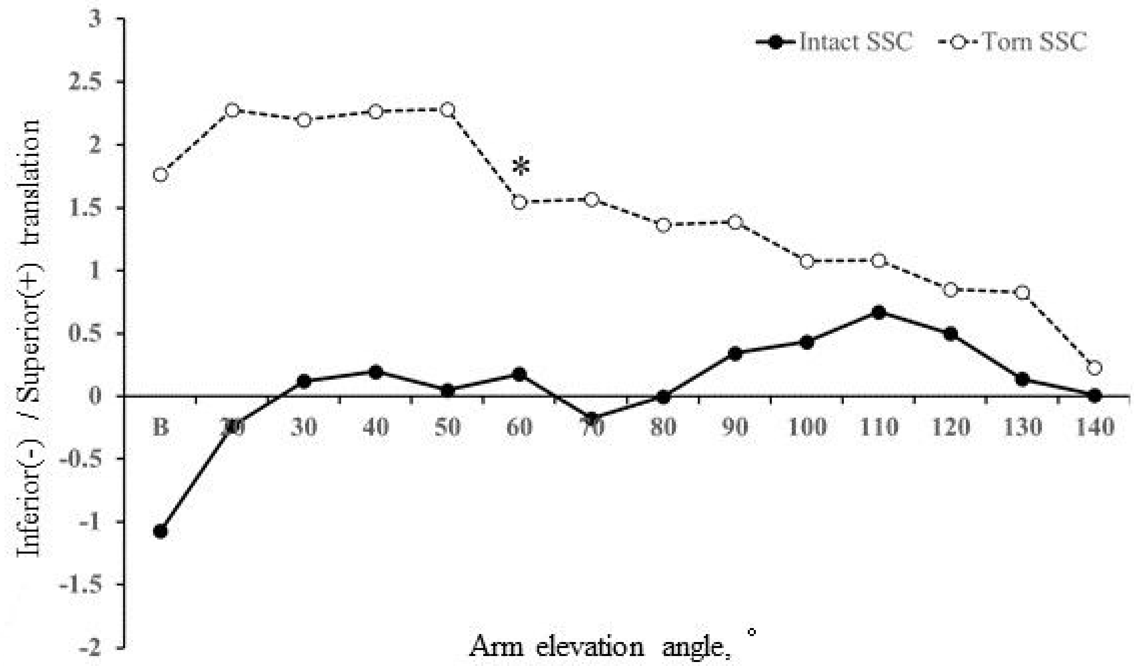

Figure 2

Figure 2

Superior-inferior translation of the humeral head during arm elevation In the Torn SSC group, the center of the humeral head migrated superiorly, then significantly downward at 60° arm elevation ($P < 0.05$). In the Intact SSC group, there was no significant difference in the superior-inferior translation of the humeral head between the elevation angles. *, statistically significant; B, Beginning of arm elevation

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Table.xlsx