Dynamic scapulohumeral rhythm: Comparison between healthy shoulders and those with large or massive rotator cuff tear

Naoya Kozono¹, Naohide Takeuchi¹, Takamitsu Okada¹, Satoshi Hamai¹, Hidehiko Higaki², Takeshi Shimoto³, Satoru Ikebe⁴, Hirotaka Gondo², Takahiro Senju¹ and Yasuharu Nakashima¹

Abstract
Introduction: Assessment of scapular kinematics and the dynamics of the scapulohumeral rhythm (SHR) would be important for understanding pathologies of the shoulder and to inform treatment. Our aim in this study was to evaluate the SHR and scapular kinematics in patients with a rotator cuff tear (RCT), compared to a control group with healthy shoulders using image-matching techniques. Materials and Methods: The shoulder kinematics of large or massive RCT patients were evaluated and compared to a control group with healthy shoulders. Radiographic surveillance was performed throughout the full range of external rotation and scapular plane abduction. Computed tomography imaging of the shoulder complex was performed, with three-dimensional image reconstruction and matching to the radiographs to measure three-dimensional positions and orientations. SHR and angular values of the scapula were measured. Results: Scapular external rotation in the late phase of external rotation movement was greater in the RCT group than in the control group (p < 0.05), but with no difference in the SHR. During scapular plane abduction, there were significant differences in SHR, scapular posterior tilt and scapular upward rotation between the RCT and control group (p < 0.05). Conclusions: Regarding clinical relevance, this study clarified the differences of SHR and angular values of the scapula between the RCT and control group. These results underline the importance of assessing the SHR and scapular kinematics in individuals with a RCT. RCT is associated with specific compensation in the kinematics of the scapula and SHR during external rotation and scapular plane abduction, which could inform treatment.

Keywords
image-matching techniques, rotator cuff tear, scapular kinematics, scapulohumeral rhythm, shoulder joints

Date received: 25 August 2020; Received revised 12 October 2020; accepted: 27 November 2020
**Introduction**

A rotator cuff tear (RCT) is a common shoulder dysfunction associated with decreased range of shoulder movement and pain. Altered shoulder biomechanics are widely theorized to contribute to musculoskeletal disorders of the shoulder. As scapular kinematic alterations are associated with RCTs and subacromial impingement, understanding scapular kinematics is particularly important in the analysis of shoulder pathologies, including RCT, impingement syndrome, glenohumeral osteoarthritis, cuff tear arthropathy, and frozen shoulder.

Several studies have reported on the ratio of glenohumeral motion to scapulothoracic motion, known as the scapulohumeral rhythm (SHR), with a change in the SHR generally accepted as one of the signs of a musculoskeletal impairment of the shoulder. Using motion capture with reflective markers, Robert-Lachaine et al. reported that in patients with a RCT who were able to elevate the arm to 85° in the scapular plane, an increased scapulohumeral contribution compensated for the loss of glenohumeral motion. Using image-matching techniques, Kijima et al. reported that there were no significant differences in the upward rotation of the scapula and the SHR during scapular plane abduction between patients with symptomatic RCTs and individuals with healthy shoulders. This discrepancy in the scapular kinematics may be because of difference in anatomical coordinate systems. Several studies showed that the differences of scapular kinematics during scapular plane abduction between normal and RCT shoulders. However, to our knowledge, there have been no previous published reports on the SHR and scapular kinematics in individuals with a RCT during full external rotation movement with arm at the side.

The selection of motion capture systems is important to consider. The use of external markers attached to the skin, reported in various studies, is likely to be associated with substantial error due to soft tissue movement artifacts. Recently, image-matching techniques have been developed for knee and hip joint kinematics research, providing high accuracy to evaluate three-dimensional (3D) kinematics.

Therefore, our aim in this study was to evaluate the SHR and scapular kinematics in patients with a RCT, compared to a control group with no history of shoulder trauma, surgery, or pain, during dynamic movements of external rotation (performed with arm at the side) and scapular plane abduction, using image-matching techniques. We hypothesized that a RCT would be associated with increased scapular movement to compensate for the loss of glenohumeral motion during both movements.

**Materials and methods**

**Statement of ethics**

Our study was approved by our Institutional Ethics Review Board (ID number of the approval: 2019–511) and all participants provided informed consent.

**Participants**

The study group included 10 participants with no history of shoulder trauma/injury, surgery or pain (control group) and 11 with a confirmed diagnosis of RCT (RCT group), awaiting surgical rotator cuff repair. The control group included 10 men, with a mean age of 32 years (range, 30–37 years), mean height of 174 cm (range, 167–186 cm), and mean weight of 70 kg (range, 61–80 kg). The RCT group included 6 men and 5 women, with a mean age of 72 years (range, 65–75 years), mean height of 158 cm (range, 149–167 cm) and mean weight of 57 kg (range, 47–75 kg). All 11 participants in the RCT group had a pre-operative diagnosis of a large or massive RCT, based on magnetic resonance imaging, and the size of the tear was confirmed intra-operatively, according to the classification of DeOrio and Cofield.

**Experimental set up**

Periodic radiographs were obtained during the movements of full external rotation and full scapular plane abduction movements, at a sampling rate of 10 frames/s. All participants were positioned in standing in front of a flat-panel detector, with the coronal plane set perpendicular to the X-ray beam. All participants were specifically instructed to keep their torsos upright in a standing posture. Both external rotation and scapular plane abduction movements were performed dynamically. External rotation was performed with arm at the side, from a position of full internal rotation to full external rotation. A scapular plane abduction was performed from a starting point of the arm at the side to maximum scapular plane abduction. Computed tomography (CT: Aquilion, Toshiba, Tochigi, Japan) imaging of the shoulder was performed for each participant, using a 512 × 512 image matrix, a 0.35 mm × 0.35 pixel dim, and a 1-mm thickness spanning the entire shoulder joint.

**Image-matching techniques**

Virtual digitally reconstructed radiographs (DRRs) were generated from 3D gray-scale digital models using the CT data and were then compared to the serial radiograph images acquired during the movement. Correlations of the pixel values between the DRRs and real radiographs were used to fine-tune the 3D model (Figure 1). Anatomical coordinate systems of the scapula and humerus were embedded in each density-based volumetric bone model that was derived from CT data, as per the methods previously described (Figure 2). Anatomical coordinate systems of the scapula and humerus were defined according to the International Society of Biomechanics standard. The following in vivo 3D kinematics parameters of the shoulder were analyzed: scapulohumeral rhythm (SHR), scapular posterior/anterior (+/−) tilting about the z-axis, scapular upward/downward (+/−) rotation about the
x-axis, and scapular external/internal (+/-) rotation about the y-axis (Figure 2). Scapular rotations were determined using a y-x-z sequence (external/internal rotation-upward/downward rotation-posterior/anterior tilting). Humeral rotations were determined using a x-z-y sequence (abduction/adduction-flexion/extension-external/internal rotation).

For external rotation, the SHR was defined as the ratio of the difference between humeral external rotation and scapular external rotation against the scapular external rotation. For scapular plane abduction, the SHR was defined as the ratio of the difference between humeral abduction and scapular upward rotation against the scapular upward rotation. The accuracy of measured values was previously evaluated, and the root mean square (RMS) errors for bone were 0.16 mm for in-plane translation, 0.12 mm for out-of-plane translation, and 0.22° for rotations. The RMS error represents the standard deviation of differences between true values and measured values.

**Statistical analysis**

Statistical analyses were performed using JMP software version 13.0 (SAS Institute Inc., Cary, NC). Statistical
significance was set at \( p \)-value <0.05. The SHR and the angular values of scapular movement were compared between the control and RCT groups using a repeated-measures analysis of variance (ANOVA). Post-hoc unpaired \( t \) tests were used for further significance testing when significant differences were identified in the ANOVA.

### Results

**Full external rotation movement with arm at the side**

Figure 3 summarizes the mean SHR, scapular posterior tilting, scapular upward rotation, and scapular external rotation values as a function of the humeral external rotation angle. Scapular external rotation was significantly greater in the RCT group than in the control group at values of 30° and 45° of humeral external rotation (\( p = 0.024, p = 0.0085 \)), with no difference in the SHR and the other angular values between the two groups.

**Scapular plane full abduction movement**

Figure 4 summarizes the mean SHR, scapular posterior tilting, scapular upward rotation, and scapular external rotation values as a function of humeral abduction angle. The SHR was significantly smaller in the RCT group than in the control group at values of 60°, 75°, 90°, and 105° of humeral abduction (\( p = 0.0031, p < 0.0001, p < 0.0001, p = 0.0013 \)). The SHR was significantly higher in the RCT group than in the control group at values of 15° and 150° of humeral abduction (\( p = 0.0003, p = 0.0001 \)). Scapular posterior tilt was significantly smaller in the RCT group than in the control group at values of 15° and 30° of humeral abduction (\( p = 0.041, p = 0.047 \)). Scapular upward rotation was significantly greater in the RCT group than in the control group at values of 105°, 120°, and 135° of humeral abduction (\( p = 0.024, p = 0.014, p = 0.011 \)). There was no difference in values associated with scapular external rotation between the two groups.

### Discussion

The two major findings of our study are as follows. First, external rotation of the scapula was significantly greater in the RCT group than in the control group in the late phase of the full external rotation movement with arm at the side. Second, there were significant differences in SHR, scapular posterior tilting and scapular upward rotation between the RCT and control group during scapular plane abduction. With regard to external rotation of the scapula, significant between group differences were identified at two positions of humeral external rotation, 30° and 45°.
The effect of RCT on scapular kinematics has previously been reported. The causes underlying changes in scapular kinematics with a RCT are multifactorial. In this study, we considered the possibility of compensatory mechanisms in large-to-massive full-thickness RCTs that increase scapular external rotation during external rotation movement with arm at the side and upward rotation of the scapula during scapular plane abduction. Of note, we did not identify a difference in the SHR during external rotation movement with arm at the side. By contrast, significant differences in the SHR were identified between the RCT and control groups during scapular plane abduction, with the SHR being significantly smaller in the RCT group than in the control group at every point between 60° and 105° of humeral abduction. Additionally, scapular upward rotation was significantly greater in the RCT group than in the control group at every point between 105° and 135° of humeral abduction. Furthermore, scapular plane full abduction movement, changes in the SHR (a), scapular posterior tilting (b), scapular upward rotation (c), and scapular external rotation (d) are shown. The asterisk indicates a significant difference between the rotator cuff tear and control group (p < 0.05).

The limitations of our study were as follows. First, the kinematics of the thorax were not included in our analysis because of the difficulty in defining the thoracic spine or sternum with the image-matching technique. Second, our control group included only 10 young men, due to the demands of the protocol with regard to CT and radiographic surveillance. We do note that the number of control participants included was comparable to that in previous studies using fluoroscopy and is consistent with the principle of minimizing exposure to radiation. We did not consider the possible effects of age and sex in our analysis, as these issues were beyond the scope of our study. Third, single-plane fluoroscopy was used in this study. Bi-plane imaging theoretically has a higher level of accuracy for out-of-plane translation measurements. Importantly, none of the uncertainty would bias our measures to show differences with respect to SHR and scapular kinematics values between control and RCT groups. Fourth, fluoroscopy equipment providing measurements 30 frames/s is now commercially available. However, the frame rate was set at 10 frames/s because capturing radiograph images with faster frames increases radiation exposure.

With regard to the clinical relevance, this study clarified the differences of SHR and angular values of the scapula...
between the RCT and control group. These results may assist surgical and conservative treatment to improve the shoulder range of motion in RCT patients.

Conclusions
Our analysis, using image-matching techniques, identified differences in the SHR and scapular kinematics in individuals with a RCT, compared to a control group with no history of shoulder trauma/injury, surgery, or pain. In the presence of a RCT, we identified greater scapulothoracic motion in the late phase of external rotation with arm at the side and greater scapulothoracic motion and less glenohumeral motion in the mid-phase of scapular plane abduction. These kinematic patterns may have resulted from the compensatory mechanisms in response to the loss of glenohumeral motion. These findings underline the importance of assessment the SHR and scapular kinematics in individuals with a RCT, providing therapeutic insight for functional recovery and to inform surgical and conservative treatment.

Declaration of conflicting interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This research was supported by JPJS Kakenhi Grant No. JP20K18032 and grant from the Ogata Memorial Foundation for the Promotion of Science, 2019.

ORCID iD
Naoya Kozono  https://orcid.org/0000-0002-2042-640X

References
1. Milgrom C, Schaffler M, Gilbert S, et al. Rotator-cuff changes in asymptomatic adults. The effect of age, hand dominance and gender. J Bone Joint Surg Br 1995; 77: 296–298.
2. Ludewig PM and Reynolds JF. The association of scapular kinematics and glenohumeral joint pathologies. J Orthop Sports Phys Ther 2009; 39: 90–104.
3. Borsa PA, Timmons MK and Sauers EL. Scapular-positioning patterns during humeral elevation in unimpaired shoulders. J Athl Train 2003; 38: 12–17.
4. Braman JP, Engel SC, Laprade RF, et al. In vivo assessment of scapulohumeral rhythm during unconstrained overhead reaching in asymptomatic subjects. J Shoulder Elbow Surg 2009; 18: 960–967.
5. De Groot JH, Valstar ER and Arwert HJ. Velocity effects on the scapulohumeral rhythm. Clin Biomech 1998; 13: 593–602.
6. Doody SG, Freedman L and Waterland JC. Shoulder movements during abduction in the scapular plane. Arch Phys Med Rehabil 1970; 51: 595–604.
7. Kijima T, Matsuki K, Ochiai N, 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.
8. Kon Y, Nishinaka N, Gamada K, et al. The influence of handheld weight on the scapulohumeral rhythm. J Shoulder Elbow Surg 2008; 17: 943–946.
9. Matsuki K, Matsuki KO, Mu S, et al. In vivo 3-dimensional analysis of scapular kinematics: comparison of dominant and nondominant shoulders. J Shoulder Elbow Surg 2011; 20: 659–665.
10. Robert-Lachaine X, Allard P, Godbout V, et al. Scapulohumeral rhythm relative to active range of motion in patients with symptomatic rotator cuff tears. J Shoulder Elbow Surg 2016; 25: 1616–1622.
11. Kim D, Lee B, Yeom J, et al. Three-dimensional in vivo comparative analysis of the kinematics of normal shoulders and shoulders with massive rotator cuff tears with successful conservative treatment. Clin Biomech 2020; 75: 104990.
12. Miura Y, Kai Y, Morihara T, et al. Three-dimensional scapular kinematics during arm elevation in massive rotator cuff tear patients. Prog Rehabil Med 2017; 2: 20170005.
13. Zdravkovic V, Alexander N, Wegener R, et al. How do scapulothoracic kinematics during shoulder elevation differ between adults with and without rotator cuff arthropathy? Clin Orthop Relat Res 2020; 478: 2640–2649.
14. Kolk A, de Witte PB, Henseler JF, et al. Three-dimensional shoulder kinematics normalize after rotator cuff repair. J Shoulder Elbow Surg 2016; 25: 881–889.
15. Scibek JS, Mell AG, Downie BK, et al. Shoulder kinematics in patients with full-thickness rotator cuff tears after a subacromial injection. J Shoulder Elbow Surg 2008; 17: 172–181.
16. Hamai S, Moro-oaka TA, Dunbar NJ, et al. In vivo healthy knee kinematics during dynamic full flexion. Biomed Res Int 2013; 2013: 717546.
17. Hara D, Nakashima Y, Hamai S, et al. Dynamic hip kinematics during the golf swing after total hip arthroplasty. Am J Sports Med 2016; 44: 1801–1809.
18. DeOrio JK and 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.
19. Kozono N, Okada T, Takeuchi N, et al. In vivo kinematic analysis of the glenohumeral joint during dynamic full axial rotation and scapular plane full abduction in healthy shoulders. Knee Surg Sports Traumatol Arthrosc 2017; 25: 2032–2040.
20. 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.
21. Kozono N, Okada T, Takeuchi N, et al. Dynamic kinematics of the glenohumeral joint in shoulders with rotator cuff tears. J Orthop Surg Res 2018; 13: 9.
22. Graichen H, Stammberger T, Bonel H, et al. Three-dimensional analysis of shoulder girdle and supraspinatus motion patterns in patients with impingement syndrome. *J Orthop Res* 2001; 19: 1192–1198.

23. McCully SP, Suprak DN, Kosek P, et al. Suprascapular nerve block disrupts the normal pattern of scapular kinematics. *Clin Biomech* 2006; 21: 545–553.

24. Mell AG, LaScalza S, Guffey P, et al. Effect of rotator cuff pathology on shoulder rhythm. *J Shoulder Elbow Surg* 2005; 14: 58S–64S.

25. Giphart JE, Brunkhorst JP, Horn NH, et al. Effect of plane of arm elevation on glenohumeral kinematics: a normative biplane fluoroscopy study. *J Bone Joint Surg Am* 2013; 95: 238–245.

26. Matsuki K, Matsuki KO, Yamaguchi S, et al. Dynamic in vivo glenohumeral kinematics during scapular plane abduction in healthy shoulders. *J Orthop Sports Phys Ther* 2012; 42: 96–104.

27. Millett PJ, Giphart JE, Wilson KJ, et al. Alterations in glenohumeral kinematics in patients with rotator cuff tears measured with biplane fluoroscopy. *Arthroscopy* 2016; 32: 446–451.

28. Nishinaka N, Tsutsui H, Mihara K, et al. Determination of in vivo glenohumeral translation using fluoroscopy and shape-matching techniques. *J Shoulder Elbow Surg* 2008; 17: 319–322.