# Alterations in Glenohumeral Kinematics in Patients With Rotator Cuff Tears Measured With Biplane Fluoroscopy

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**Purpose:** To quantitatively measure the 3-dimensional (3D) glenohumeral translations during dynamic shoulder abduction in the scapular plane, using a biplane fluoroscopy system, in patients with supraspinatus rotator cuff tears. **Methods:** A custom biplane fluoroscopy system was used to measure the 3D position and orientation of the scapula and humerus of 14 patients with full-thickness supraspinatus or supraspinatus and infraspinatus rotator cuff tears and 10 controls as they performed shoulder abduction over their full range of motion. The 3D geometries of the scapula and humerus were extracted from a computed tomography scan of each shoulder. For each frame, the 3D bone position and orientation were estimated using a contour-based matching algorithm, and the 3D position of the humeral head center was determined relative to the glenoid. For each subject the superior-inferior and anterior-posterior translation curves were determined from 20° through 150° of arm elevation. **Results:** The humeral head in shoulders with rotator cuff tears was positioned significantly inferior compared with controls for higher elevation angles of 80° to 140° ($P < .05$). For both groups the humeral head translated inferiorly during shoulder abduction from 80° ($P = .044$; rotator cuff tear *v* controls: $-0.2 \pm 1.3$ *v* $1.2 \pm 1.4$ mm) up to 140° ($P = .047$; rotator cuff tear *v* controls: $-1.3 \pm 2.2$ *v* $0.44 \pm 1.4$ mm). There was no significant translation in the anterior- posterior direction. **Conclusions:** Patients with well-compensated single or 2-tendon rotator cuff tears show no dynamic superior humeral head migration but unexpectedly show an inferior shift during active elevation. It is unclear whether the size of the translational differences found in this study, while statistically significant, are also of clinical significance. **Level of Evidence:** Level III, comparative study.

*See commentary on page 452*

Rotator cuff tears are a common cause of shoulder pain, weakness, and decreased range of motion. One of the primary functions of the rotator cuff is stabilization of the shoulder joint by compressing the humeral head into the glenoid cavity and allowing concentric rotation of the joint.[1-3] This dynamic stabilization relies on balanced muscle force couples around the joint in the transverse and coronal planes. In the transverse plane, this balance is maintained by the subscapularis muscle anteriorly and the infraspinatus and teres minor muscles posteriorly. In the coronal plane, the force couple is the balance among the deltoid muscle, the rotator cuff, and the weight of the arm.[1,4,5]

While it is theorized that a tear in the rotator cuff could disrupt the balanced muscle forces, how it alters glenohumeral kinematics remains to be defined. A variety of methods have been used in the literature to statically measure translation of the humeral head relative to the glenoid during shoulder elevation. Previous methods of measuring glenohumeral joint motion with a torn rotator cuff have relied on cadaveric simulations,[4,6,7] 2-dimensional (2D) radiographs,[8,9] and static 3-dimensional (3D) radiographs.[10] It has been reported that proximal migration of the humeral head occurs during elevation,[6-8,10] and this has become

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clinically accepted. However, each of these static measurement techniques is associated with limitations, and the results have not been validated by an in vivo dynamic 3D joint motion study.

This study used a dynamic 3D method of analyzing glenohumeral kinematics following rotator cuff tear—biplane fluoroscopy with computed tomography (CT). Biplane fluoroscopy is a recently emerging, highly accurate way to measure the in vivo 3D kinematics of the bony structures of a joint.[11-19] It has had some use on the shoulder joint[20,21] but limited work on the kinematic effects of rotator cuff tears. Bey et al.[22-25] studied patients postoperatively to determine how well surgical repair of the rotator cuff returned glenohumeral kinematics compared with asymptomatic controls.

The purpose of this study was to quantitatively measure the 3D glenohumeral translations during dynamic shoulder abduction in the scapular plane, using a biplane fluoroscopy system, in patients with supraspinatus rotator cuff tears. It was hypothesized that during shoulder abduction in the scapular plane (scaption), subjects with rotator cuff tears would demonstrate dynamic superior migration of the humeral head relative to subjects with asymptomatic shoulders.

## Methods

### Subject Selection

Subjects presenting to the clinic of the senior surgeon (P.J.M.) for evaluation of shoulder pain were assessed for eligibility. Clinical examination and imaging were performed to identify patients with repairable full-thickness tears of the supraspinatus with or without 1-cm extension into the infraspinatus. Subjects were not enrolled if they had a history of shoulder surgery or documented instability, degenerative arthritis, or palsy of the axillary or suprascapular nerves or if a subject did not meet the radiation safety criteria including pregnancy. Patients with prior repair or with pseudoparalysis were excluded. An asymptomatic control group was recruited for comparison, the results of which have been previously published.[21] This study was approved by the governing Institutional Review Board, and informed consent was obtained from all subjects before participation.

### Study Procedures

A high-resolution CT scan of the involved shoulder was obtained from each patient in the supine position in the scanner (Aquilion 64, Toshiba America Medical Systems, Tustin, CA, U.S.A.) by a sequence of axial images (0.5 mm slice thickness, 512 × 512 resolution, 120 kVp, 200 mA). The scapula and humerus were segmented from the CT data, and the 3D geometry of these bones was reconstructed using image analysis software (Mimics Version 14, Materialise Inc., Leuven, Belgium).

The custom biplane fluoroscopy system consisted of 2 BV Pulsera C-arms (Philips Medical Systems, Best, The Netherlands) with an 80° interbeam angle. A detailed description of the biplane fluoroscopy system was used, and a validation of its accuracy has been published previously for the shoulder.[20,21] Mean bias and precision were calculated using cadaveric shoulders for anterior-posterior, superior-inferior, and distraction-compression translations (0.2 ± 0.5, 0.3 ± 0.3, and 0.3 ± 0.4 mm, respectively) and glenohumeral plane of elevation, elevation angle, and internal-external rotation (0.1° ± 0.8°, 0.2° ± 0.2°, 1.7° ± 1.2°, respectively). In the current study, subjects performed scaption with their glenohumeral joint within the field of view of the biplane fluoroscopy system and their shoulder positioned approximately 25 cm from the image intensifiers. Motions were recorded at 100 Hz in continuous fluoroscopy mode (12 mA, approximately 60 kV) and were analyzed at 12.5 Hz (every eighth frame) since the motion was sufficiently slow. A calibration cube was used to determine the position and orientation of the 2 fluoroscopes, and image distortion was corrected using a square grid.

The motion of the subject's arm and torso were simultaneously recorded with an optical motion analysis system (Motion Analysis Corp, Santa Rosa, CA, U.S.A.) to provide reference locations for the biplane fluoroscopy data. Reflective markers were placed on the subject's trunk, arm, forearm, and hand, and motion was recorded at 250 Hz. The motion analysis data were then synchronized with the biplane fluoroscopy data.

Patients performed scaption within the biplane fluoroscopy system over the course of 2 seconds and elevated their arm from 20° up to the maximum they were comfortable with. The exercise was performed while seated with a straight back and the arm hanging by the side of the body. The arm was then elevated in the scapular plane with the thumb pointing upward (Fig 1).

A contour matching algorithm was then used to estimate the position and orientation of the humerus and scapula using model-based RSA software (RSAcore, Leiden, The Netherlands) (Fig 2). For each frame, bone contours were automatically extracted from the biplane fluoroscopy images and then manually selected for each bone. Using the 3D system configuration measured during calibration, the selected bone contours were projected onto the biplane fluoroscopy images. The position and orientation of the bones were subsequently adjusted using a fully automated, 6-degree-of-freedom contour matching optimization algorithm, which matched the projected contours to the manually selected contours in each image frame.

Glenohumeral translation was calculated from the optimized bone positions throughout the scaption motion. Translation was defined as motion of the humeral head center relative to the glenoid in the

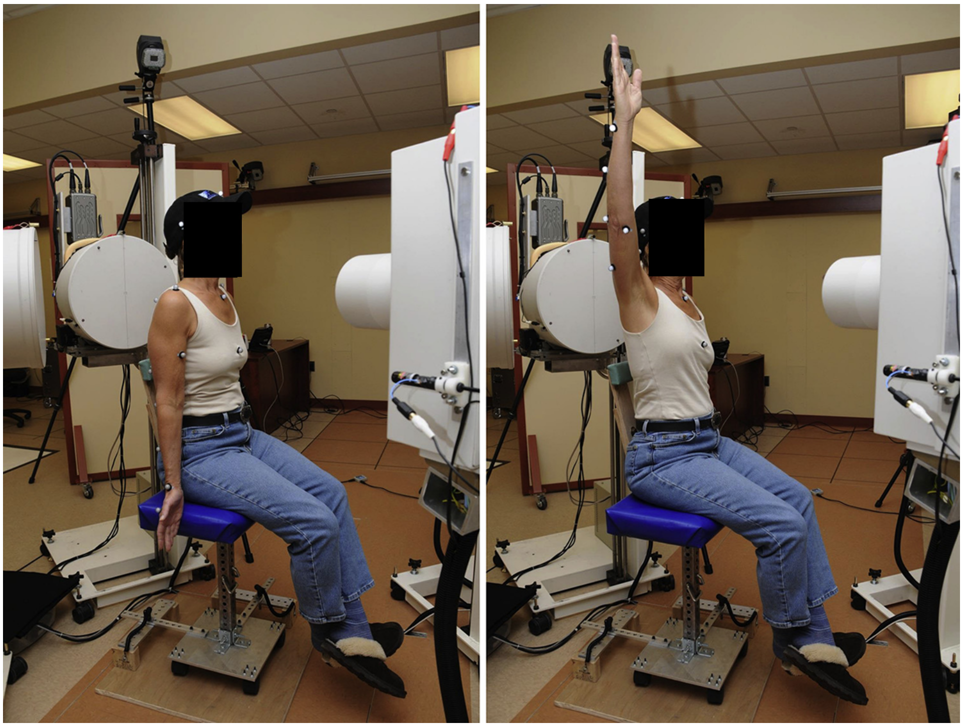

**Fig 1.** Patients performed scaption within the biplane fluoroscopy system, elevating their arm from 20° to 150° in the scapular plane with the thumb pointing upward.

anterior-posterior and superior-inferior directions. As described elsewhere,[20,21] glenohumeral translations were quantified by fitting a sphere to the articular surface of the humeral head and measuring the translation of the center of the sphere to a clinically based glenoid coordinate system. For each subject, the superior-inferior and anterior-posterior translation curves were resampled in 10° increments. Results were compared between the rotator cuff tear patients and the asymptomatic controls.

## Statistical Methods

Initially, 2-factor linear mixed-effects models were built with independent effects of subject group (rotator cuff patient and asymptomatic controls; nonrepeated) and arm elevation angle (20° to 150°; repeated). A significant nonlinear interaction was found for both models between the 2 independent factors, indicating that the subject group effect on superior-inferior and anterior-posterior translation depended on elevation angle. As a result, we chose to collapse the analysis

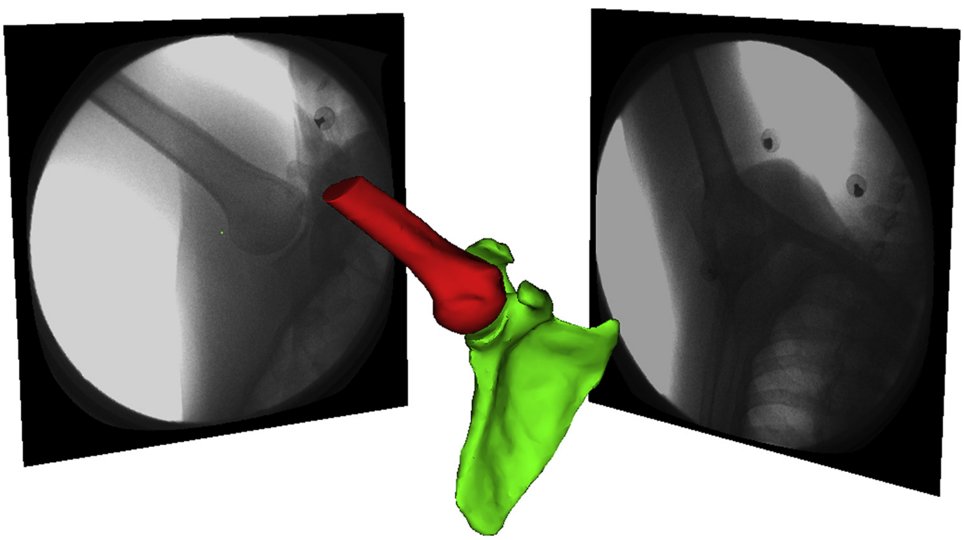

**Fig 2.** The humerus and scapula bone models were aligned with the biplane fluoroscopy images using model-based RSA software (RSAcore, Leiden, The Netherlands).

**Table 1.** *T*-Test Results for Superior-Inferior Translation of the Humeral Head in Rotator Cuff Tear and Control Groups During Scaption

| | Superior-Inferior Translation | | | | | | |
|---|---|---|---|---|---|---|---|
| | Control | | RCT | | | 95% Confidence Interval of Difference | |
| Elevation Angle, ° | Mean | SD | Mean | SD | Welch-T *P* Value | Lower | Upper |
| 20 | 0.7 | 1.9 | 0.3 | 0.4 | .586 | −1.3 | 2.2 |
| 30 | 0.9 | 1.8 | 0.6 | 0.7 | .659 | −1.3 | 2.0 |
| 40 | 0.9 | 1.9 | 0.5 | 0.8 | .637 | −1.4 | 2.1 |
| 50 | 1.2 | 1.6 | 0.5 | 1.2 | .308 | −0.8 | 2.3 |
| 60 | 1.2 | 1.6 | 0.3 | 1.2 | .176 | −0.5 | 2.3 |
| 70 | 1.1 | 1.6 | 0.2 | 1.3 | .179 | −0.5 | 2.2 |
| 80 | 1.2 | 1.4 | 0.0 | 1.3 | .044* | 0.0 | 2.4 |
| 90 | 1.1 | 1.5 | −0.4 | 1.4 | .034* | 0.1 | 2.7 |
| 100 | 1.2 | 1.5 | −0.5 | 1.5 | .016* | 0.3 | 3.0 |
| 110 | 1.0 | 1.6 | −0.6 | 1.6 | .022* | 0.3 | 3.1 |
| 120 | 1.0 | 1.5 | −0.8 | 1.7 | .016* | 0.4 | 3.1 |
| 130 | 0.8 | 1.5 | −0.9 | 1.9 | .025* | 0.2 | 3.2 |
| 140 | 0.4 | 1.4 | −1.3 | 2.2 | .047* | 0.0 | 3.5 |
| 150 | 0.3 | 1.3 | −1.9 | 2.7 | .087 | −0.4 | 4.7 |

NOTE. Mean and standard deviation (SD) are reported for each group, as well as Welch-T *P* value to identify significance between the 2 groups and the 95% confidence interval lower and upper bounds. Positive values indicate superior translation, and negative values indicate inferior translation.

RCT, rotator cuff tear.

*$P < .05$.

down to separate independent Welch *t*-test comparisons between subject groups at each elevation angle. Significance was defined as a $P < .05$, and no adjustments were made for multiple testing. Analysis was performed using statistical software (SSPS Statistics v20, IBM Corp., Somers, NY, U.S.A.).

## Results

Fourteen consecutive patients diagnosed with repairable full-thickness rotator cuff tears of the supraspinatus or supraspinatus and infraspinatus of at least 1 cm participated in this controlled laboratory study (age, 60.4 ± 6.9 years; height, 1.76 ± 0.08 m; weight, 83.8 ± 13.9 kg). Within the 14 subjects there were 3 acute and 11 chronic tears, with 90 days being used as the cutoff for chronicity. Nine of the recruited patients had a tear in the supraspinatus tendon only, and 5 patients had a supraspinatus tear extending into the infraspinatus tendon. The tear size was confirmed by standard clinical magnetic resonance imaging. A clinical shoulder examination was used to confirm that patients had a minimum active and unassisted range of motion of 120° of abduction and 30° of external rotation. No subjects had static superior migration of the humeral head, and all were concentrically reduced on plain radiographs. The asymptomatic control group consisted of 10 patients (age, 29.7 ± 6.6 years; height, 1.84 ± 0.05 m; weight, 89.8 ± 9 kg; mean ± standard deviation).

The humeral head in shoulders with rotator cuff tears was positioned significantly more inferior than in the control patients during higher elevation angles of 80° to 140° (Table 1). The amount of inferior translation in rotator cuff tear patients was significantly greater during shoulder abduction from 80° ($P = .044$; rotator cuff tear *v* controls: −0.2 ± 1.3 *v* 1.2 ± 1.4 mm) up to 140° ($P = .047$; rotator cuff tear *v* controls: −1.3 ± 2.2 *v* 0.44 ± 1.4 mm) compared with the controls. The maximum difference between the 2 groups was seen at 150° of elevation, with the rotator cuff tear group positioned 2.2 mm inferior to the asymptomatic controls (−1.9 ± 2.7 and 0.3 ± 1.3 mm, respectively).

There was no significant difference in humeral head position in the anterior-posterior direction, even though the humeral head was positioned slightly anterior to the controls during 60° to 150° of abduction (Table 2). The maximum difference between the 2 groups was also found at 150° of elevation, with the rotator cuff tear group positioned 2.2 mm anterior to the asymptomatic controls (−2.3 ± 2.6 and −4.5 ± 1.7 mm, respectively).

## Discussion

Disproving our hypothesis, subjects with rotator cuff tears did not demonstrate a dynamic superior translation of the humeral head during scaption. The results demonstrate that the humeral heads of the subjects with

**Table 2.** *T*-Test Results for Anterior-Posterior Translation of the Humeral Head in Rotator Cuff Tear and Control Groups During Scaption

| | Anterior-Posterior Translation | | | | | | |
|---|---|---|---|---|---|---|---|
| | Control | | Rotator Cuff Tear | | | 95% Confidence Interval of Difference | |
| Elevation Angle, ° | Mean | SD | Mean | SD | Welch-T *P* Value | Lower | Upper |
| 20 | −4.1 | 0.8 | −4.3 | 3.1 | .838 | −2.4 | 2.9 |
| 30 | −3.9 | 0.9 | −4.2 | 3.1 | .774 | −1.8 | 2.4 |
| 40 | −4.0 | 1.1 | −4.0 | 3.0 | .995 | −2.0 | 2.0 |
| 50 | −3.8 | 1.1 | −4.0 | 2.6 | .842 | −1.5 | 1.9 |
| 60 | −4.1 | 1.3 | −3.7 | 2.5 | .664 | −2.0 | 1.3 |
| 70 | −4.1 | 1.3 | −3.4 | 2.5 | .365 | −2.4 | 0.9 |
| 80 | −4.5 | 1.5 | −3.1 | 2.6 | .108 | −3.2 | 0.3 |
| 90 | −4.4 | 1.5 | −3.0 | 2.7 | .122 | −3.3 | 0.4 |
| 100 | −4.3 | 1.3 | −2.9 | 2.6 | .107 | −3.1 | 0.3 |
| 110 | −4.4 | 1.3 | −2.9 | 2.5 | .094 | −3.2 | 0.3 |
| 120 | −4.1 | 1.5 | −2.9 | 2.5 | .152 | −3.0 | 0.5 |
| 130 | −4.1 | 1.4 | −2.9 | 2.4 | .149 | −2.9 | 0.5 |
| 140 | −4.0 | 1.7 | −2.9 | 2.6 | .259 | −3.2 | 0.9 |
| 150 | −4.5 | 1.7 | −2.3 | 2.6 | .073 | −4.7 | 0.2 |

NOTE. Mean and standard deviation (SD) are reported for each group, as well as Welch-T *P* value to identify significance between the 2 groups and the 95% confidence interval lower and upper bounds. Positive values indicate anterior translation, and negative values indicate posterior translation.

rotator cuff tears were positioned in a more inferior direction compared with the controls throughout scaption. While these findings are contrary to our hypothesis and to other published studies that found proximal migration,[6-8,10] this study analyzed glenohumeral kinematics in subjects with rotator cuff tears in a seated position during dynamic weight-bearing 3D motion using technology with submillimeter accuracy.

The inferior translation found in the current study may be due to the patients primarily having isolated tears to the supraspinatus tendon. Yanagawa et al.[26] used a computerized 3D model to simulate the glenohumeral joint during abduction and theorized that the supraspinatus muscle functioned primarily as a joint stabilizer and applied all its force to compressing the humeral head into the glenoid. They reported that the net muscle force on the glenohumeral joint was directed superiorly from 15° to 105° of abduction with the supraspinatus contributing to this superiorly directed force, while the infraspinatus and subscapularis applied inferiorly directed forces. Therefore a tear in the supraspinatus could reduce the superior force component and may explain the inferior migration of the humeral head. Further, a study by Werner et al.[27] suggested that the presence of intact supraspinatus and infraspinatus tendons could create a spacer effect in the joint and prevent superior migration of the humeral head. This was determined by applying a suprascapular nerve block to each tendon and finding that even while inactive, the tendons acted as a subacromial spacer preventing upward migration of the humeral head. It should be noted that the subjects in the current study were all "copers" in that they had been able to preserve active glenohumeral motion, despite having a rotator cuff tear. It has been reported that a tear to only the supraspinatus muscle may not necessarily cause glenohumeral instability and that the other rotator cuff muscles (infraspinatus, teres minor, and subscapularis) can maintain the position of the humeral head.[9,28] It is possible that there is a threshold of rotator cuff tear size beyond which the shoulder becomes destabilized and the kinematics change with superior migration of the humeral head.

A recent study by Gerber et al.[29] reported that there could be a link between the morphologic geometry of the scapula and instability of the glenohumeral joint at low angles of abduction. They found that a larger critical shoulder angle (CSA; radiographic measure of glenoid inclination and lateral extension of the acromion) caused an increased force on the supraspinatus, particularly at 33° to 37° of shoulder elevation. This study used a mean CSA of 33° for the asymptomatic group and 38° for the rotator cuff group. Interestingly, when we reproduced these measurements for our subjects,[30] we found the critical shoulder angle for our asymptomatic control group (mean ± standard deviation, 31.3° ± 2.2°) was also lower than that for the rotator cuff tear group (35.7° ± 3.9°). Further study is needed to define the relationship between critical shoulder angle and rotator cuff tears and whether this could have an effect on glenohumeral kinematics.

The inferior translation of the humeral head differs from what is clinically expected. The results present a look at patients who are actively coping with their injury and do not represent those suffering from massive rotator cuff tears. These observations may also lead to better understanding of tear propagation and compensation mechanisms in patients who cope with their rotator cuff tears.

### Limitations

A limitation of this study is the lack of a well-matched control group with respect to age and rotator cuff tear location and size. While the rotator cuff tear group was older, it is currently unknown whether shoulder kinematics are affected by age. Another limitation is that the subjects did not all have the same rotator cuff tear location and size. Furthermore, the number of subjects in the study is relatively small, and they were a homogenous patient group, which may not be the case in a larger group of patients. Therefore, further study is needed to confirm these results and eventually compare them to postoperative data. Another limitation of the current study is that pain at the time of the motion was not measured. Pain may induce muscular compensation to avoid painful abduction. Therefore, painful glenohumeral joint kinematics may be different from pain-free joint kinematics. A further limitation of the study design is that the field of view of the fluoroscopes was not wide enough to adequately image both the glenohumeral joint and the thorax to measure scapulothoracic motion. Therefore, the fraction of glenohumeral to scapulothoracic motion was not available. Lastly, it is unclear whether the size of the translation differences found in this study, while statistically significant, is also of clinical significance.

## Conclusions

Patients with well-compensated single or 2-tendon rotator cuff tears show no dynamic superior humeral head migration but unexpectedly show an inferior shift during active elevation. It is unclear whether the size of the translational differences found in this study, while statistically significant, is also of clinical significance.

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## References

1. Burkhart SS. Arthroscopic treatment of massive rotator cuff tears. *Clin Orthop Relat Res* 1991;267:45-56.

2. Lippitt S, Matsen F. Mechanisms of glenohumeral joint stability. *Clin Orthop Relat Res* 1993;291:20-28.
3. Inman VT, Saunders JB, Abbott LC. Observations on the function of the shoulder joint. *J Bone Joint Surg* 1944;26-A:1-30.
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.
5. Halder AM, Zhao KD, O'Driscoll SW, Morrey BF, An KN. Dynamic contributions to superior shoulder stability. *J Orthop Res* 2001;19:206-212.
6. Mura N, O'Driscoll SW, Zobitz ME, 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.
7. Konrad GG, Markmiller M, Jolly JT, et al. Decreasing glenoid inclination improves function in shoulders with simulated massive rotator cuff tears. *Clin Biomech* 2006;21:942-949.
8. Yamaguchi K, Sher JS, Andersen WK, 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.
9. Keener JD, Wei AS, Mike Kim H, 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.
10. Paletta GA Jr, Warner JJ, Warren RF, Deutsch A, Altchek DW. Shoulder kinematics with two-plane X-ray evaluation in patients with anterior instability or rotator cuff tearing. *J Shoulder Elbow Surg* 1997;6:516-527.
11. 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.
12. Li G, Papannagari R, Li M, et al. Effect of posterior cruciate ligament deficiency on in vivo translation and rotation of the knee during weightbearing flexion. *Am J Sports Med* 2008;36:474-479.
13. Tashman S, Kolowich P, Collon D, Anderson K, Anderst W. Dynamic function of the ACL-reconstructed knee during running. *Clin Orthop Relat Res* 2007;454:66-73.
14. Giphart JE, Zirker CA, Myers CA, Pennington WW, LaPrade RF. Accuracy of a contour-based biplane fluoroscopy technique for tracking knee joint kinematics of different speeds. *J Biomech* 2012;45:2935-2938.
15. Myers CA, Torry MR, Peterson DS, et al. Measurements of tibiofemoral kinematics during soft and stiff drop landings using biplane fluoroscopy. *Am J Sports Med* 2011;39:1714-1722.
16. Myers CA, Torry MR, Shelburne KB, et al. In vivo tibiofemoral kinematics during 4 functional tasks of increasing demand using biplane fluoroscopy. *Am J Sports Med* 2012;40:170-178.
17. Torry MR, Myers C, Pennington WW, et al. Relationship of anterior knee laxity to knee translations during drop landings: a bi-plane fluoroscopy study. *Knee Surg Sports Traumatol Arthrosc* 2011;19:653-662.
18. Torry MR, Myers C, Shelburne KB, et al. Relationship of knee shear force and extensor moment on knee translations in females performing drop landings: A biplane fluoroscopy study. *Clin Biomech* 2011;26:1019-1024.
19. Torry MR, Shelburne KB, Peterson DS, et al. Knee kinematic profiles during drop landings: A biplane fluoroscopy study. *Med Sci Sports Exerc* 2011;43:533-541.
20. 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.
21. Giphart JE, Brunkhorst JP, Horn NH, Shelburne KB, Torry MR, Millett PJ. Effect of plane of arm elevation on glenohumeral kinematics. *J Bone Joint Surg Am* 2013;95:238-245.
22. Bey MJ, Brock SK, Beierwaltes WN, Zauel R, Kolowich PA, Lock TR. In vivo measurement of subacromial space width during shoulder elevation: Technique and preliminary results in patients following unilateral rotator cuff repair. *Clin Biomech* 2007;22:767-773.
23. Bey MJ, Kline SK, Zauel R, Lock TR, Kolowich PA. Measuring dynamic in-vivo glenohumeral joint kinematics: Technique and preliminary results. *J Biomech* 2008;41:711-714.
24. Bey MJ, Kline SK, Zauel R, Kolowich P, Lock TR. In vivo measurement of glenohumeral joint contact patterns. *EURASIP J Adv Signal Process* 2010;1-6.
25. Bey MJ, Peltz CD, Ciarelli K, et al. In vivo shoulder function after surgical repair of a torn rotator cuff: Glenohumeral joint mechanics, shoulder strength, clinical outcomes, and their interaction. *Am J Sports Med* 2011;39:2117-2129.
26. Yanagawa T, Goodwin CJ, Shelburne KB, Giphart JE, Torry MR, Pandy MG. Contributions of the individual muscles of the shoulder to glenohumeral joint stability during abduction. *J Biomech Eng* 2008;130:021024.
27. Werner CM, Weishaupt D, Blumenthal S, Curt A, Favre P, Gerber C. Effect of experimental suproscapular nerve block on active glenohumeral translations in vivo. *J Orthop Res* 2006;24:491-500.
28. Steenbrink F, de Groot JH, Veeger HE, van der Helm FC, Rozing PM. Glenohumeral stability in simulated rotator cuff tears. *J Biomech* 2009;42:1740-1745.
29. Gerber C, Snedeker JG, Baumgartner D, Viehöfer AF. Supraspinatus tendon load during abduction is dependent on the size of the critical shoulder angle: a biomechanical analysis. *J Orthop Res* 2014;32:952-957.
30. Moor BK, Bouaicha S, Rothenfluh DA, Sukthankar A, Gerber C. Is there an association between the individual anatomy of the scapula and the development of rotator cuff tears or osteoarthritis of the glenohumeral joint? *Bone Joint J* 2013;95-B:935-941.