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Rotator Cuff Fatigue and Glenohumeral Kinematics in Participants Without Shoulder Dysfunction

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Context: Researchers have established that superior migration of the humeral head increases after fatigue of the rotator cuff muscles. In these studies, the investigators used imaging techniques to assess migration of the humeral head during statically held shoulder positions. Their results may not represent the amount of superior humeral head migration that occurs during dynamic arm elevation.

Objective: To investigate the effect of rotator cuff fatigue on humeral head migration during dynamic concentric arm elevation (arm at the side [approximately 0°] to 135°) in healthy individuals and to determine the test-retest reliability of digital fluoroscopic video for assessing glenohumeral migration.

Design: Test-retest cohort study.

Setting: Research laboratory.

Patients or Other Participants: Twenty men (age = 27.7 ± 3.6 years, mass = 81.5 ± 11.8 kg) without shoulder disorders participated in this study.

Intervention(s): Three digital fluoroscopic videos (2 prefatigue and 1 postfatigue) of arm elevation were collected at 30 Hz. The 2 prefatigue arm elevation trials were used to assess test-retest reliability with the arm at the side and at 45°, 90°, and 135° of elevation. The prefatigue and postfatigue digital fluoroscopic videos were used to assess the effects of rotator cuff fatigue on glenohumeral migration. All measurements were taken in the right shoulder.

Main Outcome Measure(s): The dependent measure was glenohumeral migration (in millimeters). We calculated the intraclass correlation coefficient and standard error of the measurement to assess the test-retest reliability. A 2 × 4 repeated-measures analysis of variance was used to assess the effects of fatigue on arm elevation at the 4 shoulder positions.

Results: The test-retest reliability ranged from good to excellent (.77 to .92). Superior migration of the humeral head increased postfatigue ($P < .001$), regardless of angle.

Conclusions: Digital fluoroscopic video assessment of shoulder kinematics provides a reliable tool for studying kinematics during arm elevation. Furthermore, superior migration of the humeral head during arm elevation increases with rotator cuff fatigue in individuals without shoulder dysfunction.

Key Words: biomechanics, humeral head migration, imaging

Key Points

- Superior migration of the humeral head increased during dynamic arm elevation after the supraspinatus, infraspinatus, and teres minor muscles of the rotator cuff were fatigued.
- When used to analyze humeral head migration relative to the glenoid fossa, digital fluoroscopic video had good to excellent intrarater reliability.
- Research is required to determine the influence of rotator cuff fatigue on glenohumeral migration in individuals with underlying shoulder disorders.

Investigators[1,2] have suggested that abnormal glenohumeral (GH) kinematics are a major contributing factor in common shoulder lesions, such as shoulder impingement syndrome and subacromial bursitis. One of the leading theories is that rotator cuff (RTC) weakness, fatigue, or shoulder dysfunction contributes to superior GH migration during arm elevation and causes impingement of the soft tissues in the subacromial space, specifically the tendons of the RTC and the subacromial bursa.[3–6] When analyzing the RTC with isometrically held shoulder postures, researchers[7–11] discovered that superior humeral head migration increases with fatigue of the RTC.

Glenohumeral kinematics have been analyzed with standard radiographs,[7–10,12] magnetic resonance imaging,[13–16] ultrasound,[17] and computed tomography.[18] In most studies using these methods, images were taken with the GH joint held in static positions. Thus, findings from these studies describe static GH arthrokinematics but do not provide a suitable description of dynamic GH arthrokinematics. Although digital fluoroscopic video (DFV) results in a poorer-quality image, recent technological advances may enable DFVs to be used to analyze GH kinematics throughout a dynamic range of motion. The use of DFV to analyze the GH joint remains a relatively novel approach, but it may enable more accurate and functional analysis of GH joint biomechanics. Specifically, if the traditional measurement techniques used to assess GH positional data are reliable when obtained with these dynamic assessment techniques, DFV may be a reliable technique to assess changes in velocity and acceleration associated with RTC fatigue, musculoskeletal dysfunction, and different shoulder lesions.

The DFV imaging of the GH joint has been used to study subacromial spurs,[19] scapulohumeral rhythm,[20] and

Table 1. Exclusion Criteria[22]

History
1. Shoulder pain
2. Previous diagnosis of shoulder impingement syndrome
3. History of shoulder dislocation, subluxation, or fracture
4. Cervical radiculitis or radiculopathy
5. History of cervical, shoulder, or upper back surgery
6. Physical therapy or chiropractic treatment for cervical, shoulder, or upper back problems in the last 12 months
7. History of systemic or neurologic disease
Physical Examination
1. Positive Hawkins-Kennedy impingement sign
2. Positive Neer sign
3. Pain with active shoulder abduction
4. Positive Spurling test
5. Positive distraction test
6. Pain with resisted shoulder abduction (break test)
7. Pain with resisted shoulder internal rotation (break test)
8. Pain with resisted shoulder external rotation (break test)

subtle instability of the GH joint under anesthesia.[21] However, to our knowledge, no investigators have applied this technology for the analysis of GH arthrokinematics of active motion and reported the effect of RTC fatigue on GH migration. Additionally, although researchers[7–10] have reported the reliability of applying measurement techniques to assess GH arthrokinematics with static radiographs, they have not reported this reliability with DFV images. The purposes of our study were to investigate the effect of RTC fatigue on GH migration during dynamic concentric arm elevation (arm at the side [approximately 0°] to 135°) in healthy participants and to determine the test-retest reliability of DFV for assessing GH migration.

METHODS

Participants

We recruited 20 healthy male participants with an average age of 27.7 ± 3.6 years (range = 19–35 years) and an average mass of 81.5 ± 11.8 kg (range = 63.0–112.1 kg) from the Department of Defense beneficiary population. We did not record their heights. Participants were included based on no history of shoulder disorders reported on a screening questionnaire and no shoulder lesions found during physical examination. To ensure that the study participants lacked shoulder lesions, we used exclusion criteria based on those of Bang and Deyle[22] (Table 1). Seventeen individuals had participated in overhead sports, 17 were right-hand dominant, 2 were left-hand dominant, and 1 was ambidextrous. Each participant signed an informed consent form approved by the Brooke Army Medical Center Internal Review Board, which also approved the study.

Instrumentation

We obtained all DFV sequences with a Digital Motion X-Ray System (VF-Works Inc, Palm Harbor, FL) that had a resolution of 480 × 640 pixels per image. The images were collected at 30 Hz and were recorded using an S-VHS videocassette recorder (AG-1980; Panasonic Corp of North America, Secausus, NJ). A Pro-Series Capture Kit MV (version 1.0; Media Cybernetics, Inc, Bethesda, MD) and a desktop computer were used to digitize the videos at 30 Hz. The digital images were analyzed with Image-Pro Plus software (version 4.5; Media Cybernetics).

Figure 1. Experimental set-up with the participant in anatomic position and his entire body rotated 30° from the frontal plane with respect to the X-ray beam. The right shoulder was positioned near (less than 2 cm from) the image intensifier to minimize distortion. The height of the C-arm was adjusted to ensure that the glenohumeral joint and the proximal humeral shaft were visible during the entire range of motion. Foot, scapular, and hand markings were used to ensure similar positioning between trials.

Imaging Protocol

The DFVs were obtained using a technique modeled after the work of Poppen and Walker[8] and Chen et al.[9] The participant stood in anatomic position with his entire body rotated 30° from the frontal plane with respect to the X-ray beam (Figure 1). This position was chosen to align the X-ray beam perpendicularly with the plane of the scapula. Based on limitations in positioning the C-arm, the right shoulder of each participant was imaged. The right shoulder was positioned near (less than 2 cm from) the image intensifier to minimize distortion. The height of the C-arm was adjusted to ensure that the GH joint and the proximal humeral shaft were visible during the entire range of motion. Static images were used to confirm proper shoulder position within the field of view throughout the range of motion analyzed and to calibrate the pixel dimensions. To calibrate pixel width, we placed a radiopaque calibration device on the anterior portion of the shoulder. After we confirmed with static imaging that the area of interest was within the field of view during the entire range of motion, we used foot, scapular, and hand markings to ensure similar positioning between trials. To minimize trunk movement during right arm elevation, the participant stabilized his trunk by holding onto a height-adjustable stationary object with his left hand and maintained the upright posture throughout the range of motion. The procedures that we used to position the participant within the field of view were designed to minimize error associated with out-of-plane movement. One researcher observed arm elevation; any trunk motion or out-of-plane motion necessitated recollection of the DFV.

Arm elevation in the plane of the scapula was performed from the arm positioned at the side with the palm facing forward through the available range of motion. To be consistent with the procedures of previous researchers[7–10] who studied GH kinematics, the participant held a 1.36-kg weight in the hand with the thumb positioned toward the ceiling during the motion. Three DFVs of arm elevation were obtained for each participant. Two DFVs were taken before the fatigue protocol to establish test-retest reliability. Between the prefatigue DFVs, each participant was removed from the fluoroscopic device, allowed to rest for 3 minutes, and repositioned into the machine. The participants then completed the RTC fatigue protocol, and a third (postfatigue) DFV was obtained. To ensure dynamic motion throughout the entire DFV, images were taken on the second repetition in a series of 3 arm elevations. Additionally, audio, oral, and visual cues were used to ensure a 3-second timeframe for each arm elevation. Audio cues were provided by a metronome and were reinforced with oral cues from a researcher. Visual cues were given by a researcher who performed arm elevation in real time with the participant.

Rotator Cuff Fatigue Protocol

For this study, we defined the RTC as the supraspinatus, infraspinatus, and teres minor muscles. An RTC fatigue protocol using prone horizontal abduction was established based on the works of Blackburn et al[23] and Chen et al.[9] Participants were positioned prone, with the shoulder abducted 90° and the arm externally rotated so that the thumb pointed up to the ceiling. Blackburn et al[23] found that this exercise effectively isolated the supraspinatus, infraspinatus, and teres minor muscles. Next, the participant slowly performed the arm elevation exercise (approximately 2 seconds per repetition) while lifting 5% of his body mass until fatigue was established. Visual and oral cues were provided to ensure proper form, rate, and angle of the exercise.

Prefatigue and postfatigue RTC strength were measured with a hand-held mechanical dynamometer (BASELINE, Milan, Italy) that was placed proximal to the radial styloid process of the right arm in the exercise position. Based on its reliability (.92–.95) in measurements with inexperienced or experienced testers, we used a "make" test rather than a break test (reliability, .87–.93).[24,25] To stabilize the dynamometer during the strength measurement, a semicircular force plate was used. Additionally, 1 tester placed both hands on the dynamometer during the test motion, and another tester stabilized the participant's torso.

Rotator cuff fatigue initially was estimated as the inability of the participant to horizontally abduct 5% of his body mass more than 45° from the ground on 3 consecutive attempts.[9] Furthermore, RTC fatigue was confirmed if, after the exercise regimen, the participant's strength decreased by 40% from the prefatigue strength. If a 40% decrement was not measured, exercise was resumed. After measuring a decrease in strength of at least 40%, we obtained the postfatigue DFV.

When we confirmed fatigue, we repositioned the participant for the postfatigue DFV. To minimize the time between establishment of RTC fatigue and the postfatigue DFV, we instructed participants before the exercise protocol on repositioning quickly and accurately into the established marked positions. The fatigue protocol was performed adjacent to the imaging device to facilitate a quick transition. Practice sessions were provided until the participant was able to enter the machine on the established marks within 30 seconds, which minimized muscle recovery.[26,27]

Radiographic Analysis

The method of determining GH migration and humeral angle was based on protocols by Poppen and Walker[8] and Chen et al,[9] who used digital point placement techniques. Geometric shapes were used to represent the anatomic features of interest with the Image-Pro Plus software package. The glenoid fossa was represented by a line, with the ends of the line representing the superior and inferior aspects of the glenoid rim (Figure 2). The humeral head was represented by a "best-fit" circle template that the software package created based on 5 manually located points along the humeral head (Figure 2). Each participant's circular template was used to represent the humeral head for all subsequent angle analyses. The center of the circle represented the center of the humeral head. Migration was defined as the distance between the perpendicular projection of the center of the humeral head to the glenoid line and the center of the glenoid line (Figure 3). Superior migration resulted when the projection of center of the humeral head to the glenoid line was superior to the center of the glenoid line. Humeral angle was defined as the angle between a line drawn on the medial border of the shaft of the humerus and a line drawn vertically (Figure 2). To minimize the error associated with point placement technique, a fourth-order Butterworth filter with a cut-off frequency of 1 Hz was applied to the positional data that were used to generate the center of the humeral head and glenoid line throughout the range of motion before analysis of GH migration. Additionally, the measurement technique used to assess GH migration compared the adjacent midpoints representing the center of the glenoid fossa with the center of the humeral head. Based on theories of distortion-compensated roentgen analysis,[28–30] this type of approach to assess displacement helps to control for out-of-plane motions that could compromise the findings.

Data Analysis

We established reliability by comparing GH migration within participants with the arm at the side (approximately 0°) and at 45°, 90°, and 135° of elevation from the 2

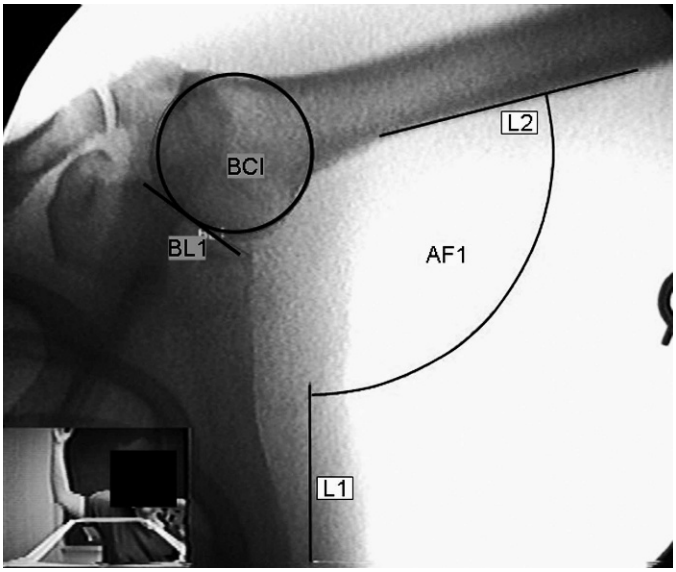

Figure 2. Example of the data extraction technique from a single frame from the digital fluoroscopic video. BC1 depicts the best-fit circle representing the humeral head. BL1 depicts a best-fit line, the ends of which represent the superior and inferior borders of the glenoid fossa. Humeral head migration was defined as the distance between the center of the glenoid line (BL1) and the perpendicular projection of the center of the BC1 to BL1. AF1 is the humeral angle. It was determined as the angle between vertical (L1) and a line drawn on the medial border of the humeral shaft (L2).

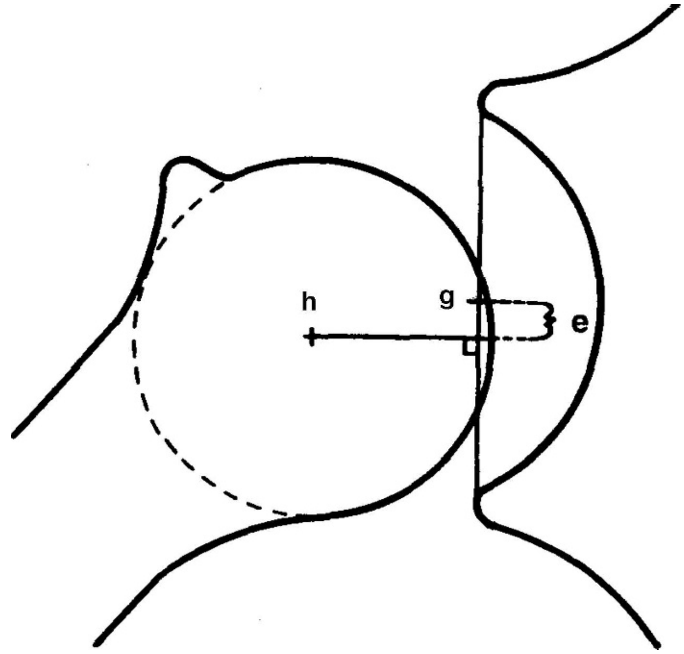

Figure 3. Radiographic measurement of humeral head migration was adapted based on a technique described by Deutsch et al.[10] Humeral head migration (e) was defined as the distance between the center of the glenoid line (g) and the perpendicular projection of the center of the humeral head (h) to the glenoid line. This value was expressed as positive if the center of the humeral head was superior to the center of the glenoid or negative if it was inferior to the center of the glenoid. In this figure, the center of the humeral head was inferior to the center of the glenoid line. Reprinted from the *Journal of Shoulder and Elbow Surgery*, volume 8, Chen SK, Simonian PT, Wickiewicz TL, Otis JC, Warren JF, Radiographic evaluation of glenohumeral kinematics: a muscle fatigue model, p 49–52, 1999, with permission from the Journal of Shoulder and Elbow Surgery Board of Trustees.

prefatigue DFVs. An intraclass correlation coefficient (ICC) model (2,1) was used to measure the test-retest reliability, and the standard error of the measurement (SEM) was calculated to determine response stability.[31]

The effects of RTC fatigue on GH kinematics were tested with a 2 × 4 repeated-measures analysis of variance (ANOVA). The independent variables in the study were the fatigue state of the RTC (prefatigue and postfatigue) and the angles of measurement (arm at the side, 45°, 90°, and 135°). The dependent variable was the amount of superior-inferior GH migration, which was measured in millimeters. The angular values were selected to enable comparison with the results from Chen et al.[9] The α level was set at .05. Post hoc analysis for variables with a significant difference consisted of paired t tests with a Bonferroni correction. A Greenhouse-Geisser correction was applied when the Mauchly test of sphericity was significant.

Data analysis was accomplished with the following software packages: MATLAB (student version release 12; The Math Works, Inc, Natick, MA), Excel (Professional Edition 2003; Microsoft Corp, Redmond, WA), and SPSS (version 10.1; SPSS Inc, Chicago, IL).

RESULTS

Reliability testing of the measurement technique with the arm at the side, 45°, 90°, and 135° revealed that the ICC (2,1) ranged from .77 to .92. The response stability of the measurement technique resulted in an SEM that ranged from 0.57 mm to 0.66 mm at the assessed angles (Table 2). The SEM was less than 2 pixels in all positions.

Descriptive data of GH migration are provided in Table 3. The 2 × 4 repeated-measures ANOVA revealed no interaction between angle and fatigue state (P = .064) and no main effect for angle (P = .11). However, the difference in mean values between the fatigue states (0.79 mm) was significant ($P < .001$). The mean prefatigue GH migration during arm elevation was −0.71 ± 1.93 mm, and the mean postfatigue GH migration during arm elevation was 0.08 ± 1.92 mm.

Overall, the average degree of fatigue was indicated by a 54.0 ± 8.8% reduction in prone horizontal abduction strength after the fatigue protocol. The average weight used for the fatigue protocol was 3.94 ± 0.06 kg. Time to fatigue averaged 84.2 ± 21.2 seconds. The average prefatigue strength was 7.15 ± 1.59 kg. The average postfatigue strength was 3.16 ± 0.27 kg. The greatest time from fatigue to start of first-run postfatigue was less than 36 seconds (mean, 14.1 ± 10.3 seconds). The radiation exposure per

Table 2. Intrarater Reliability for Measuring Glenohumeral Migration Using Digital Fluoroscopic Video, Intraclass Correlation Coefficient (2,1), and Standard Error of Measurement (SEM)

Arm Elevation Angle	Reliability (Intraclass Correlation Coefficient 2,1)	SEM, mm	SEM, pixels
Arm at side (approximately 0°)	.92	0.57	1.4
45°	.78	0.54	1.4
90°	.81	0.57	1.4
135°	.77	0.66	1.6

Table 3. Descriptive Data of Glenohumeral Migration of the Rotator Cuff Muscles Prefatigue and Postfatigue (Mean ± SD)

Arm Elevation Angle	Prefatigue, mm[a,b]	Postfatigue, mm[a,b]
Arm at side (approximately 0°)	−1.48 ± 1.82	−0.39 ± 1.73
45°	−0.85 ± 1.14	+0.32 ± 1.49
90°	−0.73 ± 2.15	+0.32 ± 1.75
135°	+0.22 ± 2.14	+0.07 ± 2.58

[a] Negative values indicate that the center of the humeral head was inferior to the center of the glenoid line.
[b] Positive values indicate that the center of the humeral head was superior to the center of the glenoid line.

participant ranged from 16 to 40 seconds (mean, 25.1 ± 8.7 seconds), resulting in an effective dose of approximately 50 millirems (0.0005 Sv).

DISCUSSION

Superior humeral head migration increased by an average of 0.79 mm (range, 0.15–1.18 mm) during arm elevation after fatigue of the supraspinatus, infraspinatus, and teres minor muscles. Although migration is a multidimensional phenomenon, this magnitude of superior migration may represent a 6% to 40% reduction in subacromial space, which is reported to be between 2 mm and 14 mm.[32–36] Thus, the subacromial space appears to be compromised more after fatigue of the RTC. In addition, researchers[32–34,37] have suggested that shoulder lesions can reduce this space by 53% to 68%. Therefore, a slight additional increase in superior migration of the humeral head may be clinically significant. However, more research is needed.

The more superiorly migrated position of the humeral head on the glenoid fossa during arm elevation after RTC fatigue may be due to the intricate muscular interactions between the RTC and deltoid muscles. Investigators[3,38,39] have demonstrated that the deltoid has a superior translatory force that is counteracted by the RTC during the first 90° of arm elevation. Based on the 54 ± 8.8% reduction in the RTC strength and the minimal amount of time from the fatigue protocol to the postfatigue DFV (14.3 ± 10.6 seconds), we propose that induced RTC fatigue led to the increased superior humeral head migration measured in our study and that the resulting inefficiency of the fatigued RTC could not counteract the superiorly directed force from the deltoid muscle. Furthermore, future researchers should conduct prospective studies to address the associations between RTC fatigue and altered GH arthrokinematics in patients with shoulder lesions that have been associated with a decrease in subacromial space, such as shoulder impingement syndrome.[32]

Our measures of prefatigue GH migration are consistent with those of Ludewig and Cook,[38] who reported between 1.5 mm and 1.7 mm of superior GH migration. The amount of superior GH migration prefatigue was also similar to that measured in individuals without RTC fatigue in studies conducted by Deutsch et al[10] and Yamaguchi et al.[7] These researchers analyzed GH arthrokinematics with the arm positioned at predetermined, statically held angles and found relatively no humeral head migration in individuals without shoulder disorders or injuries compared with migration values found in individuals with shoulder disorders or injuries. Additionally, our findings closely support the research by Chen et al,[9] in which individuals without shoulder lesions were studied both prefatigue and postfatigue in predetermined, statically held angles of arm elevation. Chen et al[9] found that superior migration was greater after RTC fatigue. Therefore, the RTC appears to stabilize the shoulder in both static and dynamic conditions, and its ability to stabilize the shoulder is dependent on its fatigue condition.

The other purpose of our study was to determine the test-retest reliability of DFV as a technique for assessing GH arthrokinematics before the fatigue protocol. We found that the measurement technique used to analyze humeral head migration relative to the glenoid fossa resulted in good to excellent intrarater reliability (ICC [2,1] = .77 to .92).[31] Reliability was highest with the arm at the side and lowest with the arm at 135° of elevation. At 135°, the clarity of the images often was degraded because of the overlapping anatomic structures, which increased the difficulty in distinguishing specific anatomic landmarks. The response stability associated with this measurement technique resulted in an average SEM of 1.45 pixels (mean = 0.58 mm). The SEM obtained from DFV was within the range of 0.1 to 2.0 mm that Deutsch et al[10] reported when using higher-quality static radiographs. Although the SEM values were relatively small compared with both the pixel size and previous reports, they were relatively high compared with the differences found before and after RTC fatigue. Specifically, the increase in the postfatigue values of humeral head migration was more than the SEM (representing 68% confidence that the changes were more than measurement error) but was less than the 2 × SEM (mean = 1.16 mm), which would have indicated 95% confidence that the differences observed were more than measurement error. Therefore, future researchers should consider using a DFV system with greater resolution. Additionally, future investigators should establish interrater reliability using the described measurement technique and should establish reliability values associated with the postfatigue state.

Although we did not find a main effect for condition (arm elevation angle) or an interaction effect (Figure 4, Table 3), we recommend that future researchers continue to address the interaction between RTC fatigue and arm angle during shoulder abduction in patients with shoulder lesions. The influence of greater superior migration through a longer arc of motion, and hence a longer time, may be an important factor in patients with shoulder disorders. More study is needed.

The use of DFV to describe underlying arthrokinematics is potentially helpful in describing aberrant motion in patients with shoulder disorders. It could be used to assess changes in velocity and acceleration associated with RTC fatigue and shoulder disorders. Additionally, the ability to assess dynamic arthrokinematics with DFV at either 30 Hz or 60 Hz provides a tool for future researchers to compare measurements obtained with skin markers and motion analysis capture systems.[40–42] Ultimately, this could enable a more accurate assessment of GH arthrokinematics without the risk associated with exposure to radiation.

Although our research revealed a significant difference in the amount of superior humeral head migration between prefatigue and postfatigue conditions, our study had

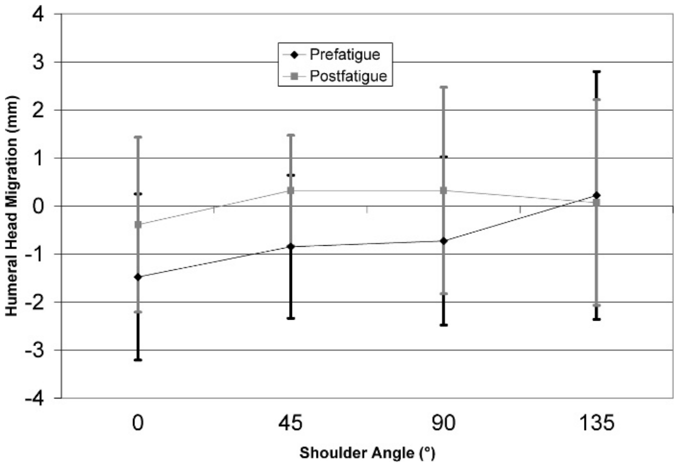

Figure 4. Mean superior migration of the humeral head with elevation during prefatigue and postfatigue conditions. Mean prefatigue migration with the arm at the side (approximately 0°), 45°, 90°, and 135° was −1.48 ± 1.82 mm, −0.85 ± 1.14 mm, −0.73 ± 2.15 mm, and 0.22 ± 2.14 mm, respectively. Mean postfatigue migration with the arm at the side, 45°, 90°, and 135° was −0.39 ± 1.73 mm, 0.32 ± 1.49 mm, 0.32 ± 1.75 mm, and 0.07 ± 2.58 mm, respectively.

limitations that need to be addressed with future investigation. We analyzed GH arthrokinematics using a 2-dimensional imaging technique that assumes that a superior translation should lead to a decrease in the subacromial space. Authors[7–10] have used this technique, but they have not shown a correlation between GH positioning and acromiohumeral distance. Three-dimensional imaging (eg, biplanar fluoroscopy) would provide a tool to assess the effect of the position of the scapula (eg, scapular tilting); the shape of the acromion; the humeral position in the anterior-posterior direction; and superior migration, which we addressed in our study. In addition, we analyzed only dynamic concentric contraction during arm elevation. Eccentric conditions may display a different direction of humeral head migration because different arthrokinematics (rolling and gliding) are required.[1] Therefore, researchers should investigate the GH arthrokinematics under eccentric conditions (lowering the arm against gravity in the plane of the scapula).

Another limitation was that only young, healthy men participated in our study. Generalizing our results to other age groups, women, or those with shoulder disorders is difficult. Differences in GH migration based on sex have not been analyzed. However, Graichen et al[43] reported that the subacromial space was dependent on sex and was smaller in women. Future researchers using DFV should assess GH arthrokinematics between the sexes and in participants with shoulder disorders. Additionally, researchers should analyze GH migration while measuring electromyography of shoulder muscle activation to better understand the relationship between RTC fatigue and GH migration.

CONCLUSIONS

We demonstrated that DFV measurement of humeral head migration has good to excellent reliability, making it a viable technique for assessing GH arthrokinematics. Dynamic assessment of GH migration in participants without shoulder disorders demonstrated a more superiorly positioned humeral head relative to the glenoid fossa during arm elevation under conditions of fatigue of the suprapsinatus, infraspinatus, and teres minor muscles. Future researchers should use DFV to study the effects of shoulder disorders on GH arthrokinematics.

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REFERENCES

1. Levangie PK, Norkin CC. *Joint Structure and Function: A Comprehensive Analysis*. 3rd ed. Philadelphia, PA: FA Davis; 2001.
2. Moore KL, Dalley AF. *Clinically Oriented Anatomy*. 4th ed. Philadelphia, PA: Lippincott Williams and Wilkins; 1999.
3. Bigliani LU, Levine WN. Subacromial impingement syndrome. *J Bone Joint Surg Am*. 1997;79(12):1854–1868.
4. Newhouse KE, el-Khoury GY, Nepola JV, Montgomery WJ. The shoulder impingement view: a fluoroscopic technique for the detection of subacromial spurs. *AJR Am J Roentgenol*. 1988;151(3): 539–541.
5. Soslowsky LJ, Flatow EL, Bigliani LU, Mow VC. Articular geometry of the glenohumeral joint. *Clin Orthop Relat Res*. 1992;285:181–190.
6. Soslowsky LJ, Flatow EL, Bigliani LU, Pawluk RJ, Ateshian GA, Mow VC. Quantitation of in situ contact areas at the glenohumeral joint: a biomechanical study. *J Orthop Res*. 1992;10(4):524–534.
7. 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(1):6–11.
8. Poppen NK, Walker PS. Normal and abnormal motion of the shoulder. *J Bone Joint Surg Am*. 1976;58(2):195–201.
9. Chen SK, Simonian PT, Wickiewicz TL, Otis JC, Warren RF. Radiographic evaluation of glenohumeral kinematics: a muscle fatigue model. *J Shoulder Elbow Surg*. 1999;8(1):49–52.
10. Deutsch A, Altchek DW, Schwartz E, Otis JC, Warren RF. Radiologic measurement of superior displacement of the humeral head in the impingement syndrome. *J Shoulder Elbow Surg*. 1996;5(3):186–193.
11. Prato N, Peloso D, Franconeri A, et al. The anterior tilt of the acromion: radiographic evaluation and correlation with shoulder diseases. *Eur Radiol*. 1998;8(9):1639–1646.
12. Rossi F, Ternamian PJ, Cerciello G, Walch G. [Posterosuperior glenoid rim impingement in athletes: the diagnostic value of traditional radiology and magnetic resonance.] *Radiol Med (Torino)*. 1994;87(1–2):22–27.
13. Shibuta H, Tamai K, Tabuchi K. Magnetic resonance imaging of the shoulder in abduction. *Clin Orthop Relat Res*. 1998;348:107–113.
14. Bonutti PM, Norfray JF, Friedman RJ, Genez BM. Kinematic MRI of the shoulder. *J Comput Assist Tomogr*. 1993;17(4):666–669.
15. Graichen H, Stammberger T, Bonel H, et al. Magnetic resonance-based motion analysis of the shoulder during elevation. *Clin Orthop Relat Res*. 2000;370:154–163.
16. Rhoad RC, Klimkiewicz JJ, Williams GR, et al. A new in vivo technique for three-dimensional shoulder kinematics analysis. *Skeletal Radiol*. 1998;27(2):92–97.
17. Collins RA, Gristina AG, Carter RE, Webb LX, Voytek A. Ultrasonography of the shoulder: static and dynamic imaging. *Orthop Clin North Am*. 1987;18(3):351–360.
18. Baratelli M, Cabitza P, Parrini L. Role of computerized tomography in the evaluation of the stability of the glenohumeral articulation. *Radiol Med (Torino)*. 1984;70(10):714–717.
19. Maki NJ. Cineradiographic studies with shoulder instabilities. *Am J Sports Med*. 1988;16(4):362–364.
20. Mandalidis DG, McGlone BS, Quigley RF, McInerney D, O'Brien M. Digital fluoroscopic assessment of the scapulohumeral rhythm. *Surg Radiol Anat*. 1999;21(4):241–246.

21. Papilion JA, Shall LM. Fluoroscopic evaluation for subtle shoulder instability. *Am J Sports Med*. 1992;20(5):548–552.
22. Bang MD, Deyle GD. Comparison of supervised exercise with and without manual physical therapy for patients with shoulder impingement syndrome. *J Orthop Sports Phys Ther*. 2000;30(3):126–137.
23. Blackburn TA, McLeod WD, White B, Wofford L. EMG analysis of posterior rotator cuff exercises. *J Athl Train*. 1990;25(1):40–45.
24. Brinkmann JR. Comparison of a hand-held and fixed dynamometer in measuring strength of patients with neuromuscular disease. *J Orthop Sports Phys Ther*. 1994;19(2):100–104.
25. Stratford PW, Balsor BE. A comparison of make and break tests using a hand-held dynamometer and the Kin-Com. *J Orthop Sports Phys Ther*. 1994;19(1):28–32.
26. Allman BL, Rice CL. Neuromuscular fatigue and aging: central and peripheral factors. *Muscle Nerve*. 2002;25(6):785–796.
27. Milner-Brown HS, Mellenthin M, Miller RG. Quantifying human muscle strength, endurance and fatigue. *Arch Phys Med Rehabil*. 1986;67(8):530–535.
28. Frobin W, Brinckmann P, Leivseth G, Biggemann M, Reikeras O. Precision measurement of segmental motion from flexion-extension radiographs of the lumbar spine. *Clin Biomech (Bristol, Avon)*. 1996;11(8):457–465.
29. Frobin W, Leivseth G, Biggemann M, Brinckmann P. Sagittal plane segmental motion of the cervical spine: a new precision measurement protocol and normal motion data of healthy adults. *Clin Biomech (Bristol, Avon)*. 2002;17(1):21–31.
30. Muggleton JM, Allen R. Insights into the measurement of vertebral translation in the sagittal plane. *Med Eng Phys*. 1998;20(1):21–32.
31. Portney LG, Watkins MP. *Foundations of Clinical Research: Applications to Practice*. 2nd ed. Upper Saddle River, NJ: Prentice Hall; 2000.
32. Graichen H, Bonel H, Stammberger T, et al. Three-dimensional analysis of the width of the subacromial space in healthy subjects and patients with impingement syndrome. *AJR Am J Roentgenol*. 1999;172(4):1081–1086.
33. Hinterwimmer S, Von Eisenhart-Rothe R, Siebert M, et al. Influence of adducting and abducting muscle forces on the subacromial space width. *Med Sci Sports Exerc*. 2003;35(12):2055–2059.
34. Flatow EL, Soslowsky LJ, Ticker JB, et al. Excursion of the rotator cuff under the acromion: patterns of subacromial contact. *Am J Sports Med*. 1994;22(6):779–788.
35. Di Mario M, Fraracci L. MR study of the intrinsic acromial angle in 74 symptomatic patients. *Radiol Med (Torino)*. 2005;110(3): 273–279.
36. van de Sande MA, Rozing PM. Proximal migration can be measured accurately on standardized anteroposterior shoulder radiographs. *Clin Orthop Relat Res*. 2006;443:260–265.
37. Tillander B, Norlin R. Intraoperative measurements of the subacromial distance. *Arthroscopy*. 2002;18(4):347–352.
38. Ludewig PM, Cook TM. Translations of the humerus in persons with shoulder impingement symptoms. *J Orthop Sports Phys Ther*. 2002; 32(6):248–259.
39. Soslowsky LJ, Carpenter JE, Bucchieri JS, Flatow EL. Biomechanics of the rotator cuff. *Orthop Clin North Am*. 1997;28(1):17–30.
40. McClure PW, Bialker J, Neff N, Williams G, Karduna A. Shoulder function and 3-dimensional kinematics in people with shoulder impingement syndrome before and after a 6-week exercise program. *Phys Ther*. 2004;84(9):832–848.
41. McClure PW, Michener LA, Karduna AR. Shoulder function and 3-dimensional scapular kinematics in people with and without shoulder impingement syndrome. *Phys Ther*. 2006;86(8):1075–1090.
42. Ebaugh DD, McClure PW, Karduna AR. Scapulothoracic and glenohumeral kinematics following an external rotation fatigue protocol. *J Orthop Sports Phys Ther*. 2006;36(8):557–571.
43. Graichen H, Bonel H, Stammberger T, Englmeier KH, Reiser M, Eckstein F. Sex-specific differences of subacromial space width during abduction, with and without muscular activity, and correlation with anthropometric variables. *J Shoulder Elbow Surg*. 2001;10(2):129–135.

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