Effect of Increased Scapular Internal Rotation on Glenohumeral External Rotation and Elbow Valgus Load in the Late Cocking Phase of Throwing Motion

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Background: Scapular dyskinesis among throwers is thought to affect kinetic chain function and increase the load demands on the shoulder and/or elbow. However, the biomechanical relationship between scapular orientation and elbow valgus load, which is associated with ulnar collateral ligament (UCL) injury, has not been determined.

Purpose: To evaluate the effect of increased scapular internal rotation (IR) and glenohumeral external rotation (GHER) on elbow valgus load in a static simulation of the late cocking phase of throwing.

Study Design: Controlled laboratory study.

Methods: Seven fresh-frozen male cadaveric upper extremities were used with a custom testing system to simulate the late cocking phase. First, the authors evaluated the effect of increasing scapular IR on maximum GHER and forearm angle (forearm axis relative to the ground). Each parameter was evaluated at 20° to 40° (5° increments) of scapular IR by applying 2.2-N·m external rotation torque to the humerus and 0.75-N·m valgus torque to the forearm. Next, to evaluate elbow valgus stability, the humerus was locked in maximal GHER at 40° of scapular IR, and sequentially increasing torque (0.75-7.5 N·m by 0.75-N·m increments) was applied to the forearm. Valgus angle and joint gap were evaluated at each torque.

Results: Increases in scapular IR ≥5° significantly decreased GHER ($P < .01$). With increasing valgus torque, forearm angle also increased linearly ($R^2 = 0.85$, $P < .001$). To compensate for the GHER deficit at 40° of scapular IR, a linear regression model showed that 25.3 N·m of valgus torque would be necessary to reach the original forearm position. In the intact condition, applying elbow valgus torque ≥5.25 N·m significantly increased valgus angle and the joint gap ($P < .01$).

Conclusion: Increased scapular IR significantly decreased GHER. Compensation for the GHER deficit significantly increased the elbow valgus load required to reach the same forearm position.

Clinical Relevance: Increased scapular IR may increase the risk of elbow UCL injury among throwing athletes.

Keywords: scapula; ulnar collateral ligament; shoulder; baseball; overhead athletes; biomechanics

Ulnar collateral ligament (UCL) injury of the elbow is common among throwing athletes, particularly younger players (15-20 years old).[10,12,18] The throwing motion places stress on the medial side of the elbow, which is greatest when the shoulder is near its maximum external rotation (ER) and the elbow is flexed to about 90°.[15] Excessive elbow valgus load during the late cocking phase was proven to be a risk factor for UCL injuries.[2,7,15,41]

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The kinetic chain acts to optimize the efficiency of proximal segment activation and to minimize the load on the distal segments. Pitchers attempt to throw the ball from the same hand position to generate the same energy output even when they become fatigued.[13] However, muscular fatigue has been proved to diminish kinetic chain function.[34,46] Muscular fatigue attributed to high pitch counts significantly increases internal rotation (IR) and decreases upward rotation of the scapula.[4] With respect to the kinetic chain, compensation for scapular dysfunction must occur at the shoulder and/or elbow joints.[6,19,20,36]

Glenohumeral IR deficit (GIRD) has been considered a risk factor for throwing-related injuries. Decreased scapular upward rotation[39] and increased scapular protraction[21,39] are considered to be associated with GIRD. There have been many attempts to identify the risk factors for throwing-related injuries from medical examination data, including GIRD,[5,11] total arc of motion deficit (sum of IR and ER),[45] and insufficient shoulder ER.[5,9,43,44] In 2009, Dines et al[11] reported that pathologic GIRD might be associated with elbow valgus instability. Subsequently, Garrison et al[16] and Wilk et al[43] reported that a deficit in total arc of motion was associated with an UCL injury. Camp et al[9] recently advocated that glenohumeral ER (GHER) deficits were a risk factor for elbow injuries.

Scapular dysfunction among throwing athletes is thought to be associated with pathologic internal impingement.[22] Previous biomechanical studies showed that an increase in scapular IR and a decrease in scapular upward rotation increased shoulder internal impingement and decreased GHER.[28] In addition, excessive glenohumeral horizontal abduction, which is closely related to scapular IR, translated the humeral head anteriorly and increased the internal impingement area in the late cocking phase.[29] To date, the biomechanical relationship among scapular orientation, GHER and elbow valgus load in the late cocking phase of throwing motion has not been documented. The purpose of this study was to evaluate the effect of increased scapular IR on elbow valgus load in a static simulation of the late cocking phase of the throwing motion. Our hypothesis was that increased scapular IR would decrease GHER and increase elbow valgus load.

METHODS

Specimen Preparation

Seven fresh-frozen male cadaveric upper extremities from 4 donors were used (3 right and 4 left; mean age, 66.3 years; range, 51-76 years). Specimens were donated by Arthrex Inc. Institutional review board approval was waived by our institution, as this was a basic science cadaveric study. The specimens were thawed at room temperature overnight before dissection. Each specimen was dissected free of skin and subcutaneous tissue. All specimens were macroscopically screened for rotator cuff tear, UCL tear, and bone abnormalities before testing. The rotator cuff muscles and capsule of the shoulder and the coracohumeral and coracoacromial ligaments were kept intact. Deltoid muscles were detached from the acromion, and the muscle belly was removed to visualize the movement of the humeral head. The scapula was rigidly fixed to the scapular plate with 3 bolts. For the muscle loading, Krackow stitches with No. 2 sutures (FiberWire; Arthrex Inc) were used on each tendinous insertion of the rotator cuff. Forearms were fixed in neutral rotation with a 3.5-mm Steinmann pin through the radius and ulna and cut 20 cm distal to the transepicondylar axis. The humeral shaft and forearm were centered and potted with plaster of Paris in PVC pipes (polyvinyl chloride): 1.5 inch (diameter) × 2.75 inch (length) and 2.0 inch (diameter) × 3.95 inch (length), respectively. A medial muscle-splitting approach to the elbow was performed to expose the anterior bundle of the UCL. To isolate the anterior bundle of the UCL, a longitudinal split at the anterior and posterior borders of the UCL was performed. Three markers on the distal humerus (posterior aspect of the humeral shaft, medial epicondyle, and lateral epicondyle) and 3 markers on the proximal ulna (distal end of the sublime tubercle, 2 on the ulnar shaft) were placed for point digitization. Soft tissues were kept moist with 0.9% saline solution throughout testing.

Testing Setup

The upper extremity was mounted on a custom testing system that allowed 6 degrees of freedom positioning of the scapula and humerus (Figure 1). The scapula was first mounted onto a scapular plate and positioned in 30° of scapular IR, 0° of upward rotation (the medial border of the scapula aligned vertical to the ground), and 0° posterior tilt (the scapular body vertical to the ground) (Figure 2). To simulate the late cocking phase of the throwing motion, the arm was positioned in 60° of glenohumeral abduction (90° of shoulder abduction), 0° of horizontal abduction,[22,24,26,33] and 90° of elbow flexion,[8] with the forearm in the neutral position in the same coronal plane. Initial positional relationships among the scapula, humerus, and forearm were determined per clinical data in the late cocking phase of throwing.[8,22,24,26,33] The scapular plate was rotated to change scapular IR from 20° to 40°. The potted humerus was fixed in the center of the metal cylinder, which allowed the humerus to rotate around its long axis. A supportive arc on the testing system kept the forearm at 90° of elbow flexion. The following muscle forces were applied to simulate conditions during throwing motion with a pulley-cable system: 36 N for the subscapularis, 4 N for the supraspinatus, 24 N for the infraspinatus, and 3 N for the teres minor. These values were determined per the maximum potential muscle force from the physiologic cross-sectional area of each muscle and the ratio of maximal electromyographic signals of each muscle during the throwing motion.[3,17,28] Humeral ER torque was applied

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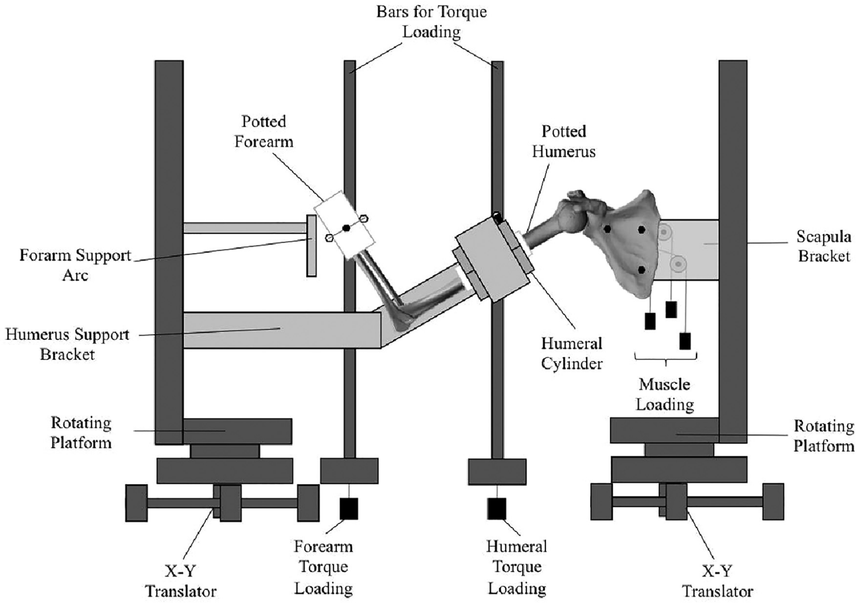


Figure 1. Testing setup.

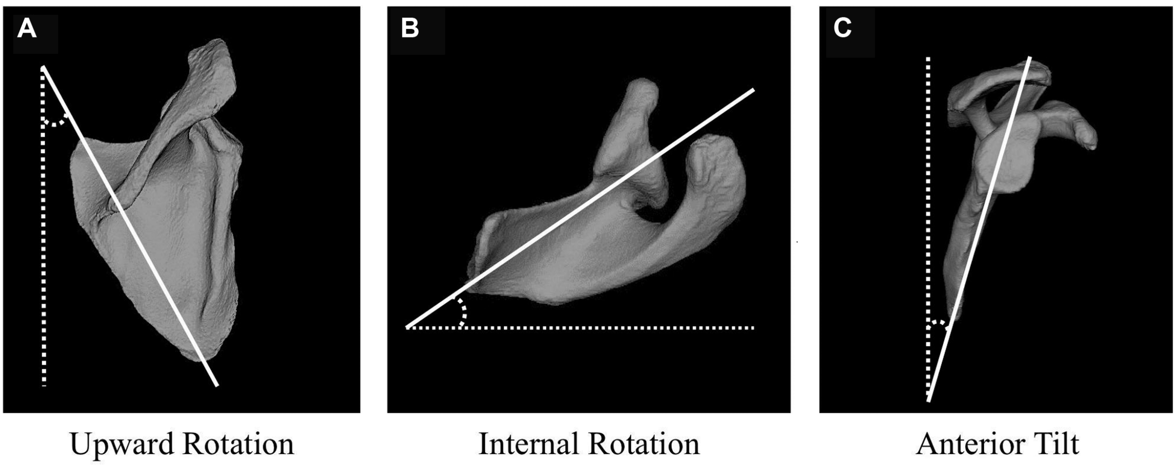
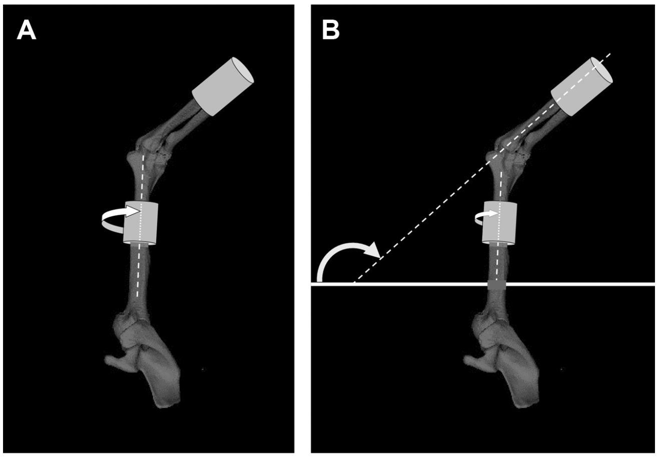


Figure 2. Definition of scapular motion in this study: (A) upward rotation, (B) internal rotation, and (C) anterior tilt.

to the humerus and elbow valgus torque to the center of the forearm with a pulley-cable system. During testing, we confirmed that the humeral head was not subluxated with the application of muscle and torque loading at each scapular IR angle.

To evaluate the GHER forearm angle, valgus angle, forearm rotation, and joint gap, 13 markers were digitized with a 3-dimensional digitizer (MicroScribe 3DLX; Rev): 3 for the cylinder, 3 for the distal humerus, 3 for the proximal ulna, and 4 for the joint gap.[23] GHER was measured with the 3 markers on the metal cylinders, and 90° of GHER was defined as the position at which the shaft of the potted forearm lined up perpendicular to the ground (Figure 3A). Forearm angle was measured as the ulnar shaft axis relative to the ground with respect to the humeral shaft axis, which corresponds to what is classically seen as shoulder ER (Figures 3B and 4A). Valgus angle was defined as the angle between the ulnar shaft and an axis orthogonal to the transepicondylar line (Figure 4B). As forearm angle may be overestimated by an increase in elbow valgus laxity,[31] GHER, valgus angle, and forearm angle were evaluated separately. Forearm rotation was defined as the angle between the transepicondylar axis and the vector from the distal end of the sublime tubercle to the distal marker on the ulna (Figure 4C). Valgus angle and forearm rotation were evaluated according to a local coordinate system defined by 3 markers on the distal humerus. Anterior and posterior joint gap was evaluated at the border of the anterior bundle of the UCL (Figure 4D). For the gap calculations, the



Glenohumeral ER Forearm Angle

Figure 3. Measurements of (A) glenohumeral external rotation (ER) and (B) forearm angle while allowing for glenohumeral rotation. Dashed line, ulnar shaft axis; solid line, line parallel to the ground. Forearm angle was measured as the ulnar shaft axis relative to the ground with respect to the humeral shaft axis in the sagittal plane.

initial gap was determined as the gap with a varus torque of 1.5 N·m.

Measurements

First, we evaluated the effect of increased scapular IR on maximum GHER, forearm angle, and valgus angle (Figure 3). Each parameter was evaluated at 20°, 25°, 30°, 35°, and 40° of scapular IR by applying 2.2 N·m of ER torque to the humerus and 0.75 N·m valgus torque to the forearm. Humeral rotation was allowed around the axis of the humeral shaft at 60° of glenohumeral abduction in the same coronal plane and with the elbow flexed to 90°. The specimen was preconditioned with 2.2 N·m of humeral ER torque to the humerus and 0.75 N·m of valgus torque to the forearm at 40° of scapula IR: 30° of scapular IR was defined as the neutral scapular position on the basis of clinical data[22,28,33]; 2.2 N·m of humeral ER torque was chosen to prevent capsular stretching and tearing[27,30,35]; and 0.75 N·m valgus torque to the forearm was applied to create a consistent baseline position.

Next, we evaluated elbow valgus stability in 40° of scapular IR at 90° of elbow flexion. The humeral rotation was locked in maximum GHER at 40° of scapular IR, and sequentially increasing torque (0.75-7.5 N·m by 0.75-N·m increments) was applied to the forearm. Forearm angle, changes in valgus angle, changes in forearm rotation, and joint gap were evaluated at each level of torque (Figure 4). Simple linear regression analysis was performed to evaluate the association between valgus torque and forearm angle. The forearm angle regression model was then used to calculate the amount of torque needed to reach the same maximum forearm angle at 30° of scapular IR.

Statistical Analysis

Two measurements were taken to ensure repeatability of the GHER within 2.0°, forearm angle within 1.0°, valgus angle within 1.0°, joint gap within 1.0 mm, and forearm rotation within 1.0°. The mean values of 2 trials each were used for analysis. A repeated measures analysis of variance with a post hoc Tukey test was used to statistically analyze the effect of scapular IR on GHER forearm angle, and valgus angle. Two-way repeated measures analysis of variance with Tukey post hoc test was conducted to compare the joint gap, valgus angle, and forearm rotation at the various levels of valgus torque for relevant testing conditions. Data are presented as mean ± SE, and the level of significance was set at $P < .05$. All statistical analyses were performed through SigmaPlot (v 13.0; Systat Software Inc).

RESULTS

Effect of Increased Scapular IR on Maximum GHER, Maximum Forearm Angle, and Valgus Angle

Increases in scapular IR ≥5° significantly decreased GHER relative to the resting scapular position of 30° IR ($P < .01$) (Figure 5). Increasing scapular IR from 30° to 40° decreased maximum forearm angle by 12.6° ± 1.6° (Appendix Table A1, available in the online version of this article). There were no significant differences in valgus angle among the 5 conditions of the scapular IR (Appendix Table A1, available online).

Association Between Valgus Torque and Forearm Angle

As valgus torque increased, the change in forearm angle increased linearly while the humeral rotation was locked in the maximum GHER at 40° of scapular IR in the intact condition ($R^2 = 0.85$, $P < .001$) (Figure 6). A 1-N·m increase in valgus torque was associated with a 0.47° increase in forearm angle. To compensate for the forearm angle deficit at 40° of scapular IR, the simple linear regression model showed that 25.3 ± 2.6 N·m of valgus torque would be necessary to reach the same forearm angle found at 30° of scapular IR.

Valgus Stability and Forearm Rotation

Elbow valgus torque ≥5.25 N·m significantly increased the valgus angle and joint gap of the elbow ($P < .01$). However, there were no significant differences in forearm rotation at each valgus torque (Table 1).

DISCUSSION

The current study demonstrated that increases in scapular IR ≥5° significantly decreased GHER when compared with the resting scapular position of 30° IR. To compensate for the GHER deficit owing to the increased scapular IR, a significant increase in elbow valgus load was needed to reach

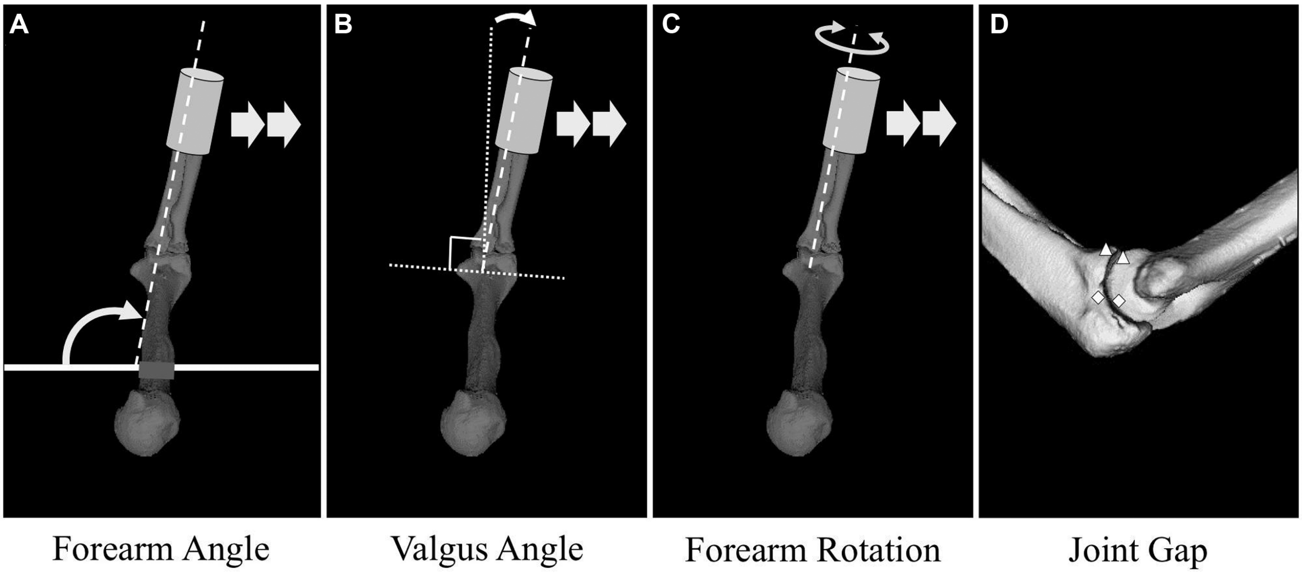


Figure 4. Measurements performed with the humerus locked in maximum glenohumeral external rotation at 40° of scapular internal rotation. Dashed line, ulnar shaft axis; solid line, line parallel to the ground; dotted line, transepicondylar line and its orthogonal axis. (A) Forearm angle: measured as the ulnar shaft axis relative to the ground with respect to the humeral shaft axis in the sagittal plane. (B) Valgus angle: defined as the angle between the ulnar shaft and an axis orthogonal to the transepicondylar line. (C) Forearm rotation: calculated with ulnar points relative to the local coordinate system of the distal humerus. (D) Joint gap: △, anterior; ◇, posterior.

TABLE 1
Valgus Stability of Intact Condition During Sequential Loading

	Valgus Torque Applied to the Forearm, N·m, Mean ± SE									
	0.75	1.50	2.25	3.00	3.75	4.50	5.25	6.00	6.75	7.50
Change in										
Valgus angle	0.0 ± 0.0	0.2 ± 0.1	0.5 ± 0.2	0.6 ± 0.2	0.8 ± 0.3	1.0 ± 0.3[a]	1.1 ± 0.2[a,b]	1.3 ± 0.2[a,b]	1.3 ± 0.3[a,b]	1.5 ± 0.2[a,b,c]
Forearm rotation,[d] deg	0.0 ± 0.0	–0.2 ± 0.1	0.2 ± 0.2	0.1 ± 0.3	–0.3 ± 0.3	–0.1 ± 0.3	–0.3 ± 0.2	–0.4 ± 0.3	–0.7 ± 0.3	–0.8 ± 0.4
Gap, mm										
Anterior	1.4 ± 0.2	1.5 ± 0.2	1.7 ± 0.2	1.7 ± 0.2	1.9 ± 0.3	1.9 ± 0.2	2.1 ± 0.2[a]	2.2 ± 0.2[a,b]	2.3 ± 0.2[a,b,c]	2.3 ± 0.2[a,b]
Posterior	1.8 ± 0.2	2.1 ± 0.2	2.1 ± 0.2	2.1 ± 0.3	2.3 ± 0.3	2.3 ± 0.3	2.5 ± 0.3[a]	2.5 ± 0.3[a]	2.5 ± 0.3[a]	2.7 ± 0.4[a,b,c,e]

[a] $P < .05$ vs 0.75 N·m.
[b] $P < .05$ vs 1.5 N·m.
[c] $P < .05$ vs 2.25 N·m.
[d] Positive values mean forearm pronation.
[e] $P < .05$ vs 3.0 N·m.

the maximum forearm position in the late cocking phase of the throwing motion. These results suggest that increased scapular IR may also be associated with decreased GHER, although increased scapular IR has been historically considered to be associated mainly with GIRD, which might increase the risk for shoulder and elbow injuries.[5,11,32,37,42]

In this study, increases in scapular IR ≥5° significantly decreased GHER as compared with the resting scapular position of 30° IR, although increased scapular IR was shown to be associated with posterior capsule tightness of the shoulder,[6,19,38] which decreases glenohumeral IR.[32,38,40] This result suggests that an increase in scapular IR may restrict GHER and IR. In addition, previous biomechanical studies demonstrated that an increase in scapular IR[28] and excessive glenohumeral horizontal abduction[29] increased shoulder internal impingement. Thus, among throwing athletes with increased scapular IR, decreased GHER may be seen because of internal impingement.

This study revealed that the amount of elbow valgus torque needed to reach the same forearm position had a significant linear correlation with the decrease in GHER. Furthermore, elbow valgus torque ≥5.25 N·m significantly increased the joint gap of the elbow and valgus angle. In previous studies utilizing 3-dimensional motion analysis,

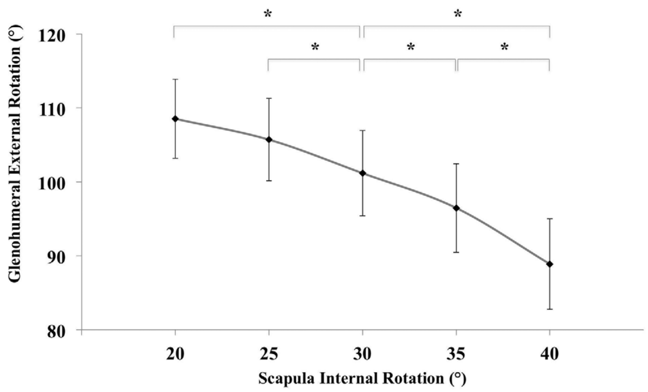


Figure 5. Effect of scapular internal rotation on maximum glenohumeral external rotation. Error bar indicates SE. *$P < .05$.

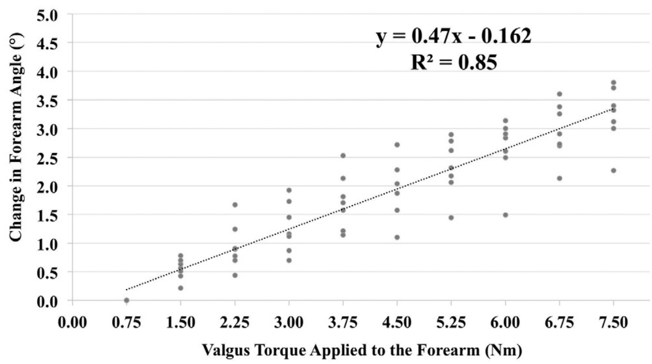


Figure 6. Relationship between valgus torque applied to the forearm and change in forearm angle with the humerus locked in the maximum glenohumeral external rotation at 40° of scapular internal rotation.

Anz et al[2] reported a significant correlation of higher elbow valgus torque with elbow injury in the late cocking phase, and Aguinaldo and Chambers[1] reported that reduced shoulder ER was associated with increased elbow valgus torque. Using preseason medical checkup data, Camp et al[9] recently reported that decreased shoulder ER is an independent risk factor for the development of elbow injuries during the upcoming season. Our findings suggest that from the view of a kinetic chain, increased compensation at the elbow for GHER deficit would increase the risk of UCL injuries, including UCL tear.

This study revealed that compensation for the GHER deficit owing to increased scapular IR increased elbow valgus load in the late cocking phase of the throwing motion. Although GIRD has been considered a risk factor for elbow injuries, recent studies revealed that total arc of motion deficits[16,43] and GHER deficits[9] may be larger contributors to elbow injuries. Our findings suggest that the compensation for GHER deficit in the late cocking phase may increase the risk of UCL injury. Rehabilitation programs that correct GHER deficit, such as stretching or scapular exercises, may be helpful to reduce the elbow valgus load in the late cocking phase.

Scapular kinematics was shown to be associated with muscular fatigue, and altered scapular kinematics increases the risk of shoulder and elbow injuries.[14,25,34] Pitchers attempt to keep the same ball release point to generate the same energy output despite altered throwing kinematics attributed to muscular fatigue.[4,13] This study demonstrated that to compensate for the decreased GHER attributed to increased scapular IR, an increased elbow valgus load was required to return to the same hand position. Therefore, implementing pitching intervals to allow for recovery and enhanced exercises against muscular fatigue need to be built into recovery and prevention protocols.

Our study had several limitations. First, we did not account for scapulothoracic movement and assumed that the compensation for the decreased GHER owing to increased scapular IR occurred only at the elbow joint. Although compensation occurs at the thoracic spine, shoulder, and elbow, sudden onset of UCL injuries was found among some pitchers without excessive anterior capsular laxity of the shoulder. We believe that our model, which simulates the worst-case scenario for the elbow, could occur in clinical situations. Second, we applied elbow valgus torque up to 7.5 N·m, which is lower than the ultimate tensile strength of the isolated UCL. This valgus torque was determined through pilot studies as the maximum force applicable without tearing of the UCL. Third, muscle force was less than what is shown in clinical data of the throwing motion. Fourth, our static loading condition did not represent the dynamic nature of throwing. However, our muscle forces were determined according to the muscle cross-sectional area ratio, so the relative proportions of muscle forces were similar to those in physiologic conditions. Fifth, we evaluated valgus laxity only at 90° of elbow flexion to simulate the late cocking phase of the throwing motion. Sixth, the age of the cadaveric specimens (mean, 66.3 years) was greater than that of throwing athletes.

CONCLUSION

Increased scapular IR significantly decreased glenohumeral external rotation. Compensation for glenohumeral external rotation deficits significantly increased the elbow valgus load required to reach the same forearm position. These results suggest that increased scapular IR may increase the risk of UCL injury.

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