J Shoulder Elbow Surg (2013) 22, 986-992

ELSEVIER

Journal of Shoulder and Elbow Surgery

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The effect of simulated scapular winging on glenohumeral joint translations

Andreas M. Mueller, MD[a,b], Vahid Entezari, MD[a], Claudio Rosso, MD[a,b], Brett McKenzie, BS[a], Andrew Hasebrock[a], Andrea Cereatti, PhD[c], Ugo Della Croce, PhD[c], Joseph P. DeAngelis, MD[d], Ara Nazarian, PhD[a,*], Arun J. Ramappa, MD[d]

[a]*Center for Advanced Orthopaedic Studies, Beth Israel Deaconess Medical Center and Harvard Medical School, Boston, MA, USA*
[b]*Orthopaedic Department, University Hospital Basel, Basel, Switzerland*
[c]*Department of Biomedical Sciences, University of Sassari Medical School, Sassari, Italy*
[d]*Department of Orthopaedic Surgery, Beth Israel Deaconess Medical Center and Harvard Medical School, Boston, MA, USA*

Hypothesis: In this study, we aim to test whether scapular winging results in a significant change in glenohumeral translation in the initial phase of the throwing motion.
Methods: Six shoulders underwent an abbreviated throwing motion (ATM) from late cocking to the end of acceleration by use of a validated robotic system. The intact specimens were tested to establish a baseline. The position of the scapula was then affected to simulate scapular winging by placing a cylindrical wedge under the inferior angle of the scapula, and the ATM was performed again. For both conditions, the average glenohumeral translations and scapular rotations were plotted over time to calculate the area under the curve, as a representative of the overall glenohumeral translations and scapular rotations observed during the ATM.
Results: Throughout the motion, the winged scapulae showed, on average, 7.7° more upward rotation, 1.6° more internal rotation, and 5.3° more anterior tipping as compared with the baseline. The scapular position relative to the hanging arm was significantly different between the baseline and scapular winging conditions in all arm positions, except for maximal external rotation and the neutral position. Comparing the area under the curve at baseline and with scapular winging indicated that scapular winging significantly increased anterior translation of the glenohumeral joint whereas translation in the superior/inferior and medial/lateral directions did not result in a change in translation.
Discussion: These results may suggest a more important role of abnormalities in scapular position in predisposing throwing athletes to shoulder injuries of the anterior capsulolabral structures and consecutive glenohumeral instability.
Level of evidence: Basic Science Study, Biomechanics.

Keywords: Shoulder; scapula; winging; dyskinesia; joint motion; translation

No institutional review board approval was required for this study.
*Reprint requests: Ara Nazarian, PhD, Center for Advanced Orthopaedic Studies, 330 Brookline Ave, RN115, Boston, MA 02215, USA.
E-mail address: anazaria@bidmc.harvard.edu (A. Nazarian).

Scapular dyskinesia is believed to be a common cause of shoulder pain and dysfunction in the overhead athlete.[3,4,9] Imbalances in the periscapular stabilizers

1058-2746/$ - see front matter © 2013 Journal of Shoulder and Elbow Surgery Board of Trustees.
http://dx.doi.org/10.1016/j.jse.2012.09.010

may result in abnormal scapulothoracic kinematics that negatively affect glenohumeral motion.[9] Some authors have suggested that medial winging of the scapula may even contribute to glenohumeral instability.[9,13,17,23,24] With medial winging of the scapula, the scapula internally rotates, opening the face of the glenoid, which may result in increased anterior translation of the humeral head.[9,24] In throwing athletes, scapular winging often results in significant functional impairment.[4,9,16,19] Given that an extreme range of motion is required to throw competitively, the slightest disturbance in shoulder mechanics may be amplified as the arm is abducted and maximally externally rotated in the late cocking and early acceleration phases of the throwing motion.[1,4,18] To address these effects, several biomechanical studies have investigated the effect of scapular position on glenohumeral stability.[8,10,17,22-24] Unfortunately, these investigations have yielded contradictory findings and have fundamental limitations. In all of the cadaveric models,[8,10,24] the position of the scapula was rigidly fixed whereas the humerus was manipulated by use of a custom device. This model eliminates scapulothoracic motion and does not replicate the complex shoulder motions observed during throwing. In comparison, in vivo studies have allowed for analysis of both glenohumeral and scapulothoracic motion over a full range of motion.[17,22,23] However, the accuracy of motion analysis is limited by the use of superficial skin markers. This technique introduces substantial error, because the skin markers experience considerable motion relative to the underlying bony landmarks.[21] Alternatively, advanced imaging techniques are used for kinematic analysis.[22] However, these techniques cannot register dynamic motions continuously, resulting in an incomplete description of the motion examined. To overcome these limitations, we created an automated, programmable, 7-axis robotic systemcapable of re-creating normal and complex passive shoulder motions in cadaveric torsos with a high degree of reproducibility.[7] Glenohumeral and scapulothoracic kinematics are captured by use of bone-embedded marker clusters tracked by high-speed cameras. As a cadaveric model, this technique does not benefit from the dynamic stability provided by the rotator cuff; however, this might be negligible in internal and external rotation when the arm is held in 90° of abduction.[2] Thus, by limiting the analysis to the late cocking and early throwing phases of the throwing motion, the ligamentous stability of the glenohumeral joint may provide a reliable construct for our investigation. Using this approach, we hypothesize that scapular winging (an increase in internal scapular rotation) will lead to an increase in anterior glenohumeral translation during late cocking and early acceleration. To that end, we aim to test whether scapular winging results in a significant change in glenohumeral translation in the initial phase of the throwing motion.

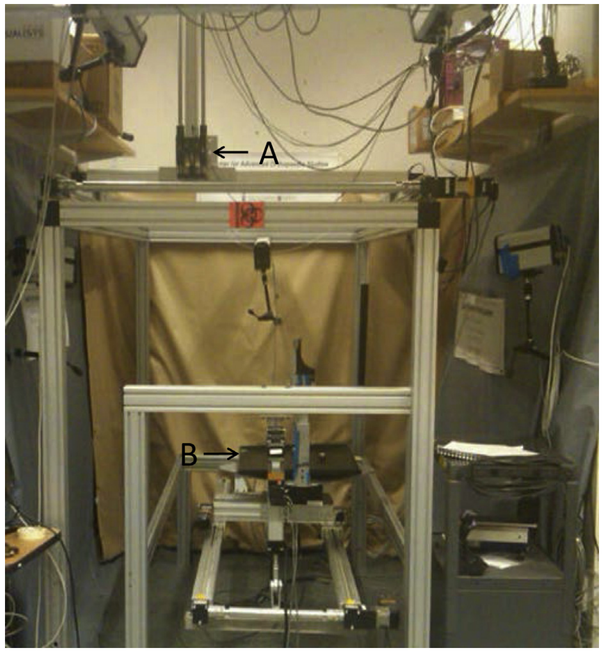

Figure 1 Testing setup with a lower (smaller) frame and an upper (larger) frame. The actuator (**A**) of the upper frame can move along the x-, y-, and z-axes, whereas the lower frame (**B**) can move along the x-, y-, and z-axes and rotate around the y-axis.

Materials and methods

Testing apparatus

A validated robotic system was used for this study[7] (Fig. 1). The system consists of a lower (torso) frame and an upper (hand) frame to re-create complex linear and rotational motion paths along 7 axes. The torso frame can move along the x-, y-, and z-axes and rotate around the z-axis, whereas the hand frame can move along the x-, y-, and z-axes. The axes are moved by actuators and controlled by a programmable central controller to generate any motion trajectory within the actuators' limits with high reproducibility and accuracy. Limit and home switches are combined with encoders to create a closed-loop feedback system for each axis, ensuring safety and precision.

Cadaveric torsos

Three fresh-frozen human cadavers were acquired from Medcure Anatomical Tissue Bank (Orlando, FL, USA). The torsos were obtained from 3 white male cadavers with a mean age of 55 ± 4 years, height of 190 ± 4 cm, and body mass index of 27.1 ± 1.85 kg/m^2. Both shoulders from each cadaver were tested. Each torso was mounted on a rod fixture and held in place with expanding foam. The hand was disarticulated at the distal radioulnar joint, and the arm was secured directly to the hand frame with a Schanz pin inserted through the radius and ulna. The skin was removed, and passive retro-reflective marker clusters were placed in the humeral shaft, the posterolateral acromion, and the sternum. Before testing, the apparatus was calibrated by a validated protocol.[7]

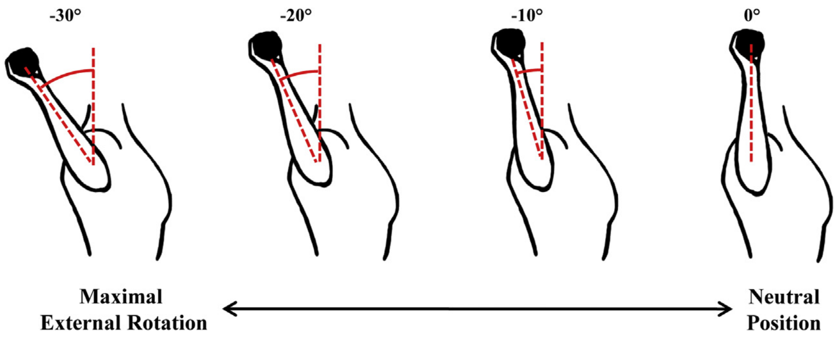

Figure 2 Distinct points and segments of abbreviated throwing motion. The distinct points were defined during the late cocking phase at −30° (maximal external rotation), −20°, −10°, and 0° (neutral position).

Figure 3 Torso mounted in test apparatus. The torso is connected to the hand actuator at the level of the wrist to simulate an abbreviated throwing motion. A posterior restraint (*arrow*) enables full external rotation at the beginning of the motion. Bone markers are used to track shoulder kinematics.

Simulation of throwing motion and scapular winging

Each shoulder was tested using an abbreviated throwing motion. This motion began at maximal external rotation with the arm abducted (late cocking) to 90° and concluded as the hand arrived at the mid coronal plane (90° of external rotation) (early acceleration) (Fig. 2). External rotation was achieved by placing a posterior restraint against the abducted humerus (Fig. 3).

During the investigation, each specimen served as its own internal control, and changes in the kinematics were recorded as a difference from the prior condition to control for hysteresis and other irreversible thermodynamic effects. All conditions were tested in triplicate, and the average data were analyzed.

The intact specimen was tested to establish a baseline. The position of the scapula was then affected to simulate scapular winging by placing a cylindrical wedge (height, 24 mm; diameter, 50 mm) under the inferior angle of the scapula (Fig. 4). The wedge was secured to the scapula with 2 screws placed through the inferior angle of the scapula to allow for unaffected scapulothoracic motion, and the abbreviated throwing motion was performed on the specimen again. To protect the cadaveric specimens, testing was performed at a reduced speed (duration of motion, 28.6 seconds).

Motion analysis

Five Qualisys ProReflex high-speed cameras (Qualisys AB, Gothenburg, Sweden) (120 Hz) were used to collect the motion of the passive retro-reflective, bone-embedded marker clusters.

Statistical analysis

Glenohumeral translations and scapular rotations were recorded continuously. For each condition, the average glenohumeral translation and scapular rotation were plotted over time to calculate the area under the curve, and the total translation during each motion segment was measured. The absolute glenohumeral translation, scapular rotation, and area under the curve were calculated at baseline and after scapular winging. A paired Student *t* test was used to compare the absolute scapular rotation, glenohumeral translation, and area under the curve in 3 repeated motions between baseline and scapular winging. Bonferroni correction was applied to scapular position to account for 4 different looks at the data (−30°, −20°, −10°, and 0°) in each dimension (x, y, and z). Calculations were performed with SPSS software (version 19; IBM/SPSS, Chicago, IL, USA). $P < .05$ was considered significant.

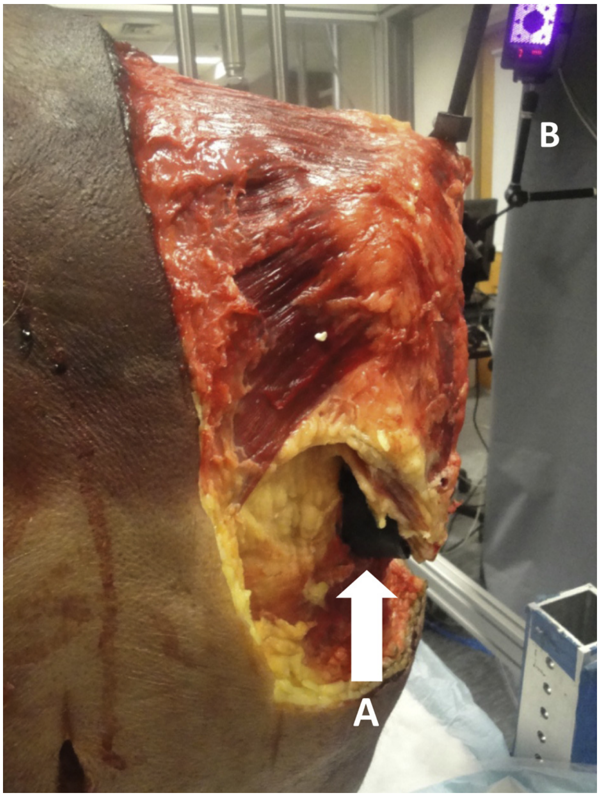

Figure 4 Implementation of scapular winging. A wedge (A) was placed underneath the inferior angle of the scapula and secured with 2 screws after gentle release of the rhomboids. A motion analysis camera (B) is visible in the setup.

Results

The position of the scapula at baseline and during scapular winging was compared at the start of the abbreviated throwing motion (maximal external rotation), −20°, −10°, and 0° (neutral position). Throughout the motion, the winged scapula showed, on average, 7.7° more upward rotation, 1.6° more internal rotation, and 5.3° more anterior tipping as compared with baseline (Table I).

The scapular position in X and Z coordinated relative to the hanging arm was significantly different between the baseline and scapular winging conditions (all $P < .004$), whereas Y rotation was not significantly different between baseline and scapular winging except for external rotation at −20° ($P = .04$) (Table I).

Scapular winging resulted in 1.8 mm (±0.2) of anterior translation in the glenohumeral joint between −30° and −10° of external rotation; however, from −10° to 0°, it translated 1.9 mm (±0.5) posteriorly compared with baseline (Fig. 5, *A*). Winging of the scapula resulted in 0.4 mm (±0.1) of superior translation of the glenohumeral joint (Fig. 5, *B*). Putting the scapula in the winging position led to 1.1 mm (±0.2) of lateral translation of the glenohumeral joint from −30° to −10° of external rotation, whereas between −10° and 0°, the glenohumeral joint translated 2.3 mm (±0.5) medially (Fig. 5, *C*).

The area under the curve of glenohumeral translation was used as a measure of average translation throughout the motion. Comparing the areas under the curve at baseline and with scapular winging indicated that scapular winging significantly increased anterior translation of the glenohumeral joint ($P = .03$), whereas it did not significantly change translations in the superior/inferior and medial/lateral directions (Table II).

Discussion

The aim of this study was to study the effect of scapular winging on glenohumeral translation in a cadaveric model during the initial phase of throwing. To test our hypothesis, we used a validated robotic system that allows for a highly reproducible simulation of an abbreviated throwing motion with unrestrained scapulothoracic motion. With winging of the scapula, there was a 1.9-mm increase in anterior glenohumeral translation between −30° and −10° of external rotation compared with baseline. At the same time, the winged scapulae showed a significant increase in internal rotation compared with the baseline condition.

These results support previous hypotheses describing scapular internal rotation—as observed with scapular winging—as a possible cause of anterior glenohumeral instability in throwers, which could put them at risk for increased shear stress and injury to the anterior capsulolabral structures.[9] Our findings may also highlight the importance of rehabilitation interventions in patients with scapular positioning abnormalities to treat or prevent glenohumeral instability.

On the other hand, our results also suggest that the capsuloligamentous complex was able to compensate for the implemented relative glenoid anteversion at some points of the throwing motion. At maximal external rotation and abduction, the inferior glenohumeral ligament (IGHL) is strained at its maximum.[11] It can therefore resist the anterior glenohumeral translation triggered by the changes in glenoid orientation. In the subsequent motion segment until neutral rotation, the IGHL becomes increasingly loose, giving way to the anterior shift of the humeral head within the glenohumeral joint. These considerations may also explain why the previous cadaveric study by Weiser et al[24] could not reproduce the association between an increase in scapular internal rotation and an increase in anterior glenohumeral instability. In their study, the increase in scapular internal rotation was much higher than that in our study (10° and 20°) and thus caused a significant increase in IGHL strain, preventing an increase in anterior glenohumeral translations. Yet, the degrees of scapular protraction simulated in this study definitively exceed the increase in scapular internal rotation that has been found in throwers with scapular positioning abnormalities.[20]

In vivo, dynamic stabilizers such as the rotator cuff and deltoid muscle become important once the anterior

Table I Scapular orientation at baseline and with scapular winging compared with hanging-arm position

Arm position (external rotation)	Condition	Posterior (+)/anterior (−) tipping (°)					Internal (+)/external (−) rotation (°)					Downward (+)/upward (−) rotation (°)				
		Mean	SD	SE	Δ	*P* value	Mean	SD	SE	Δ	*P* value	Mean	SD	SE	Δ	*P* value
−30°	BL	4.0	18.4	8.2	4.3	.008*	16.8	9.3	4.2	−1.5	.28	−23.5	11.9	5.3	8.2	.004*
	SW	−0.3	20.0	9.0			18.3	8.9	4.0			−31.7	9.4	4.2		
−20°	BL	3.5	18.3	8.2	5.0	.004*	18.5	9.3	4.1	−2.1	.04*	−22.1	12.6	5.6	7.7	.004*
	SW	−1.5	19.6	8.8			20.7	9.2	4.1			−29.8	10.1	4.5		
−10°	BL	3.2	18.1	8.1	5.3	.004*	23.5	9.7	4.4	−1.9	.08	−17.8	13.7	6.1	7.7	.004*
	SW	−2.1	19.6	8.8			25.4	9.6	4.3			−25.4	10.2	4.6		
0°	BL	3.4	17.6	7.9	6.4	.004*	31.1	11.3	5.1	−1.0	.76	−11.9	13.7	6.1	7.1	.004*
	SW	−3.1	19.0	8.5			32.1	11.0	4.9			−19.0	9.9	4.4		

BL, Baseline; *SE*, standard error; *SW*, scapular winging.
* Statistically significant.

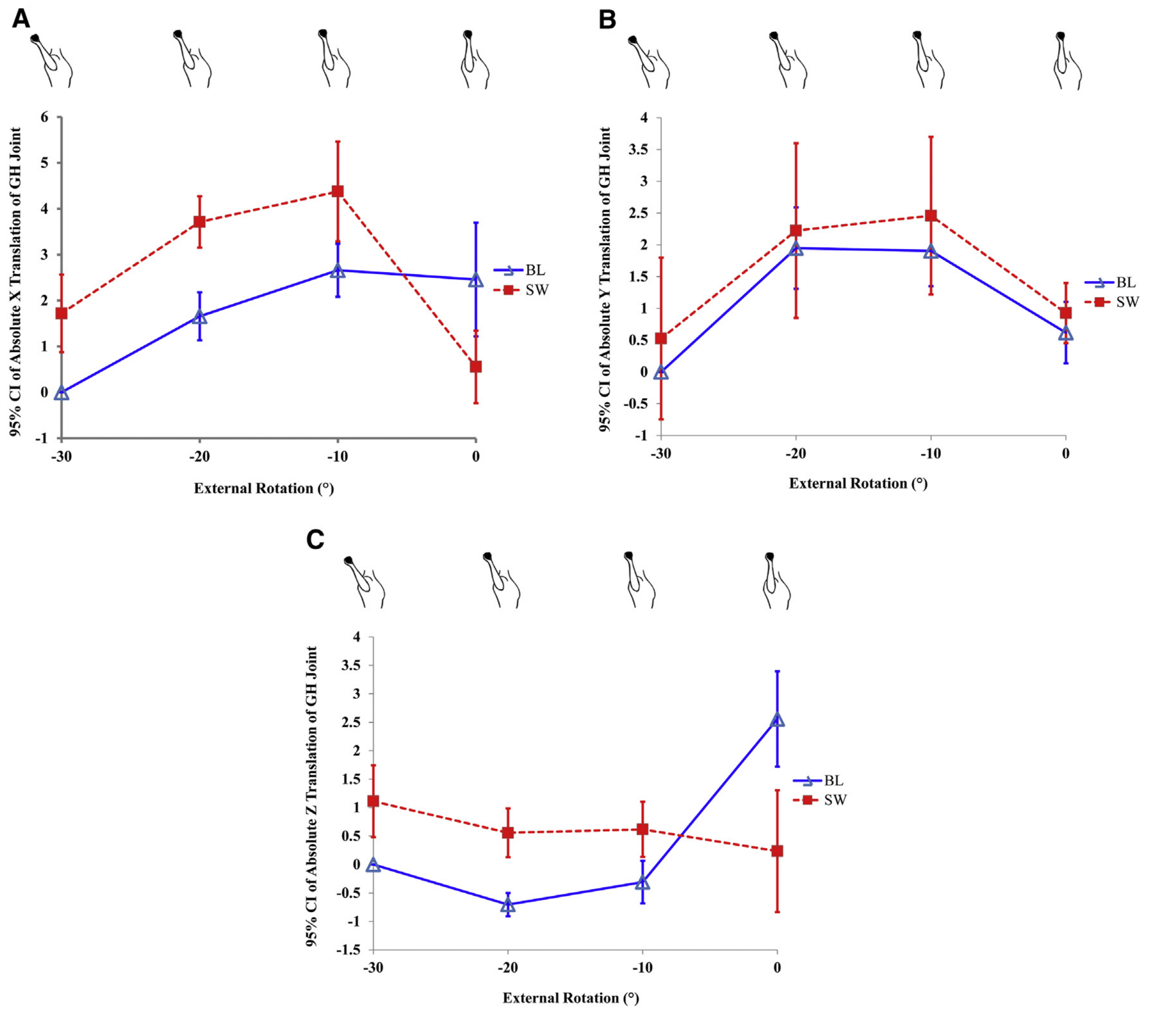

Figure 5 (**A**) Absolute glenohumeral (*GH*) translation in anterior direction (positive values) and posterior direction (negative values) was plotted over arm external rotation during the initial cocking phase of the throwing motion. (**B**) Absolute glenohumeral translation in the lateral direction (positive values) and medial direction (negative values) was plotted against arm external rotation. (**C**) Absolute glenohumeral translation in the superior direction (positive values) and inferior direction (negative values) was plotted against arm external rotation. *BL*, Baseline; *CI*, confidence interval; *SW*, scapular winging.

Table II Area under curve of glenohumeral translation at baseline and with scapular winging

Plane	Direction	Conditions	AUC of glenohumeral translation (mm)			*P* value
			Mean	SD	SE	
x	Anterior (+)/ posterior (−)	BL	29.8	18.7	8.3	.03*
		SW	54.1	34.2	15.3	
y	Lateral (+)/ medial (−)	BL	11.3	36.7	16.4	.52
		SW	20.9	64.5	28.9	
z	Superior (+)/ inferior (−)	BL	−5.1	7.2	3.2	.15
		SW	9.8	16.8	7.5	

AUC, Area under curve; *BL*, baseline; *SE*, standard error; *SW*, scapular winging.
* Statistically significant.

capsuloligamentous complex loosens. However, Boettcher et al[2] and Dark et al[5] showed that the moment arm of these muscles alters significantly with internal and external rotation. Future testing setups in which both scapulothoracic motion and the dynamic forces of the deltoid and rotator cuff are simulated may further elucidate whether active muscle forces can effectively compensate for glenohumeral translation patterns observed in this passive cadaveric model.

With our model of scapular winging, we achieved an increase in scapular lateral and internal rotation, as well as an increase in scapular flexion. In essence, this model not only corresponds to scapular winging observed with trapezius and rhomboid palsy but also replicates some aspects of scapular positioning abnormalities, which are effectively observed in throwers as compared with control subjects. As was shown by Thomas et al[19] and Myers et al,[16] throwers with internal rotation deficiencies and posterior capsule tightness also show an increase in upward (lateral) and internal rotation.

Our results should be interpreted in light of the limitations of the study. We used 6 shoulders from 3 cadavers in this study, which is a relatively small sample size. Despite the small sample size, we reported the absolute translation and area under the curve of glenohumeral translation relative to arm position and presented observed trends and statistically significant results. There was substantial variability between the left and right shoulders of a single cadaver, as well as the shoulders from different cadavers; this convinced us to compare each specimen with itself to assess the impact of scapular winging. Another possible source of variability is changes in tissue elasticity during the thawing process.

In our study, glenohumeral translations were calculated based on regression analysis of the instant center of rotation. The precision of this estimation for the glenohumeral center of rotation depends on the reliability of the anatomic landmark calibrations. In addition, there is an inherent variability associated with manual calibration of anatomic landmarks, because these landmarks are areas rather than discrete points.[6]

Finally, the use of a cadaveric model may implicate some additional, intrinsic limitations. The cadaveric shoulders may not fully represent tissue characteristics observed in real pitchers, whose shoulders may show variable degrees of anterior joint laxity.[15] In addition, the effect of scapular, deltoid, and rotator cuff muscle forces cannot be replicated in our passive model. However, they may be less relevant in extreme ranges of motion,[12] as tested in this study. In addition, the passive scapular motions observed in our study may not be substantially different from those documented in real pitchers in early phases of throwing.[14]

Conclusion

We have shown that from maximal external to neutral rotation in a throwing motion, a significant increase in scapular internal rotation, as observed with scapular winging, is associated with a significant increase in anterior glenohumeral translation. These results may suggest a more important role of abnormalities in scapular positioning in predisposing throwing athletes to shoulder injuries of the anterior capsulolabral structures and consecutive glenohumeral instability. Rehabilitation of scapular dysfunction may therefore be useful to prevent and treat glenohumeral instability in throwers.

Disclaimer

Arun J. Ramappa and Ara Nazarian report that they have received funding from the Medical Advisory Committee for Major League Baseball and the Department of Orthopaedic Surgery at Beth Israel Deaconess Medical Center for work related to the subject of this article.

Claudio Rosso and Andreas M. Mueller report that they have received funding from the Swiss National Science Foundation for work related to the subject of this article.

The other authors, their immediate families, and any research foundations with which they are affiliated have not received any financial payments or other benefits from any commercial entity related to the subject of this article.

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