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Greater Shoulder Elevation Variability During Arm Cocking Is Associated with Decreased Elbow Varus Torque in NCAA Division I Baseball Pitchers

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1. Introduction

Ulnar collateral ligament (UCL) injuries are the most common and significant injuries in baseball pitchers. UCL injury is strongly linked to peak elbow varus torque (pEVT), which represents the mechanical loading experienced at the medial elbow (Petty et al., 2004). Considerable effort has been devoted to identifying pitching mechanics that contribute to elbow loading, with a focus on peak shoulder external rotation (MER) and shoulder elevation (Slowik et al., 2019). Previous studies have emphasized the importance of maintaining approximately 90° of shoulder elevation during the pitching cycle, particularly around peak shoulder external rotation (MER) (Matsuo et al., 2002; Sabick et al., 2005). However, shoulder elevation has primarily been assessed using isolated measurements rather than continuous pitching motion, and it is considered that maintaining 90° during the pitching cycle is important (Matsuo et al., 2002; Sabick et al., 2005).

Discrete measures provide only single time-point representations of shoulder elevation and do not reflect how consistently the arm is maintained near the mechanically preferred 90° elevation throughout the pitching phase. As a result, they may fail to characterize the magnitude of deviation from this position across time, potentially limiting interpretation of its relationship with joint loading. This study introduced a biomechanical variable to characterize shoulder elevation. Shoulder elevation control was quantified as the root mean square (RMS) deviation from 90° relative to the trunk–upper arm angle during the arm-cocking phase. The primary objective was to examine the relationship between shoulder elevation RMS deviation pEVT.

2. Methods

Data were collected during NCAA Division I baseball games (2023-2025 seasons). Inclusion criteria were: (1) Only fastballs; (2) Trials without pose-tracking errors; (3) Pitchers with a minimum of 5 pitches; and (4) minimum speed threshold of 35.76 m/s (80mph). 362 pitchers met the criteria (91.12±10.14 kg; 1.88±0.06 m; ball velocity: 40.58±1.32 m/s). Procedures were approved by the Institutional Review Board of the University. Data were collected at 300 Hz using an 8-camera KinaTrax markerless motion-capture system. Data were processed from C3D files using Butterworth low-pass filters (trunk and pelvis: 10 Hz; legs: 6 Hz; arms: 20 Hz) following KinaTrax procedures. Variables were extracted during the arm-cocking phase (foot contact (FC) to MER) and included shoulder elevation and pEVT. Shoulder elevation was defined as the angle between the thorax and throwing upper arm (**Figure 1**), and RMS deviation was calculated as the square root of the mean squared deviation from 90° across time points.

A two-level linear mixed model was used to examine whether RMS deviation of shoulder elevation predicted pEVT, with pitches nested within pitchers. An unconditional model partitioned within- and between-pitcher

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variance, followed by random intercept models estimating both between- and within-pitcher effects utilizing fixed (Model 1) and random slopes (Model 2) to account for individual differences. Analyses were conducted in R, with significance set at $p<.05$.

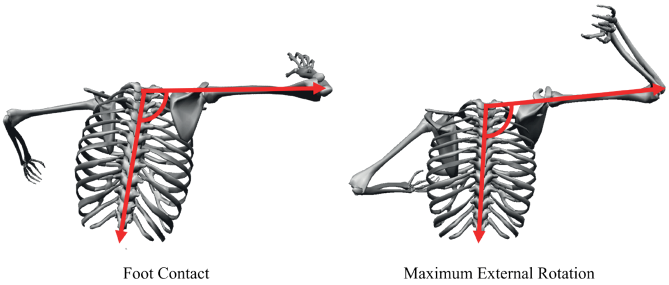

Figure 1. Shoulder Elevation Angle at FC and MER.

3. Results and discussion

Model comparison revealed Model 2 ($\chi^2(2)=381.02$, $p<.001$) showed superior fit. While Model 2 revealed an insignificant within-pitcher effect, the between-pitcher effect indicated that a 1° increase in RMS deviation led to a .3 N.m decrease in pEVT. Fixed and random effects are in Table 1. Pitchers with higher shoulder elevation RMS deviation during the arm-cocking phase exhibited lower average pEVT, suggesting that the variable reflects differences in mechanical loading rather than a discrete positional effect. Although the estimated change in pEVT per 1° increase in RMS deviation appears small (≈0.3 N·m), it should be interpreted in the context of how RMS deviation is defined. RMS deviation summarizes the magnitude of deviation from 90° across all frames of the arm-cocking phase rather than reflecting a single time-point. Accordingly, the practical relevance may be more apparent when considering realistic between-pitcher differences (e.g., several degrees of RMS deviation), which scales to larger N·m differences in pEVT. Given that EVT is associated with pitching intensity and ball velocity (Slowik et al., 2019), these differences may represent meaningful variation in mechanical loading. A measurement-related limitation should be noted. The KinaTrax system has demonstrated reliability in human movement analyses (Schoenwether et al., 2025), but direct validation against marker-based motion capture has not been established for high-velocity throwing.

Table 1. Effects from Random Slopes and Intercepts Model (Model 2).

Parameters	Est	SE	95%	*df*	*t*	*p*
Fixed effects						
Intercept	125.09	1.47	[122.4, 128.17]	219.43	84.87	0.00
RMS (degree)(BS)	-0.30	0.14	[-0.67, 0.02]	176.77	-2.19	0.03
RMS (degree)(WS)	-0.11	0.29	[-0.81, 0.2]	219.16	-0.37	0.71
Random effects						
Intercept variance (level 2: person)	464.34					
RMS (degree)(WS)	1.43					
Residual variance Fixed effects	67.55					

RMS: Root Mean Square of deviation of shoulder elevation from 90° from FC to BR; Est. = estimate; SE = standard error; BS = between-subject; WS = within-subject.

4. Conclusions

This study employed shoulder elevation RMS deviation during arm-cocking as a continuous indicator of shoulder control in competitive pitching. Using in-game markerless motion capture from NCAA Division I pitchers, greater deviation from approximately 90° between FC and MER was associated with lower pEVT. These findings suggest that shoulder elevation RMS deviation was not associated with pEVT at the within-pitcher level. Although a near 90° angle is commonly regarded as biomechanically advantageous, the observed association with pEVT was small, indicating only a modest influence on elbow loading. Shoulder elevation patterns may instead affect pEVT indirectly via pitch velocity, which was not measured in this study. Accordingly, RMS deviation in shoulder elevation appears to be a limited standalone metric, warranting further investigation into its relationship with pitch velocity.

Conflict of Interest Statement

The authors have no conflicts of interest to disclose.

Contributor Roles

GO: Validation, supervision, writing review, editing; KJC: Conceptualization, methodology, analysis, review; IJ: writing, review, editing; RZ: writing, review, editing; KRC: writing, review, editing.

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