Kinematic and Kinetic Comparisons of Arm Slot Position Between High School and Professional Pitchers

Joseph E. Manzi,* MD, Joseph J. Ruzbarsky,† MD, Spencer Krichevsky,‡ MS, Suleiman Y. Sudah,§ MD, Jennifer Estrada,‖ MS, Zhaorui Wang,* BS, Jay Moran,¶ BS, Kyle N. Kunze,‖ MD, Michael C. Ciccotti,# MD, Frank R. Chen,** MD, and Joshua S. Dines,‖†† MD

Investigation performed at the Hospital for Special Surgery, New York, New York, USA

Background: Throwing arm kinetics differ in pitchers at varying arm slot (AS) positions (frontal-plane arm position at ball release relative to the vertical axis).

Purpose: To determine how kinematic and kinetic values differ between professional and high school pitchers with varying AS positions, and whether these differences are similarly observed in both populations.

Methods: High school (n = 130) and professional (n = 288) pitchers threw 8 to 12 fastballs under 3-dimensional motion capture technology. Pitchers in each cohort were subdivided based on mean AS position at ball release: AS_1 (least degree of AS: most overhand throwing styles), AS_2 (intermediate degree of AS: three-quarter throwing styles), or AS_3 (greatest degree of AS: most sidearm throwing styles). Kinetic and kinematic parameters were compared between groups.

Study Design: Controlled laboratory study.

Results: High school pitchers had a more overhand AS at ball release (50° ± 11°) compared with professional pitchers (58° ± 14°) ($P <$ .001). In both cohorts, AS_1 pitchers had significantly greater shoulder abduction (high school, $P <0.001$; professional, $P <0.0001$) and lateral trunk flexion (high school, $P < 0.001$; professional, $P <0.0001$) at ball release compared with AS_3 pitchers. Professional pitchers with an AS_3 position had significantly delayed timing of maximum upper trunk angular velocity compared with AS_1 pitchers (64% ± 7% vs 57% ± 7% of pitch time, respectively; $P < .0001$). A significant positive correlation between AS and elbow flexion torque was found in high school pitchers ($P = .002$; $\beta = 0.28$), and a significant negative correlation between AS and elbow varus torque ($P < .001$; $\beta = -0.22$) and shoulder internal rotation torque ($P < .001$; $\beta = -0.20$) was noted in professional pitchers.

Conclusion: AS position was related to shoulder abduction and trunk lateral tilt. Professional and high school pitchers with varying AS positions did not experience similar changes in throwing arm kinetics.

Clinical Relevance: In professional pitchers, the earlier onset of maximum upper trunk angular velocity with overhand throwing style may reflect inappropriate pelvis-trunk timing separation, a parameter implicated in upper extremity injury, and the negative correlation between AS and elbow varus and shoulder internal rotation torque suggests that both excessive and minimal AS positions have negative implications.

Keywords: arm slot; elbow flexion torque; elbow varus torque; motion capture

Upper extremity injuries, especially those affecting the shoulder and elbow, are among the most common injuries in baseball pitchers at all levels.[12,45] The incidence of shoulder and elbow injury in high school, collegiate, and professional pitchers has increased sharply in recent years.[10,11,37] Approximately 10% of Major League Baseball pitchers have undergone ulnar collateral ligament (UCL) reconstruction, a procedure that keeps these pitchers sidelined for some time following surgery.[19,47] It remains a high priority for all stakeholders to reduce the incidence of these injuries by identifying risk factors.

Pitchers have unique delivery styles, with arm slot (AS) position as a variable that can differ among pitchers.[22] The AS angle is composed of a combination of trunk lateral tilt, shoulder abduction, and elbow flexion (Figure 1). Before 2018, AS was estimated using either qualitative assessment of video or lateral trunk flexion as a proxy.[22] However, there are inconsistencies in the literature with respect to the effect that lateral trunk flexion has on pitching kinetics, making lateral trunk flexion unreliable as a proxy measurement for AS.[2,38] To account for this unreliability, Escamilla et al[22] differentiated pitchers by

The Orthopaedic Journal of Sports Medicine, 11(10), 23259671221147874
DOI: 10.1177/23259671221147874

Figure 1. Arm slot angle demonstrated in the coronal plane.

throwing style (sidearm [greatest degree of AS], overhand [least degree of AS], or three-quarter [between sidearm and overhead]) and conducted a biomechanical evaluation of pitchers based on this feature.

Escamilla et al[22] reported that AS was correlated with significant differences in throwing arm kinematics among professional pitchers. AS was also correlated with significant differences in throwing arm kinetics. Near the instant of ball release, maximum elbow flexion torque was significantly greater in the three-quarter and sidearm groups than in the overhand group. Near the instant of maximum shoulder external rotation, maximum shoulder anterior force was significantly greater in the three-quarter group than in the sidearm group.

While significant differences were noted by Escamilla et al,[22] the applicability of these findings to different pitching populations is unclear. Ramappa et al[41] reported that shoulder anterior force was significantly higher for professional compared with youth pitchers, even after normalization by body weight (BW). Key differences in patterns of segmental motion have also been established between professional and high school pitchers.[32] These include the timing of maximum pelvic rotation velocity, maximum trunk rotation, and maximum shoulder internal rotation velocity, all of which act to optimize the kinetic chain.[3] In addition, high school pitchers do not demonstrate the same shoulder and elbow joint characteristics that are found typically in professional and collegiate pitchers, such as UCL thickening and ulnohumeral joint space laxity, differences that may be chronologic, adaptive, or pathologic.[33] As pitchers age and continue to fine-tune their delivery styles, structural and kinematic adaptations likely ensue. Therefore, combining these cohorts together for biomechanical evaluation is likely an inappropriate methodology.[17]

Oyama et al[38] investigated the biomechanics of high school pitchers based on lateral trunk flexion and found that excessive lateral trunk flexion was associated with increased joint loading (elbow proximal force, shoulder proximal force, elbow varus torque, and shoulder internal rotation torque). While lateral trunk flexion has been utilized as a proxy for AS positioning, AS has yet to be directly measured in this population. Therefore, the purpose of this study was to determine how professional and high school pitchers' kinematic and kinetic values differ based on varying AS positions and whether these differences are similarly observed in both pitching populations. It was hypothesized that elbow flexion torque would be highest in pitchers with greatest AS angle (ie, a more sidearm pitching style), for both high school and professional playing levels. We also hypothesized that professional pitchers would have a decreased AS angle (ie, a more overhand throwing style) at ball release compared with high school pitchers, given that a meta-analysis has shown adult pitchers as having greater shoulder abduction at ball release compared with youth pitchers.[49]

[††]Address correspondence to Joshua S. Dines, MD, Hospital for Special Surgery, HSS Sports Medicine Institute West Side, 610 West 58th Street, New York, NY 10019, USA (email: jdinesmd@gmail.com).

[*]Weill Cornell Medicine, New York, New York, USA.

[†]Steadman-Philippon Research Institute, Vail and Aspen, Colorado, USA.

[‡]Stony Brook University, Department of Biomedical Informatics, Stony Brook, New York, USA.

[§]Department of Orthopaedic Surgery, Monmouth Medical Center, Monmouth, New Jersey, USA.

[‖]Sports Medicine Institute, Hospital for Special Surgery, New York, New York, USA.

[¶]Yale School of Medicine, New Haven, Connecticut, USA.

[#]Rothman Orthopaedic Institute, Philadelphia, Pennsylvania, USA.

[**]Anesthesia Department, Hospital of the University of Pennsylvania, Philadelphia, Pennsylvania, USA.

Final revision submitted September 28, 2022; accepted October 21, 2022.

One or more of the authors has declared the following potential conflict of interest or source of funding: J.J.R. has received hospitality payments from Smith & Nephew. M.C.C. has received education payments from Liberty Surgical. J.S.D. has received education payments from Gotham Surgical; consulting fees from Arthrex, Merck Sharp & Dohme, and Trice Medical; nonconsulting fees from Arthrex; and royalties from Arthrex and Linvatec. AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.

Ethical approval for this study was obtained from the Hospital for Special Surgery (ref No. 2020-1957).

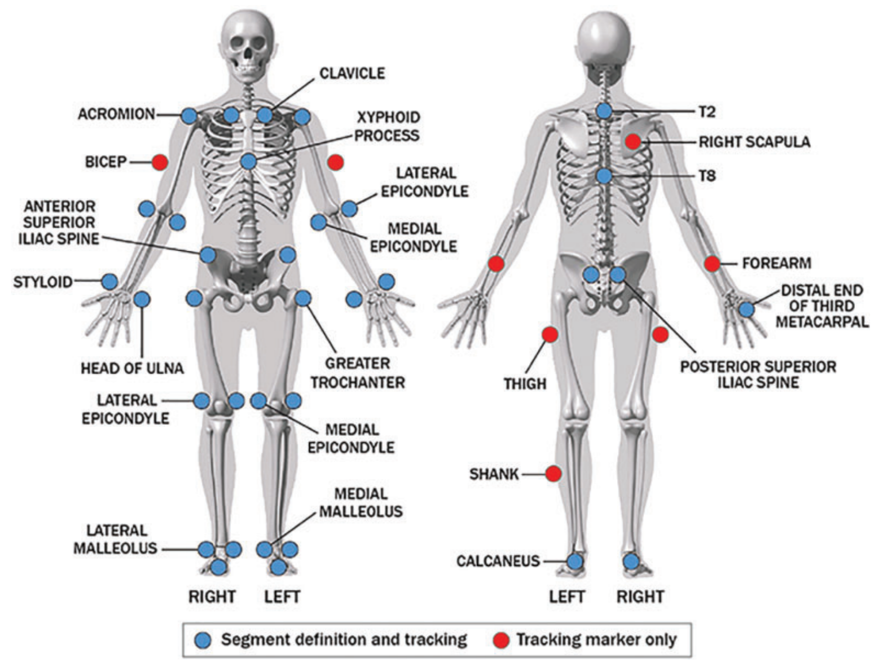

Figure 2. Marker setup used in the pitching evaluation.

METHODS

This was a retrospective analysis of prospectively collected pitching data on pitchers from the high school and professional levels. The study protocol received institutional review board approval. Professional pitchers were included if they were currently on a Major League or Minor League (low A, high A, AA, and AAA team) roster and they had not had a severe injury (requiring >2 weeks rest or rehabilitation) within the past 6 months. High school pitchers were included if they were currently on a high school or club baseball team, had not had a severe injury (requiring >2 weeks rest or rehabilitation) within the past 6 months, and had been cleared to participate in baseball activities by their primary care provider. Before participation, all participants agreed to a privacy waiver and provided written informed consent. For underage pitchers, the parent/guardian signed the waiver and pitchers gave assent.

All pitchers were tested during either spring training or fall instructional league by Motus Global, and all data were deidentified before distribution. Pitching evaluations were conducted according to previously published methodology.[29] Demographic data reported by each pitcher included age, preferred throwing arm, experience, and injury history. Body height (BH) and BW were measured and recorded by the investigators for each pitcher. The pitcher was given unlimited time to warm up with his preferred routine to pitch at maximal effort. Once the pitcher indicated he was ready, 42 reflective markers were placed on standard anatomical landmarks to create a full body model (Figure 2). Position coordinate data of the reflective markers were collected with a motion capture system using an 8-camera system (Motion Analysis Corp) at 480 Hz. The global coordinate system was set up based on International Society of Biomechanics standards: Y was vertically upward, X was from the pitching rubber toward home plate perpendicular to Y, and Z was the cross-product of X and Y.

Pitchers were instructed to deliver 8 to 12 fastballs with gamelike effort from a dirt mound to a catcher behind home plate using regulation distance (18.4 m). The pitchers were allowed to pitch from the wind-up or stretch, as previous research has shown no difference in mechanics exist between the 2 types.[18] They were instructed to aim at the center of the strike zone. Ball velocity was collected with a radar gun positioned behind the pitcher (Stalker Sports Radar).

All data processing to build full-body kinematics and throwing arm kinetics was performed in MATLAB scripts (The MathWorks) as previously described.[29] Marker data were low-pass filtered (fourth order, zero lag Butterworth filter, cutoff frequency of 13.4 Hz).[18,29] The pitching motion was divided into 6 phases as described by Escamilla et al[22]: wind-up (initial movement to maximum knee height), stride (maximum knee height to foot contact), arm cocking (foot contact to maximum shoulder external rotation), arm acceleration (maximum shoulder external rotation to ball release), arm deceleration (ball release to maximum internal rotation), and follow-through (maximum internal rotation to end of motion).

Foot contact was defined as the first frame when either the toe or heel marker reached the vertical minimum within the global coordinate system. Maximum external rotation was defined as the frame when the throwing arm reached maximum external rotation. Ball release was estimated as the instant 0.01 seconds after the throwing wrist passed the elbow in the forward direction.[21] To establish a standardized pitch time, the pitch was calculated as a percentage of the pitch motion, where foot contact represented time 0% and ball release represented time 100%. Peak segment and joint velocities were calculated by taking the first and second derivative of the trunk and pelvis center of mass and orientation using the 5-point central differences approximations.[30] AS was calculated as the angle between a vertical vector and a vector connecting the throwing shoulder joint center to the hand, when viewed from home plate in a global reference frame (Figure 1). Trunk flexion was defined as the angle between the pelvis and upper trunk in the coronal plane, where 0° was when the upper trunk was parallel to pelvis line, a positive value indicated flexion toward the glove arm, and a negative value denoted tilt toward the throwing arm. Lateral trunk flexion was calculated from the pelvis and the upper trunk line in the coronal plane, in which lateral trunk flexion increased as the pitcher's trunk moved toward the glove hand. The horizontal adduction of the shoulder was defined as the angle between the upper throwing arm and the upper trunk vector in the transverse plane of the upper trunk, so that a negative value was considered abduction and positive was adduction. Joint forces were normalized to the pitcher's BW, and joint torques were normalized to the product of the pitcher's BH and BW.[15]

Kinematic and kinetic variables included elbow flexion, shoulder external rotation, shoulder abduction, knee flexion, stride length, stride width, foot rotation, forearm pronation, and trunk flexion at the point of the lead foot's contact; maximum elbow flexion, shoulder horizontal adduction, maximum shoulder external rotation, and forearm pronation at the point of maximum shoulder external rotation; ball velocity, elbow flexion, AS, shoulder abduction, trunk flexion, lateral trunk flexion, knee flexion, and forearm pronation at ball release; maximum pelvic angular velocity, time of maximum pelvic angular velocity, maximum upper trunk angular velocity, and time of maximum upper trunk angular velocity during the arm-cocking phase; angular velocity at maximum elbow extension, time of maximum elbow extension's angular velocity, angular velocity at maximum shoulder internal rotation, and time of maximum shoulder internal rotation's angular velocity during the arm acceleration phase; and peak values for elbow varus torque, shoulder horizontal adduction torque, shoulder internal rotation torque, shoulder anterior force, elbow flexion torque, elbow proximal force, and shoulder proximal force.

Data Collection

Separate analyses were conducted for high school and professional pitchers accordingly. Each individual pitch was treated as an independent event, and kinematic variables were aggregated across each pitcher's series of pitches. Pitchers threw a mean of 11 pitches per session. Median values were derived for aggregated kinematic (29 variables) and kinetic (7 variables) data for every pitcher to reduce noise and minimize bias favoring pitchers who threw a greater number of pitches. Professional and high school pitchers were then each stratified into pitching style groups: AS_1 (least degree of AS; most overhand throwing styles), AS_2 (intermediate degree of AS; three-quarter throwing styles), or AS_3 (greatest degree of AS; most sidearm throwing styles). Whereas Escamilla et al[22] used AS values associated with sidearm, three-quarter, and overhead pitching styles, we used a method of stratification based on the mean AS (±0.5 SD) for each cohort:

$$AS_1 : \leq Mean(AS) - 0.5 * SD(AS)$$
$$AS_2 : > Mean(AS) - 0.5 * SD(AS) \text{ and} < Mean(AS) + 0.5 * SD(AS)$$
$$AS_3 : > Mean(AS) + 0.5 * SD(AS)$$

We believed that a more natural distribution of the pitchers' AS angles would be demonstrated with this method. Furthermore, using a threshold of 0.5 from the cohort mean has been conducted previously in baseball-pitching biomechanical evaluations.[16,34]

Statistical Analysis

An analysis of variance (ANOVA) was applied to kinetic and kinematic data to examine whether there were any differences between the overhand (AS_1), three-quarter (AS_2), or sidearm (AS_3) groups. A Tukey test was applied as a post-ANOVA analysis to further examine differences between pitching style groups and to identify which specific groups were in fact different.

Kinetic variables identified as statistically significant ($P < .01$) or approaching statistical significance ($P < .05$) via ANOVA evaluation, or previously identified as a kinetic of interest with AS,[22] were then maintained as independent variables in a regression analysis. A linear regression model was constructed with AS at ball release as the outcome of interest. A P value of $<.01$ was used to define statistical significance. Data manipulation and analyses were performed in 64-bit R statistical computing software (Version 3.6.0; The R Foundation).

RESULTS

This study included 130 high school and 288 professional baseball pitchers. The number of high school pitchers in each group and the intragroup mean ASs were as follows: AS_1 (n = 35), 37.1° ± 7.4°; AS_2 (n = 61), 49.7° ± 2.9°; and AS_3 (n = 34), 63.2° ± 6.6°. Similarly, the number of professional pitchers in each group and the intragroup mean ASs were as follows: AS_1 (n = 80), 43.7° ± 6.5°; AS_2 (n = 142), 57.9° ± 4.1°; and AS_3 (n = 66), 75.0° ± 14.6°.

Professional pitchers were older (21.9 ± 2.1 vs 16.3 ± 1.2 years; $P < .001$), heavier (94.7 ± 9.6 vs 74.4 ± 12.0 kg; $P < .001$), taller (189.7 ± 5.8 vs 180.0 ± 7.7 cm; $P < .001$), and had faster ball velocity (38.1 ± 4.1 vs 31.4 ± 3.2 m/s; $P < .001$) compared with high school pitchers. High school pitchers had a more overhand AS at ball release compared with professional pitchers (50° ± 11° vs 58° ± 14°; $P < .001$).

High School Pitchers

Descriptive statistics for demographic, kinetic, and kinematic variables collected from high school pitchers are presented in Table 1. High school pitchers grouped by AS did not differ significantly from one another by height ($P_{minimum}$ [P_{min}] =

TABLE 1
Demographic, Kinematic, and Kinetic Values Among High School Pitchers by AS Group[a]

	AS_1 (n = 35)	AS_2 (n = 61)	AS_3 (n = 34)	P^b
Demographics				
Mass, kg	75.8 ± 13.1	75.3 ± 12.4	70.6 ± 11.0	(a) .980, (b) .186, (c) .176
Height, m	1.8 ± 0.1	1.8 ± 0.1	1.8 ± 0.1	(a) .995, (b) .995, (c) .995
At lead foot contact				
Elbow flexion, deg	100 ± 21	102 ± 17	91 ± 24	(a) .886, (b) .155, (c) .031
Shoulder external rotation, deg	44 ± 25	40 ± 28	48 ± 29	(a) .772, (b) .818, (c) .367
Shoulder abduction, deg	85 ± 12	85 ± 15	88 ± 13	(a) .995, (b) .637, (c) .566
Knee flexion, deg	45 ± 8	46 ± 9	44 ± 10	(a) .860, (b) .890, (c) .556
Stride length, % height	76 ± 9	76 ± 5	75 ± 5	(a) .995, (b) .789, (c) .741
Stride width	0.2 ± 0.2	0.2 ± 0.1	0.2 ± 0.1	(a) .995, (b) .995, (c) .995
Foot rotation, deg	9 ± 17	13 ± 17	18 ± 14	(a) .480, (b) .060, (c) .326
Forearm pronation, deg	103 ± 40	108 ± 22	103 ± 25	(a) .689, (b) .995, (c) .694
Trunk flexion, deg	2 ± 9	–6 ± 11	–10 ± 9	(a) **<.001**, (b) **<.0001**, (c) .152
At max shoulder external rotation				
Max elbow flexion, deg	90 ± 14	90 ± 11	88 ± 11	(a) .995, (b) .764, (c) .712
Shoulder horizontal adduction, deg	10 ± 9	11 ± 9	13 ± 10	(a) .867, (b) .374, (c) .573
Max shoulder external rotation, deg	159 ± 13	159 ± 11	166 ± 12	(a) .995, (b) .040, (c) .018
Forearm pronation, deg	92 ± 33	99 ± 11	92 ± 14	(a) .228, (b) .995, (c) .234
At ball release				
Ball velocity, m/s	31.0 ± 2.9	31.5 ± 3.1	31.2 ± 2.6	(a) .700, (b) .966, (c) .881
Elbow flexion, deg	32 ± 10	33 ± 8	33 ± 7	(a) .839, (b) .873, (c) .995
AS, deg	37 ± 7	50 ± 3	63 ± 7	(a) **<.0001**, (b) **<.0001**, (c) **<.0001**
Shoulder abduction, deg	95 ± 9	91 ± 9	87 ± 8	(a) .083, (b) **<.001**, (c) .087
Trunk flexion, deg	5 ± 10	11 ± 12	13 ± 10	(a) .030, (b) **.008**, (c) .673
Lateral trunk flexion, deg	34 ± 9	28 ± 7	26 ± 7	(a) **<.001**, (b) **<.001**, (c) .437
Knee flexion, deg	46 ± 13	43 ± 13	40 ± 13	(a) .523, (b) .138, (c) .530
Forearm pronation, deg	90 ± 36	95 ± 15	90 ± 13	(a) .542, (b) .995, (c) .548
At arm-cocking phase				
Max pelvic angular velocity, deg/s	557.7 ± 79.1	660.4 ± 90.1	673.5 ± 94.1	(a) **<.0001**, (b) **<.0001**, (c) .768
Time of max pelvic angular velocity, % pitch time[c]	45.5 ± 15.8	42.1 ± 12.0	42.5 ± 9.4	(a) .411, (b) .584, (c) .988
Max upper trunk angular velocity, deg/s	653.0 ± 251.1	545.9 ± 164.7	581.2 ± 133.1	(a) .020, (b) .245, (c) .647
Time of max upper trunk angular velocity, % pitch time[c]	53.8 ± 7.5	55.5 ± 10.8	59.0 ± 7.2	(a) .656, (b) .051, (c) .178
At arm-acceleration phase				
Max elbow extension angular velocity, deg/s	2171.6 ± 279.4	2137.6 ± 280.3	2068.1 ± 256.8	(a) .829, (b) .264, (c) .465
Time of max elbow extension angular velocity, % pitch time[c]	91.6 ± 4.1	91.5 ± 3.8	90.9 ± 2.8	(a) .991, (b) .707, (c) .724
Max shoulder internal rotation angular velocity, deg/s	5883.5 ± 1546.8	5633.4 ± 1155.3	5474.4 ± 979.0	(a) .606, (b) .356, (c) .819
Time of max shoulder internal rotation angular velocity, % pitch time[c]	100.7 ± 3.4	101.4 ± 3.5	100.8 ± 2.4	(a) .563, (b) .991, (c) .660
Peak kinetics				
Max elbow varus torque, %BW × BH	3.8 ± 0.9	4.0 ± 0.8	4.0 ± 0.7	(a) .471, (b) .558, (c) .995
Max shoulder horizontal adduction torque, %BW × BH	4.6 ± 1.0	4.4 ± 1.1	4.7 ± 1.1	(a) .656, (b) .921, (c) .395
Max shoulder internal rotation torque, %BW × BH	4.0 ± 0.6	4.1 ± 0.8	4.1 ± 0.7	(a) .793, (b) .835, (c) .995
Max shoulder anterior force, %BW	34.8 ± 6.6	34.3 ± 6.3	34.8 ± 6.3	(a) .928, (b) .995, (c) .929
Max elbow flexion torque, %BW × BH	2.7 ± 0.9	3.0 ± 0.5	3.2 ± 0.5	(a) .069, (b) **.003**, (c) .305
Max elbow proximal force, %BW	79.3 ± 16.0	86.2 ± 13.9	86.0 ± 13.7	(a) .066, (b) .135, (c) .995
Max shoulder proximal force, %BW	81.6 ± 17.7	86.2 ± 14.3	88.8 ± 14.8	(a) .340, (b) .132, (c) .711

[a]Values are presented as mean ± SD. Boldface values indicate statistically significant difference ($P < .01$). AS, arm slot; AS_1, least degree of AS (most overhand styles); AS_2, intermediate degree of AS (three-quarters style); AS_3, greatest degree of AS (most sidearm styles); BH, body height; BW, body weight; max, maximum.
[b]*P* values for differences between (a) AS_1 and AS_2, (b) AS_1 and AS_3, and (c) AS_2 and AS_3.
[c]Where foot contact is 0% and ball release is 100%.

.995), mass (P_{min} = .176), or ball velocity (P_{min} = .700). The AS_3 pitchers had significantly less trunk flexion at foot contact compared with AS_1 (–10° ± 9° vs 2° ± 9°; $P < .0001$). At ball release, AS_1 pitchers had significantly greater shoulder abduction (95° ± 9° vs 87° ± 8°; $P < .001$) and lateral trunk flexion (34° ± 9° vs 26° ± 7°; $P < .001$) compared with AS_3

pitchers. Maximum pelvic angular velocity was significantly less for AS_1 compared with AS_2 and AS_3 (558 ± 79 vs 660 ± 90 deg/s and 674 ± 94 deg/s; $P < .0001$ for both). Maximum elbow flexion torque was significantly lower for AS_1 compared with AS_3 (2.7% ± 0.9% vs 3.2% ± 0.5% BW × BH; $P = .003$).

Professional Pitchers

Descriptive statistics for demographic, kinetic, and kinematic variables collected from professional pitchers are presented in Table 2. Professional pitchers grouped by AS did not differ significantly among one another by height ($P_{min} = .995$), mass ($P_{min} = .435$), or ball velocity ($P_{min} = .062$). At foot contact, AS_1 pitchers had significantly greater knee flexion than AS_3 pitchers (49° ± 7° vs 44° ± 9°; $P < .001$). AS_3 pitchers had significantly higher shoulder horizontal adduction at maximum shoulder external rotation versus AS_1 (11° ± 7° vs 7° ± 9°; $P = 0.009$) and AS_2 (11° ± 7° vs 7° ± 8°; $P = .003$). Elbow flexion at ball release was significantly higher for AS_3 than for AS_1 (34.9° ± 5.6° vs 29.6° ± 5.9°; $P < .0001$) or AS_2 (34.9° ± 5.6° vs 31.6° ± 5.3°; $P < .001$). At ball release, AS_1 had significantly greater shoulder abduction, decreased trunk flexion, and increased lateral trunk flexion compared with AS_3 ($P < .0001$ for all). AS_1 achieved faster maximum shoulder internal rotation angular velocity compared with AS_3 (6149 ± 1153 vs 5456 ± 990 deg/s; $P < .001$). Professional pitchers in the AS_3 group had a significant delay in the timing of their maximum upper trunk angular velocity compared with pitchers in the AS_1 group (64% ± 7% vs 57% ± 7% pitch time; $P < .0001$).

Linear Regression Analysis

Results from the linear regression analysis in the high school pitchers are shown in Table 3. A significant positive correlation was detected between AS and elbow flexion torque ($P = .002$). No other peak kinetics had a significant relationship with AS for high school pitchers, including shoulder anterior force ($P = .245$). For every 10° increase in AS in high school pitchers, elbow flexion torque increased by 0.2% BW × BH (B = 0.02, β = 0.28; $P = .002$).

Results from the linear regression analysis in the professional pitchers are shown in Table 4. A significant negative correlation between AS and elbow varus torque ($P < .001$) as well as shoulder internal rotation torque ($P < .001$) was noted for professional pitchers. For every 10° increase in AS for professional pitchers (increasing sidearm throwing style), elbow varus torque (B = –0.01; β = –0.22; $P < .001$) and shoulder internal rotation torque (B = –0.01; β = –0.20; $P < .001$) decreased by 0.1% BW × BH.

DISCUSSION

The following findings were noted in this study: (1) pitching with more sidearm slot was weakly to moderately positively correlated with elbow flexion torque for high school pitchers, while weakly to moderately negatively correlated with elbow varus torque and shoulder internal rotation torque for professional pitchers; (2) with more sidearm slot, professional and high school pitchers demonstrated consistent change in shoulder abduction and lateral trunk flexion parameters; and (3) professional pitchers with the overhand AS at ball release had earlier onset of maximum upper trunk angular velocity.

Sidearm slot showed a positive correlation with elbow flexion torque in high school pitchers, which neared significance for professional pitchers ($P = .064$), a finding previously corroborated in professional pitichers.[22] Elbow flexion torque has been implicated in injury, specifically as a risk factor for superior labrum anterior-posterior (SLAP) tears of the glenohumeral joint as well as bicep tendinopathy, due to the role the biceps brachii plays in generating this torque.[25] The muscular contraction required to generate elbow flexion torque may induce strain upon the biceps tendon-labrum complex.[9]

High school pitchers, in particular, demonstrated the highest standardized regression coefficient association between elbow flexion torque and AS ($P = .002$; β = 0.28). Targeting this group may be most appropriate given that (1) these novice pitchers are likely most amenable to change pitching mechanics, as they continue to learn and refine their skills; and (2) this may have the greatest long-term impact if a pitcher anticipates continuing a career for a longer span of time. Future studies evaluating direct injury incidence and throwing AS style are likely more appropriate and warranted. Interestingly, Albright et al[4] did note a higher incidence and severity of elbow pain in collegiate and Little League pitchers when pitching with a sidearm throwing style.

Regression analysis for professional pitchers showed a significant negative correlation between AS and shoulder internal rotation torque as well as elbow varus torque, a finding not observed for the high school cohort. These distinctions may be attributed to the significantly different AS between the 2 cohorts, with professional pitchers on average achieving a more sidearm slot style, as well as additional differences in pitching styles that have been demonstrated between playing levels.[26] Even more, Ramappa et al[41] have shown that youth pitchers have significantly less shoulder anterior force compared with professional pitchers, even after normalization by BW. As a result, playing level may act as a confounder in determining the influence of specific kinematics as predictors for kinetics, yet again demonstrating the importance in evaluating distinct playing levels as separate cohorts with biomechanical evaluation. For professionals, a trade-off may be observed with varying shoulder and elbow kinetics of the throwing arm at both extremes of the AS spectrum (ie, overhand and sidearm pitching styles). Given that ball velocity did not differ between groups, adopting a moderate or “in-between” AS position may be most appropriate in minimizing throwing arm kinetics. This in-between position has previously been characterized as a “three-quarters throwing style.”

Given that shoulder internal rotation torque has been implicated in SLAP tears and elbow varus torque has been correlated directly with elbow injury,[6,43] minimizing these kinetic values may prove a theoretical benefit to professional pitchers. The long head of the biceps serves to halt

TABLE 2
Demographic, Kinematic, and Kinetic Values in Professional Pitchers by AS Group[a]

	AS_1 (n = 80)	AS_2 (n = 142)	AS_3 (n = 66)	P^b
Demographics				
Mass, kg	94.1 ± 9.2	95.8 ± 9.8	95.1 ± 10.7	(a) .435, (b) .815, (c) .883
Height, m	1.9 ± 0.05	1.9 ± 0.06	1.9 ± 0.06	(a) .995, (b) .995, (c) .995
At lead foot contact				
Elbow flexion, deg	101 ± 15	95 ± 17	93 ± 19	(a) .032, (b) .014, (c) .709
Shoulder external rotation, deg	31 ± 27	32 ± 24	27 ± 25	(a) .956, (b) .604, (c) .377
Shoulder abduction, deg	85 ± 12	84 ± 11	82 ± 10	(a) .795, (b) .235, (c) .448
Knee flexion, deg	49 ± 7	46 ± 8	44 ± 9	(a) .021, (b) **<.001**, (c) .215
Stride length, % height	76 ± 9	76 ± 5	75 ± 5	(a) .995, (b) .613, (c) .544
Stride width	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	(a) .995, (b) .995, (c) .995
Foot rotation, deg	16 ± 12	16 ± 15	17 ± 13	(a) .995, (b) .900, (c) .878
Forearm pronation, deg	26 ± 27	25 ± 25	28 ± 23	(a) .957, (b) .882, (c) .703
Trunk flexion, deg	–3 ± 11	–8 ± 10	–17 ± 14	(a) **.005**, (b) **<.0001**, (c) **<.0001**
At max external rotation				
Elbow flexion, deg	90 ± 11	89 ± 10	89 ± 9	(a) .758, (b) .822, (c) .995
Shoulder horizontal adduction, deg	7 ± 9	7 ± 8	11 ± 7	(a) .995, (b) **.009**, (c) **.003**
Max external rotation, deg	165 ± 9	164 ± 10	168 ± 10	(a) .743, (b) .154, (c) .017
Forearm pronation, deg	13 ± 11	8 ± 12	9 ± 12	(a) **.007**, (b) .102, (c) .935
At ball release				
Ball velocity, m/s	38 ± 2	39 ± 4	38 ± 2	(a) .062, (b) .995, (c) .086
Elbow flexion, deg	30 ± 6	32 ± 5	35 ± 6	(a) .028, (b) **<.0001**, (c) **<.001**
AS, deg	44 ± 7	58 ± 4	75 ± 15	(a) **<.0001**, (b) **<.0001**, (c) **<.0001**
Shoulder abduction, deg	95 ± 7	91 ± 7	84 ± 9	(a) **<.001**, (b) **<.0001**, (c) **<.0001**
Trunk flexion, deg	7 ± 11	10 ± 11	15 ± 12	(a) .138, (b) **<.0001**, (c) **.009**
Lateral trunk flexion, deg	34 ± 8	30 ± 9	24 ± 11	(a) **.006**, (b) **<.0001**, (c) **<.0001**
Knee flexion, deg	39 ± 16	33 ± 15	34 ± 17	(a) .019, (b) .138, (c) .905
Forearm pronation, deg	7 ± 13	2 ± 14	4 ± 15	(a) .030, (b) .401, (c) .603
At arm-cocking phase				
Max pelvic angular velocity, deg/s	621.7 ± 83.3	657.4 ± 89.4	717.0 ± 91.5	(a) .012, (b) **<.0001**, (c) **<.0001**
Time of max pelvic angular velocity, % pitch time[c]	36.1 ± 13.6	35.7 ± 12.0	38.6 ± 8.0	(a) .968, (b) .405, (c) .222
Max upper trunk angular velocity, deg/s	741.6 ± 221.0	761.1 ± 182.0	711.1 ± 228.1	(a) .775, (b) .643, (c) .231
Time of max upper trunk angular velocity, % pitch time[c]	56.5 ± 7.1	60.0 ± 8.0	63.9 ± 7.4	(a) **.003**, (b) **<.0001**, (c) **.002**
At arm-acceleration phase				
Max elbow extension angular velocity, deg/s	2402.5 ± 269.1	2326.1 ± 276.7	2191.3 ± 289.2	(a) .122, (b) **<.0001**, (c) **.004**
Time of max elbow extension angular velocity, % pitch time[c]	89.8 ± 2.0	89.7 ± 1.7	89.2 ± 2.3	(a) .928, (b) .151, (c) .195
Max shoulder internal rotation angular velocity, deg/s	6149.4 ± 1152.8	5822.4 ± 1089.1	5455.5 ± 989.8	(a) .081, (b) **<.001**, (c) .062
Time of max shoulder internal rotation angular velocity, % pitch time[c]	99.1 ± 1.6	99.1 ± 1.6	98.8 ± 1.9	(a) .995, (b) .528, (c) .453
Peak kinetics				
Max elbow varus torque, %BW × BH	5.1 ± 0.9	4.9 ± 0.8	4.8 ± 0.7	(a) .182, (b) .067, (c) .685
Max shoulder horizontal adduction torque, %BW × BH	5.6 ± 1.0	5.6 ± 1.0	5.6 ± 0.9	(a) .995, (b) .995, (c) .995
Max shoulder internal rotation torque, %BW × BH	5.2 ± 0.8	4.9 ± 0.7	4.9 ± 0.7	(a) .010, (b) .037, (c) .995
Max shoulder anterior force, %BW	42.4 ± 8.0	41.9 ± 7.5	42.1 ± 6.9	(a) .883, (b) .969, (c) .982
Max elbow flexion torque, %BW × BH	3.8 ± 0.6	4.0 ± 0.6	4.1 ± 0.5	(a) .037, (b) **.006**, (c) .479
Max elbow proximal force, %BW	112.1 ± 13.6	115.8 ± 16.1	112.4 ± 16.9	(a) .211, (b) .992, (c) .313
Max shoulder proximal force, %BW	113.9 ± 13.6	117.1 ± 16.3	114.2 ± 17.2	(a) .319, (b) .992, (c) .437

[a]Values are presented as mean ± SD. Boldface values indicate statistically significant difference ($P < .01$). AS, arm slot; AS_1, least degree of AS (most overhand styles); AS_2, intermediate degree of AS (three-quarters style); AS_3, greatest degree of AS (most sidearm styles); BH, body height; BW, body weight; max, maximum.
[b]*P* values for differences between (a) AS_1 and AS_2, (b) AS_1 and AS_3, and (c) AS_2 and AS_3.
[c]Where foot contact is 0% and ball release is 100%.

the rapidly extending elbow during the deceleration phase of the pitch, transmitting a sufficient portion of this force to the origin of the long head of the biceps tendon, generating notable traction on the superior labrum.[25] Pathology of the bicep–labral complex can eventually follow with sufficient repetition.[5,36,40] More relevant to this study, during the late

TABLE 3
Univariate Linear Regression Findings for AS in High School Pitchers[a]

	Regression Coefficient (95% CI)	Standardized Regression Coefficient	*P*
Elbow flexion torque	0.02 (0.01 to 0.03)	0.28	**.002**
Elbow varus torque	0.00 (–0.01 to –0.01)	0.00	.999
Shoulder internal rotation torque	0.00 (–0.02 to 0.01)	–0.06	.535
Shoulder anterior force	0.06 (–0.04 to 0.16)	0.10	.245

[a]Boldface *P* value indicates statistical significance ($P < .01$). AS, arm slot.

TABLE 4
Univariate Linear Regression Findings for AS in Professional Pitchers[a]

	Regression Coefficient (95% CI)	Standardized Regression Coefficient	*P*
Elbow flexion torque	0.00 (0.00 to 0.00)	0.11	.064
Elbow varus torque	–0.01 (–0.02 to –0.01)	–0.22	**<.001**
Shoulder internal rotation torque	–0.01 (–0.02 to –0.01)	–0.20	**<.001**
Shoulder anterior force	–0.06 (–0.12 to 0.00)	–0.11	.062

[a]Boldface *P* values indicate statistical significance ($P < .01$). AS, arm slot.

cocking phase when maximal external rotation is achieved, the long head of the biceps attains an unfavorable position that places torsional strain on its origin at the glenoid, objectified by the shoulder internal rotation torque values that were calculated in this study. This torsional force pulls the bicep tendon and posterior labrum off the glenoid rim that can progressively worsen with sufficient repetition.[9] Additional investigation analyzing AS and the incidence of such injuries of the shoulder labrum would be of interest in future studies.

AS is intrinsically related to motions of the trunk and shoulder abduction, with this study noting consistent changes in pitcher trunk and shoulder with varying degrees of AS for both cohorts.[35,38,46] With more sidearm slot at ball release, shoulder adduction increases while lateral trunk flexion decreases. With more of an overhand AS throwing style, shoulder abduction increases while lateral trunk flexion increases. Matsuo et al[35] noted that shoulder abduction and lateral trunk flexion independently could not predict elbow varus torque; however, these kinematic values together could predict elbow varus torque in computer simulation models. Therefore, suggestions of independent changes in kinematic variables are likely unwise. Instead, pitchers can adjust their AS angle while concurrently altering parameters of the trunk and shoulder to maintain proper balance and form.

Professional pitchers who achieved more of an overhand throwing style had significantly earlier onset of maximum upper trunk angular velocity ($AS_1 = 57\%$ vs $AS_3 = 64\%$ pitch; $P < 0.0001$). A similar trend was noted for high school pitchers, though statistical significance was not achieved ($P = .051$). This may be rooted in the fact that younger, more novice pitchers demonstrate less pelvis-trunk rotation than their older, elite counterparts.[1,27] Alternatively, high school pitchers who demonstrate this attribute may be self-selected for later success. Aguinaldo et al[1] demonstrated that professional pitchers in comparison with collegiate, high school, and youth pitchers significantly delayed the onset of trunk rotation, a finding the authors suggested as a mechanism by which to allow the throwing shoulder to move with decreased joint loading by conserving the momentum generated by the trunk. Oyama et al[39] also noted that high school pitchers who had proper sequence of maximum pelvic and trunk angular velocity (ie, those with proper pelvis-trunk separation) also had decreased shoulder proximal force and decreased shoulder external rotation angle compared with those with improper sequence. Though the strength of the associations was small to moderate, the results of our study suggest that minimization of shoulder internal rotation torque and elbow varus torque may be acquired with more sidearm slot positions, a proposed mechanism of which may be delayed onset of upper trunk rotational velocities. With a sidearm pitching style, there may be a delayed motion of the cocked arm relative to the trunk. In doing so, conservation of kinetic energy generated from the pelvis-trunk separation is impeded, which may prevent pitchers from achieving proper pitching form,[13] greater ball velocity,[44] and minimized kinetics,[29] and instead increase their risk of throwing arm injury requiring surgery.[14]

Ultimately, it may be useful for professional pitchers to achieve a more sidearm slot pitching style to prevent the trunk from rotating prematurely and preventing compensation at the level of the throwing arm to generate equivalent ball velocities. However, given that pitchers with the most sidearm style (AS_3) also had the highest elbow flexion torque, an ideal position may lie at a moderate-high AS position (60°-70°). This also may explain why professional pitchers' mean AS was significantly higher than high schoolers, and was closer to this moderate-high AS range ($58° \pm 14°$ vs $50° \pm 11°$, respectively; $P < .001$), a finding that may potentially delineate a key factor in aiding pitchers in transitioning to higher levels of play. Even so, AS is composed of a combination of shoulder abduction, elbow flexion, and trunk lateral tilt. Simply suggesting a change in AS is not specific enough and warrants further specific recommendation.

Previous evaluations of AS have noted mixed results. The current study's findings agreed with those of Escamilla et al,[22] who found that professional pitchers with sidearm slot had the greatest elbow flexion torque and least elbow flexion at foot contact. They also noted that trunk lateral flexion, forward trunk flexion, and shoulder abduction were greatest at ball release for the overhand group, similar to the current study. Conversely, Escamilla et al[22] also noted decreased shoulder anterior force and greater foot rotation for the overhand AS group, which was not observed in our results. Aguinaldo and Chambers[2] noted higher elbow varus torque in adult pitchers with a sidearm throwing style, the exact opposite of the correlation we observed. These differences can be attributed to study design, where Escamilla et al[22] arbitrarily picked AS angle cutoffs for pitch classifications, rather than our method of classification based off mean and standard deviation. Aguinaldo and Chambers[2] also observed a small cohort of adult pitchers not differentiated by skill level with only 14 pitchers in the sidearm cohort. Both studies also evaluated pitchers at a lower frame capture rate than this study (240 Hz in both studies).

Strengths and Limitations

The strengths of the current study include the use of a higher frame capture rate relative to previous motion capture studies (480 Hz vs 240 Hz) along with the use of 8 motion-capture cameras. This study has a robust sample size of professional and high school pitchers and delineates and compares appropriately between these 2 distinct playing levels. Relative to previous AS studies, this study is the first to conduct regression analysis, making use of all pitches during calculations.

There are several limitations and areas for further investigation for this study. One limitation is the lower number of high school pitchers included compared with professional pitchers (130 vs 288, respectively). Given the different-sized study groups, we were unable to determine whether biomechanical parameters were truly statistically insignificant for high schoolers or due to a lack of statistical power. Another limitation is that whereas there were statistically significant differences across the 3 different AS positions, the clinical significance of these differences is unclear, with kinetics only acting as a surrogate for ligamentous tensile loads rather than direct measurements. The role of other noted risk factors for injury should also be considered in addition to AS angle (ie, ball velocity,[28] pitcher fatigue,[20] number of pitches thrown per inning per game per season) as contributors to pitchers' risk of throwing arm injury.[23,24,31,37,48,50] The data set utilized did not encompass range-of-motion parameters, and this is a shortcoming of the study. Previous evaluations have noted relationships between physical examinations' range-of-motion parameters with shoulder stiffness[7] and glenohumeral translation,[8] as well as parameters of pitching mechanics and ball velocity.[42] While significant relationships were established between AS and specific throwing arm kinetics in both cohorts, these relationships were, at best, of small-to-moderate strength; and thus, the clinical applicability of these findings is likely limited.

CONCLUSION

AS is intrinsically related to shoulder abduction and trunk lateral tilt positions. Professional and high school pitchers with varying AS positions do not experience changes in throwing arm kinetics equally. An increasing sidearm throwing style was correlated positively with elbow flexion torque for high school pitchers and negatively with elbow varus torque and shoulder internal rotation torque for professional pitchers. In addition, professional pitchers with an overhand throwing AS had earlier onset of maximum upper trunk rotational angular velocity, a parameter that may reflect inappropriate pelvis-trunk separation timing. AS impact on decreased shoulder and elbow injury rates should be explored in future evaluations. Finally, while utilizing cohort-specific metrics of central tendency to delineate AS cohorts for the playing levels of interest distinctly, this methodology may render comparisons between different playing levels inappropriately.

REFERENCES

1. Aguinaldo AL, Buttermore J, Chambers H. Effects of upper trunk rotation on shoulder joint torque among baseball pitchers of various levels. *J Appl Biomech*. 2007;23(1):42-51.
2. Aguinaldo AL, Chambers H. Correlation of throwing mechanics with elbow valgus load in adult baseball pitchers. *Am J Sports Med*. 2009;37(10):2043-2048.
3. Aguinaldo A, Escamilla R. Segmental power analysis of sequential body motion and elbow valgus loading during baseball pitching: comparison between professional and high school baseball players. *Orthop J Sports Med*. 2019;7(2):2325967119827924.
4. Albright JA, Jokl P, Shaw R, Albright JP. Clinical study of baseball pitchers: correlation of injury to the throwing arm with method of delivery. *Am J Sports Med*. 1978;6(1):15-21.
5. Andrews JR, Carson WG, Mcleod WD. Glenoid labrum tears related to the long head of the biceps. *Am J Sports Med*. 1985;13(5):337-341.
6. Anz AW, Bushnell BD, Griffin LP, Noonan TJ, Torry MR, Hawkins RJ. Correlation of torque and elbow injury in professional baseball pitchers. *Am J Sports Med*. 2010;38(7):1368-1374.
7. Borsa PA, Dover GC, Wilk KE, Reinold MM. Glenohumeral range of motion and stiffness in professional baseball pitchers. *Med Sci Sports Exerc*. 2006;38(1):21-26. doi:10.1249/01.MSS.0000180890.69932.15
8. Borsa PA, Wilk KE, Jacobson JA, et al. Correlation of range of motion and glenohumeral translation in professional baseball pitchers. *Am J Sports Med*. 2005;33(9):1392-1399.
9. Burkhart SS, Morgan CD. The peel-back mechanism: its role in producing and extending posterior type II SLAP lesions and its effect on SLAP repair rehabilitation. *Arthroscopy*. 1998;14(6):637-640.
10. Camp CL, Conte S, D'Angelo J, Fealy SA. Epidemiology of ulnar collateral ligament reconstruction in Major and Minor League Baseball pitchers: comprehensive report of 1429 cases. *J Shoulder Elbow Surg*. 2018;27(5):871-878.
11. Chalmers PN, Erickson BJ, D'Angelo J, Ma K, Romeo AA. Epidemiology of shoulder surgery among professional baseball players. *Am J Sports Med*. 2019;47(5):1068-1073.
12. Chalmers PN, Wimmer MA, Verma NN, et al. The relationship between pitching mechanics and injury: a review of current concepts. *Sports Health*. 2017;9(3):216-221.

13. Davis JT, Limpisvasti O, Fluhme D, et al. The effect of pitching biomechanics on the upper extremity in youth and adolescent baseball pitchers. *Am J Sports Med*. 2009;37(8):1484-1491.
14. Douoguih WA, Dolce DL, Lincoln AE. Early cocking phase mechanics and upper extremity surgery risk in starting professional baseball pitchers. *Orthop J Sports Med*. 2015;3(4):2325967115581594.
15. Dowling B, Laughlin WA, Gurchiek RD, et al. Kinematic and kinetic comparison between American and Japanese collegiate pitchers. *J Sci Med Sport*. 2020;23(12):1202-1207.
16. Dowling B, Manzi JE, Raab G, Coladonato C, Dines JS, Fleisig GS. The relationship among lead knee extension, fastball velocity and elbow torque in professional baseball pitchers. Published online March 17, 2022. *Sports Biomech*. doi:10.1080/14763141.2022.2050801
17. Dun S, Fleisig GS, Loftice J, Kingsley D, Andrews JR. The relationship between age and baseball pitching kinematics in professional baseball pitchers. *J Biomech*. 2007;40(2):265-270.
18. Dunn S, Kingsley D, Fleisig GS, Loftice J, Andrews JR. Biomechanical comparison of the fastball from wind-up and the fastball from stretch in professional baseball pitchers. *Am J Sports Med*. 2008;36(1):137-141.
19. Erickson BJ, Gupta AK, Harris JD, et al. Rate of return to pitching and performance after Tommy John surgery in Major League Baseball pitchers. *Am J Sports Med*. 2014;42(3):536-543.
20. Erickson BJ, Sgori T, Chalmers PN, et al. The impact of fatigue on baseball pitching mechanics in adolescent male pitchers. *Arthroscopy*. 2016;32(5):762-771.
21. Escamilla RF, Fleisig GS, Barrentine SW, Zheng N, Andrews JR. Kinematic comparisons of throwing different types of baseball pitches. *J Appl Biomech*.1998;14(1):1-23.
22. Escamilla RF, Slowik JS, Diffendaffer AZ, Fleisig GS. Differences among overhand, 3-quarter, and sidearm pitching biomechanics in professional baseball players. *J Appl Biomech*. 2018;34(5):377-385.
23. Feeley BT, Schisel J, Agel J. Pitch counts in youth baseball and softball: a historical review. *Clin J Sports Med*. 2018;28(4):401-405.
24. Fleisig GS, Andrews JR, Cutter GR, et al. Risk of serious injury for young baseball pitchers: a 10-year prospective study. *Am J Sports Med*. 2011;39(2):253-257.
25. Fleisig GS, Andrews JR, Dillman CJ, Escamilla RF. Kinetics of baseball pitching with implications about injury mechanisms. *Am J Sports Med*. 1995;23(2):233-239.
26. Fleisig G, Chu Y, Weber A, Andrews J. Variability in baseball pitching biomechanics among various levels of competition. *Sports Biomech*. 2009;8(1):10-21.
27. Fleisig GS, Diffendaffer AZ, Ivey B, et al. Changes in youth baseball pitching biomechanics: a 7-year longitudinal study. *Am J Sports Med*. 2018;46(1):44-51.
28. Keller RA, Marshall NE, Guest JM, Okoroha KR, Jung EK, Moutzouros V. Major League Baseball pitch velocity and pitch type associated with risk of ulnar collateral ligament injury. *J Shoulder Elbow Surg*. 2016;25(4):671-675.
29. Luera MJ, Dowling B, Magrini MA, Muddle TWD, Colquhoun RJ, Jenkins NDM. Role of rotational kinematics in minimizing elbow varus torques for professional versus high school pitchers. *Orthop J Sports Med*. 2018;6(3):2325967118760780.
30. Luera MJ, Dowling B, Muddle TWD, Jenkins NDM. Differences in rotational kinetics and kinematics for professional baseball pitchers with higher versus lower pitch velocities. *J Appl Biomech*. 2020;36(2):68-75.
31. Lyman S, Fleisig GS, Andrews JR, Osinski ED. Effect of pitch type, pitch count, and pitching mechanics on risk of elbow and shoulder pain in youth baseball pitchers. *Am J Sports Med*. 2002;30(4):463-468.
32. Manzi JE, Dowling B, Wang Z, et al. Association of pitch timing and throwing arm kinetics in high school and professional pitchers. *Am J Sports Med*. 2021;49(12):3386-3394. doi:10.1177/03635465211031853
33. Marshall NE, Keller RA, van Holsbeeck M, Moutzouros V. Ulnar collateral liga adaptations in high school baseball pitchers. *Sports Health*. 2015;7(6):484-488.
34. Matsuo T, Escamilla RF, Fleisig GS, Barrentine SW, Andrews JR. Comparison of kinematic and temporal parameters between different pitch velocity groups. *J Appl Biomech*. 2001;17(1):1-13. doi:10.1123/jab.17.1.1
35. Matsuo T, Fleisig GS, Zheng N, Andrews JR. Influence of shoulder abduction and lateral trunk tilt on peak elbow varus torque for college baseball pitchers during simulated pitching. *J Appl Biomech*. 2006;22(2):93-102.
36. Mileski RA, Snyder SJ. Superior labral lesions in the shoulder: pathoanatomy and surgical management. *J Am Acad Orthop Surg*. 1998;6(2):121-131.
37. Olsen SJ, Fleisig GS, Dun S, Loftice J, Andrews JR. Risk factors for shoulder and elbow injuries in adolescent baseball pitchers. *Am J Sports Med*. 2006;34(6):905-912.
38. Oyama S, Yu B, Blackburn JT, Padua DA, Li L, Myers JB. Effect of excessive contralateral trunk tilt on pitching biomechanics and performance in high school baseball pitchers. *Am J Sports Med*. 2013;41(10):2430-2438.
39. Oyama S, Yu B, Blackburn JT, Padua DA, Li L, Myers JB. Improper trunk rotation sequence is associated with increased maximal shoulder external rotation angle and shoulder joint force in high school baseball pitchers. *Am J Sports Med*. 2014;42(9):2089-2094.
40. Park S, Loebenberg M, Rokito A, Zuckerman J. The shoulder in baseball pitching: biomechanics and related injuries—-part 1. *Bull Hosp Jt Dis*. 2003;61(1):68-79.
41. Ramappa AJ, Chen PH, Hawkins RJ, et al. Anterior shoulder forces in professional and little league pitchers. *J Pediatr Orthop*. 2010;30(1):1-7.
42. Robb AJ, Fleisig G, Wilk K, MacRina L, Bolt B, Pajaczkowski J. Passive ranges of motion of the hips and their relationship with pitching biomechanics and ball velocity in professional baseball pitchers. *Am J Sports Med*. 2010;38(12):2487-2493. doi:10.1177/0363546510375535
43. Sabick MB, Torry MR, Kim YK, Hawkins RJ. Humeral torque in professional baseball pitchers. *Am J Sports Med*. 2004;32(4):892-898.
44. Sgroi T, Chalmers PN, Riff AJ, et al. Predictors of throwing velocity in youth and adolescent pitchers. *J Shoulder Elbow Surg*. 2015;24(9):1339-1345.
45. Smucny M, Kolmodin J, Saluan P. Shoulder and elbow injuries in the adolescent athlete. *Sports Med Arthrosc Rev*. 2016;24(4):188-194.
46. Solomito MJ, Garibay EJ, Woods JR, Õunpuu S, Nissen CW. Lateral trunk lean in pitchers affects both ball velocity and upper extremity joint moments. *Am J Sports Med*. 2015;43(5):1235-1240.
47. Vitale MA, Ahmad CS. The outcome of elbow ulnar collateral ligament reconstruction in overhead athletes: a systematic review. *Am J Sports Med*. 2008;36(6):1193-1205.
48. Whiteside D, Martini DN, Lepley AS, Zernicke RF, Goulet GC. Predictors of ulnar collateral ligament reconstruction in major league baseball pitchers. *Am J Sports Med*. 2016;44(9):2202-2209.
49. Wicke J, Keeley DW, Oliver GD. Comparison of pitching kinematics between youth and adult baseball pitchers: a meta-analytic approach. *Sports Biomech*. 2013;12(4):315-323. doi:10.1080/14763141.2013.838692
50. Zaremski JL, Zeppieri G, Jones DL, et al. Unaccounted workload factor: game-day pitch counts in high school baseball pitchers—-an observational study. *Orthop J Sports Med*. 2018;6(4):2325967118765255.