Epidemiologic Comparison of Pitching Mechanics, Pitch Type, and Pitch Counts Among Healthy Pitchers at Various Levels of Youth Competition

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Purpose: To determine differences among healthy pitchers at various levels of competition regarding pitching history, pitching mechanics, and prevalence of breaking pitches. **Methods:** Demographic, anthropometric, pitching history, and kinematic data were collected on healthy youth pitchers using dual orthogonal high-speed video analysis. Players were grouped by maturity level (9 to 12 [prepubescent], 13 to 15 [pubescent], 16 to 17 [mature], and 18 to 22 years [adult]). Groups were compared regarding pitch counts, pitching mechanics, and use of breaking pitches. Mechanics were assessed for favorable observational parameters (e.g., closed foot orientation at foot-strike) and measurable parameters at cocking, foot-strike, and ball release (e.g., knee flexion). **Results:** Two hundred ninety-five pitchers were included. Sixty-three were 9 to 12, 130 were 13 to 15, 78 were 16 to 17, and 24 were 18 to 22 years of age. Older pitchers threw more pitches per game (41, 52, 69, and 50 by age group; $P < .001$), per season (766, 975, 1,079, and 881; $P = .017$), and per year (901, 1,343, 2,064, and 1,302; $P < .001$). They were more likely to pitch for multiple teams, for more than 9 months, in showcases, and in violation of pitch count recommendations. Older pitchers were more likely to maintain their hand on top of the ball, maintain closed shoulders at foot-strike, achieve hip and shoulder separation, and lead with their hips. Older pitchers achieved greater relative stride-length, greater knee flexion at front-foot contact, and increased lead hip flexion at ball release. Pitchers began throwing curveballs and sliders at 12.6 and 13.5 years, respectively. **Conclusions:** As pitchers age, they throw more pitches per game, per season, and per year and are more likely than younger pitchers to violate pitch count recommendations. Older pitchers tend to pitch with improved mechanics and velocity. The proportion of pitchers throwing breaking pitches increases with age, with the greatest increase occurring between ages 12 and 13. **Level of Evidence:** Level II, cross-sectional study.

See commentary on page 1569

The incidence of serious shoulder and elbow injuries in pitchers is 5% and increasing at an alarming rate (serious injury was defined as that requiring surgery or retirement from baseball).[1-3] Inadequate rest, poor pitching mechanics, and breaking pitches have been broadly cited as the 3 most significant modifiable risk

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A.A.R. receives support from the Journal of Shoulder and Elbow Surgery, *SLACK Incorporated,* Orthopedics Today, Orthopedics, Sports Health, Techniques in Shoulder and Elbow Surgery, Operative Techniques in Sports Medicine, Orthopaedic Journal of Sports Medicine, *American Orthopaedic Society for Sports Medicine, American Shoulder and Elbow Surgeons, and the Arthroscopy Association of North America; Arthrex; DJO Surgical, Smith and Nephew, Ossur, and Saunders/Mosby-Elsevier. N.N.V. receives support from* Knee Surgery, Arthroscopy, *SLACK Incorporated, and the Arthroscopy Association Learning Center Committee; Minivasive, Smith & Nephew; Arthrex, Athletico, ConMed Linvatec, Miomed, Mitek, Arthrosurface, and DJ Orthopaedics; Vindico Medical-Orthopaedcs Hyperguide, Arthroscopy; Cymedica, Omeros. B.J.C. receives support from American Academy of Orthopaedic Surgeons,* American Journal of Orthopedics, American Journal of Sports Medicine, Cartilage, Journal of Bone and Joint Surgery—American, Journal of Shoulder and Elbow Surgery; *Educational Committee, the Arthroscopy Association of North America (AANA); International Committee, AANA; Elsevier, Arthrex, Regentis, Zimmer, Johnson & Johnson, and Medipost.*

The work for this study was performed at Accelerated Rehabilitation and Rush University Medical Center in Chicago, Illinois, U.S.A.

Received August 26, 2015; accepted January 25, 2016.

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0749-8063/15818/$36.00

http://dx.doi.org/10.1016/j.arthro.2016.01.048

factors for pitching-related injury.[3-9] Therefore, coaches and governing bodies have attempted to reduce stresses on the pitching shoulder and elbow by enforcing age-specific pitch counts, emphasizing the importance of proper mechanics, and discouraging breaking pitches in younger pitchers.[10-12] Although literature is sparse, a few smaller-sample-size biomechanical studies using quantitative motion analysis have elucidated kinematic and kinetic commonalities and differences witnessed among youth, high school, collegiate, and professional pitchers in an attempt to establish "normal" pitching characteristics within various age groups.[1,4,6,7]

In one of the first published comparisons of pitching mechanics among various levels of development, Fleisig and colleagues compared kinematic and kinetic parameters among 231 pitchers at the youth (10 to 15), high school (15 to 20), college (17 to 23), and professional level (20 to 30). The authors found no significant differences among levels with regard to 16 of 17 temporal and position parameters and concluded that pitchers should be taught proper adult mechanics from an early age.[1-3] More recent literature has shown that youth pitchers, compared with skeletally mature pitchers, have a propensity for early trunk rotation and have reduced range of external shoulder rotation during pitching.[3-9] There is limited literature comparing pitchers of different age groups with regard to pitch counts and prevalence of breaking pitches. The purpose of this study was to determine differences among healthy pitchers at different levels of competition with regard to pitching history, pitching mechanics, and prevalence of breaking pitches. We hypothesized that as pitchers aged, they would be more likely to pitch with favorable mechanics; however, they would also be more likely to throw breaking pitches and pitch with inadequate rest.

Methods

This study was approved by our institutional review board. This is a single-episode, preseason, cross-sectional study. Youth, high school, and collegiate overhand baseball pitchers from our metropolitan area were recruited and underwent a standardized evaluation. We included overhand male pitchers aged 9 to 22 currently in pre-season training. We excluded pitchers with a history of injury, discomfort, or prior surgery to the throwing arm, because the presence of injury or discomfort was considered likely to alter pitchers' participation and/or kinematic pitching parameters. Participants used their own self-definition of the term *injury* based on their and their parents' interpretation of the data collection form. After completing the survey, patients were specifically questioned about the type of injury that they had sustained for confirmation. Pitchers with a history of injury also underwent survey and video analysis, and differences in the healthy and injury cohorts are discussed in another publication.[13] We excluded pitchers younger than 9 years and sidearm (or "submarine") style pitchers, because the kinematic data for both groups were felt to introduce substantial variation at baseline. Finally, we excluded pitchers who had transitioned to another position and did not plan to pitch during their upcoming season. No participants were aware of the study hypothesis. No a priori power analysis was performed, and as many players as possible were recruited.

Data Collection

All pitchers, and when possible, their parents, completed a self-administered survey to obtain demographic information, pitching history, and injury history. All data were collected between November 2013 and April 2014. The study was performed during this time period because mechanics were thought to be least affected by overuse, because most pitchers underwent a period of rest in the winter months. Survey data included number of years pitching, years pitching at the highest level, use of breaking pitches (changeup, curveball, and slider), pitching for more than 1 team, pitching for more than 9 months/year, participation in showcases, and returning to the mound after being removed. Pitch counts and pitches used were all based on the pitcher and his parent's recollection of numbers of pitches thrown and which pitches were used. Pitchers were not questioned regarding other positions played. Paper surveys were administered in a standardized fashion by 2 study authors. Investigators reviewed all completed surveys with the pitchers to ensure understanding and completeness.

Subjects then underwent a standardized physical examination performed by 1 of 2 experienced doctors of physical therapy to evaluate range of motion of both shoulders. Subjects were positioned supine with the shoulder at 0° of flexion and 90° of abduction and the elbow at 90° of flexion with the scapula stabilized anteriorly. Full passive external rotation (ER) and passive internal rotation (IR) were measured using a goniometer. Internal and external rotation measurements were used to calculate total arc of rotation (TRM), glenohumeral internal rotation deficit (GIRD), and glenohumeral external rotation excess (GERE). Goniometry performed in this manner to measure shoulder internal and external rotation has been shown in the literature to be accurate with high levels of intra- and interobserver reliability ($\kappa \geq 0.94$ for both).[14]

Finally, all subjects underwent video motion analysis in a manner similar to prior studies in the literature.[5,15-25] Subjects were filmed at 210 Hz in high definition from both the frontal and lateral views pitching from a regulation practice mound as appropriate for the pitcher's age. Pitch speed was simultaneously measured with a radar gun (JUGS Sports, Tualatin, OR). Subjects

were provided with as much time as necessary to perform their routine warm-up. Once subjects felt ready to pitch at 100% velocity, they then pitched while being filmed. All pitches were fastballs pitched from the windup. All pitches were thrown over a regulation distance for their age at an appropriately positioned and sized strike zone target.

Video data were analyzed using a standardized protocol by 2 study authors (M.L. and T.S.) (Dartfish, Atlanta, GA). The dominant extremity was measured in all cases. Those kinematic variables previously shown to correlate with kinetic variables were identified a priori and were manually measured (Table 1). Observational mechanics were also recorded by these same 2 study authors as a "yes versus no" as previously described.[1-3] These included whether the subject (1) led with his hips, (2) had his hand on top of the ball during the stride phase, (3) had his arm in the throwing position at front foot contact, (4) had closed shoulders at the hand-set position, (5) had a closed foot orientation at front foot contact, (6) had separation of rotation in the hips and shoulders, and (7) was in the fielding position at follow-through.[3-9] These parameters were selected because they have been suggested elsewhere to improve mechanics and reduced shoulder and elbow pain in youth pitchers.[3] We did not assess intra- and interobserver reliability of these observable parameters; however, Quatromoni reported acceptable intra-observer reliability for all 6 observable parameters they evaluated (including the hand-on-top position, closed shoulders at hand-set position, and closed foot orientation) and acceptable interobserver reliability of 3 of 6 parameters (acceptable defined as $\kappa > 0.5$).[26]

Data Analysis

All analyses were performed in Excel X (Microsoft, Redmond, WA) and SPSS 21 (IBM, Armonk, NY). An independent observer who was not aware of the study hypothesis entered all data. The following analyses were planned a priori. Continuous data were tested for normality using the Kolmogorov-Smirnov test, and ANOVA or Kruskal-Wallis tests were used as appropriate based on data normality. Discrete data were tested using χ^2-square tests. All collected variables were compared between groups of pitchers stratified by age into those 9 to 12 years of age (prepubescent/middle school), 13 to 15 years of age (pubescent/early high school), 16 to 17 years of age (mature/late high school), and 18 to 22 years of age (adult/post-high school). These age groups were selected to best group pitchers by both degree of development and level of education. A P value of $<.05$ was considered significant.

Table 1. Kinematic Data Collected

Variable	Phase
Maximal knee height (% ht)	Front foot contact
Stride length (% ht)	Front foot contact
Elbow flexion	Front foot contact
Knee flexion	Front foot contact
Shoulder abduction	Front foot contact
Foot angle	Front foot contact
Max ER	Cocking
Maximum shoulder abduction	Cocking
Lateral trunk tilt (at Max ER)	Cocking
Elbow flexion	Ball release
Forward trunk tilt	Ball release
Knee flexion	Ball release
Shoulder abduction	Ball release
Lead hip flexion	Ball release

Max ER, maximal shoulder external rotation; % ht, as a percentage of patient height.

Results

Four hundred twenty-nine pitchers were recruited. One hundred twenty-eight were excluded because of a history of injury or discomfort, 3 were excluded because after recruitment they were found to be planning not to pitch in the upcoming season, 2 were excluded because they were sidearm or submarine pitchers, 3 were excluded because they felt too much pain to pitch, and 1 was excluded because he did not complete the survey, for a total included sample size of 295. Of the included pitchers, 63 were 9 to 12 years of age, 130 were 13 to 15 years of age, 78 were 16 to 17 years of age, and 24 were 18 to 22 years of age.

There were numerous anthropometric, kinematic, and demographic factors that changed with increasing pitcher age. All reported changes were statistically significant ($P < .05$). In general, from lower to higher levels, there were progressions in height, weight, and body mass index (Table 2). With increasing experience, there was a steady increase in external rotation and decrease in internal rotation, and increase in total range of motion of the dominant extremity; however, we did not observe a statistically significant increase in GIRD. Although pitchers had increased total arc of motion with age, they had a concomitant increased arc of motion on the contralateral shoulder and no difference in the side-to-side differential arc of motion.

With advancing age, pitchers were significantly more likely to play for more than 1 team, pitch for more than 9 months of the year, participate in showcases, throw a curveball, throw a slider, and throw a change-up (Table 3). Between 9 and 17 years of age, pitchers progressively threw more pitchers per game (41 in pitchers 9 to 12, 54 in pitchers 13 to 15, and 69 in pitchers 16 to 17 years old; $P < .001$), per season (767 in pitchers 9 to 12, 975 in pitchers 13 to 15, and 1,079 in pitchers 16 to 17 years old; $P < .001$), and per year (781 in pitchers 9 to 12, 1,217 in pitchers 13 to 15, and 2,007 in pitchers 16 to 17 years old; $P < .001$) (Fig 1). Of note, the 18- to 22-year-old cohort was an exception to this trend with 50, 880, and 1,300 pitches per game, season, and year, respectively. Of note, older players

Table 2. Mean Anthropometric and Physical Examination Data Comparing Pitchers by Age

	Age, years					
Pitcher Characteristic	9-12 (n = 63)	13-15 (n = 130)	16-17 (n = 78)	18-22 (n = 24)	Total	*P* Value
Height, inches	60	67	71	72	68	<.001*
Weight, pounds	100	139	169	180	142	<.001*
Body mass index	19	22	23	24	22	<.001*
ER dominant	113	117	119	116	116	.007*
IR dominant	52	55	54	53	54	.025*
GIRD dominant	5.4	5.1	6.3	7.3	5.6	.633
TRM dominant	165	172	173	168	170	<.001*
TRM non-dominant	162	169	174	168	169	<.001*
TRM differential	−3	−3	−1	0	−1	.016*

NOTE. Unless otherwise specified, all variables are expressed in degrees.
ER, external rotation; GIRD, glenohumeral internal rotation deficit; IR, internal rotation; TRM, total arc of rotation.
*Significant difference.

were no more likely to return to the mound once removed from the game, assume a fielding position at follow-through, or maintain a closed lead foot. Among pitchers 9 to 12 years of age, 1.6% were in violation of recommendations of per-game pitch totals outlined by USA Baseball Medical & Safety Advisory Committee. Within that same group, 9.5% and 0% violated per-week and per-season pitch total guidelines, respectively. Among pitchers 13 to 14 years of age, 3.4%, 12.6%, and 26.4% were in violation of per-game, per-week, and per-season pitch total recommendations, respectively. Although per-game recommendations have been recently established for pitchers older than 14,[12] per week and season recommendations are not available.

From the standpoint of observable metrics, older pitchers increasingly developed the ability to pitch with their hand on top of the ball, maintain closed shoulders at heal strike, lead with their hips, and achieve hip and shoulder separation (Table 4). From the standpoint of measurable kinematics, as pitchers aged they achieved increased stride length as a percentage of their height, had greater knee flexion at front-foot contact, had greater lead hip flexion at ball release, had reduced elbow flexion during front-foot contact, had higher maximum knee height during windup as a percentage of their height, had greater knee flexion at ball release, and had greater shoulder flexion at ball release (Table 4). There was a steady increase in pitching velocity with age (49 mph in pitchers 9 to 12, 63 mph in pitchers 13 to 15, 72 mph in pitchers 16 to 17, and 74 mph in pitchers 18 to 22 years old). As pitchers aged,

Table 3. Pitching Experience, Breaking Pitch, Overuse, and Pitch Velocity Comparisons Among Pitchers of Increasing Age

	Age, years					
Pitching Characteristic	9-12	13-15	16-17	18-22	Total	*P* Value
Pitching experience, years	3.4	5.1	7.3	6.7	5.5	<.001*
Curveball	31.1	77.7	93.5	75.0	71.9	<.001*
Slider	5.0	16.4	26.7	41.7	18.8	<.001*
Change-up	83.9	89.1	97.5	79.2	89.4	.019*
More than 1 team	25.4	36.2	64.9	60.9	43.3	<.001*
More than 9 months	17.5	38.5	53.8	66.7	40.3	<.001*
Showcases	0.0	12.3	50.0	62.5	23.7	<.001*
Return to mound	4.8	6.3	9.0	16.7	7.5	.249
Violation of pitches per game	1.6	3.4	n/a	n/a	2.7	n/a
Violation of pitches per week	9.5	12.6	n/a	n/a	11.3	n/a
Violation of pitches per season	0.0	26.4	n/a	n/a	15.3	n/a
Velocity, m/h	49.5	62.7	71.8	73.5	63.4	<.001*

NOTE. Unless otherwise specified, all variables are expressed in percentage. *P* values were derived from the independent-samples Kruskal-Wallis test.
n/a, not available.
*Significant difference.

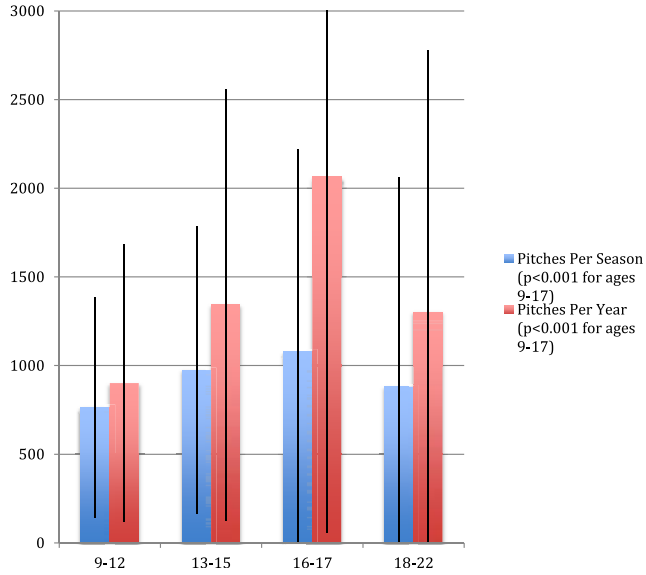

Fig 1. Per-season and per-year pitch count averages among pitchers of increasing age showing that per-season totals remain relatively consistent as pitchers age, but older pitchers have much increased "off-season" involvement. This trend is disrupted when incorporating the less experienced and less competitive cohort of pitchers 18 to 22 years of age.

Table 4. Kinematic and Observed Mechanics Comparing Pitchers by Age

Biomechanical Characteristic	Age, years 9-12	13-15	16-17	18-22	Total	*P* Value
Leading with hips, %	81	93	91	96	90	.042*
Hand on top of ball, %	92	100	100	100	98	<.001*
Arm in throwing position, %	87	84	80	63	82	.055
Closed shoulders at foot strike, %	62	79	83	67	76	.012*
Foot closed, %	91	92	90	88	90	.927
Hip shoulder separation, %	21	39	60	58	43	<.001*
Fielding position, %	87	94	95	86	93	.266
Max knee height, % of height	63	64	67	68	65	.001*
Stride length, % of height	73	77	80	80	77	<.001*
Elbow flexion at FFC	96	89	84	93	90	.009*
Knee flexion at FFC	39	41	47	44	42	<.001*
Shoulder abduction at FFC	83	84	86	92	85	.125
Foot closed at FFC	26	23	19	20	23	.016*
Max external rotation at AC	179	179	178	180	179	.937
Max shoulder abduction at AC	99	99	100	102	99	.057
Lateral trunk tilt at Max ER	17	18	19	20	18	.580
Elbow flexion at BR	23	23	21	21	22	.705
Forward trunk tilt at BR	32	33	34	33	33	.731
Knee flexion at BR	38	43	48	44	44	.012*
Shoulder abduction at BR	93	92	95	95	94	.014*
Lead hip flexion at BR	78	85	87	88	84	.001*
Lat trunk tilt at BR	25	26	27	29	26	.53

NOTE. Unless otherwise specified, all variables are expressed in degrees. *P* values were derived from the independent-samples Kruskal-Wallis test.

AC, arm cocking; BR, ball release; FFC, front foot contact; Max ER, maximal shoulder external rotation.

*Significant difference.

they were consistently more likely to throw breaking pitches, with the most significant differences occurring between the 9 to 12− and 13 to 15−year age groups (Fig 2).

Discussion

This study showed that as healthy pitchers age, several changes can be expected: (1) pitchers develop increased shoulder external rotation and decreased internal rotation as well as an increase in total arc of motion; (2) pitchers are more likely to play for more than 1 team, pitch for more than 9 months of the year, participate in showcases, throw a curveball, throw a slider, and throw a changeup; and (3) pitchers throw with improved throwing mechanics. Among youth and adolescent pitchers, pitching-related injuries are common and their incidence is increasing. Fleisig and colleagues have showed that roughly 5% of youth pitchers develop serious injuries requiring surgery or retirement from baseball.[2,10,11] Within our initially recruited cross-sectional cohort, 31% of subjects had a history of pitching-related shoulder or elbow injury and 12% had attended physical therapy. In another publication using the same pitcher cohort, we found that pitch velocity, pitcher height, and pitching for more than 1 team were the only independent correlates with a history of shoulder and elbow injury.[13] Overuse, poor pitching mechanics, and breaking pitches (specifically the curveball and slider) have been broadly cited as 3 of the most significant modifiable risk factors for pitching related injury.[1-3,5,8,9] We performed this cross-sectional study to elucidate the differences between developmental levels with regard to pitching history, pitching mechanics, and prevalence of breaking pitches. We hypothesized that as youth and adolescent pitchers aged, they would be more likely to pitch with favorable mechanics; however, they would also be more likely to throw breaking pitches and pitch with inadequate rest. Our hypothesis was confirmed because older pitchers showed an increased tendency for overuse, mechanics thought to confer lower risk of injury, and increased use of breaking pitches.

Pitching History

Overuse represents the most broadly accepted risk factor in the literature for pitching related injury. Various parameters have been used as indicators of overuse including pitches per game/week/season, pitching for more than 9 months, pitching for more than 1 team, pitching in showcases, and returning to the mound after being removed. In our study, we showed that with advancing age, pitchers consistently threw more pitches per game, per week, per season, and per year (Fig 2) and were consistently more likely to pitch for more than 1 team, pitch for more than 9 months, and pitch in showcases. Three prior studies in the literature have correlated pitching factors with injury and both have placed the most significant weight on overuse. Olsen and colleagues[9] showed that injury was correlated with number of months per year, games per year, innings per game, pitches per game, pitches per year, warm-up pitches before a game, showcase participation, and pitch velocity and was unrelated to the use of breaking pitches or age of initial breaking pitch.[3-8] Likewise, Lyman and colleagues[5] found a significant increase in risk of shoulder and elbow injury with an increase in pitches per game, pitches per season, and use of breaking pitches; however, they found no correlation between pitching mechanics and injury risk.[15-25,27] A study performed with the same cohort of pitchers evaluated in this study revealed that pitching for more than 1 team, pitcher height, and pitch velocity were independent predictors of pitching-related injury and together could predict 77% of pitching injuries.[13]

In light of available evidence regarding the risks of overuse, the USA Baseball Medical and Safety Advisory Committee has established specific pitching guidelines

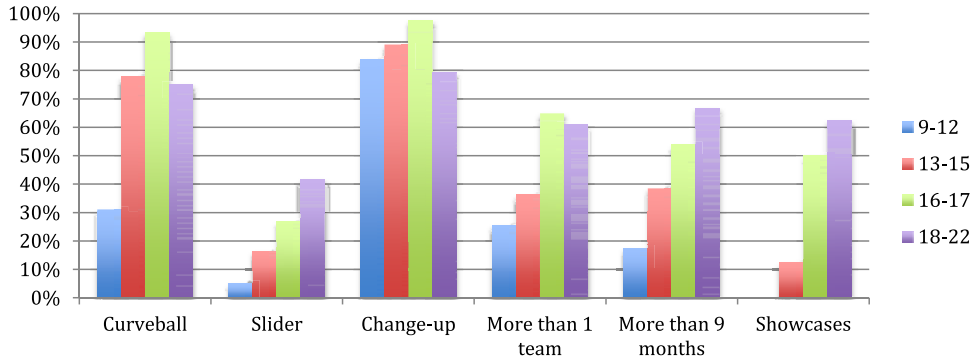

Fig 2. Breaking pitch and pitching experience comparisons among pitchers of increasing age.

regarding the number of pitches that each player can throw per game, per week, per season, and per year; ages before which pitchers should not throw breaking pitches; and strategies to increase the amount of rest pitchers receive.[11,12] Nonetheless, adherence to these guidelines has been modest. Fazarale and colleagues[28] conducted a survey of 228 youth baseball coaches and reported that only 73% of coaches admitted to compliance with USA Baseball Medical and Safety Advisory Committee pitching guidelines and only 53% felt that other coaches generally follow the guidelines.[1-3] Coaches of younger pitchers (9 to 10—year age group) were much more likely to answer questions regarding the guidelines correctly (62% of questions) than coaches of older pitchers (13 to 14 age group) (42% of questions). Our study also suggests that compliance with existing guidelines deteriorates as pitchers age. Among pitchers 9 to 12 years of age, 0% were in violation of season pitch total recommendations compared with 26.4% of those 13 to 14 years of age. To curtail pitching-related injuries, an increased effort should be made to educate coaches of older youth pitchers of the existing safety guidelines and the importance of complying with those guidelines.

Pitching Mechanics

From the standpoint of observed mechanics, our study shows that as pitchers age they generally adopt strategies that may minimize risk and improve pitching efficiency. Older pitchers are more likely to maintain their hand on top of the ball (Fig 3), maintain closed shoulders at foot-strike, lead with their hips, and achieve hip and shoulder separation (Fig 4).

Each of these parameters has important implications with regard to minimizing stress on the shoulder and elbow and/or optimizing pitch velocity. The hand-on-top position and closed-shoulder position are 2 of the more easily observed and commonly discussed parameters among pitching coaches. The hand-on-top position has been shown to be associated with lower humeral internal rotation torques, lower elbow valgus loads, and improved pitching efficiency (decreased ratio of normalized humeral internal rotation torque and elbow valgus load to velocity).[3-9] Conversely, the hand-under-ball position promotes early external rotation and scapulohumeral hyperangulation of the throwing shoulder, which results in increased valgus load on the medial elbow and predisposes to internal impingement of the shoulder.[10-12,29] The closed-shoulder position is similarly advocated to avoid the common error of "opening-up too soon." Early opening has also been implicated in increasing scapulohumeral hyperangulation. In our study, we found that 92% of pitchers younger than 13 years were able to maintain their hand on top of the ball compared with 100% of pitchers aged 13 years and older. We found that the proportion of

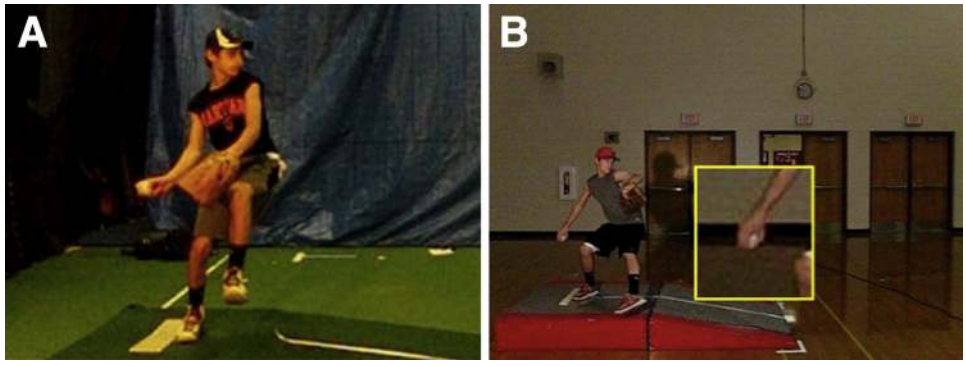

Fig 3. (A) A youth pitcher (9 to 12 years) with hand under ball and (B) an older pitcher (16 to 17 years) with hand on top of ball.

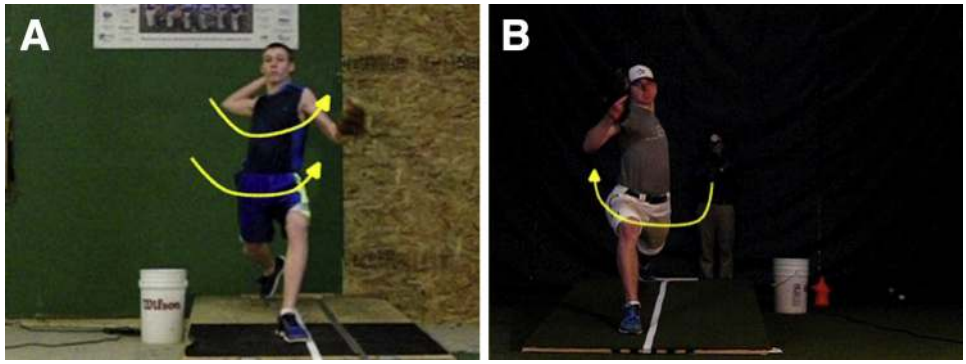

Fig 4. (A) A youth pitcher who fails to achieve hip and shoulder separation and (B) an older pitcher who succeeds in achieving hip and shoulder separation.

pitchers maintaining a closed shoulder position also increased steadily with age, with a significant increase between the 9 to 12− and the 13 to 15−year age groups (62% *v* 79%). These data support previous literature by Keeley and colleagues that showed that youth pitchers have a greater propensity for initiating trunk rotation before the humerus and scapulae are appropriately positioned,[1,4,6,7] which increases the horizontal abduction angle of the shoulder and leads to hyperangulation.

Hip and shoulder separation is another tactic recommended by pitching coaches to improve pitching efficiency. Proper hip and shoulder separation involves appropriately timing the movement of the pelvis and trunk such that trunk rotation is initiated at the moment of maximum angular velocity of the pelvis.[1-3,30,31] This strategy results in efficient transfer of momentum from the pelvis to the throwing arm via the "summation of speed" principle. Pitchers who fail to appropriately time sequential body motion (i.e., fail to achieve hip and shoulder separation) tend to lose angular momentum and frequently compensate by increasing internal rotation torque.[3-9,30]

Leading with the hips is defined as the pelvis leading the trunk toward home plate during the early cocking phase. This promotes more efficient force transfer and, as a result, pitchers who maintain their head and trunk behind their hips have been shown to throw with greater velocity than pitchers who allow the head to pass the hips too early.[13,24] Davis and colleagues revealed that leading with the hips renders increased humeral internal rotation torques, increased elbow valgus loads, and reduced pitching efficiency; however, the authors concluded that leading with the hips was necessary to generate optimum throwing velocity.[3,14]

From the standpoint of measured kinematics, as pitchers aged, they developed many kinematic characteristics that improve pitching velocity. Evidence suggests that throwing arm performance is strongly linked to the ability to regulate forward momentum, and that the lower body kinematics play an essential roll in transferring momentum up the kinetic chain. In our study, we found that as pitchers aged they displayed significant increases in stride length as percentage of height (Fig 5), increased knee flexion at front-foot contact (Fig 6), and increased hip flexion at front-foot contact (Fig 7). Pitchers who take longer strides generate increased forward momentum[5,15-25,32] and, as a result, increase pitching velocity without sacrificing accuracy.[1-3,33] Increased knee flexion at front-foot contact better absorbs loads associated with stride, stabilizes the lead leg for trunk rotation, and also "preloads" the lower extremity to generate power through front leg extension.[3-9,24] The ability to extend the knee

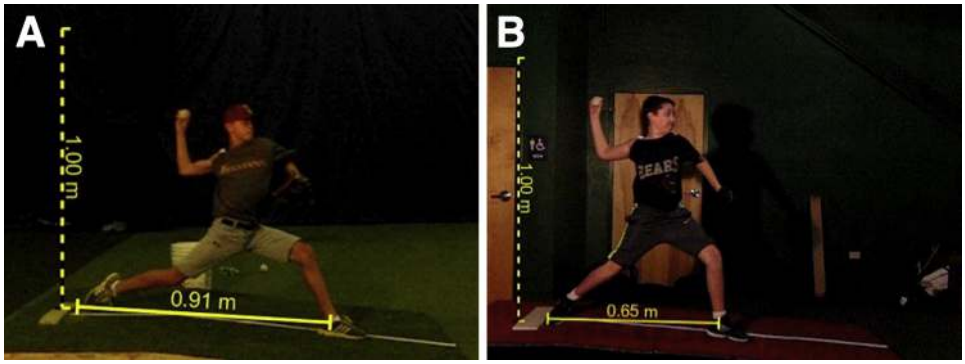

Fig 5. Increased stride length in (A) an older pitcher relative to (B) a youth pitcher.

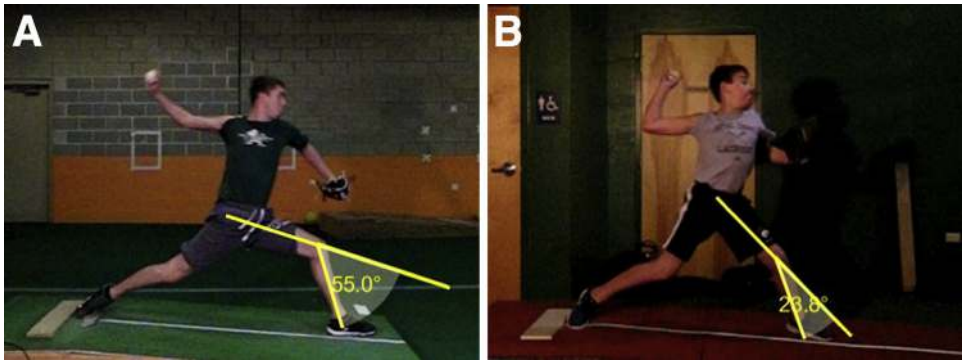

Fig 6. Increased lead knee flexion at front foot contact in (A) an older pitcher relative to (B) a youth pitcher.

during the delivery phase improves the ability to forward flex the trunk, resulting in a more smooth force transfer from the legs through the core to the ball.[3,34] Finally, studies have consistently shown that increased forward trunk tilt contributes to increased pitching velocity because it allows the pitcher to impart muscular forces to the ball over an increased distance.[26,35,36] Although we did not specifically witness an increase in forward trunk tilt, we did see an increase in lead hip flexion, which helps pitchers generate increased forward trunk tilt.

Breaking Pitches

In our cohort, the prevalence of pitchers who threw curveballs and sliders increased steadily as pitchers aged. Just 31% of pitchers 9 to 12 years of age (and 15% of pitchers aged <11 years) threw curveballs, compared with at least 75% of pitchers in all other age groups. Likewise, just 5% of pitchers 9 to 12 and 16% of pitchers 13 to 15 years old threw sliders compared with >25% of pitchers in the 2 older age groups. Among pitchers who threw breaking pitches, the average ages at which they began throwing curveballs and sliders were 12.6 and 13.5 years, respectively. This increase coincides with USA Baseball's recommendation that pitchers wait until age 13 to begin throwing breaking pitches.[11,12] Experts have theorized that to cause a pitch to break, the pitcher must place his arm in a position that increases medial elbow strain.[2,10,11] For this reason, many governing bodies have advocated that pitchers avoid throwing curveballs until they are old enough to shave. The prevalence of pitchers in our cohort who threw breaking pitches was reduced compared with data published in 2002 by Lyman and colleagues[5] who reported curveballs in 39% of pitchers 9 to 12 years of age (and 30% of pitchers <11) and sliders in 11% of pitchers 9 to 12 years of age.[1-3,8,9] This reduction in prevalence may be the result of efforts to reduce breaking pitches among youth pitchers or the result in regional variation in pitching education.

Range of Motion

With increasing pitcher age, we witnessed a significant increase in external rotation of the pitching shoulder (113° for those 9 to 12, 117° for those 13 to 15, 119° for those 16 to 17, and 116° for those 18 to 22 years of age). This trend supports published data suggesting that GIRD and glenoid retrotorsion represent an adaptive change that occurs with increasing pitching experience[3-9,37] and data suggesting that the greatest retrotorsion adaptation occurs between the ages of 11 and 12.[5,15-25,27,38] We did not witness an age-related increase in GIRD or decrease in total range of motion. Of note, Wilk and colleagues[39] recently showed that

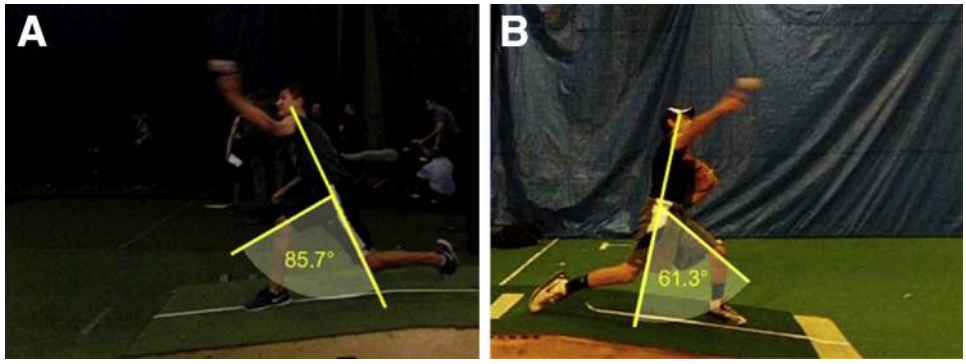

Fig 7. Increased front hip flexion at ball release in (A) an older pitcher of advanced age than (B) a youth pitcher.

pitchers with deficits in total range of motion (>5° than the nondominant shoulder) were 2.6 times more likely to be placed on the disabled list for elbow injury.[13] Although it may seem inconsistent that pitchers in the 18 to 22 group had less external rotation than those in the 16 to 17 group, this discrepancy is explained by the fact that pitchers in the older group actually had less pitching experience (6.7 *v* 7.3 years). The reduction in external rotation witnessed between the 16 to 17 and 18 to 22 cohorts is interesting in that it reinforces this is a change that occurs with increased pitching experience and not increased age.

Strengths

The primary strengths of this study relate to the significant number of pitchers recruited and the broad extent of information that was gleaned from each pitcher. Nonetheless, no power analysis was performed because the study sought to recruit as many pitchers as was felt possible.

Limitations

This study has several limitations. First, much of our data regarding pitching experience and use of breaking pitches was obtained via a single-episode survey and is subject to recall and estimation bias. Second, high-speed video motion analysis was used instead of traditional marker-based motion analysis. Because multiple prior pitching motion analysis studies have used video-based systems, this methodology is well accepted if not validated.[5,11,12,15,17-21,23-25,40,41] Accuracy of video motion analysis in the form that we used was not readily available. Additionally, a power analysis was not performed. By evaluating only healthy pitchers, detection bias is likely introduced because pitchers who have remained healthy through years of pitching are more likely to have adopted favorable pitching mechanics. Finally, as mentioned previously, the oldest group in our cohort (18 to 22) had less pitching experience than the second oldest group (16 to 17) (6.7 *v* 7.3 years), and this resulted in several inconsistencies in our data. As a result, pitchers in the oldest group were less likely than those in the second oldest group to throw a curveball, throw a changeup, pitch for more than 1 team, maintain closed shoulders at foot-strike, achieve hip and shoulder separation, and assume a fielding position after follow-through. In each case, this group represented the only deviation from a trend of increasing prevalence among the younger age groups. The differential in experience as well as differential in pitch counts and use of breaking pitches likely stems from the fact that our 18 to 22 cohort represented a relatively less competitive group, because more competitive 18- to 22-year-old pitchers are more likely to rely on personal pitching coaches and institutional resources rather than using commercially available pitching evaluation at a local physical therapy center.

Conclusions

As pitchers age, they consistently throw more pitches per game, per week, per season, and per year and are more likely than younger pitchers to violate pitch count recommendations. Older pitchers tend to pitch with improved mechanics and velocity. The proportion of pitchers throwing breaking pitches increases as pitchers age, with the greatest increase in breaking pitch use occurring between ages 12 and 13 years.

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