The Impact of Fatigue on Baseball Pitching Mechanics in Adolescent Male Pitchers

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Purpose: To determine if shoulder and elbow kinematics, pitching velocity and accuracy, and pain change during a simulated baseball game in adolescent pitchers. **Methods:** Adolescent male pitchers aged 13 to 16 years were included. Pitchers were excluded if they had undergone previous shoulder or elbow surgery, currently had a known shoulder or elbow injury, or were unable to complete the simulated game for any reason. Shoulder range of motion was assessed before and after the game. Velocity and accuracy were measured for every pitch, and every 15th pitch was videotaped from 2 orthogonal views in high definition at 240 Hz. Quantitative and qualitative mechanics were measured from these videos. Perceived fatigue and pain were assessed after each inning using a visual analog scale. Data were statistically analyzed using a repeated-measures analysis of variance. **Results:** Twenty-eight elite adolescent pitchers were included. These pitchers, on average, were aged 14.6 ± 0.9 years (mean ± standard deviation), had been pitching for 6.3 ± 1.7 years, and threw 94 ± 58 pitches per week. Our experimental model functioned as expected in that pitchers became progressively more fatigued (0.3 ± 0.6 to 3.5 ± 2.1), had more pain (0.1 ± 0.4 to 1.6 ± 2.2), and pitched with a lower velocity (73 ± 5 mph to 71 ± 6 mph) as pitch number increased ($P < .001$, $P = .001$, and $P < .001$, respectively). Knee flexion at ball release progressively increased (49° ± 15° to 53° ± 15°) with pitch number ($P = .008$). Hip-to-shoulder separation significantly decreased as pitch number increased, from 90% ± 40% at pitch 15 to 40% ± 50% at pitch 90 ($P < .001$). Upper extremity kinematics remained unchanged ($P > .271$ in all cases, 91% power for elbow flexion at ball release). External rotation and total range of motion in the pitching shoulder significantly increased after pitching ($P = .007$ and $P = .047$, respectively). **Conclusions:** As pitchers progress through a simulated game, they throw lower-velocity pitches, become fatigued, and have more pain. Core and leg musculature becomes fatigued before upper extremity kinematics changes. **Clinical Relevance:** On the basis of these results, there is the potential that core strengthening and leg strengthening may be valuable adjuncts to prevent upper extremity injury. Further studies specifically looking at this must be conducted.

Five million children aged between 6 to 17 years are involved in baseball leagues throughout the United States.[1] Baseball pitchers, including youth and adolescent pitchers, place a significant amount of stress on their shoulder and elbow during the overhand pitch.[2,3] As a result, elbow and shoulder pain and injury in these adolescents are common, occurring at rates of 30% to 50% and 23%, respectively.[4,5] This injury problem appears to be worsening in adults: The number of Major League Baseball pitchers who are undergoing shoulder and elbow surgery, specifically ulnar collateral ligament reconstruction, is increasing.[6,7] In addition, these operations are occurring earlier in their careers.[6,8] Similarly, the number of adolescent pitchers undergoing operative treatment for pitching-related injuries is increasing.[9]

To help slow this upward trend of injuries, research and regulations have focused on prevention. Pitcher fatigue, including pitching on consecutive days, pitching multiple games on the same day, and pitching on multiple teams, places adolescent pitchers at

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increased risk of shoulder and elbow injuries.[1,10] Specifically, adolescents who pitch more than 100 innings per year are at a 3.5 times higher risk of becoming injured than those who pitch fewer innings.[11] Thus preventive efforts have focused on reducing fatigue as well as pitch selection. These efforts include pitch counts and admonitions against pitching year-round, pitching on multiple teams, and throwing breaking pitches before specific ages.[1,4,10] However, not all adolescent pitchers abide by the pitch counts or the rules regarding rest.[11,12] Furthermore, there are many adolescent pitchers who will continue to pitch despite fatigue and shoulder or elbow pain, which is thought to significantly increase their risk of injury.[10,11,13]

The purpose of this study was to determine if shoulder and elbow kinematics, pitch velocity and accuracy, and pain change as experienced adolescent pitchers aged between 13 and 16 years progress through a simulated game. We hypothesized that as pitchers progress through a simulated game, pain would increase, velocity would decrease, and accuracy would decrease. Furthermore, we hypothesized that these changes would be accompanied by altered kinematics linked with increased shoulder and elbow torques.

Methods

Male baseball pitchers aged between 13 and 16 years were recruited. Pitchers were excluded if they had undergone previous shoulder or elbow surgery,

Fig 1. Testing protocol.

currently had a known shoulder or elbow injury, were female pitchers, were aged younger than 13 or older than 16 years on the day of filming, or were unable to complete the simulated game for any reason. Our institutional review board approved this study on July 25, 2014 (protocol No. 14052803-IRB01). Pitchers were recruited between August 1, 2014, and January 20, 2015. No participants were aware of the study hypothesis.

All pitches were thrown over a regulation distance from an age-appropriate, regulation-sized mound. Each subject threw a “simulated game” in which each player threw 90 pitches, split evenly between 6 innings (15 pitches per inning), with a 10-pitch warm-up before each inning, for a total of 150 pitches (Fig 1). Athletes wore sleeveless spandex shirts and shorts to allow visualization of anatomic landmarks. Subjects and, when possible, their parents completed a self-administered survey to obtain demographic information, pitching history, and injury history (Fig 2). The pitchers were instructed to throw fastballs at 100% velocity from the windup. Velocity and accuracy were measured for every pitch, and every 15th pitch was videotaped from orthogonal frontal and lateral views in high definition at 240 Hz. Velocity was measured with a radar gun (JUGS Sports, Tualatin, OR). Accuracy was measured with the Pitchers Pocket (Better Baseball, Marietta, GA), with the height adjusted for the youth thrower. Pain and fatigue were each assessed on a 10-point visual analog scale after each inning.

Video data were analyzed using a standardized protocol (Dartfish, Atlanta, GA). In all cases the dominant extremity was measured. Pitching angles were measured by means shown in Table 1. Pitches were randomized and blinded such that the individual measuring each pitch was not aware of which subject or which pitch was being measured. Those kinematic variables previously shown to correlate with kinetic variables were identified a priori and were manually measured to a tenth of a degree (Table 2).[14-17] Qualitative mechanics were also recorded as a binary yes or no as previously described.[18] These included whether

PATIENT HISTORY: Age ____Height _____ Weight _____ BMI_____☐ Right ☐ Left handed ID #_____

How many **years** have you been pitching for? ____

How many **pitches** do you throw per week? ____

Do you throw **breaking pitches?** *Curveball* ☐ Yes ☐ No *Slider* ☐ Yes ☐ No *Changeup* ☐ Yes ☐ No

If yes, at what age did you start? *Curveball* ____________*Slider* _____________*Changeup*__________

Do you or did you ever pitch on **more than one team at a time**? ☐ Yes ☐ No

Do you or did you ever play baseball for **>nine months/year**? ☐ Yes ☐ No

For how many years? _________ How many months a year did you participate? ____________________

Has your arm ever hurt while pitching ☐ Yes ☐ No If **Yes** was it your shoulder ☐ elbow ☐ or **both** ☐

Has your arm ever felt **fatigued** while pitching? ☐ Yes ☐ No If **Yes**, how often?________________

Do you feel your pitching velocity has ever been affected by fatigue? ☐ Yes ☐ No If **Yes**, how often?_____

Do you feel your pitching accuracy has ever been affected by fatigue? ☐ Yes ☐ No If **Yes**, how often?______

Do you feel your pitching performance has ever been affected by fatigue? ☐ Yes ☐ No If **Yes**, how often?___

Did you ever continue to pitch in a game after your shoulder or elbow started to **hurt**?_______________

Do you or did you ever participate in “**showcases**”? ☐ Yes ☐ No

Do you or did you ever **return to the mound** after having been removed? ☐ Yes ☐ No

Do you currently have any current **pain** in your shoulder or elbow with pitching? ☐ Yes ☐ No

Have you ever been diagnosed with any **pitching-related injuries**? ☐ Yes ☐ No

If yes, what **injury** were you diagnosed with?_______________________At what age?_____________

Did you ever have shoulder or elbow **surgery**? ☐ Yes ☐ No

Fig 2. Survey completed by all pitchers before participating in the throwing program. (BMI, body mass index.)

the subject (1) led with the hips, (2) had the hand on top of the ball during the stride phase, (3) had the 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.[18] All measurements were performed by 1 author (T.S.) who has performed over 1,000 throwing video analyses. Pre- and post-game total arc of motion was measured for each pitcher. Two examiners (T.S. and P.V.) measured this using a true axis bubble goniometer with the pitcher supine, the shoulder abducted to 90°, the elbow flexed to 90°, and a towel roll under the distal humerus. The scapula was stabilized and each shoulder rotated until scapulothoracic motion was noted. Internal rotation, external rotation, and total rotational arc were measured, and any glenohumeral internal rotation

Table 1. Methods for Measuring Throwing Angles

Windup
- Maximum knee height (% of height)
  - Draw straight line horizontal to ground at center of rotation of knee joint
  - Draw second horizontal line across stance-foot toes
  - Measure distance between 2 lines as % of height

Front-foot contact
- Stride length (% of height)
  - Draw line from front edge of rubber to medial malleolus of pitcher's lead ankle after heel contact has been established
  - Measure this as % of player's height
- Elbow flexion
  - Draw line across medial midline of humerus
  - Axis: medial epicondyle of humerus
  - Moving arm to be aligned with medial midline of ulna toward ulnar styloid process
- Knee flexion
  - Draw line extending from opposite greater trochanter, medial midline of femur extending through medial epicondyle
  - Axis: medial epicondyle of femur
  - Moving arm: medial midline of tibia
- Shoulder abduction
  - Draw vertical line parallel to sternum crossing through anterior aspect of acromion process
  - Horizontal axis through midline of humerus to medial epicondyle of ulna
  - Axis: anterior aspect of acromion process
- Foot position
  - Axis: anterior aspect of talocrural joint
  - Draw straight line extending from anterior aspect of talocrural joint
  - Moving arm: anterior midline of second metatarsal
  - Draw line extending from anterior aspect of talocrural joint through midline of second metatarsal and measure angle between them

Arm cocking
- Maximum external rotation
  - Draw line consistent with forward trunk tilt (aligned with spine through greater trochanter)
  - Draw line at 90° to forward trunk tilt line to obtain true stationary arm
  - Axis: olecranon process of ulna
  - Moving arm: ulnar border of forearm toward ulnar styloid process

Ball release
- Elbow flexion
  - Draw line across medial midline of humerus through medial epicondyle
  - Axis: medial epicondyle of humerus
  - Moving arm to be aligned with medial midline of ulna toward ulnar styloid process
- Forward trunk tilt
  - Draw plumb line extending through greater trochanter of hip
  - Axis: greater trochanter
  - Moving arm: draw line extending through midline of body and measure resulting angle
- Lateral trunk tilt
  - Draw plumb line through mid pelvis
  - Draw straight line extending along cervical, thoracic, and lumbar spine
  - Axis: intersection of 2 lines
- Knee flexion
  - Draw line extending from opposite greater trochanter, medial midline of femur extending through medial epicondyle
  - Axis: medial epicondyle of femur
  - Moving arm: medial midline of tibia
- Shoulder abduction
  - Draw vertical line parallel to sternum crossing through anterior aspect of acromion process
  - Horizontal axis through midline of humerus to medial epicondyle of ulna
  - Axis: anterior aspect of acromion process

Table 2. Mean Kinematics in Each Phase During Each Inning of Simulated Game

	Inning 1	Inning 2	Inning 3	Inning 4	Inning 5	Inning 6	*P* Value
Pitch number	15	30	45	60	75	90	NA
Fatigue score	0.3 ± 0.6	0.9 ± 1	1.5 ± 1.3	2.2 ± 1.7	2.9 ± 2	3.5 ± 2.1	<.001*
Pain score	0.1 ± 0.4	0.4 ± 0.7	0.7 ± 1.1	0.9 ± 1.4	1.4 ± 2	1.6 ± 2.2	.001*
Strikes	7.5 ± 2.4	8.1 ± 2	8.3 ± 2.3	7.4 ± 2	7.4 ± 1.9	7.5 ± 2	.225
Velocity, mph	73 ± 5	73 ± 5	72 ± 5	72 ± 5	71 ± 5	71 ± 6	<.001*
Windup							
Maximum knee height, %	70 ± 5	70 ± 6	70 ± 6	70 ± 5	70 ± 5	70 ± 6	.663
Front-foot contact							
Stride length, %	82 ± 7	83 ± 6	83 ± 7	82 ± 6	82 ± 7	82 ± 7	.501
Elbow flexion, °	94 ± 16	95 ± 17	95 ± 17	95 ± 17	96 ± 17	95 ± 18	.875
Knee flexion, °	52 ± 8	53 ± 9	51 ± 9	51 ± 7	53 ± 8	52 ± 9	.528
Shoulder abduction, °	81 ± 8	79 ± 7	80 ± 8	79 ± 7	80 ± 7	78 ± 13	.377
Foot closed, °	19 ± 17	18 ± 18	18 ± 20	18 ± 20	20 ± 18	21 ± 17	.371
Cocking							
Maximum ER, °	184 ± 12	184 ± 11	185 ± 11	184 ± 12	184 ± 12	181 ± 20	.306
Maximum abduction, °	101 ± 9	101 ± 10	102 ± 10	102 ± 11	102 ± 10	102 ± 10	.945
Lateral trunk tilt, °	22 ± 9	21 ± 9	21 ± 9	22 ± 9	21 ± 9	21 ± 9	.271
Ball release							
Elbow flexion, °	20 ± 6	20 ± 5	21 ± 6	21 ± 5	21 ± 5	20 ± 6	.413
Forward trunk tilt, °	39 ± 6	39 ± 6	38 ± 6	39 ± 6	39 ± 6	38 ± 6	.414
Knee flexion, °	49 ± 15	48 ± 16	47 ± 17	48 ± 17	51 ± 15	53 ± 15	.008*
Shoulder abduction, °	94 ± 11	96 ± 11	96 ± 11	96 ± 10	95 ± 11	96 ± 11	.096
Lead hip flexion, °	97 ± 12	98 ± 14	97 ± 14	98 ± 12	99 ± 12	97 ± 12	.836
Lateral trunk tilt, °	29 ± 11	29 ± 10	28 ± 10	29 ± 10	28 ± 9	29 ± 10	.167
Qualitative mechanics							
Leading with hips, %	100 ± 0	100 ± 0	100 ± 0	100 ± 0	100 ± 0	100 ± 0	>.99
Hand on top of ball, %	100 ± 0	100 ± 0	100 ± 0	100 ± 0	100 ± 0	100 ± 0	>.99
FFC arm throwing position, %	100 ± 0	100 ± 0	100 ± 0	100 ± 0	100 ± 0	100 ± 0	>.99
Closed shoulders at HS, %	100 ± 20	100 ± 20	100 ± 20	100 ± 20	90 ± 30	90 ± 30	.420
Foot closed, %	90 ± 30	90 ± 30	90 ± 30	90 ± 30	90 ± 30	100 ± 20	.420
Hip/shoulder separation, %	90 ± 40	80 ± 40	70 ± 50	60 ± 50	50 ± 50	40 ± 50	<.001*

NOTE. Data are presented as mean ± standard deviation. *P* values from repeated-measures analysis-of-variance testing show whether each variable changed with pitch number.

ER, external rotation; FFC, front-foot contact; HS, hand-set position; NA, not applicable.

*Statistically significant.

deficit or glenohumeral external rotation excess was also recorded.

Statistical Methods

All statistical analyses were performed in SPSS, version 21 (IBM, Armonk, NY). Descriptive statistics were calculated. A repeated-measures analysis of variance was used for each variable to determine whether each variable changed with pitch number. In cases in which sphericity was violated by the Mauchly test, the Greenhouse-Geisser correction was used to determine the *P* value. Pre- and post-testing range-of-motion variables were compared with a paired-samples *t* test. $P < .05$ was considered significant. Fatigue and pain scores were considered as positive controls to assess how the pitching model functioned. Elbow flexion at ball release was selected as a primary outcome to power the study based on the relation between this kinematic variable and kinetic variables in multiple prior studies.[19-21] Elbow position at ball release plays a significant role in sequential body motion and, as such, affects the amount of valgus force seen across the elbow.[20] Prior studies have also shown that with increased elbow flexion (thereby causing a more horizontal arm slot), 73% of pitchers will exhibit some symptoms of elbow injury.[22]

No data were available a priori to allow a reliable determination of sample size. A post hoc power analysis was thus calculated using G*Power.[23] Elbow flexion at ball release was selected as a primary outcome to power the study based on the relation between this kinematic variable and kinetic variables in multiple prior studies.[19-21]

Results

Twenty-nine subjects were recruited. One subject was excluded because he had development of pain too great to continue testing after 45 pitches. Achieved power was 91.4% for our primary outcome variable, elbow flexion at ball release.

Included subjects had a mean age of 14.6 ± 0.9 years (mean ± standard deviation). Subjects were 71 ± 3 inches in height and 157 ± 17 lb in weight, with a body mass index of 21.9 ± 2.4 kg/m^2. Eighty-six percent of

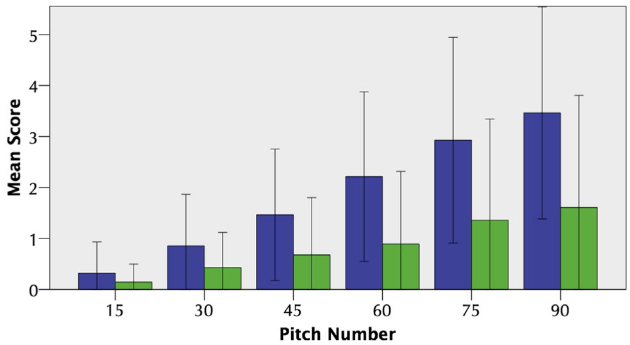

Fig 3. Mean fatigue (blue) and pain (green) scores by pitch number. Both scores were rated on a scale from 0 to 10, with higher scores denoting more fatigue and more pain. Both significantly increased with pitch number ($P < .001$ and $P = .001$, respectively). Error bars show 1 standard deviation.

the subjects were right handed. Subjects had spent an average of 6.3 ± 1.7 years pitching and threw an average of 94 ± 58 pitches per week. Regarding breaking pitches, 96% of subjects threw a changeup, 82% threw a curveball, and 21% threw a slider. Pitchers started throwing a changeup at 10.8 ± 1.4 years of age, a curveball at 12.5 ± 1.1 years of age, and a slider at 13.7 ± 1.2 years of age.

Regarding current pitching recommendations, 46% of subjects pitched for multiple teams, 39% pitched for more than 9 months a year, 61% participated in showcases, and 11% had been returned to the mound after being removed. Those players who pitched for greater than 9 months had been doing so for 2.8 ± 1.1 years and played for 9.9 ± 1.7 months per year.

Regarding to pain and injury, 43% of subjects stated their arm had hurt in the past while pitching and 36% of subjects stated their elbow specifically hurt while pitching. Thirty-two percent of pitchers stated they had continued to pitch through pain. No pitchers were having any current pain, but 39% had been previously diagnosed with an injury. These injuries were described by the pitchers as follows: "biceps tendonitis" (1), "elbow tendonitis" (4), "growth plate issues" (1), "little leaguer's elbow" (1), "little leaguer's shoulder" (2), "UCL [ulnar collateral ligament] strain" (1), and "UCL tendonitis" (1). These injuries occurred at 11.8 ± 1.7 years of age. No pitcher had required prior surgical treatment.

Most pitchers had experienced fatigue and believed that it affected their velocity, accuracy, and performance frequently. Seventy-five percent of pitchers had felt arm fatigue in the past while pitching. Sixty-four percent of pitchers felt fatigue had affected their pitch velocity in the past. Seventy-one percent of pitchers felt their accuracy had been affected by fatigue. Seventy-nine percent of pitchers felt fatigue had affected their performance.

In total, 2,520 100% velocity pitches were thrown during testing, with a mean velocity of 72 ± 6 mph (range, 56 to 82 mph) and a mean strike rate of 51.3%. Every 15th pitch from each pitcher was orthogonally videotaped and measured for kinematics and qualitative mechanics, for a total of 168 pitches measured. Pitchers became progressively more fatigued and had more pain as pitch number increased ($P < .001$ and $P = .001$, respectively; Table 2, Fig 3). Pitchers remained accurate throughout testing and despite increasing pitch count ($P = .225$). Pitch velocity significantly decreased (73 ± 5 mph to 71 ± 6 mph) as pitch number increased ($P < .001$; Table 2, Fig 4).

Regarding kinematics, knee flexion at ball release progressively increased (49° ± 15° to 53° ± 15°) with pitch number ($P = .008$; Table 2, Fig 5). Kinematics during the windup, at front-foot contact, and during the cocking phase was not affected by pitch number ($P > .271$ in all cases, Table 2). No significant differences were seen in ball release kinematics with increasing pitch number, including the primary endpoint of elbow flexion angle at ball release ($P > .096$; Table 2, Fig 6).

Regarding qualitative mechanics, hip-to-shoulder separation significantly decreased as pitch number increased, from 90% ± 40% at pitch 15 to 40% ± 50% at pitch 90 ($P < .001$; Table 2, Figs 7 and 8). Otherwise, no significant changes in qualitative mechanics were seen as pitch number increased ($P > .420$, Table 2).

Regarding range of motion, significant increases in external rotation and total range of motion were seen in the dominant arm after pitching ($P = .007$ and $P = .047$, respectively; Table 3). No significant differences were seen in the nondominant arm between pre-pitching and post-pitching data ($P > .094$ in all cases, Table 3).

Discussion

We found that our experimental model functioned as expected in that pitchers became progressively more fatigued, had more pain, and pitched with a lower velocity as pitch number increased, although accuracy did not change. We found that whereas upper extremity kinematics was unchanged, knee flexion at

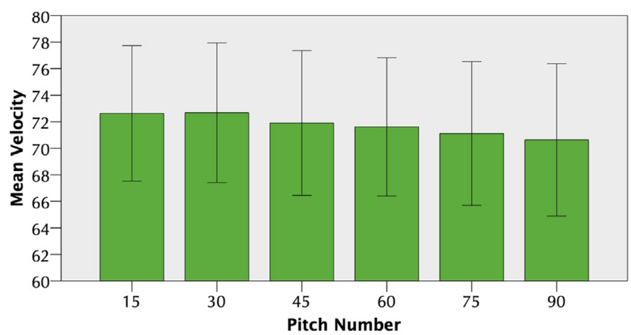

Fig 4. Mean velocity (in miles per hour) by pitch number. Velocity significantly decreased with increasing pitch number ($P < .001$). Error bars show 1 standard deviation.

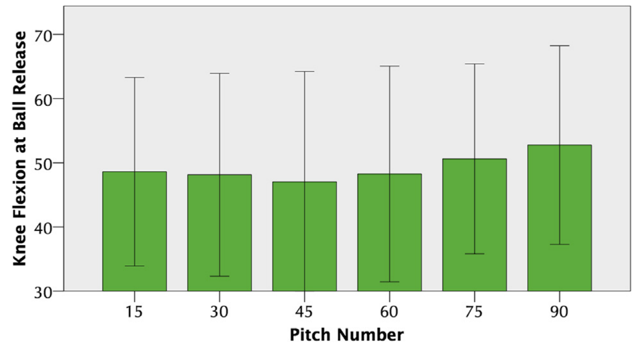

Fig 5. Mean knee flexion angle at ball release (in degrees) by pitch number. Knee flexion at ball release significantly increased with pitch number ($P = .008$). Error bars show 1 standard deviation.

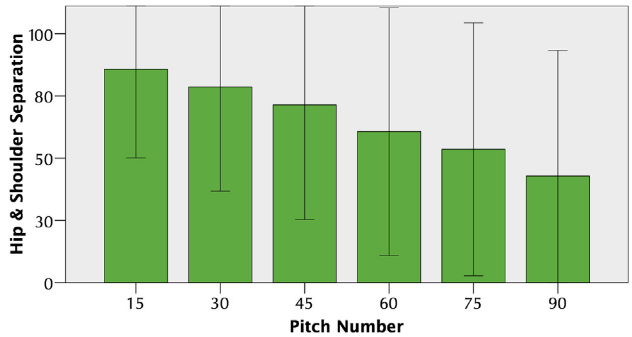

Fig 7. Percentage of pitchers showing separation of rotation within hips and shoulders, by pitch number. Hip-to-shoulder separation significantly decreased with pitch number ($P <$ .001). Error bars show 1 standard deviation.

ball release progressively increased and hip-to-shoulder separation significantly decreased with pitch number, suggesting that leg musculature and core musculature fatigue before upper extremity musculature.

Within our population, several risk factors for injury were identified: 21% of pitchers threw a slider, 96% threw a changeup, and 82% threw a curveball. Although epidemiologic studies have identified breaking pitches as a risk factor for injury, motion analysis studies have not shown any increase in shoulder and elbow torques with breaking pitches.[4,24-26] In addition, 39% of pitchers in this study pitched for more than 9 months out of the year, which is in violation of current regulations and has been identified as a risk factor for injury.[10] Furthermore, 43% of subjects in this study stated their arm had hurt in the past while pitching, 36% of subjects stated their elbow specifically hurt while pitching, and 32% stated they had continued to pitch through pain. It is extremely important to realize that almost one-third of patients continued to pitch through pain because, if a coach is relying on a pitcher to pull himself out when pitching becomes painful, this clearly will not work at least one-third of the time. These risk factors may explain the high rate of prior shoulder and elbow pain within our study population.

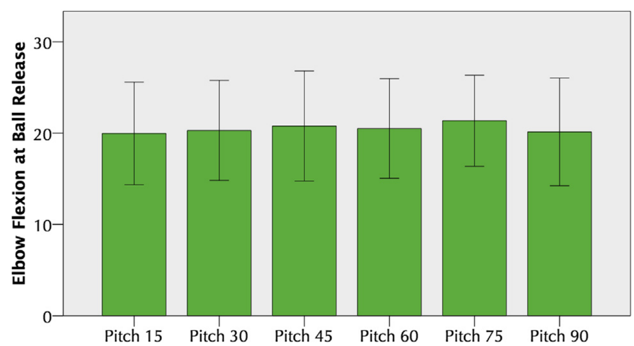

Fig 6. Mean elbow flexion angle at ball release (in degrees) by pitch number. Elbow flexion at ball release did not significantly differ with pitch number ($P > .096$). Error bars show 1 standard deviation.

Prior epidemiologic studies have used pain as a marker for risk of injury.[11,12,27] However, within our study, pitchers regularly had pain, with a mean score of 1.6 ± 2.2, and fatigue, with a mean score of 3.5 ± 2.1, after throwing 90 pitches, that is, fewer than the current recommendation of 95 maximum pitches per day for this age group.[28] This finding suggests that pain and fatigue are normal aspects of pitching even when the current recommendations are followed, and therefore these cannot reliably be used as an indicator of impending injury. The clinical significance of these findings is unclear at this time. No definitive data are available to determine the clinically significant change in pitch velocity or pain/fatigue scores. Future high-volume studies of elite pitchers should aim to characterize this.

Neither the primary endpoint of this study, elbow flexion at ball release, nor any other upper extremity kinematic factor changed significantly with pitcher fatigue. Upper extremity kinematics appears to be highly conserved despite fatigue and pain. Knee flexion at ball release significantly increased with pitcher fatigue. Murray et al.[29] found that Major League Baseball pitchers had significantly decreased knee flexion at ball release and maximum external rotation in the last inning of a game compared with the first. Differences in pitching experience, in lower extremity strength, or in game play may explain these discordant findings. Regardless, the slight change in knee flexion seen in both studies, although statistically significant, is likely clinically insignificant. Given the overall preserved mechanics after 90 pitches in our population, this study supports the current daily pitch count of 95 within this age group.

Hip-to-shoulder separation significantly decreased from 90% to 40% linearly with pitcher fatigue.

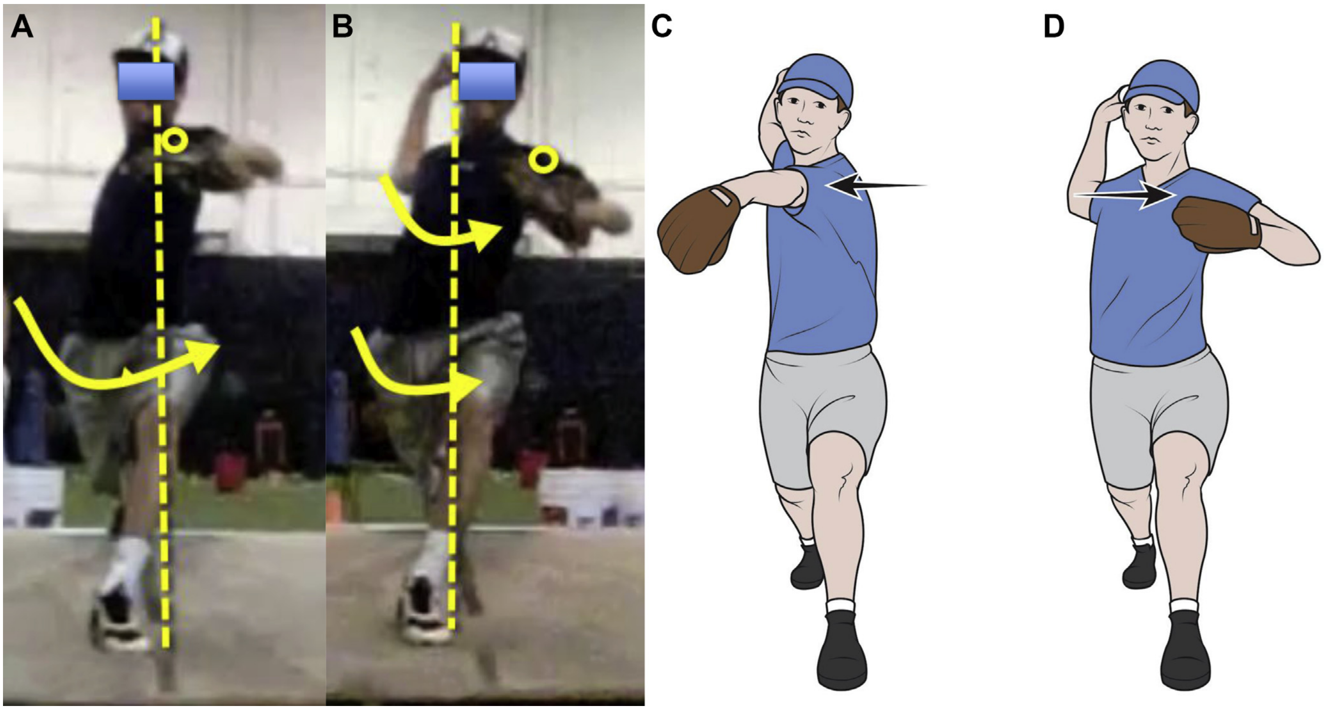

Fig 8. (A, B) Still images of one pitcher included in this study showing (A) closed and (B) open hip-to-shoulder separation at front-foot contact. The circles indicate the position of the lead shoulder at front-foot contact. (C, D) Cartoons showing (C) closed and (D) open hip-to-shoulder separation at front-foot contact. The arrows indicate the position of the lead shoulder at front-foot contact. Notice the closed versus open position.

"Hip-to-shoulder separation" refers to the position of the hips relative to the shoulder just before foot contact and has been linked with proper mechanics and pitch velocity creation.[30,31] Ideally, just before foot contact, the hips rotate to face home plate while the shoulder and torso continue to face third base (for a right-handed pitcher). This differential allows pitchers to obtain additional acceleration through the powerful muscles of the core with trunk rotation, thereby transferring the most energy to the arm in the kinetic chain. As pitchers fatigue, this aspect of the kinetic chain breaks down and the hips and shoulders rotate in unison, preventing the pitcher from obtaining additional power through the torso. Although further study will be necessary to identify whether this factor may also explain the connection between fatigue and injury, loss of hip-to-shoulder separation may place increased torques through the shoulder and elbow, increasing the risk of injury. Other studies have also found a change in trunk mechanics with fatigue.[13,32] Crotin et al.[13] found that a shortened stride length was a sign of fatigue in college and elite high school pitchers. Escamilla et al.[32] examined college pitchers and found that, as these pitchers fatigued, they showed a more vertical trunk position at ball release. Oyama et al.[33] showed that high school baseball pitchers who had improper trunk rotation showed an increased maximal shoulder external rotation angle and shoulder proximal force compared with pitchers with proper trunk rotation. These results indicate that the core musculature of adolescent pitchers fatigues before the extremity muscles. Core strengthening may therefore play a role in injury prevention. In addition, pitching coaches examining pitchers in game situations may watch for loss of hip-to-shoulder separation as a marker for fatigue.

Table 3. Mean Range-of-Motion Variables

	Dominant			Nondominant		
	ER	IR	TRM	ER	IR	TRM
Before testing, °	121 ± 8	45 ± 7	166 ± 9	112 ± 7	53 ± 6	165 ± 9
After testing, °	125 ± 8	44 ± 8	169 ± 8	111 ± 9	55 ± 7	167 ± 9
P value	.007	.362	.047	.858	.098	.094

NOTE. Data are presented as mean ± standard deviation.
ER, external rotation; IR, internal rotation; TRM, total rotational motion.

Limitations

Limitations include the use of video instead of a marker analysis. However, video has been widely used in the pitching motion analysis literature with reliable results.[4,34-37] Another limitation is that the pitchers were stopped at 90 competitive pitches. Had the pitchers been allowed to throw more pitches, more fatigue and therefore greater kinematic differences may have been encountered. Given current pitching recommendations, we believed that a greater number of pitches could have increased the risk of injury during testing and thus the current protocol was used.

Conclusions

As pitchers progress through a simulated game, they throw lower-velocity pitches, become fatigued, and have more pain. Core and leg musculature becomes fatigued before upper extremity kinematics changes.

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