Correlates With History of Injury in Youth and Adolescent Pitchers

Peter N. Chalmers, M.D., Terrance Sgroi, P.T., D.P.T., M.T.C., Andrew J. Riff, M.D., Matthew Lesniak, D.P.T., Eli T. Sayegh, B.S., Nikhil N. Verma, M.D., Brian J. Cole, M.D., M.B.A., and Anthony A. Romeo, M.D.

Purpose: To determine the factors within pitcher demographic characteristics, pitching history, and pitch kinematics, including velocity, that correlate with a history of pitching-related injury. **Methods:** Demographic and kinematic data were collected on healthy youth and adolescent pitchers aged 9 to 22 years in preseason training during a single preseason using dual orthogonal high-speed video analysis. Pitchers who threw sidearm and those who had transitioned to another position were excluded. Players were asked whether they had ever had a pitching-related shoulder or elbow injury. Multivariate logistic regression analysis was performed on those variables that correlated with a history of injury. **Results:** Four hundred twenty pitchers were included, of whom 31% had a history of a pitching-related injury. Participant height ($P = .009$, $R^2 = 0.023$), pitching for more than 1 team ($P = .019$, $R^2 = 0.018$), and pitch velocity ($P = .006$, $R^2 = 0.194$) served as independent correlates of injury status. A model constructed with these 3 variables could correctly predict 77% of injury histories. Within our cohort, the presence of a 10-inch increase in height was associated with an increase in a history of injury by 20% and a 10-mph increase in velocity was associated with an increase in the likelihood of a history of injury by 12%. Playing for more than 1 team increased the likelihood of a history of injury by 22%. **Conclusions:** Pitch velocity, pitcher height, and pitching for more than 1 team correlate with a history of shoulder and elbow injury. Current recommendations regarding breaking pitches may not prevent injury. Pitchers should be cautioned about pitching for more than 1 team. Taller pitchers and high-velocity pitchers may be at risk of injury.

Pitching is one of the fastest human motions, with arm internal rotation velocities exceeding 7,000°/s in professional pitchers.[1] These speeds place enormous torques on the shoulder and elbow, regularly exceeding 1,000 N in professional pitchers.[1] These forces reliably produce pain and injury within the shoulder and elbow.[2-4] Over the course of a single season, over half of all overhand baseball pitchers aged 9 to 14 years will have shoulder and elbow pain,[5,6] and the incidence of shoulder and elbow injury among pitchers is increasing.[3,7-9]

Previous studies at the American Sports Medicine Institute (ASMI) have identified pitch counts and pitching while fatigued; breaking pitches, specifically the curveball and the slider; and lack of rest, specifically pitching on multiple teams or for greater than 9 months per year, as predictors of shoulder and elbow pain in youth and adolescent pitchers.[5,6,10] These factors have since been codified into injury-prevention recommendations.[11,12] Although these studies also performed video pitching analysis on a subset of pitchers within their original cohorts, none of the kinematic factors measured as a portion of the analysis correlated with shoulder or elbow pain during the season.[5,6]

Laboratory pitching motion-analysis biomechanical data conflict with these findings. Several authors have shown no difference in shoulder and elbow torques between the fastball, the curveball, and the slider.[7,13] In

From the Department of Orthopaedic Surgery, Rush University Medical Center (P.N.C., A.J.R., N.N.V., B.J.C., A.A.R.); Accelerated Rehabilitation Centers (T.S., M.L.), Chicago, Illinois; and College of Physicians and Surgeons, Columbia University (E.T.S.), New York, New York, U.S.A.

The authors report the following potential conflict of interest or source of funding: N.N.V. receives support from SLACK Incorporated, Arthrex, DJO Surgical, Smith & Nephew, and Ossur. B.J.C. receives support from Arthrex, Regentis, Zimmer, Johnson & Johnson, Medipost, DJ Orthopaedics, Lippincott, Smith & Nephew, and Carticept. A.A.R. receives support from SLACK Incorporated, Arthroscopy Association Learning Center Committee, Minivasive, Smith & Nephew, Arthrex, Athletico, ConMed Linvatec, Miomed, Mitek, Arthrosurface, DJ Orthopaedics, Cymedica, and Omeros.

Received November 1, 2014; accepted March 12, 2015.

Address correspondence to Peter N. Chalmers, M.D., Department of Orthopaedic Surgery, Rush University Medical Center, 1611 W Harrison St, Chicago, IL 60612, U.S.A. E-mail: p.n.chalmers@gmail.com

0749-8063/14921/$36.00

http://dx.doi.org/10.1016/j.arthro.2015.03.017

addition, numerous studies have demonstrated that maximal shoulder external rotation, elbow flexion at ball release, initiation of trunk rotation after front-foot contact, shoulder abduction at foot strike, and elbow flexion at front-foot contact correlate with shoulder and elbow torques.[14-17] Shoulder and elbow torques predict elbow injury in overhand pitchers.[18] It thus follows that kinematic measurements, which can be reliably measured with video motion analysis,[5,6,15,18-24] should correlate with pain and injury in empirical studies. If kinematic factors that correlate with injury could be identified, then at-risk pitchers could potentially be identified with motion analysis and injuries could be prevented.

We performed a cross-sectional study to determine which demographic and kinematic variables correlate with pitching-related injury. The specific aim of this study was to determine the factors within pitcher demographic characteristics, pitching history, and pitch kinematics, including velocity, that correlate with a history of pitching-related injury. We hypothesized that velocity and kinematic variables such as elbow flexion angle at ball release and maximal shoulder external rotation would serve as the most important correlates of a history of pitcher injury.

Methods

This study was approved by our institutional review board (protocol No. 13090101). This is a single-episode cross-sectional study that was performed during a single preseason. All possible youth and adolescent overhand baseball pitchers from our metropolitan area were recruited and underwent a standardized evaluation. We included overhand pitchers aged 9 to 22 years currently in preseason training. We excluded pitchers aged younger than 9 years, sidearm or "submarine"-style pitchers because their kinematic data were believed to be too substantially altered at baseline, pitchers who had transitioned to another position and did not plan to pitch during their upcoming season, and pitchers unable to pitch because of pain at the time of evaluation. The age cutoff of 9 years was chosen to allow better comparison with past studies performed at ASMI and because USA Baseball recommendations were not available for pitchers aged younger than 9 years. Pitchers with a history of injury or current discomfort were included if they felt able to throw and were throwing in practice. 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

Participants, and where possible their parents, completed a self-administered survey to obtain demographic information, pitching history, and injury history. All data were collected between November 26, 2013, and March 23, 2014. The data collection form is shown in Figure 1. Participants were asked if they had any current discomfort and if they had ever had a history of a pitching-related injury. All surveys were administered in paper format in a standardized fashion by 2 study authors (T.S., M.L.). Completed surveys were reviewed with all participants to ensure clarity and completeness. Participants used their own self-definition of the term "injury" based on their and their parents' interpretation of the data collection form (Fig 1). All injuries reported by the participants were included, and no objective follow-up was performed to determine injury data accuracy. Of note, data regarding pitch counts were collected but not used as a covariate in this study because participants were frequently unable to accurately recall the number of pitches thrown per game, week, season, and year; thus we considered it inappropriate to report these data in this single-episode study because of excessive recall bias. Participants then underwent a standardized physical examination. With the participant in the supine position with the shoulder at 0° of flexion and 90° of abduction and the elbow at 90° of flexion with the scapula stabilized anteriorly by one of the examiner's hands, the shoulder was brought into full passive external rotation and full passive internal rotation while a second examiner, viewing from the lateral aspect and using a goniometer, measured rotation. These measurements were then used to calculate total arc of rotation, glenohumeral internal rotation deficit, and glenohumeral external rotation excess.

Once survey data had been collected, all participants underwent video motion analysis similar to that previously described.[5,6,15,18-24] Participants were filmed at 210 Hz in high definition from both the frontal and lateral views while pitching from a regulation practice mound as appropriate for the pitchers' age. Pitch speed was simultaneously collected with a radar gun (JUGS Sports, Tualatin, OR). Participants were provided with as much time as necessary to perform their routine warm-up. Once participants felt ready to pitch at 100% velocity, they then pitched while being filmed. All pitches were fastballs pitched from the wind-up position. All pitches were thrown over a regulation distance for the pitchers' age at an appropriately positioned and sized strike-zone target. A single pitch that the participant believed was representative of the participant's best effort was recorded for each pitcher.

Video data were analyzed using a standardized protocol by 2 study authors (T.S., M.L.; Dartfish, Atlanta, GA). In all cases the dominant extremity was measured. In all cases the individuals performing the measurements were blinded to the participant's injury status. Those kinematic variables previously shown to correlate with kinetic variables were identified a priori and

PATIENT HISTORY: Age ________ Height ______ Weight ______ ☐ Right ☐ Left handed ID #________

	Preinjury/Uninjured	Post-injury (if applicable)
Number of years pitching:		
Highest level of play (high school, college, semi-pro, etc.)		
Number of years pitched at highest level		
Average pitches per game		
Average pitches per week		
Average pitches per season		
Average pitches per year		

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? ____________________

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 have any current **discomfort** in your shoulder or elbow with pitching? ☐ Yes ☐ No

If yes, **where** does it hurt? ____

If yes, **when** during the throw does it hurt?

Injury History: Please fill out the following questions only if you are or have been hurt.

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

If yes, what **injury** were you diagnosed with?_______________________ At what age?______________

What **treatments** did you receive for your injury?____

Did you ever have **surgery** as a treatment for this injury? ☐ Yes ☐ No At what age?______________

Procedure performed:____

Fig 1. Data collection form. Data regarding pitch counts were collected but not used because participants were frequently unable to accurately recall these data.

Table 1. Kinematic Data Collected and Whether Variables Were Measured on Frontal or Lateral Video View

	View
Front-foot contact	
Maximal knee height, % of participant height	L
Stride length, % of participant height	L
Elbow flexion	L
Knee flexion	L
Shoulder abduction	L
Foot angle	F
Cocking	
Max ER	L
Maximal shoulder abduction	F
Lateral trunk tilt (at Max ER)	F
Ball release	
Elbow flexion	F/L
Forward trunk tilt	L
Knee flexion	L
Shoulder abduction	F
Lead hip flexion	L

F, frontal; L, lateral; Max ER, maximal shoulder external rotation.

were manually measured (Table 1). Observational mechanics were also recorded by these same 2 study authors as yes versus no, as previously described.[25] These included whether participants (1) led with the hips, (2) had their hand on top of the ball during the stride phase, (3) had their 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.[25]

Data Analysis

All analyses were performed using Excel X (Microsoft, Redmond, WA) and SPSS, version 21 (IBM, Armonk, NY). An independent observer (E.T.S.) 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 Student *t* tests or Mann-Whitney *U* tests were used as appropriate based on data normality. Discrete data were tested using χ^2 tests. All collected variables were compared between participants with a history of injury and those without. The "hot deck" procedure was used to substitute for missing data as previously described.[26] Because multiple comparisons were performed before regression, *P* values underwent Bonferroni correction and $P < .00147$ was considered significant. Those variables that significantly differed between the group with a history of injury and the group without a history of injury were then entered into a multivariate stepwise logistic regression model to determine the most important correlates with history-of-injury status. Within this model, $P < .05$ was considered significant. From this model, correlation coefficients and R^2 values (by the Nagelkerke method[27]), as an estimation of percent of variance in history-of-injury status explained by each variable, were determined. A post hoc comparison of shoulder and elbow injuries was performed.

Results

We recruited 429 pitchers, of whom 3 were excluded because they were found after recruitment to not be planning to pitch in the upcoming season, 2 were excluded because they were sidearm or submarine pitchers, 3 were excluded because they had too much pain to pitch, and 1 was excluded because he did not complete the survey, for a total included sample size of 420 (98% enrollment). Of the included pitchers, 30% had current pitching-related discomfort. Of those who reported upper-extremity pain, 45% had pain in the elbow, 39% in the shoulder, and 15% in both. Of the included pitchers, 31% had a history of a pitching-related injury, all within the upper extremity, of which 60% were elbow injuries and 40% were shoulder injuries. Among the elbow injuries, the most commonly reported included flexor pronator tendinitis, ulnar collateral ligament (UCL) injuries, Little Leaguer's elbow, medial epicondylitis, and olecranon stress fractures. Among the shoulder injuries, the most commonly reported included SLAP tears, biceps tendinitis, and rotator cuff injuries. All injured pitchers had undergone conservative treatment for their injuries including rest, ice, and anti-inflammatories. Of injured patients, 60% (12% of the total cohort) underwent supervised physical therapy. Eight percent (1.6% of the total cohort) had undergone prior surgical treatment, including 2 prior SLAP repairs, 1 rotator cuff repair, 1 elbow arthroscopy with plica excision, 1 UCL reconstruction, 1 subcutaneous ulnar nerve transposition, and 1 open reduction—internal fixation of a persistent proximal ulnar physis with compression plating. Pitchers with a history of injury were significantly more likely to have current pitching-related pain ($P < .001$) (Table 2), but current pain served as an imperfect marker for a history of injury. Only 37% of those with current discomfort had a history of a pitching-related injury, and of those with a history of a pitching-related injury, only 46% had current discomfort.

There were significant differences between pitchers with a history of injury and those without a history of injury in age, height, weight, body mass index, years pitching, percent of pitchers who threw a slider, percent of pitchers who threw for more than 1 team, and percent of pitchers who threw in showcases ($P < .00147$ in all cases) (Table 2). There were no significant differences between groups in years pitching at the highest level attained, percent of pitchers who threw a curveball, percent of pitchers who threw a changeup, percent of pitchers who threw for more than

Table 2. Demographic, Pitching History, and Physical Examination Data Comparing Pitchers With History of Injury and Those Without

Variable	Injured Pitchers		Uninjured Pitchers		*P* Value
	Mean	SD	Mean	SD	
Age, yr	16.1	2.4	14.3	2.4	< .001*
Height, cm	70.7	3.4	66.6	5.4	< .001*
Weight, kg	166	30	140	39	< .001*
Body mass index, kg/m^2	23.3	3.7	21.7	3.8	< .001*
Years pitching	7.3	3.3	5.3	2.6	< .001*
Years pitching at highest level	2.2	1.4	2.1	1.5	.561
% throwing curveball	86	NA	70	NA	.002
% throwing slider	33	NA	16	NA	< .001*
% throwing changeup	96	NA	96	NA	.038
% pitching for >1 team	60	NA	38	NA	< .001*
% pitching for >9 mo per year	53	NA	37	NA	.007
% pitching in showcases	37	NA	21	NA	.001*
% returning to mound after being removed	11	NA	7	NA	.252
% with current pitching-related discomfort	46	NA	26	NA	< .001*
External rotation of dominant extremity, °	117.9	11.7	116.4	10.2	.092
Internal rotation of dominant extremity, °	54.1	8.8	53.9	8.3	.813
Total arc of rotation of dominant extremity, °	172.0	12.4	170.3	11.8	.167
External rotation of nondominant extremity, °	109.8	12.1	109.3	11.5	.697
Internal rotation of nondominant extremity, °	61.5	9.7	59.3	9.0	.046
Total arc of rotation of nondominant extremity, °	171.2	13.3	168.6	13.6	.167
Glenohumeral internal rotation deficit, °	7.3	8.1	5.4	9.6	.073
Glenohumeral external rotation excess, °	8.1	9.3	7.1	8.4	.332

NOTE. Because multiple comparisons were performed, *P* values underwent Bonferroni correction and $P < .00147$ was considered significant. NA, not applicable.
*Significant difference.

9 months a year, or percent of pitchers who returned to the mound after being removed ($P > .00147$ in all cases) (Table 2). There were no significant differences in physical examination findings, including external rotation, internal rotation, total arc of rotation, glenohumeral internal rotation deficit, and glenohumeral external rotation excess ($P > .00147$ in all cases) (Table 2). Within the kinematic data, only pitch velocity differed between pitchers with a history of injury and those without ($P < .001$) (Table 3). There were no significant differences in the remainder of the measured kinematic variables and the observed mechanics between pitchers with a history of injury and those without ($P > .00147$) (Table 3). Our post hoc comparison between shoulder and elbow injuries showed no significant differences in any of the demographic, pitching history, physical examination, measured kinematic, or observed-mechanics data ($P > .00147$ in all cases).

After we entered those variables that differed between pitchers with a history of injury and pitchers without a history of injury into a multivariate logistic regression analysis, only participant height ($P = .009$, $\beta = 0.116 \pm 0.045$, $R^2 = 0.023$) (Fig 2), pitching for more than 1 team ($P = .019$, $\beta = 0.607 \pm 0.259$, $R^2 = 0.018$), and pitch velocity ($P = .006$, $\beta = 0.059 \pm 0.021$, $R^2 = 0.194$) (Fig 3, Table 4) served as independent correlates with history-of-injury status. In combination, these 3 variables explained 23.5% of the variance in history-of-injury status, and a model constructed with the aforementioned coefficients for these 3 variables and a cutoff value of 0.5 for likelihood of injury could correctly predict 77% of injuries.

Discussion

Pitchers with a history of injury and those without a history of injury did differ significantly in age, height, weight, body mass index, years pitching, likelihood of throwing a slider, likelihood of throwing for more than 1 team, likelihood of throwing in showcases, and pitch velocity. With multivariate analysis, only participant height, pitching for more than 1 team, and pitch velocity served as independent correlates of a history of injury. In combination, these 3 variables explained 23.5% of the variance in injury status and could correctly predict 77% of injuries. A linear relation between height and a history of injury was observed across the reported data such that a 10-inch increase in height was associated with an increase in a history of injury by 20%. A linear relation between velocity and a history of injury was observed across the reported data such that a 10-mph increase in velocity was associated with an increase in the likelihood of a history of injury by 12%. Playing for more than 1 team increased the likelihood of a history of injury by 22%. Although pitch counts were not able to be assessed in our study,

Table 3. Kinematic Variables and Observed Mechanics Comparing Pitchers With History of Injury and Those Without

	Injured Pitchers		Uninjured Pitchers		
Variable	Mean	SD	Mean	SD	*P* Value
Pitch velocity, mph	70.4	7.3	62.3	9.9	< .001*
Maximal knee height, % of participant height	65.1	7.2	65.2	7.4	.748
Stride length, % of participant height	78.2	6.0	77.0	7.3	.103
Elbow flexion at FFC	87.8	22.8	89.8	20.8	.436
Knee flexion at FFC	44.1	8.9	41.9	11.6	.048
Shoulder abduction at FFC	84.4	18.6	85.1	16.1	.604
Foot angle closed at FFC	22.0	17.2	22.3	21.2	.746
Maximal shoulder external rotation during AC	178.5	13.9	178.5	13.6	.584
Maximal shoulder abduction during AC	100.1	10.0	98.7	11.1	.193
Lateral trunk tilt at maximal external rotation	20.4	21.6	18.2	7.7	.580
Elbow flexion at BR	20.8	5.9	22.2	8.1	.167
Forward trunk tilt at BR	33.0	7.1	33.0	8.2	.948
Knee flexion at BR	31.2	14.2	32.0	16.4	.868
Shoulder abduction at BR	65.5	26.9	64.0	26.5	.580
Lead hip flexion at BR	91.2	11.6	89.6	13.1	.392
Lateral trunk tilt at BR	62.8	31.3	61.7	30.5	.655
% leading with hips	93	NA	91	NA	.623
% with hand on top of ball during stride	100	NA	97	NA	.100
% with arm in throwing position at FFC	73	NA	83	NA	.025
% with closed shoulders at hand-set position	81	NA	72	NA	.061
% with closed foot position at BR	86	NA	89	NA	.420
% with hip/shoulder rotational separation	53	NA	37	NA	.005
% in fielding position at follow-through	92	NA	93	NA	.638

NOTE. Unless otherwise specified, all variables are expressed in degrees. Because multiple comparisons were performed, *P* values underwent Bonferroni correction and $P < .00147$ was considered significant.

AC, arm cocking; BR, ball release; FFC, front-foot contact; NA, not applicable.

*Significant difference.

playing for more than 1 team would likely increase a player's overall counts and thus our data indirectly supports a positive correlation between higher pitch counts and higher incidence of injury.

Among youth and adolescent pitchers, pitching-related injuries are common. Within our cross-sectional cohort, 31% of participants had a history of a pitching-related injury and 12% had undergone physical therapy. Pitch counts and pitching while fatigued; breaking pitches, specifically the curveball and the slider; and lack of rest, specifically pitching on multiple teams or for greater than 9 months per year, have been identified as predictors of shoulder and elbow pain in youth and adolescent pitchers,[5,6,10,12] and these factors have since been incorporated into recommendations from USA Baseball and Little League International for youth and adolescent pitchers.[11,12] However, other comparative trials,[28] as well as laboratory pitching motion analysis,

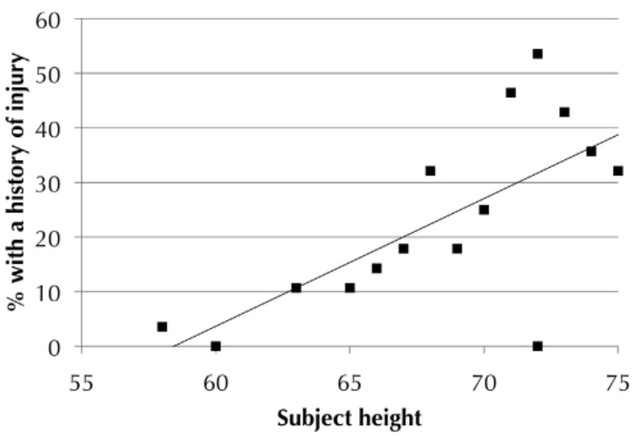

Fig 2. The percent of pitchers with a history of injury significantly correlated with participant height ($P = .009$, $\beta = 0.116 \pm 0.045$, $R^2 = 0.023$).

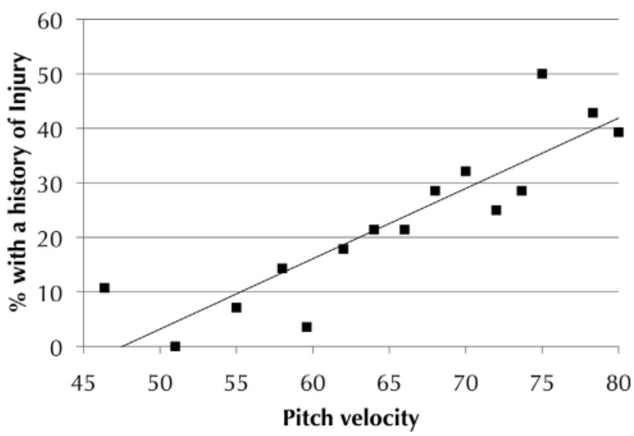

Fig 3. The percent of pitchers with a history of injury significantly correlated with pitch velocity ($P = .006$, $\beta = 0.059 \pm 0.021$, $R^2 = 0.194$).

Table 4. Velocity at Each Percentile of Our Population for Each Age

Age	Velocity at Each Percentile, mph				
	2nd	16th	50th	84th	98th
9 yr	33	38	43	48	48
10 yr	39	43	47	51	51
11 yr	43	47	50	54	54
12 yr	40	46	51	57	57
13 yr	49	54	59	64	64
14 yr	54	59	64	68	68
15 yr	56	62	68	73	73
16 yr	62	66	70	74	74
17 yr	64	69	74	78	78
18 yr	64	69	74	79	79

suggest that there is no difference in shoulder and elbow torques between the fastball, the curveball, and the slider[7,13] and that other kinematic factors correlate with shoulder and elbow torques[14-17] and thus with elbow injury.[18,29]

Although only 2 previous studies have been conducted to determine those factors that correlate with pitching-related injury,[5,6,28,29] numerous biomechanical studies have been conducted to determine which kinematic variables correlate with high shoulder and elbow forces and torques. These analyses have also identified knee flexion at front-foot contact and elbow flexion at ball release as important kinematic correlates of shoulder and elbow kinetics.[14-17] Several analyses have shown elbow flexion to be a critical factor in pitching kinetics and velocity, likely because changes in elbow flexion alter the lever arm that humeral rotation applies to the medial elbow.[14,16,30] An analysis of older versus younger pitchers showed more lead knee flexion in older pitchers, which was interpreted as an adaptive change to allow high-velocity pitching despite increased age.[31] Other analyses have shown knee flexion at front-foot contact to be a highly conserved and therefore biomechanically important aspect of the pitch.[32] However, on a cross-sectional basis, these kinematic factors do not correlate with a history of injury, suggesting that pitching motion analysis may not be an effective method of identifying pitchers at risk of injury.

There are several explanations for the differences between the original ASMI data[5,6] and our findings. One possibility is that velocity, a variable that was not measured in ASMI's original cohort, may be an underlying covariate with all of the previously identified demographic and kinematic factors and the actual determinant of injury. Faster pitchers are more likely to be used more frequently by their teams, are more likely to be taught the curveball and the slider at a younger age, and are more likely to be invited to pitch for traveling teams and in showcases and are thus more likely to pitch year-round. Thus, although these variables may be then identified as markers of injury, they are only, in fact, reflective of the fact that they also select for pitchers throwing with higher velocity. In a prospective study of professional pitchers, Bushnell et al.[8] showed a correlation between velocity and injury. Several biomechanical studies have shown pitch velocity to co-vary with shoulder and elbow torques.[21,33] One clinical study showed that pitch velocity correlates with magnetic resonance imaging abnormalities within the UCL.[34] A subsequent case-control study identified velocity as a correlate of surgical intervention in youth and adolescent pitchers.[28] An additional possibility is that current shoulder and elbow pain is not an ideal marker of past or future injury. Within our cohort, only 37% of patients with current pitching-related discomfort had a history of a pitching-related injury and only 46% of patients with a history of a pitching-related injury had current discomfort. An additional difference is the identification of height as an independent correlate of a history of injury. Previous biomechanical analyses have normalized forces and torque for participant height because taller participants are known to be able to exert more force and torque through the upper extremity because of the longer lever arm.[25,35] Taller pitchers may need to take extra precautions to avoid higher pitch counts, faster-velocity pitches, pitching while fatigued, and poor mechanics.

Our hope is that these additional data will assist USA Baseball and Little League International in producing evidence-based injury-prevention recommendations. Current recommendations regarding breaking pitches may not adequately prevent injury.[11,29] Our findings indicate that (1) pitchers should be cautioned about pitching for more than 1 team, (2) taller pitchers may be at increased risk of injury, and (3) high-velocity pitchers may be at increased risk of injury. The current recommendations lead to youth and adolescent pitchers throwing a lower number of pitches at a high velocity to attempt to limit accumulated microtrauma; however, this strategy may not decrease the "peak" stresses experienced by the elbow and thus may not decrease the risk of injury, although further study is needed in this regard. Given that the incidence of UCL injury among professional pitchers has increased since the data guiding the current recommendations were reported in 2002,[5] these recommendations have not clearly shown effectiveness in preventing injury, although pitcher compliance may play a role.[3]

Limitations

This study has several limitations. Foremost among these is the single-episode study design, which precluded accurate assessment of pitch counts and does not allow prospective correlation of potential injury predictors and the longitudinal development of pitching-related pain or injury. As a result, the factors identified in this study correlate with a history of injury but do not necessarily predict future injury. In addition, the separation between the injury and non-injury groups in this case relies on the pitcher recalling having been diagnosed with a pitching-related injury, which is biased by participant recall and the subjective personal definition of having been "diagnosed with a throwing-related injury" as compared with an objective imaging finding or physical examination finding. It also leads to a potential lead-time bias because patients were asked about lifetime cumulative injury and thus older pitchers, who also pitch with higher velocity, will be more likely to have a history of injury simply because of their age. Multiple factors likely influence the participant having been diagnosed with an injury, including the pain tolerance of the participant, the concern of the parents, the behavior of the trainer, and the practice patterns of the evaluating medical professionals.

An additional limitation is the inclusion of pitchers aged older than 18 years. The dataset contains only 16 pitchers aged older than 18 years, comprising 3.7% of the dataset. The dataset was collected from several elite travel teams within our geographic area, some of which include pitchers aged older than 18 years. These pitchers were included because they were participating on the same travel teams with pitchers in late adolescence and thus they were believed to be participating at the same level and thus subject to the same injury-predictive circumstances. We selected 22 years of age as the highest age because this was the oldest age included within the travel teams surveyed in this study.

In pitchers with current discomfort but without a history of injury, a diagnosed injury could conceivably go on to develop over the course of the season. To address this particular limitation, a post hoc subgroup analysis was performed to compare pitchers with a history of injury (n = 88) and pitchers both without a history of injury and without current pain (n = 201). This analysis had very similar results, with velocity ($P = .007$, $R^2 = 0.208$) and pitcher height ($P = .017$, $R^2 = 0.024$) remaining the 2 most important correlates, followed by the observed mechanical factor of whether the arm was in the throwing position at front-foot contact ($P = .04$, $R^2 = 0.017$). These 3 factors explained 24.9% of the variance in history-of-injury status, and a model constructed with these factors correctly predicted whether participants had a history of injury in 72.3% of cases. Breaking pitches and the remaining demographic risk factors did not significant correlate with a history of injury. Thus this limitation is not operative in this dataset.

Finally, because kinematic data were collected after injury occurrence, this experimental design obscures whether these kinematic factors existed before injury or instead represent an adaptive change to the injury. Kinematic factors may also change as players age. High-speed video motion analysis was used instead of traditional marker-based motion analysis. Given that multiple prior pitching motion-analysis studies have used video-based systems, this method is well accepted if not validated.[5,6,15,18-24] Future studies should determine the validity of this system for kinematic data collection during sporting activity.

Conclusions

Pitch velocity, pitcher height, and pitching for more than 1 team correlate with a history of shoulder and elbow injury. Current recommendations regarding breaking pitches may not prevent injury. Pitchers should be cautioned about pitching for more than 1 team. Taller pitchers and high-velocity pitchers may be at risk of injury.

Acknowledgment

The authors thank Lisa Nold and the athletic trainers at Accelerated Rehabilitation Centers for organizing the filming sessions for all participants.

References

1. Fleisig GS, Andrews JR, Dillman CJ, Escamilla RF. Kinetics of baseball pitching with implications about injury mechanisms. *Am J Sports Med* 1995;23:233-239.
2. Jones KJ, Osbahr DC, Schrumpf MA, Dines JS, Altchek DW. Ulnar collateral ligament reconstruction in throwing athletes: A review of current concepts. AAOS exhibit selection. *The J Bone Joint Surg Am* 2012;94:e49.
3. 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;42:536-543.
4. Lesniak BP, Baraga MG, Jose J, Smith MK, Cunningham S, Kaplan LD. Glenohumeral findings on magnetic resonance imaging correlate with innings pitched in asymptomatic pitchers. *Am J Sports Med* 2013;41:2022-2027.
5. 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;30:463-468.
6. Lyman SL, Fleisig GS, Waterbor JW, et al. Longitudinal study of elbow and shoulder pain in youth baseball pitchers. *Med Sci Sports Exerc* 2001;33:1803-1810.
7. Fleisig GS, Kingsley DS, Loftice JW, et al. Kinetic comparison among the fastball, curveball, change-up, and slider in collegiate baseball pitchers. *Am J Sports Med* 2006;34:423-430.
8. Bushnell BD, Anz AW, Noonan TJ, Torry MR, Hawkins RJ. Association of maximum pitch velocity and elbow injury in professional baseball pitchers. *Am J Sports Med* 2010;38:728-732.
9. Cain EL, Andrews JR, Dugas JR, et al. Outcome of ulnar collateral ligament reconstruction of the elbow in 1281

athletes: Results in 743 athletes with minimum 2-year follow-up. *Am J Sports Med* 2010;38:2426-2434.
10. Petty DH. Ulnar collateral ligament reconstruction in high school baseball players: Clinical results and injury risk factors. *Am J Sports Med* 2004;32:1158-1164.
11. USA Baseball Medical & Safety Advisory Committee. Youth baseball pitching injuries. Available at http://web.usabaseball.com/news/article.jsp?ymd=20090813&content_id=6409508. Accessed April 20, 2014.
12. Axe MJ. Recommendations for protecting youth baseball pitchers. *Sports Med Arthrosc* 2001;9:147-153.
13. Dun S, Loftice J, Fleisig GS, Kingsley D, Andrews JR. A biomechanical comparison of youth baseball pitches: Is the curveball potentially harmful? *Am J Sports Med* 2008;36:686-692.
14. Sabick MB, Torry MR, Kim Y-K, Hawkins RJ. Humeral torque in professional baseball pitchers. *Am J Sports Med* 2004;32:892-898.
15. Sabick MB, Torry MR, Lawton RL, Hawkins RJ. Valgus torque in youth baseball pitchers: A biomechanical study. *J Shoulder Elbow Surg* 2004;13:349-355.
16. Aguinaldo AL, Chambers H. Correlation of throwing mechanics with elbow valgus load in adult baseball pitchers. *Am J Sports Med* 2009;37:2043-2048.
17. Keeley DW, Wicke J, Alford K, Oliver GD. Biomechanical analysis of forearm pronation and its relationship to ball movement for the two-seam and four-seam fastball pitches. *J Strength Cond Res* 2010;24:2366-2371.
18. 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;38:1368-1374.
19. Campbell BM, Stodden DF, Nixon MK. Lower extremity muscle activation during baseball pitching. *J Strength Cond Res* 2010;24:964-971.
20. Glousman RE, Barron J, Jobe FW, Perry J, Pink M. An electromyographic analysis of the elbow in normal and injured pitchers with medial collateral ligament insufficiency. *Am J Sports Med* 1992;20:311-317.
21. Guido JA, Werner SL. Lower-extremity ground reaction forces in collegiate baseball pitchers. *J Strength Cond Res* 2012;26:1782-1785.
22. Pappas AM, Zawacki RM, Sullivan TJ. Biomechanics of baseball pitching. A preliminary report. *Am J Sports Med* 1985;13:216-222.
23. Sabick MB, Kim Y-K, Torry MR, Keirns MA, Hawkins RJ. Biomechanics of the shoulder in youth baseball pitchers: Implications for the development of proximal humeral epiphysiolysis and humeral retrotorsion. *Am J Sports Med* 2005;33:1716-1722.
24. Ramappa AJ, Chen P-H, Hawkins RJ, et al. Anterior shoulder forces in professional and Little League pitchers. *J Pediatr Orthop* 2010;30:1-7.
25. 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;37:1484-1491.
26. Rubin D. *Multiple imputation for nonresponse in surveys*, Ed 1. New York, NY: John Wiley and Sons, 1987.
27. Nagelkerke N. A note on a general definition of the coefficient of determination. *Biometrika* 1999;78:691-692.
28. 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;34:905-912.
29. Bruce JR, Andrews JR. Ulnar collateral ligament injuries in the throwing athlete. *J Am Acad Orthop Surg* 2014;22:315-325.
30. Dillman CJ, Fleisig GS, Andrews JR. Biomechanics of pitching with emphasis upon shoulder kinematics. *J Orthop Sports Phys Ther* 1993;18:402-408.
31. 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;40:265-270.
32. Milewski MD, Õunpuu S, Solomito M, Westwell M, Nissen CW. Adolescent baseball pitching technique: Lower extremity biomechanical analysis. *J Appl Biomech* 2012;28:491-501.
33. Fleisig G, Chu Y, Weber A, Andrews JR. Variability in baseball pitching biomechanics among various levels of competition. *Sports Biomech* 2009;8:10-21.
34. Hurd WJ, Kaufman KR, Murthy NS. Relationship between the medial elbow adduction moment during pitching and ulnar collateral ligament appearance during magnetic resonance imaging evaluation. *Am J Sports Med* 2011;39:1233-1237.
35. 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;23:42-51.